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Lighting, backlighting and watercolor illusions and the laws of figurality

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Abstract—We report some novel 'lighting' and 'backlighting' effects in plane figures similar to those which induce the 'watercolor illusion', that is, figures made with outlines composed of juxtaposed parallel lines varying in brightness and chromatic color. These new effects show 'illumination' as an emergent percept, and show how arrangements of 'dark and light' along the boundaries of various plane figures model the volume and strengthen the illusion of depth. To account for these various effects we propose several phenomenological 'laws of figurality' to add to the Gestalt laws of organization and figure–ground segregation. We offer a set of meta-laws which are speculative but which serve to integrate and organize the phenomenological laws. These laws indicate how luminance gradient profiles across boundary contours define both the 3D appearance of figures and the properties of the light reflected from their volumetric shapes.

Keywords: Watercolor illusion; Gestalt principle of grouping; figure–ground segregation; color spreading; light.

1. INTRODUCTION

The aim of this work is twofold. First, we report two new phenomena we call 'lighting' and 'backlighting' effects in plane figures similar to those which induce the watercolor illusion (Pinna, 1987). Such figures are outlines composed of the juxtaposition of parallel lines varying in brightness and chromatic color. The novel effects were obtained by changing the number of lines (from 2 to 6) and their luminance profiles. These effects illustrate 'illumination' as an emergent percept, which depends on the way the illusory illumination appears to fall upon an object and on how arrangements of 'dark and light' along the object's boundaries model the perceived volume and depth. (Earlier work has shown that perceived lightness of achromatic surfaces depends on perceived depth, e.g. Schirillo *et al.*,1990). Second,

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we attempt to extract from these boundary profiles some 'laws of figurality'. These are similar in spirit to the well-known laws of organization of Wertheimer (1923) and of figure–ground segregation of Rubin (1915, 1921), but they add to these figural processes rules to determine the phenomenal appearance of the figure — its color and spatial volume, seen under an apparent illumination — and how this depends on luminance gradient profiles across boundary contours. We next remind the reader of the watercolor illusion, which serves as a useful starting point.

2. THE WATERCOLOR ILLUSION

The watercolor illusion is a long-range assimilative spread of color emanating from a thin colored line running contiguous to a darker chromatic contour and imparting a figure–ground effect across a large area (Pinna, 1987; Pinna *et al.*, 2001; Pinna *et al.*, 2003; Spillmann *et al.*, 2004; Pinna, 2005).

In Fig. 1, purple undulated contours flanked by orange edges are perceived as two undefined shapes evenly colored by an opaque light veil of orange tint, with a clear surface color property (*Erscheinungweise*, Katz, 1911, 1930) spreading from the orange edges. The two undefined shapes manifest a strong figure–ground organization and a solid figural appearance comparable to a bas-relief illuminated from the top. Thus the two shapes appear similar to rounded surfaces segregated in depth that extend out from the flat surface. The complementary regions appear as holes or empty spaces.

In Fig. 2 the Gulf of Mexico (a) and the Mediterranean Sea (b) immediately and clearly emerge as figures and appear illusorily colored with the same orange tint as in Fig. 1. These effects are obtained by reversing purple and orange lines, i.e. the purple/orange wiggly lines in Fig. 1 are replaced by orange/purple lines in Fig. 2. The Gulf and Sea which are easily visible in Fig. 2 are initially imperceptible in Fig. 1, and remain difficult to discern even with continued presentation.

By replacing the orange lines with purple ones in Fig. 3, the Gulf of Mexico (a) and the Mediterranean Sea (b) still emerge, but less strongly. Under these conditions the figure–ground organization can be easily reversed. It is worth noting

Figure 1. (See color plate XI) *The watercolor illusion*: purple undulated contours flanked by orange edges appear as two undefined shapes similar to rounded surfaces segregated in depth and extending out from the flat surface and evenly colored by an opaque light veil of orange tint.

Figure 2. (See color plate XI) By reversing purple and orange lines of Fig. 1, the Gulf of Mexico (a) and the Mediterranean Sea (b) immediately and clearly emerge as figures and appear colored with the same orange tint as in Fig. 1.

Figure 3. (See color plate XI) By replacing the orange lines of Fig. 2 with purple ones, the Gulf of Mexico (a) and the Mediterranean Sea (b) still emerge but with a much weaker figural and volumetric appearance. The figure–ground organization can be reversed much more easily than in Fig. 2.

that the two geographical regions now lose the coloration effect, the strong figural properties, and the bas-relief appearance which emerged in Fig. 2. Passing from Fig. 2 to Fig. 3, not only is the figure–ground segregation weakened, but also the set of peculiar phenomenal properties of the watercolor illusion that we define as 'figurality' effects, which refer to the 3D appearance, to the strong coloration with surface and object color attributes, and to the apparent illumination which depicts the three-dimensional shape of the object. Comparing Figs 2 and 3, two different kinds of figure–ground segregations are perceived with different figural effects that, in order to clarify the distinction between them, can be respectively called 'figure–ground' and 'object–hole' segregations. The object–hole, i.e. the emergence of empty space comparable to a hole, is much stronger in Fig. 2 (and in Fig. 1) than in Fig. 3 (see Grossberg *et al.*, 2005).

These figures illustrate the four main phenomenal effects that the watercolor illusion manifests: coloration, figure–ground, object–hole and illumination effects. We now summarize what has been discovered about the first two effects in detail, as a preparation for the method of the current study. Discussion of the object–hole and illumination effects is deferred.

3. THE COLORATION EFFECT

The main properties of color spreading in the water color illusion (Pinna *et al.*, 2001) are the following: (i) the coloration is approximately uniform; (ii) it extends up to about 45 deg; (iii) it is complete by 100 ms; (iv) it can be generated by all the basic colors; (v) it occurs on both colored and black backgrounds; (vi) the optimal line thickness is approx. 6 arc min; (vii) it is stronger with wiggly lines, but it also occurs with straight lines and with chains of dots (see Pinna *et al.*, 2001); (viii) high luminance contrast between inducing lines increases the coloration effect, but color spreading is clearly visible at near equiluminance (Pinna *et al.*, 2001; Devinck *et al.*, 2005); (ix) the line with a less luminance contrast relative to the background spreads proportionally more than the line with a higher luminance contrast; (x) the color spreads in directions other than the line orientation; (xi) by reversing the colors of the two adjacent lines, the coloration reverses accordingly; (xii) phenomenally, the coloration appears solid, impenetrable and epiphanous as a surface color (Katz, 1930); (xiii) similarly to neon color spreading (Varin, 1971; van Tuijl, 1975; Bressan *et al.*, 1997), the watercolor illusion induces a complementary color when one of the two juxtaposed lines is achromatic and the other chromatic (Pinna and Grossberg, 2005). The coloration effect is also scale-invariant, in that it appears to be approximately independent of viewing distance up to the point that the line colors are no longer resolvable.

4. THE FIGURE–GROUND EFFECT

The main figure–ground qualities of the watercolor illusion are the following: (i) it is hard to reverse — the figure–ground segregation is unequivocal; (ii) it determines grouping and figure–ground segregation more strongly (Pinna *et al.*, 2001) than the Gestalt principles of proximity, good continuation, prägnanz, closure, symmetry, convexity, past experience, similarity, surroundedness and parallelism; (iii) by reversing the colors of the two adjacent lines, figure–ground segregation reverses accordingly (see Figs 1 and 2); (iv) the figure–ground effect occurs on colored and black backgrounds (Pinna *et al.*, 2001); (v) by reversing the background from white to black, or black to white, while the luminance contrast of the lines is kept constant, the figure–ground segregation reverses (see Fig. 7, below) — this is in contrast to Rubin's claim that the currently figural region in the face-vase illusion is maintained even in the face of a black/white reversal; and (vi), the watercolor illusion strongly enhances the 'unilateral belongingness of the boundaries' (Pinna, 1987), the phenomenal property that the boundaries belong to the figure but not to the background (Rubin, 1915).

The phenomenal properties of coloration and figure–ground effects raise some questions. Can the two effects be considered relatively independent? Under which conditions does a possible dissociation occur? How does the dissociation of one effect, say the coloration, influence the figure–ground effect and vice versa? When dissociated, which are the phenomenal properties of each effect taken individually? Do new properties emerge when the integration of the two effects occur? The answer to these questions may help to understand if and how the two effects belong to different mechanisms, if and how they can integrate and at which processing stage. To answer these questions, spontaneous descriptions of subjects were recorded under the controlled conditions described next.

5. GENERAL METHOD

5.1. Stimuli

Stimuli were composed by the figures illustrated within the paper. The mean overall size of the stimuli was about 21 by 15 deg of visual angle. The luminance of the white (background) paper was 80.1 cd/m^2. The CIE x, y chromaticity coordinates for the main chromatic colors used were: (purple) 0.30, 0.23; (orange) 0.57, 0.42; (red) 0.62, 0.34; blue (0.201, 0.277), green (0.3, 0.5), yellow (0.46, 0.42). Black components had a luminance contrast of 0.03. The stroke width was approx. 6 arc min. Stimuli were presented on a computer screen illuminated by Osram Daylight fluorescent light (250 lux, 5600 K), and were observed binocularly from a distance of 50 cm with free viewing.

5.2. Observers

Unless otherwise stated, different groups of fourteen naive observers each described only one stimulus. (This was done in case one stimulus might influence the perception of another.) All the observers had normal color vision on the Ishihara test. Both male and female undergraduates at the University of Sassari participated.

5.3. Task

The subject's task was to report freely what they perceived by giving an exhaustive description of the main visual properties. Preceding the experiment there was a training period, where subjects viewed some known coloration effect like the figures reported by Pinna *et al.* (2001), classical examples by Gestalt psychologist of figure–ground segregation, and some examples of different color spreading effects, like neon color spreading, chromatic assimilation, simultaneous color contrast and complementary color induction. Observation time was unlimited. All the reports were quite spontaneous. The descriptions reported in quotation marks below are translations from Italian edited for brevity and typicality. There were some individual differences, especially for the weaker effects, but we report only those descriptions generated by at least 11 of the 14 subjects in each group. Our edited descriptions were judged by three other students, who were naive as to the purposes of the present research, to provide a fair representation of those provided by the observers. All the edited descriptions were approved afterwards by all subjects and evaluated as equivalent to those provided during the experimental session.

Studies of color constancy have shown the task given to an observer has a large effect on the report of color appearance; when asked to act as a colorimeter by making 'direct' matches between two surfaces seen under different illuminants, observers do so nearly perfectly; and when asked to make 'paper' matches between the surfaces, in effect discounting the illuminant and reporting the surface color alone, some observers (though not all) are capable of this as well (Arend and Reeves, 1986), even when luminance variations are introduced between the surfaces (Arend *et al.*,1991). In the current work we did not impose any restrictions on the observer's judgements. However, the descriptions that they produced are compatible with a 'paper match' or surface–color mode of judgement rather than with the alternative colorimetric mode.

RESULTS

6. DISSOCIATION BETWEEN COLORATION AND FIGURE–GROUND EFFECTS

The purpose of this section of the Results is to demonstrate, by introducing new cases of the watercolor illusion, that coloration and figure–ground are relatively independent effects. A strict dissociation implies that (i) coloration is perceived without the figure–ground effect and, conversely, (ii) the figure–ground effect is perceived without any color spreading in the inside edges. If these conditions hold, the coloration effect is not a necessary condition for the figure–ground one, and vice versa. Besides strict dissociation, other, weaker, but not less interesting, cases can be considered, with the aim of understanding if the two effects interact and how their properties might change by modifying their binding.

6.1. Coloration without figure–ground effect

Coloration without a figure–ground effect can be induced through a dichoptic composite stimulus, where the orange component is presented to one eye while the purple one is presented to the other eye (see Figs 4a and 4b). By combining dichoptically the two differently-colored borders on the left with those on the right, the 'coloration' (11 out of 14) is clearly perceived within the inner edges. However, it manifests different properties from those described in Section 3: it loses the surface color properties and appears diaphanous like a 'colored light floating (Fig. 4a) or more stable (Fig. 4b) and diffusing homogeneously within the wiggly figure' (11 out of 14). Moreover, the figure–ground effect, peculiar to the watercolor illusion under the previous conditions, is totally absent. These results suggest that coloration and figure–ground effects can be dissociated, and that by dissociating the coloration from the figure–ground effect, the phenomenal properties of coloration can change. They also suggest, perhaps not surprisingly, a cortical origin of the coloration effect.

The binding between the coloration and figure–ground effects can be weakened and modified by reversing the figure–ground organization where the coloration occurs. This can be done by making the regions where the color spreads appear as background rather than figure. Under these conditions, the coloration should not manifest the surface color quality and the solid, impenetrable and opaque appearance previously described. Figure–ground reversal can be achieved by strengthening the Gestalt grouping and figure–ground principles pitted against the watercolor illusion, so that the former wins against the latter. Hence, what is perceived as a figure should be induced by Gestalt principles, while the complementary watercolored region should be perceived as a background. Given these conditions, one may ask: Does the coloration persist? If it persists, what is its phenomenal appearance? If it changes in appearance, can coloration really be considered independent from the figure–ground effect?

Figure 4. (See color plate XI) Coloration without figure–ground effect can be induced through a dichoptic composite stimulus, where the orange component is presented to one eye while the purple one to the other eye: colored light floating (Fig. 4a) or more stable (Fig. 4b) and diffusing homogeneously within the wiggly figure is perceived, while the figure–ground effect, peculiar to the watercolor illusion, is totally absent.

In Fig. 5a, the inset square contains circles with outer and inner boundaries respectively of red and purple, while the surrounding squared frame contains circles with outer and inner boundaries of blue and purple. Under these conditions, several Gestalt factors (closure, symmetry, contrast, surroundedness, prägnanz) cooperate and win against the watercolor illusion, inducing a clear figure–ground effect in the circles. Phenomenally, 'the circles appear' not as holes or annuli, but 'as bright circular figures with purple boundaries emerging from a background, where a dense smoggy light fills the interspaces and creates an inset reddish and a surrounding blue backlighting effect' (11 out of 14). It is worthwhile noting that only 'the purple annuli' (i.e. the contours with the highest luminance contrast) 'become the boundaries of each circle', thus 'defining their shape' (11 out of 14). Conversely, 'the red and/or blue lighter-colored boundaries belong to the background and appear like haloes due to a colored light coming from behind and surrounding the purple boundaries of the circle' (11 out of 14). In Fig. 5b, the colors of the outer/inner boundaries of Fig. 5a are reversed so that all the figure–ground principles operate synergistically with the watercolor illusion. As a result 'the circles both with inner red and blue boundaries appear as solid volumetric colored circles clearly segregated in depth like red and blue spheres' (11 out of 14).

By filling the empty circles of Fig. 5a with red and blue colors, their figural properties are enhanced, becoming surfaces (see Fig. 6a). However, while in Fig. 5a there are two boundaries for each circle that split as previously described, in Fig. 6a only one boundary surrounds each circular surface. Phenomenally, 'the colored fringes around the filled circles appear as the boundaries of the circular shapes and not as components of the background' (11 out of 14). Nevertheless, 'the coloration persists but it assumes neither the surface color properties nor the appearance of colored light coming from behind. It is perceived as a diaphanous colored background' (11 out of 14). A similar result can be perceived in Fig. 6b.

A further case of coloration without a figural effect is illustrated in Figs 7 and 8. By viewing Fig. 7 from the top to the bottom, the perceived objects switch respectively from rows of eight-pointed stars (top) to rows of crosses (bottom).

This result is obtained by filling the background with a linear luminance gradient going from black to white. What is interesting for our purpose is that along the luminance gradient there is a gray range in the middle of the gradient. In the

Figure 5. (See color plate XII) In Fig. 5a, the circles appear as bright circular figures with purple boundaries emerging from a background, where a dense smoggy light fills the interspaces and creates an inset reddish and a surrounding blue backlighting effect. In Fig. 5b, the circles both with inner red and green boundaries appear as solid volumetric colored circles clearly segregated in depth like red and blue spheres.

Figure 6. (See color plate XII) In Fig. 6a, the colored fringes around the filled circles appear as the boundaries of the circular shapes and not as components of the background. The coloration persists but it assumes neither surface color properties nor the appearance of colored light coming from behind. It is perceived as a diaphanous colored background. A similar result can be perceived in Fig. 6b.

gray range 'neither the stars nor the crosses prevail as a figure against the other, thus creating a reversible condition (where) the coloration effect occurs' (12 out of 14). Coloration occurs, but not the figural effect, at least not in terms of the strong and univocal figure–ground segregation peculiar to the watercolor illusion: 'the figural appearances of the perceived objects (stars and/or crosses) are flat and not bulging as in the top or bottom regions' (11 out of 14) of Fig. 7. In other words, in about the middle region of Fig. 7 'if the crosses are perceived as figures, the stars appear as a background but, compared to what is perceived in the top and bottom regions of the figure, the crosses do not show the clear volumetric effect and the stars are not perceived as deep holes' (11 out of 14). Besides the figural effect, the coloration manifests different surface color properties: in the top and bottom regions the spreading colors appear as 'surface colors, impenetrable and solid' (11 out of 14), while in the critical central region the spreading colors (yellow for stars, and blue for crosses) appear 'empty and transparent' (11 out of 14).

Another kind of dissociation between coloration and figure–ground effects can be perceived in Fig. 8a, where quasi-equiluminant adjacent lines (gray and red) spread their colors but show 'a flat and reversible figure–ground organization or a tessellation of crosses and stars' (13 out of 14), which can be considered as a limiting case of figure–ground segregation. These results are better appreciated by comparing these regions with the complementary ones, where adjacent lines with strong luminance contrast (black and red) induce volumetric objects and holes, not comparable in terms of figurality with those induced by quasi-equiluminant adjacent lines. By comparing Figs 8a and 8b, the coloration appears 'more strongly as a surface color in Fig. 8b than in Fig. 8a' (14 out of 14).

Altogether, these results suggest that coloration can be dissociated from, or altered in the way it is connected and integrated with, the figure–ground effect. However, by splitting or changing their binding, the phenomenal properties of the coloration effect change accordingly, testifying that the dissociation from the figure–ground effect does not leave the coloration unchanged, but is strongly affected by it. Therefore, the two effects, even if they belong to different processes, may interact at a subsequent processing stage.

The aim of the next section is to ask, can the figure–ground effect be isolated or dissociated from the coloration one, and if so, do its properties change?

Figure 7. (See color plate XII) Along the luminance gradient there is a gray range, about halfway between the two colored lines and in the middle of the gradient, where neither the stars nor the crosses prevail as figure, thus creating a reversible condition where the coloration effect occurs but not the figural one. The figural appearances of the perceived objects (stars and/or crosses) are flat, not bulging as in the top or bottom regions.

Figure 8. (See color plate XIII) In Fig. 8a, quasi-equiluminant adjacent lines (gray and red) spread their colors but show a flat and reversible figure–ground organization or a tessellation of crosses and stars. In Fig. 8b, adjacent lines with strong luminance contrast (black and red) induce volumetric objects and holes. In Fig. 8b, the coloration appears more strongly as a surface color than in Fig. 8a.

6.2. Figure–ground without coloration effect

In Fig. 9, an example of figure–ground effect without coloration is illustrated. Under these conditions, 'the crosses emerge as figures' (11 out of 14) while the stars lose their boundaries and amodally complete them as a background. It is worthwhile noting that the physically homogenous gray appears not exactly as it really is, but 'the gray within the crosses is part (the inner region) of them' (11 out of 14), i.e. 'it is captured' (surface capture) and 'segregated in front of the complementary gray that is perceived as a dark empty gray space and as a background' (11 out of 14). The captured 'grays do not manifest any coloration' effect coming from the lines, so 'they do not look chromatically different from the complementary grays, but appear bright and solid, assuming the surface and opaque color properties' (12 out of 14).

The absence of the coloration effect is likely due to the admixture of the colors (see also Fig. 11) belonging to the four pairs of wiggly lines that phenomenally become 'the inner boundaries of the crosses' (13 out of 14). Under these conditions, the figure–ground effect without coloration does not present 'the bulging volumetric effect proper to Fig. 8b, where the crosses emerge from the background creating a rounded convexity', but 'the crosses bulge as upland, creating a plateau, i.e. rounded along the boundaries but on the gray elevated surfaces, whose volumetric effect is flat, without further rounded convexities' (11 out of 14). This plateau property is due to the kind of luminance gradient operating on the boundaries, where the luminance value of the gray surfaces is about intermediate between the two colored lines.

Returning to the coloration effect and to the luminance profile of Fig. 8b, the rounded volumetric effect is restored even if the gray rectangle is replaced by an oblique striped pattern (see Fig. 10). Under these conditions, 'the oblique lines within the crosses, strongly perceived as figures, appear bulging, curved in depth and segregated from those within the stars that are perceived as placed in the background or perceived through holes' (11 out of 14). This is so even if one set of oblique lines is the continuation of the other set, as in a texture. Another possible perceptual result is 'a matrix of transparent watercolored crosses above a background made of oblique parallel lines' (13 out of 14). What is interesting

Figure 9. (See color plate XII) Figure–ground effect without coloration: The crosses emerge as figures. The gray within the crosses does not manifest any coloration, and is captured (surface capture) and segregated in front of the complementary gray that is perceived as a dark empty gray space and as a background.

Figure 10. (See color plate XIII) The oblique lines within the crosses, strongly perceived as figures, appear bulging, curved in depth and segregated from those within the stars that are perceived as placed in the background or perceived through holes.

Figure 11. (See color plate XIII) The crosses clearly emerge as rounded convex figures while the coloration is absent, i.e. the inner edge of each cross appears as a dirty white, denser and brighter than the one within each star but not completely opaque. It does not appear as a white surface but fluffy and soft. The white within the stars is on the contrary completely empty and transparent.

is that even if the crosses are perceived as transparent, ‘the oblique lines appear bulging and belonging to the crosses’ (11 out of 14).

Considering Fig. 11, in which the gray of Fig. 9 is replaced with white to restore the luminance contrast gradient of Fig. 8 (see Pinna, 2005), ‘the crosses clearly emerge as rounded convex figures’ (12 out of 14), while the coloration is absent, i.e. the inner edge of each cross appears as ‘a dirty white, denser and brighter than the one within each star but not completely opaque. It does not appear as a white surface but as fluffy and soft’ (11 out of 14). In contrast, ‘the white within the stars is on the contrary completely empty and transparent’ (11 out of 14). These results also suggest that the absence of the coloration affects figure–ground segregation.

Given the previous findings, the luminance gradient along the boundaries can indeed be considered the crucial factor for the figure–ground effect. In the watercolor illusion, different conditions of the gradient strongly affect the set of properties that define a figure to be segregated in depth from a background. Figure–ground segregation happens independently of the coloration effect that is induced with quasi-equiluminant lines (see Fig. 8a), i.e. without figure–ground segregation. Note that the coloration effect is not induced when differently-colored adjacent lines defining the boundaries of a figure are used (see Figs 9 and 11), i.e. with a clear figure–ground segregation.

6.3. The lighting illusion

By increasing the length of the gradient by adding new adjacent lines, another case of the figure–ground effect without coloration is obtained. In Fig. 12a, six adjacent blue lines, placed in succession on the ascending steps of a luminance gradient, define the boundaries of an undulated irregular shape that is perceived as ‘a blue object similar to an insect, to an amoeba, or to a fish bone with very strong bulging and three-dimensional appearance illuminated from the top by a bright light’ (12 out of 14). The coloration effect is very weak, almost invisible, and ‘the inner edges appear as light and bright fuzzy white, whiter than the white of the background and like a shine or a lighting: a light reflected by a three-dimensional blue shape’ (11 out of 14). The new conditions not only define univocally what is figure and what is background, but also model the volume and strengthen the illusion of depth peculiar to the watercolor illusion by creating a 3D object–hole effect. The object–hole effect is sculptured by the inhomogeneous reflected light that depicts light and shade (the illumination effect) and leaves the color of the object unaltered and constant, i.e. a homogeneous blue. We asked the subjects ‘after discounting the illumination effect, what is the color of the fish bone?’ Six (of 14) picked the fourth lightest blue, and

Figure 12. (See color plate XIV) *The lighting illusion*. In Fig. 12a, a blue object similar to a fish bone with very strong bulging and three dimensional appearance illuminated by a bright light. The coloration effect is very weak, almost invisible, and the inner edges appear as light and bright fuzzy white, whiter than the white of the background and like a shine or lighting: a light reflected by a three dimensional blue shape. In Fig. 12b holes within a 3D green object are clearly perceived.

eight, the fifth lightest blue. (The 6 lines were clearly distinguishable in the original drawing, although they may blur together in the reproduction here). This result emerged after a comparison between Fig. 12a and six figures where the shape of Fig. 12, without adjacent lines, was homogeneously filled with the color of each of the lines. The task was to choose the color of the fish bone shape among the six filled figures after having discounted the illumination creating the lighting.

In short, by increasing the number of adjacent lines arranged on a luminance staircase, (i) the coloration effect, considered as an assimilative color spreading similar to the watercolor illusion, is absent; (ii) new kinds of long-range brightness and lightness inductions emerge in place of the coloration (see also Fig. 21); (iii) these boundary brightness and lightness effects are perceived as an illumination effect or as a glare, a shine and, more generally, as a 'lighting illusion' (see also Fig. 21); and (iv) the figure–ground segregation and the volume proper to the watercolor illusion are increased and the 3D appearances bulge much more strongly, creating a clear object–hole effect. (Note that blue is not required; green will also do, as in Fig. 12b.)

Altogether, the phenomenal results of this section indicate that the figure–ground effect can be dissociated from the coloration effect and that, by separating the two effects, new properties (illumination and lighting illusion, clear volumetric effect, brightness and lightness inductions, etc.) emerge, testifying that their independence is not absolute as both of them strongly influence each other. We infer that the two underlying processes interact and converge at a subsequent processing stage where the coded color and figure–ground properties are integrated and processed in a new way, which will be the main topic of Section 10.

The previous points suggest that it may be more important from a theoretical point of view to demonstrate how all these effects interact to create the integrated properties of our visual world, and new emergent properties, than to demonstrate their independence. The aim of the next section is to show new and emergent properties referred to the object–hole and to the illumination effects and, in a more integrated way, to figurality. The questions are: by changing the hue and the luminance across the boundaries, how does the figurality change? And, how does the phenomenal appearance of the object–hole and of the illumination effects change as a result?

7. THE OBJECT–HOLE AND THE ILLUMINATION EFFECTS

The phenomenal figurality of the surfaces, induced by the watercolor illusion and, more compellingly, by the new cases shown in Figs 12a and 12b, manifest unique emergent properties, never shown before in previous studies of figure–ground segregation. (i) The physical conditions eliciting these effects, i.e. the juxtaposition of parallel lines, not only induce a coloration effect and clearly define what is 'figure' and what 'background', but also model the volume and strengthen the illusion of depth in a flat surface by inducing a 3D appearance. (ii) Increasing the number of adjacent lines increases volumetric figurality. Going from the two-line watercolor illusion (Fig. 1), to the six-line lighting illusion (Fig. 12), the object–hole effect becomes much stronger: the resulting surface appears thick, solid, opaque and dense, and rounded similar to a high-relief. The object–hole effect is one of the new properties emerging under these conditions. (iii) With enough juxtaposed lines (e.g. six), the resulting object clearly shows new kinds of brightness and lightness inductions, in directions other than the line orientations. The continuation of the luminance gradient does not appear to stop when it reaches white, but continues increasing in brightness and lightness. (iv) The brightness and lightness inductions are perceived as an illumination effect through the figural organization of shaded and bright regions along the long gradient and within the perceived object. The illumination effect is a new and emergent property, which is not clearly perceived when only two lines are placed parallel and contiguous to each other. The fact that six juxtaposed lines weakens the coloration effect — as seen in the watercolor illusion with only two lines — may result from the illusory illumination enhancing the inner brightness and lightness of the object. It is worth noting that (v) the resulting figurality, i.e. the combination of object–hole and illumination effects, looks like that obtained through the Renaissance painting technique of *chiaroscuro*: the modeling of volume by depicting light and shade (see Pinna, 2005). A highlight marks the point where the light is more directly (orthogonally) reflected, moving away from this highlight, light hits the object less directly and therefore has a darker value of color (lower luminance).

7.1. The backlighting illusion

A further demonstration of the illumination effect and of the previous emergent properties is shown in Fig. 13, where the abrupt luminance jump of the external boundary side of Fig. 12 is reduced by replacing the black outer line with an orange one and the darkest blue line with a black one. Under these conditions ‘the black line appears as the boundary of the fish bone that maintains a strong volumetric and 3D appearance. The inner blue luminance gradient is perceived like the shade of the bone and the orange line like its backlighting. The color of the light coming from behind is orange. The object appears illuminated also from the front with a white light’ (11 out of 14). Backlighting mainly occurs when the source of light is coming from behind the subject, namely, when the observer is looking into the light source: the perceived object, intercepting the light source, should appear at least partially in shadow. This is not the case in Fig. 13, where two light sources are perceived. It is worth observing that the ‘orange backlight manifests the coloration effect by coloring the background that manifests a certain density, like a fog’ (11 out of 14). This is another example of coloration dissociated from the figure–ground effect, and, as previously shown, both effects assume new perceptual roles and new emerging ‘meanings’. The color of the backlight varies by changing the hue of the external line. If the hue is blue like the internal lines, or gray, the backlighting effect is absent.

The color of the front light can also be changed by changing the chromatic color of the innermost line. In Figs 14a and 14b 'the reflected light appears green and orange' (11 out of 14). The color of back and front lighting can be combined at will, for example one orange and the other green (not illustrated). Pilot data suggest that the hue of the innermost (outermost) lines most strongly influences the color of the front (back) lighting, whereas the luminance contrast determines the perceived intensity of the light, but not the color.

In Fig. 15, the luminance gradients in Fig. 13 increase and decrease more gradually and are more similar on both sides of the black line, but still differ slightly. Under these conditions, the line with the highest luminance contrast is again perceived as the 'boundaries of the object' (14 out of 14). However, 'the volumetric object appears fuzzy and blurred' (13 out of 14) (fuzziness effect) compared to the one perceived in Fig. 13. When the black line is placed in the middle of the other lines, so that it is the line of symmetry of the luminance gradient, the fuzziness effect reaches its maximum value (not illustrated).

Another way to create a fuzziness effect is illustrated in Fig. 16a, where the background of Fig. 12a is black. Under these conditions going from one side to the other side of the luminance gradient and vice versa, the luminance contrast gradually decreases. Phenomenally, 'a white bright fuzzy object bounded by blue neon light on a black background' (12 out of 14) is perceived. 'The boundary of the object is none of the blue lines but the entire bunch of lines appears like a beam of blue neon light surrounding and bounding a white fish bone or amoeboid object' (11 out of 14). A combination of Fig. 12a and Fig. 16a is illustrated in Fig. 16b, which

Figure 13. (See color plate XIV) *The backlighting illusion*. The black line appears as the boundary of a fish bone that maintains a strong volumetric and 3D appearance. The inner blue luminance gradient is perceived like the shade of the bone and the orange line like its backlighting. The color of the light coming from behind is orange. The object appears illuminated also from the front with a white light. The orange backlight manifests the coloration effect by coloring the background that manifests a certain density, like a fog.

Figure 14. (See color plate XIV) The color of the front light can be changed by changing the chromatic color of the innermost line. In Figs 14a and 14b the reflected light appears green and orange.

Figure 15. (See color plate XV) The line with the highest luminance contrast is perceived as the boundaries of the fish bone that appears fuzzy and blurred (fuzziness effect) compared to the one perceived in Fig. 13.

Figure 16. (See color plate XV) In Fig. 16a, a white bright fuzzy object bounded by blue neon light on a black background is perceived. The boundary of the object is not one of the blue lines but the entire bunch of lines, which appears like a beam of blue neon light surrounding and bounding a white fish bone or amoeboid object. Fig. 16b allows a direct comparison of all the figurality properties perceived on the left and right sides.

allows a direct comparison of all the figurality properties perceived on the left and right sides.

By reversing the inner and outer white and black and the blue luminance gradient of Fig. 16, ‘a black fuzzy fish bone against a blue light emerges’ (11 out of 14) (see Fig. 17). The backlighting effect perceived under these conditions is not the complement of the results obtained in Fig. 16a, where no backlight is reported. It is likely to be a direct consequence of the backlighting phenomena where the object illuminated strongly from behind appears in deep shadow. Usually, there must be enough light and details to recognize what the object is, and prevent it from looking like a flat silhouette against a strong light, but not so strong that the dramatic effect of backlighting is lost. Backlighting is especially effective when combined with reflected light, causing interesting shadows as illustrated in Fig. 13. (This is not the case in Fig. 17, where the object maintains a clear 3D appearance, perhaps due to the luminance gradient along the boundaries that casts lights of different intensities.)

Note that a phenomenal demonstration of the belongingness of the lines to the fish bone (whether or not they belong to the object) comes from the comparison of the size or width of the resulting object: for example, the width of the bone is greater in Figs 14a and 14b than in Figs 15 and 17. By increasing the number of lines belonging to the object, the width of the resulting object increases accordingly. A similar demonstration can be applied to the size of the circles perceived in Figs 5a and 5b.

In Figs 16a and 17 the juxtaposed lines appear as neon lights, not as the boundaries of the object: even if they surround the object, they are not ‘the object’. This is due to the fact that the luminance gradient does not present any abrupt luminance variation on either side of the black or white regions, so there is no abrupt luminance termination to assume the role of boundary of the perceived object. The inverse case of Fig. 16a (and 17) is illustrated in Fig. 18, where the extremes of the gradient end with very high luminance contrast variations.

Phenomenally, in Fig. 18, ‘both the inner and outer edges appear as empty spaces: The outer space as a background and the inner one as a black hole. Only the bunch of lines is perceived as a figure’ (12 out of 14). It is worthwhile noting that two different things are perceived, dark holes and white background, even if the conditions of the gradient terminations are about the same. This result is likely due to the closure and surroundedness Gestalt principles, which make the inside edge of the gradient appear as a figure. However, since the abrupt luminance termination strongly determines the perception of background in this region, the combination of the two groups of principles makes the inner edges appear as holes — ‘figures’, that

Figure 17. (See color plate XV) A black fuzzy fish bone appears against a blue light.

Figure 18. (See color plate XV) Phenomenally, both the inner and outer edges appear as empty spaces: The outer space as a background and the inner one as a black hole. Only the bunch of lines is perceived as a figure.

is, whose boundaries belong not to the figure, as expected from Gestalt principles, but rather to the complementary region. (This point will be discussed further in Section 9.3.) This interpretation applies also to Fig. 12b, where the blobs within the objects are not perceived as background, even with very deep complementary boundary differentiation, but as holes. Another factor that may play a role in Fig. 18 is that black is more easily perceived as empty space than is white; when the black and white regions of Fig. 18 are reversed (not illustrated), the perception of the inner edges as a hole is weakened.

The results presented in this section may be summarized as follows. (i) Besides the figure–ground segregation effect suggested by Rubin (1921), the so-called 'object–hole and illumination effects' emerge: when juxtaposed lines create a luminance gradient and define the boundaries of a figure, the figure becomes an illuminated 3D object and the background appears deeper — similar to a hole. (ii) Not only is the luminance of the juxtaposed lines involved in the figurality effect, but so is the hue that determines the color of the illumination. (iii) Object–hole and illumination effects cannot be easily dissociated because, as the previous examples showed, they change dramatically their 'meaning' when tiny variations within the luminance gradient are introduced. This strong link between the two effects and the fact that both of them strongly contribute to determine the figurality of an object makes it reasonable to introduce an overall effect, called 'figurality effect', that includes all the properties belonging to the object–hole and to the illumination effects. (iv) Most of the necessary information needed to define the figurality properties is in the boundaries and, more specifically, in the gradient surrounding and defining a perceptual object. Thus, varying the luminance profile of the gradient permits discovery of the laws of figurality that determine not only what is figure and what is background, as the figure–ground segregation principles do (Rubin, 1921), but also the phenomenal appearance of what is perceived as a figure within the three-dimensional space and under a defined illumination. The aim of the next section is to clarify further the necessity of introducing the laws of figurality in addition to the Gestalt grouping and to figure–ground segregation laws.

8. THE PLACE OF FIGURALITY IN A WORLD OF GROUPING AND FIGURE–GROUND SEGREGATION

On the basis of these phenomenal results several general principles can be introduced, following the example traced by Gestalt psychologists like Rubin and Wertheimer. Before defining and naming the laws of figurality, it is necessary to clarify the role of figurality in a perceptual world ruled by the well-known Gestalt laws of grouping and figure–ground segregation.

8.1. The problem of perceptual grouping

Wertheimer (1923) in his pioneering study of the factors underlying visual perception approached this problem in terms of grouping. The question he answers is:

how do the elements in the visual field 'go together' to form an integrated, holistic (*Gestalt*) percept? How do elements group in parts that in their turn group in overall objects? How do individual elements create larger wholes separated from others? In a set of classical and elegant experiments, he discovered the ten basic principles, called 'grouping factors', mentioned in the Introduction: proximity, similarity, good continuation, closure, symmetry, convexity, prägnanz, past experience, common fate, and parallelism. These principles (like Rubin's, below) represent '*ceteris paribus*' laws, namely principles defining what determines the emerging whole when all else is equal. In addition to these classical grouping factors, a number of new principles have been identified (Palmer, 1992, 1999; Palmer and Rock, 1994), but despite their novel appearance, these principles can be traced back to the classical ones, as they represent a special or limiting case of at least one known factor.

8.2. The problem of figure–ground segregation

One cannot talk about grouping without also mentioning figure–ground segregation. Rubin (1921) was the first to name the principles ruling what appears as a figure and what as a background, one being the 'surroundedness principle' stating that a surrounded region tends to become a figure while the surrounding region becomes background. (The other principles were size, orientation, contrast, symmetry, convexity, and parallelism (Note 1)). Rubin went beyond the laws of figure–ground segregation by identifying the main properties which belong to the figure but not to the background. (i) The figure appears closer to the observer than the background, implying a role for depth perception; (ii) its color appears denser than the same physical color on the background; and (iii) it assumes the shape traced by the contour, implying that the contour belongs unilaterally to the figure, not to the background. The unilateral belongingness of the boundaries is a basic property that is common to all the principles. We therefore regard it as a meta–principle, one of the rules governing all the laws of figure–ground segregation, rather than as just another property. Often ignored, it is linked to the problem of figurality and constitutes its prelude. It is considered here by studying (i) different gradient profiles across the boundary contours, (ii) the belongingness of the juxtaposed lines to the figure or to the background, and (iii) how they group or split to create emergent properties like the volumetric and illumination effects.

Unfortunately, the problem of the boundaries was not further developed by Rubin and, until now, no new principles have been added to Rubin's original ones. This is where the watercolor illusion and related cases come in. Like Wertheimer and Rubin, we used the phenomenological approach by first describing what we see (previous Results sections), then defining the boundary conditions under which all the effects and, more specifically, the figurality properties occur (next sections). Finally, we put forward a hypothesis to explain the problem of figurality (last section).

8.3. The problem of figurality

The laws of figurality complement the grouping and figure–ground principles. As shown in this work, the main figural properties defined by Rubin, and particularly the unilateral belongingness of the boundaries, can be considered as the starting point to understand what is next, i.e. the figurality properties. We do not aim to define the logical or the temporal processing order of grouping, figure–ground, and figurality, but to highlight the problem of figurality and to suggest principles that govern it. The main question the laws of figurality intend to answer is how variations in boundaries and luminance gradient profiles define both the 3D appearance of the object (its specific figural properties) and the lighting — the perceived illumination and light reflected by the object. Thus, figurality proceeds beyond the properties of the figure as defined by Rubin's laws.

9. THE LAWS OF FIGURALITY

The following laws are incomplete and require further study and integration. Still, they are not merely summary statements. Rather, they are Janus-faced, both pointing back towards the purely phenomenal (but reliable) descriptions of the figures discussed earlier, and pointing forward towards statements of regular, analytic relations (those with predictable consequences) that will eventually need explanation at a mechanistic level. These laws are consistent with the Gestalt usage of the term 'law' that does not necessarily concern causes and effects. Nevertheless, like other laws governing different scientific fields, the figurality laws represent regularities for all practical purposes that apply to certain classes of phenomena (e.g. figurality) or generalizations based on recurring facts or events. Their specific formulations, as we shall see below, describe relationships that are observed to be invariable between or among phenomena for all cases in which the specified conditions are met.

The figurality laws currently refer to just four gradient conditions, which are the ones previously considered. (i) A luminance gradient profile where the line having the highest luminance contrast is placed at one extreme of the gradient and the lowest at the other. The watercolor and the lighting effect exemplify this, the 'high–low' gradient. (ii) A luminance gradient profile with two lower luminance contrast lines placed at the extremes and the line with the highest luminance contrast is between them. The backlighting and the fuzziness effects seen in Figs 13 and 15 illustrate this, the 'low–high–low' gradient. (iii) A luminance gradient profile like the high–low one but with the extremities ending on a black or white surrounding region such that luminance contrast is low at both extremities. This is illustrated in Figs 16a and 17, the 'low–low' gradient. (iv) By making the black surrounding region of the low–low gradient white and the white region black, a high luminance contrast transition is created on both extremes of the gradient, as illustrated in Fig. 18. We call this the 'high–high' gradient. The names used to indicate the four kinds of gradients are just labels necessary to distinguish them and simplify the following descriptions.

A limiting case of these conditions is the one with only one boundary contour like those studied by Rubin. Rubin's unilateral belongingness of the boundaries, also called 'border ownership' (Nakayama and Shimojo, 1990) can be considered as the first law of figurality.

Law 1: The boundary contours belong unilaterally to the figure, but not to the background.

This law can be applied easily to the figural conditions where only one boundary contour is present, and it states that this contour belongs only to the region determined as a figure by Rubin's laws. The unilateral belongingness of the boundaries is very effective under reversible conditions, or when different laws determine complementary regions as a figure thus creating equilibrium between them. This law does not determine what appears as a figure and what as a background; thus it is not a figure–ground segregation law, but it defines the belongingness rule within figurality. Therefore it is the first of the figurality laws. These can be considered as belongingness laws, in the sense that, depending on their belongingness (to the figure or to the background), the juxtaposed lines assume different perceptual roles (lighting, backlighting, shadows, etc.). In this approach, unilateral belongingness is valid not just with only one boundary contour, as studied by Rubin, but also with many juxtaposed lines.

The second law is directly related to the first one. Given many juxtaposed lines, this law specifies which line becomes the most external unilateral boundary of the perceived object.

9.1. The role of the line with the highest luminance contrast

9.1.1. Boundary line.

Law 2: The juxtaposed line with the highest luminance contrast in relation to the homogenous surrounding regions tends to appear as the outermost boundary of the figure. We call this line the 'boundary line'.

This law clearly applies to the watercolor illusion (e.g. Figs 1 and 2), where the purple line appears as the boundary of the watercolored object, and to the equiluminant limiting case where a tessellation or a reversible figure–ground organization is perceived (Fig. 8a). Figurality also refers to the coloration and, particularly, to the surface color properties. In fact, if one line assumes the role of 'boundary', the other line specifies something else, for example, the color or shade of the object (the topic of the third law). Under high luminance contrast conditions between the two lines, not only is the role of the boundary affected, but there is an asymmetry even in the amount of color spreading from the two lines. The line with less luminance contrast relative to the background spreads proportionally more than the line with higher luminance contrast. The color spreads in directions other than the line orientation. In quasi-equiluminant conditions, both lines spread similarly, in opposite directions (Fig. 8a). Coloration and boundary belongingness proceed in agreement.

As a consequence of Law 2, the weaker surface color property under quasi-equiluminant conditions is linked to the weaker figure–ground and object–hole effects. This law applies also when coloration is absent, as illustrated in Figs 9 and 11. It also applies to the other figures, except Figs 16 and 17, where there is no line with the highest luminance contrast (see Law 8). The lighting, backlighting and fuzziness effects fall within this law in relation to the line with most contrast. Figure 18 is a special case because it has two lines with the highest luminance contrast. However, due to Law 2, both lines become the boundaries delimiting an object; therefore the object is everything in between these boundaries, i.e. the bunch of lines. Following this observation, a corollary of Law 2 can be introduced to extend this law to the cases where more than one or two lines are present within the gradient.

COROLLARY 2.1. *Given more than one line with the highest luminance contrast, all of them appear as boundaries of the figure.*

This corollary applies even to special cases as those illustrated in Fig. 19, where 'a flat figure with three boundaries' (13 out of 14) is perceived. The presence of three boundaries makes the figure lose its volumetric and 3D properties. Nevertheless, the coloration effect is much stronger than the condition where only the inner purple and orange lines are present. This is an interesting coloration case on which we are working.

If the line with the highest luminance contrast becomes the boundary of the figure, so that the perceptual role of the boundary is taken by this kind of line, the next question is: what is the perceptual role of the other lines? (We will assume that the same role cannot be played by different 'things'; therefore, if one 'thing' plays a specified role, an adjacent different 'thing' should play a different role. The meta-laws of section 10 clarify the need for this basic assumption.) On the basis of the previous phenomenal results, Law 3 can answer this question.

9.2. The role of the lines with lower luminance contrast

Law 3: Given the high–low gradient, the juxtaposed lines with lower luminance contrast in relation to the homogenous surrounding regions affect the perception of the bounded area. They do this in at least three ways: (i) *they determine the color,* (ii) *they model the volume depicting lights and shades, and* (iii) *they define the properties of the lighting (both apparent illumination and reflected light) through highlights and dark values.*

When the line with most contrast assumes the role of the boundary (Law 2), the lines with lower contrast lose their individual boundary contour status and become a single component of the bounded object, whose percept they qualify according to Law 3.

9.2.1. The role of color in Law 3. The lines with lower contrast define the color of the resulting object, as illustrated in the watercolor illusion. (An exception occurs in Figs 9 and 11, where the two adjacent lines of the crosses are divided in four different chromatic colors. None of these pairs of lines alone can define the color of the crosses due to the presence of the other three, and an admixture or even absence of coloration is obtained.) As illustrated in Fig. 12, the lower-contrast lines define the color in the lighting effect, even when the coloration is absent.

Figure 14, where the color of the light is perceived, and Fig. 13, where the backlighting emerges with a proper color, were not covered by Law 2, because the lines in these figures do not define the main object directly. Moreover, only particular lines are involved, like the line terminating the gradient in Fig. 14, or the line placed next to the line with the highest luminance contrast (see Laws 4 and 5). Nevertheless, in general, Law 3 can be applied to these figures as well.

It is interesting that it is sufficient to change the color of only one line to define the color of the object. For example, by replacing the third brighter blue line in Fig. 12a with a green one (see Fig. 20) the entire object now appears ‘aquamarine’ (12 out of 14) colored. The object color changes by varying the color of any of the other lines (not illustrated), except for the brightest one that defines the color of the light. The resulting object color is the resultant of the admixture of the colors of all the single components.

9.2.2. Modeling volume in Law 3. In Figs 9 and 11, where no coloration occurs, and in Fig. 18, where a high–high gradient is illustrated and where the bunch of lines appears as ‘a shaded cylinder depicting the perimeter of a fish bone shape’ (12 out of 14), the lines clearly model the volume. Note in particular the surface capture effects in Figs 9 and 10 that clearly show this role. By varying the luminance profile of the lines, and thus the amplitude of the bulge and of the relief, the volume of the resulting object appears to vary. This is the topic of Law 10 and Corollary 10.1, which expand on Law 3.

9.2.3. Defining the properties of the lighting in Law 3. Our phenomenal results showed the emergence of the illumination and of the lighting effect, mostly in the ‘lighting illusion’. The number of lines composing the gradient is an important

Figure 19. (See color plate XVI) The modified ‘watercolor’ figure lose its volumetric and 3D properties. Nevertheless, the coloration effect is much stronger than the condition where only the inner purple and orange lines are present.

Figure 20. (See color plate XVI) By replacing the third brighter blue line in Fig. 12a with a green one the entire object appears now aquamarine.

factor in determining the strength of the lighting effect (see Law 10). The watercolor conditions with only two juxtaposed lines show a weaker or absent lighting effect. By increasing the number of the lines, the illumination emerges more and more. Figure 21a illustrates an indirect demonstration of the role played by the lines in producing the illumination effect. If the inner region of Fig. 12a is physically filled with a light chromatic tint (e.g. light red), 'the inner region appears white' (11 out of 14), and 'the light red totally discolors' (12 out of 14). The discoloration illusion (Pinna, in press) — meaning the loss of the coloration — disappears when the gradient is reversed (not illustrated), or when the length is reduced (see Fig. 21b).

The previous observations reveal that it is not necessary for all three roles (color, volume and light) to be present at the same time. For this reason a corollary has been introduced.

COROLLARY 3.1. *The juxtaposed lines with lower luminance contrast define at least one of the three phenomenal properties of color, volume and light.*

9.2.4. Lighting line. Not all the juxtaposed lines play the same role along the high–low gradient with six lines, as illustrated in Fig. 12. The extremes play a particular role. The line with the highest luminance contrast defines the object and its boundaries (Law 2), while the role of the line with the lowest value is defined in Law 4.

Law 4: Given the high–low gradient, the line at the extreme of the gradient with the lowest luminance contrast in relation to the homogenous surrounding region defines not only the object properties, described in Law 3, but also the properties of the lighting (its color and intensity). We call this extreme line the 'lighting line'.

The extremes of the gradient are placed in the borderland between different regions, namely, the juxtaposed lines and a large white homogeneous area, so they delimit and form the boundaries of these two regions. These extremes separate the object from 'something else': that is, the line with the highest luminance contrast separates the object from the background, and the line with the lowest contrast separates the object from the most lighted area. Thus the former defines the object, the latter defines the property of the light. The other lines less strongly define the boundary and the illumination, presumably because they are placed in between the extremes.

However, they determine the color more powerfully, and also the shade and the volumetric shape of the object — these being properties not only of the object but also of the lighting, as shown by *chiaroscuro*. The different roles of the lines on the basis of their spatial positions within the gradient are demonstrated by the fact that variations in the color of the lowest line can change the color of the light, while

Figure 21. (See color plate XVI) *The discoloration illusion.* In Fig. 21a, when the inner region of Fig. 12a is physically filled with a light red tint, the inner region appears white: the light red totally discolors (Fig. 21b is a control).

color variations of the other lines change mostly the color of the object. The closer the intermediate lines are to one of the two extremes, the more their role is similar to them.

9.2.5. Backlighting line. The backlighting effect occurs in the other condition in which one or more lines define the role of the light. This is defined in Law 5; Law 7 will cover the related backlighting gradient condition.

Law 5: Given the low–high–low gradient, the line at the extreme of the gradient with a luminance contrast lower than the boundary line (and beyond) is the 'backlighting line'. This line does not define object properties, but only the properties (color and intensity) of the illumination coming from behind.

In Fig. 13, the backlighting line splits from the others both structurally, because it is placed beyond the boundary line, and phenomenally, because it is stronger when it has a chromatic color different from all the other lines. If the boundary line behaves as a watershed, the line placed beyond it does not 'talk' about the object, but rather about the apparent lighting, and more precisely the backlighting, because (once again) it is beyond the boundary line.

These laws defining the various roles of the lines are so far incomplete, as the gradient properties that determine the object–hole effect have not yet been defined. This is the topic of the next section.

9.3. The role of the gradient profiles

The following principles define (i) which regions appear as objects and which as holes depending on the properties of the luminance gradient, (ii) how the object–hole and volumetric effects vary by changing these properties, and (iii) under which gradient conditions new emergent effects (lighting, fuzziness, etc.) are created.

Law 6: Given the high–low gradient (e.g. Figs 2 and 12), *the region whose luminance transition is less abrupt is perceived as a volumetric object, relative to the complementary region with a more abrupt transition which is perceived as an empty 3D space*.

The phenomenal and physical asymmetric luminance transition across the juxtaposed lines makes the figural effect due to the watercolor and to the lighting illusions stronger than in the classical figure–ground condition, and prevents reversibility of figure–ground segregation by strengthening the unilateral belongingness of the boundaries (Pinna, 2005). In fact, so that a boundary contour can belong only to the figure (and not to the background) under the conditions studied by Rubin or as illustrated in Fig. 3, it is necessary that the visual system induces some kind of figurality asymmetry on both sides of the contour, so this contour can become the boundary of only one of the two complementary regions separated by it.

Based on this phenomenological reasoning, it follows that the luminance asymmetry between boundary contours, physically present in the high–low gradient, strengthens the belongingness of the line of highest contrast to the region where the luminance value of the lines decreases more gradually. If this is true, each line of the gradient reinforces this unidirectional figural process by creating a cascade connection due to the same asymmetrical conditions present in each pair of lines. The interruption of this structure, for example by reversing the gradient profile in some of the pairs of lines or at the extremes of the gradient, may cause phenomenal variations and the emerging of new properties. One of these cases is defined in the next law:

Law 7: Given the low–high–low gradient (see Figs 13 and 15), *the region whose luminance transition is longer is perceived as the volumetric object relative to the complementary region, with the shorter transition perceived as an empty 3D space illuminated by backlighting on the volumetric object whose color and intensity are defined by this shorter transition.*

This kind of gradient reveals the different perceptual roles played by the two sides of the line (the one with the highest luminance contrast) dividing the two regions. On the side where the gradient created by juxtaposed lines is longer, object properties emerge, whereas on the other side, background properties emerge. Therefore, the lines placed on the background regions appear as light rather than manifesting object properties, but since they are placed all around the boundary line, they appear as backlighting. As a consequence, they modulate the object, as described in the next corollary.

COROLLARY 7.1. *Given the low–high–low gradient, all else being equal, when the luminance transitions on both sides of the boundary line have the same length and the color of the lines placed on opposite sides of the boundary line are different, an equilibrium appears: each side can be perceived as an object or as a background, alternatively and reversibly. Under these conditions, the backlighting effect is absent. When the color of the lines on both sides is the same, what emerges is not a reversible object-background segregation but a fuzziness effect: an object with blurred boundaries (not illustrated).*

9.3.1. Neon Lighting. Law 8 describes a special case of Law 2, in which there is no boundary line.

Law 8: Given the low-low gradient (see Figs 16 and 17), *due to the absence of a line with a highest luminance contrast, none of the lines assume the role of the boundary line. However, all of the lines surround an object, which is segregated on the basis of Rubin's figure–ground laws. The lines now become not boundaries but rather a neon light, either surrounding* (Fig. 16) *or coming from behind* (Fig. 17).

The absence of a boundary line creates a reversible figure–ground segregation. This is not in fact perceived in Figs 16 and 17, where closure and surroundedness segregate the inner fish-bone region as a figure. However, by reproducing the low-low gradient under different geometrical conditions, where these factors are counterbalanced, a reversible figure–ground segregation can be perceived (not illustrated).

This law is a special case of Law 2, depending on the absence of a line with the highest luminance contrast. For this reason it could become corollary of 2. However, to underline the properties of the gradients, we preferred to keep this law in this section. The same reason applies to the next law, which could be read as another corollary of Law 2.

Law 9: Given the high–high gradient (see Fig. 18), *the presence of two extremes with the highest luminance contrast forces both of them to assume the role of boundary lines, inducing the perception of a bunch of lines placed within outer and inner regions perceived as empty space.*

Again, Rubin's principles play some role in Fig. 18 by inducing within the inner region a more figural appearance, making it appear as a hole that, paradoxically, can be considered as a figure whose boundaries belong not to it but to the complementary region that is, in its turn, a figure (see also Palmer, 1999; Bertamini, 2001; Bertamini and Croucher, 2003; Grossberg *et al.*, 2005; Palmer and Nelson, 2005).

9.4. The role of the properties of the gradient profile

The role of the color of the lines with lower luminance contrast placed in different positions of the gradient has been described by introducing Laws 3, 4 and 5. Not only the color, but also the length of the gradient plays a basic role in defining figurality. This role is described in the Law 10 specifically for the high–low gradient, but it applies also to low–high–low and low–low gradients (not illustrated).

Law 10: Given the high–low gradient, by increasing the length of the gradient, i.e. by enhancing the number of lines (e.g. from two lines, as in the watercolor illusion, up to six lines, as in the lighting effect), (i) *the coloration effect decreases,* (ii) *the object–hole and volumetric effects increase, and* (iii) *the lighting effect increases.*

These results accord with intuition, because increasing the gradient length increases the salience and the length of the shade that phenomenally involve all the other properties, as shown through the *chiaroscuro* technique. By increasing the length, the luminance jump between each line changes accordingly. By reducing the number of lines in Fig. 12, the bulging effect is reduced and the object becomes flatter. This observation suggests the next corollary.

COROLLARY 10.1. *Given the high–low gradient, by changing the luminance value of each line so that the spatial profile is speeded up or slowed down (while keeping the same extremes), the volume of the perceived object changes accordingly.*

What is predicted by this corollary is what the Renaissance painters used to do with the *chiaroscuro* technique to create and modify the volume of their subjects. Note that even though variations in the luminance gradient specified in Corollary

10.1 can change the volumetric effect, the other figurality properties do not change qualitatively. For this reason the precise luminance values of the lines within the figures shown here are not critical (and indeed have not been specified.)

9.5. Grouping and figure–ground laws involved in the figurality laws

The ten figurality laws complement and follow the laws of grouping and figure–ground segregation in other senses, different from those already described in Section 8. In fact, these laws operate within the juxtaposed lines, segregating some of them from others. For example, the salience of the lines of highest contrast that appears as a border line can be considered as a special case of the contrast law of figure–ground segregation suggested by Rubin. Again, the separation between the two kinds of gradients proper to the low–high–low profile can be due to the 'similarity in the direction of the luminance', which is a limiting case of Wertheimer's similarity law. The similarity of color operates in the backlighting effect and in the segregation of the lighting line. In general, the laws of Wertheimer and Rubin seem to operate at the low level of the color and luminance gradient profile by creating the conditions necessary to assign different roles to segregated or ungrouped lines.

Nevertheless, the figurality laws cannot be considered as special cases of grouping and figure–ground segregation laws, because even if the Gestalt laws group, ungroup or segregate several lines within the gradient, they do not say anything about the figurality properties of the resulting object. As a consequence, the figurality laws cannot be reduced to the Gestalt ones without leaving out many phenomenal figurality properties. Indeed, the figurality laws operate at a meta-level which defines how the 'things' (lines, gradient profiles, etc.) grouped and segregated by the Gestalt laws represent emergent properties and objects like 'shade', 'boundary line', 'illumination', 'lighting', and 'backlighting'. Thus they implicitly contain interesting general statements, placed at a meta-level of explanation, of how the visual system works and how numerous stimulus variations are organized into a small set of constant objects with emergent properties.

A problem with these laws is related to the fairly large number of them; like the Gestalt laws, which are also numerous, they may come into conflict. Further theoretical work and research is needed to develop meta-level laws to regulate such potential conflicts, in part by reducing the number of laws to fewer, but more general, principles, and to elucidate how these laws interact. What is important in this reduction process will be to retain the detailed, phenomenal level of the original laws at the 'parent' level, not to blur them into more general but less precise statements. Each subsequent set of laws should then be explained by (or reduced to a meta-level of) meta-laws that are derived from the parent and permit rebuilding it. The following section is an attempt to formulate a set of such meta-laws, but it is far from definitive. Because they represent new super-ordinate principles, the phenomenological language needed to describe them is also new, at least in places.

10. THE FIGURALITY SPLIT–UNION META-LAW OF EMERGENT THINGS

In general, a law allows the prediction with a certain precision of what happens under specified conditions. This was the aim of the ten figurality laws. However, in section 6, it was shown how difficult it is to predict exactly how the coloration should appear when the figure–ground effect is dissociated from it and, vice versa, how the figure–ground effect should appear after dissociation from the coloration. It is even more difficult to predict exactly the phenomenal result when the four effects, including the object–hole and the illumination effects, are reciprocally dissociated, as they cannot be completely disjoined without changing or losing their properties and, more importantly, without losing the new properties emerging through their union. As a consequence it can be much more interesting to understand, and define with meta-laws, how these effects create integrated properties, so that the resulting effects are 'explained' through the emergent qualities and objects.

If it is difficult to predict the exact appearance created by a specific effect, especially if multiple percepts are possible, still, the phenomenal structure common to a set of specific effects or stimuli can be determined. Such a structure has to describe the variability of appearances as well as the central tendency. We attempt next to specify the existence and nature of such variability by appealing to some 'meta-laws'. These will indicate which of the ten figurality laws is dominant, and which modulatory, and in which conditions. The specific meta-laws are somewhat speculative, but they illustrate the potential of laws at this level. Several meta-laws governing the phenomenal variability within the laws of figurality are now suggested.

Meta-law 1: Stimulus variations split in two independent and opposite phenomenal components: one component ('invariant') is perceived not directly but amodally, while the other ('variant') is perceived directly and modally. The one component acts to discount or annul the variations, while the other subsumes all the variations and attributes them to a different 'thing'.

We call this the 'split meta-law'. The first component is represented, for example, by the amodally perceived homogeneous blue color of the fish bone in Fig. 12, which is obtained by discounting the dark and bright variations among the lines of the gradient and the inner white region. The second component is represented by the directly perceived bright light, which in some sense 'explains' the variations by attributing them to the effects of lighting, in particular becoming responsible for the illumination and discoloration of the blue homogeneous surface color of the fish bone.

These examples show that the split both creates two independent emerging things', i.e. the color of the object and the lighting, and creates two 'things' that are strongly united and mutually dependent. The term 'thing' represents a perceived entity or quality that is not fixed or cannot be named specifically for all cases but can indicate a large number of properties or emergent objects. The following meta-law defines the union between the split components.

Meta-law 2: The invariant and variable components emerging from the split meta-law are mutually dependent. They reinforce their role reciprocally and join together like the two sides of the same phenomenal reality at a higher level.

We call this the 'union meta-law'. Within the previous examples, the perceived bright light determines the perception of a specific color which in its turn reinforces the perception of the bright light. They are like two sides of the same illuminated 3D perceptual reality. So, they are inseparably united, in that: they are integrated and segregated at the same time; one exists only by virtue of the other; they cannot be dissociated or disconnected without changing; one cannot be phenomenally changed without changing the other; and, finally, they contribute together to create the 3D perceptual reality. In these terms, the paradox suggested by the words 'split' and 'union' is only apparent; in fact they refer to different things belonging to different perceptual levels: modal/amodal; direct/indirect (the gradient and the lighting); and level/meta-level (the light 'talks about' the object, that in its turn 'talks about' the light). This basic relationship is described by the next meta-law.

Meta-law 3: The union between the split components requires that a certain variation of one component is counterbalanced by the contrary variation of the other component.

We call this the 'constant ratio meta-law'. By increasing the lighting intensity within the fish bone the coloration decreases. Variations from this constant ratio have to be reconsidered through the previous meta-laws, thus creating a new set of emerging constant and variable sides. The emergence of new 'things' is the topic of the next meta-law.

Meta-law 4: The two sides of the split–union meta-laws, that is, the amodal (invariant) and indirect (variant) 'things' emerging from the split–union process, are able to 'explain' the variations within the stimulus. In other words, the emergent 'things' can discount, simplify, regulate, and predict the variations within the stimulus.

We call this the 'meta-law of emergent things'. To illustrate this meta-law, the perceived lighting of Fig. 12 'explains', in the sense that it 'defines' or 'rules over' the variations within the luminance gradient and the inner white region, thus determining the surface color of the fish bone. Similarly, the amodal color of the object 'explains' the perceived gradient and the properties of the lighting. Both lighting and color are emergent things, not directly present within the stimulus pattern but the result of a meta-process.

These emergent things are only two among many others that in their turn emerge through the same rules and from the same stimulus pattern. Others things are: the boundary line that separates the object from the empty background, the shadow, the lighting line, the backlighting, the object–hole segregation, etc. The coexistence of so many emergent things suggests the next recursive meta-law.

Meta-law 5: Each stimulus variation is subjected to Law 4, the split–union meta-law of emergent things, thus creating, for each variation, pairs of emergent things that are nested one inside the other and are globally and recursively ruled by the same Law 4.

This meta-law implies that two emergent 'things', like the hole (the constant side) and the object (the variable side), are nested inside another emergent thing, the boundary line, which is nested inside the shadow, and so on. The variations are respectively the highest luminance contrast with respect to the region that appears as an empty background, the highest luminance contrast with respect to its juxtaposed line, the juxtaposed lines among them, and so on. What is interesting in this law is that, due to the recursive and nested process, the emergent things usually do not contradict one another and do not create any perceptual paradox. Studies, aimed at understanding under which conditions paradoxical things do emerge, are in progress.

These meta-laws are reminiscent of the phenomenal scission (*Spaltung*) suggested by Gestalt psychologists (Koffka, 1935; Metzger, 1954, 1963, 1975). However, like the laws of figurality, they are aimed at continuing and enlarging the Gestalt work within the context of figurality and the phenomenal and neural processes of the formation of emergent 'things'.

11. CONCLUSIONS

In this work we have reported new cases of the watercolour illusion and introduced new effects, like the lighting and the backlighting effects, suggesting what we called laws and meta-laws of figurality. By defining the conditions of the luminance gradient profiles across boundary contours, these laws define the 'figurality': the color and the volume of the object with lighted and shaded regions, and the direction and the color of the light emerging from the object. Furthermore, the definition of the figurality laws and meta-laws in these terms may provide key insights into the neural mechanisms underlying the problem of figurality.

The relative separation between the coloration and figural effects studied in Section 6 suggests the existence of parallel but strongly related mechanisms. The FACADE model (Grossberg, 1987a, b, 1994, 1997) posits that boundary grouping and surface filling-in processes can explain the two effects in the watercolor illusion. They are substantiated by the cortical interblob and blob streams, respectively, within cortical areas V1 through V4. These boundary and surface processes show complementary properties (Grossberg, 2000) and their interaction generates a consistent perceptual representation that overcomes the complementary deficiencies of each stream, acting on its own. Boundary and surface processes are modeled by the Boundary Contour System (BCS) and by the Feature Contour System (FCS), (Cohen and Grossberg, 1984; Grossberg and Mingolla, 1985a, b; Grossberg and Todorovic, 1988).

The figures illustrated and the laws described suggest that most of the basic information about the figurality resides in the boundaries and, more specifically, in the luminance gradient peculiar to these illusions. Recent findings (Zhou *et al.*, 2000; Friedman *et al.*, 2003; von der Heydt *et al.*, 2003) showed that neurons in V2 respond with different strength to the same contrast border, depending on the side of the figure to which the border belongs, implying a neural correlate process linked to the unilateral belongingness of the boundaries. Several findings showed that figure–ground segregation may be processed in areas V1 and V2 (Zhou *et al.*, 2000; von der Heydt *et al.*, 2003; Friedman *et al.*, 2003), in inferotemporal cortex (Baylis and Driver, 2001) and the human lateral occipital complex (Kourtzi and Kanwisher, 2001). Zhou *et al.* (2000) reported that approximately half of the neurons in the early cortical areas are selective in coding the polarity of color contrast, e.g. a neuron may respond to a red–gray border, but not to a gray–red border. Von der Heydt and Pierson (2006) suggest that not only the figure–ground segregation, but also the color tint of the watercolor illusion might have its explanation in the cortical representation of borders.

The laws of figurality and, more particularly, the meta-laws go further by suggesting a possible neural scenario where multiple juxtaposed lines may stimulate neurons, selective for different asymmetric luminance profiles and signaling not only the unilateral belongingness of the boundaries and the coloration effect but also the volumetric and the illumination effects. Due to the gradient variations at different scales, it can be suggested that these neurons, at the beginning undifferentiated, become more and more specialized by assuming different roles (for example, the role of boundary or lighting lines) but at the same time becoming part of a more global integrated process described in Meta-law 2. This specialization and integration process may be possible in terms of neural processing stages, where invariant and variant components of the stimulus at different scale are organized through mechanisms that trace the phenomenal structure reported within the meta-laws. More particularly, on the basis of the split–union meta-law, it can be conjectured that variations within the stimulus pattern stimulate the same set of neurons at different scale, among which some annul or discount the variations by minimizing them and some signal those variations. These opposite processes may depend on the fact that some cells signal stimulus variations at a specified scale that are not necessarily variations at a different scale (more local or global) but invariants. All these different signals (local *vs.* global), signaling or annulling stimulus variations, are integrated at a global processing stage making them to perceptually coexist within a whole ‘thing’ and to assume specialized properties and roles. All of them define synergistically the emerging thing at different levels and through different specific roles (boundary line, etc.) assumed by each component. Thus, even if these neurons signal pairs of local vs. global emergent components, constant and varying at different scales, they are integrated through a neural mechanism that is the correlate of the union meta-law and that make them becoming inseparably united and reinforcing one another.

Beyond the last conjectures just sketched out, the nature of the neural correlates of the laws and meta-laws of figurality needs to be reconsidered and deepened especially with reference to the emergent effects: what they really are and how they emerge from lower processing levels. Nevertheless, the advantage of the laws and meta-laws of figurality is that they suggest precise questions and experiments in phenomenology, psychophysics and neurophysiology that prelude to find out precise processes and mechanisms. This is due to the fact that our laws are not '*ceteris paribus*' laws like the Gestalt ones, i.e. they do not concern a list of properties (like proximity, similarity, surroundedness, etc.) useful to predict the perceptual results only when everything else is equal (see Palmer, 1999), but they provide phenomenal integrated dynamics and processes underlying whole and emergent properties that can be translated in terms of neural mechanisms. Furthermore the phenomena and the laws here shown can be interesting to: understand processing strategies centered around the problem of a 3D interpretation of 2D images (see also Zhou *et al.*, 2000; von der Heydt *et al.*, 2003; Friedman *et al.*, 2003); suggest combinations of mechanisms that also explain other phenomena (e.g. brightness and lightness induction, neon color spreading, see Pinna and Grossberg, 2005), but with a unique contextually-driven balance of the same mechanisms; determine the role of the new principles relative to the classical gestalt principles; study how coloration, figure–ground, object–hole and illumination effects are related depending on boundary conditions; clarify how the watercolor, lighting and backlighting illusions increase the figural strength of a region by creating an unambiguous and unilateral direction of the margins much stronger than in the gestalt figure–ground principles, and, finally, stimulate the study of neurons selective for some gradient border ownership cues, but not others (see also Zhou *et al.*, 2000; von der Heydt *et al.*, 2003; Friedman *et al.*, 2003).

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NOTES

1. It is reasonable to think that figure–ground segregation must operate before grouping (Hoffman and Richards, 1984; Palmer, 1999). For example, the line elements on which grouping acts must be already segregated as a figure from the ground, otherwise the visual system would not know which regions to group. However, lines do not possess the figural properties of holistic organized and segregated figures; rather, they appear as elementary components necessary to

create boundaries. Thus the lines creating the luminance gradient of (say) Fig. 12 should first be grouped to become the boundary of the fish bone, but they do not manifest figural properties: they are not surfaces, but something like perceptual 'bricks' necessary to create something more holistic. We therefore do not commit ourselves to the view that grouping must always precede segregation at the processing level. Instead we consider this as a phenomenological order between the two dynamics, grouping and figure–ground segregation, when defining the role and the place of figurality in a perceptual world built up by grouping and figure–ground segregation. Thus, we are concentrating on what the Gestalt laws state (which is phenomenological) rather than on their causal status. What the reader needs most is concrete examples to set the Gestalt laws against the 'laws of figurality' to see how they really differ.

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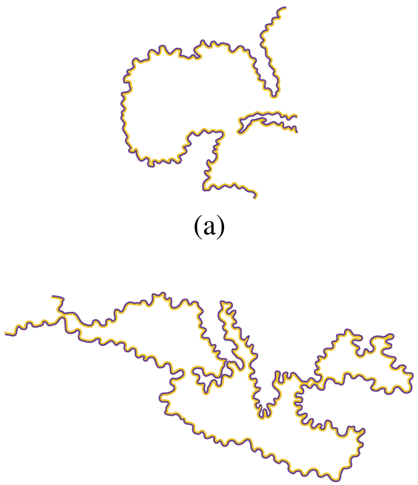
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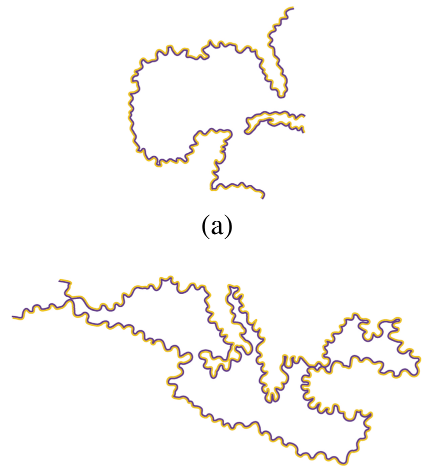
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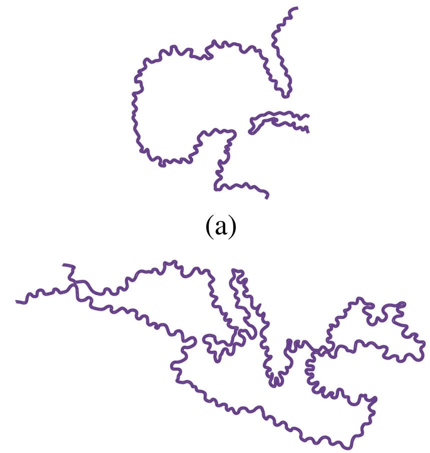
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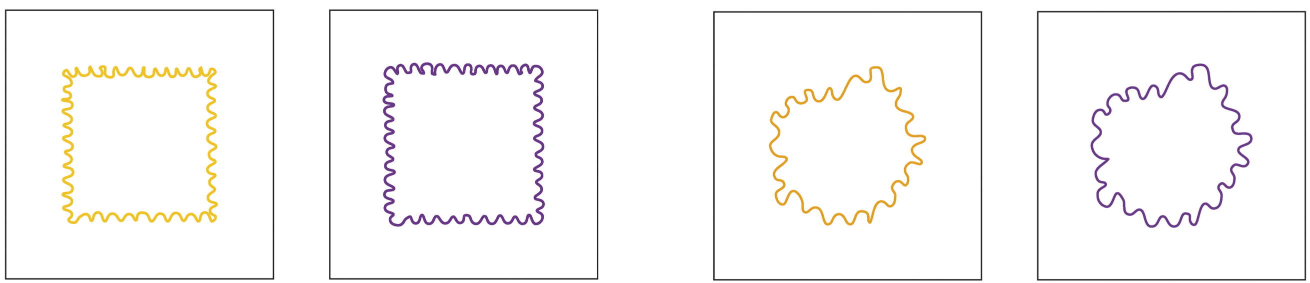
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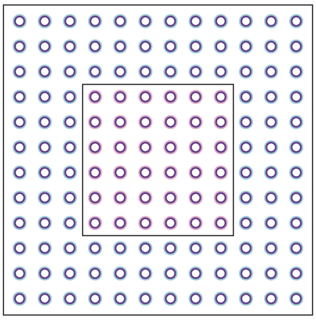

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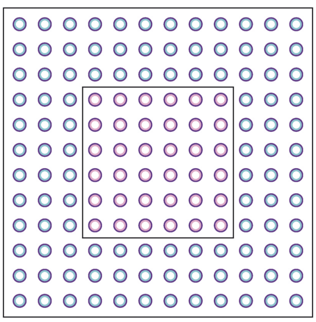

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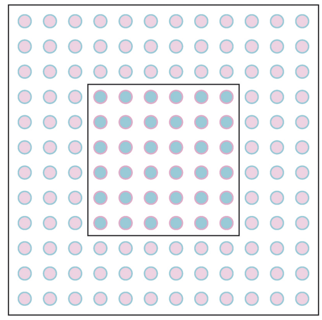

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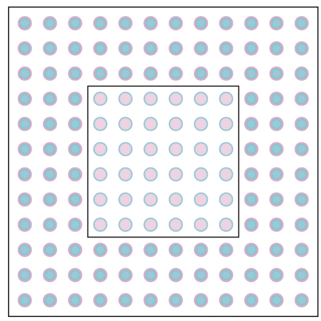

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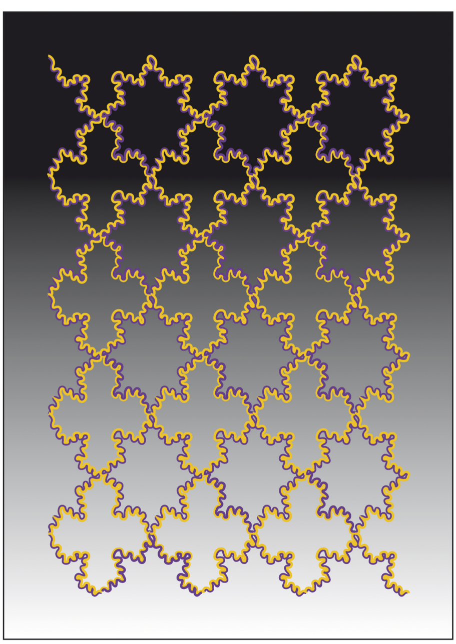

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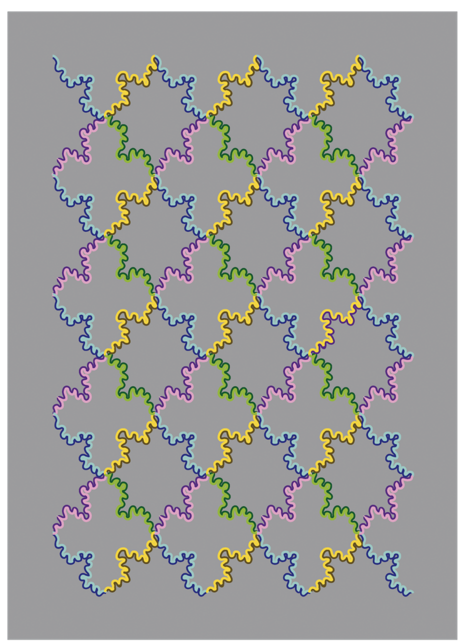

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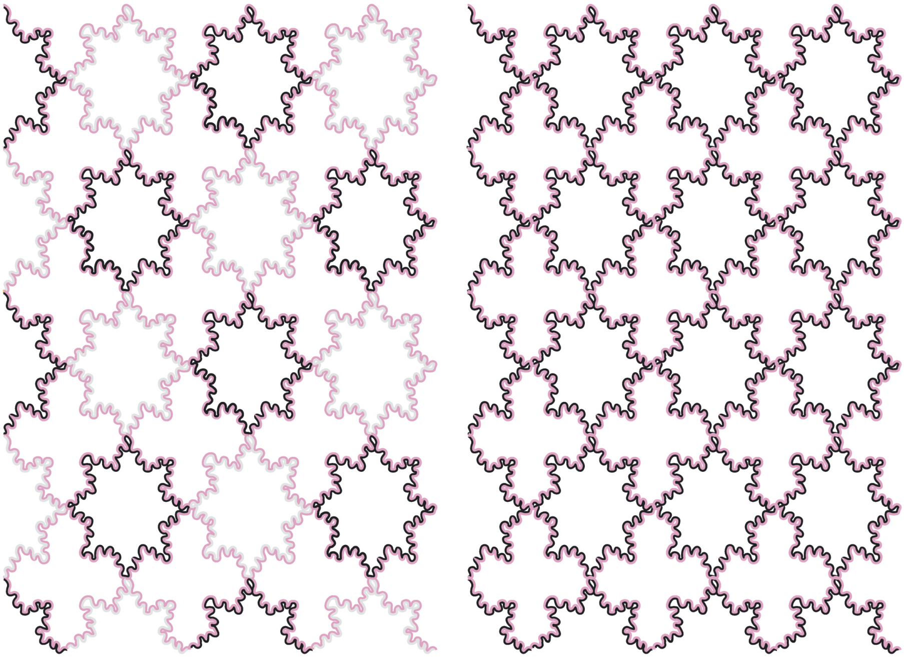

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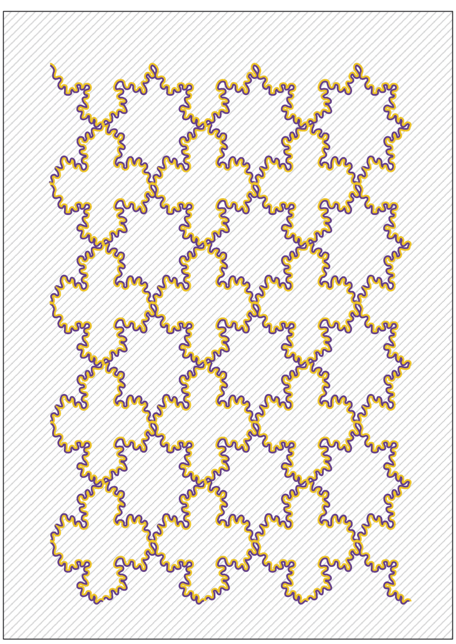

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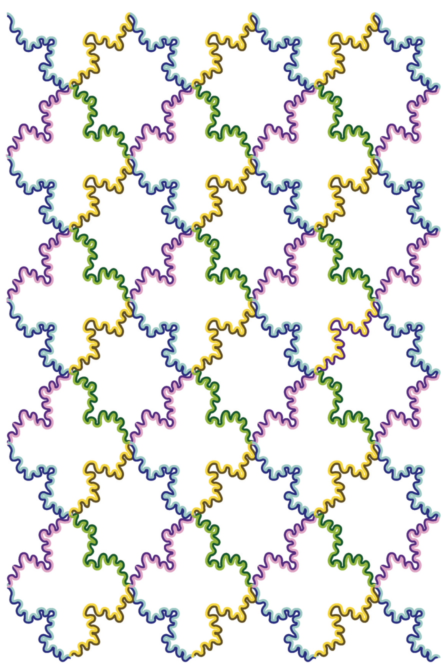

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Pinna and Reeves, Figure 13.

(a) (b)

Pinna and Reeves, Figure 14.

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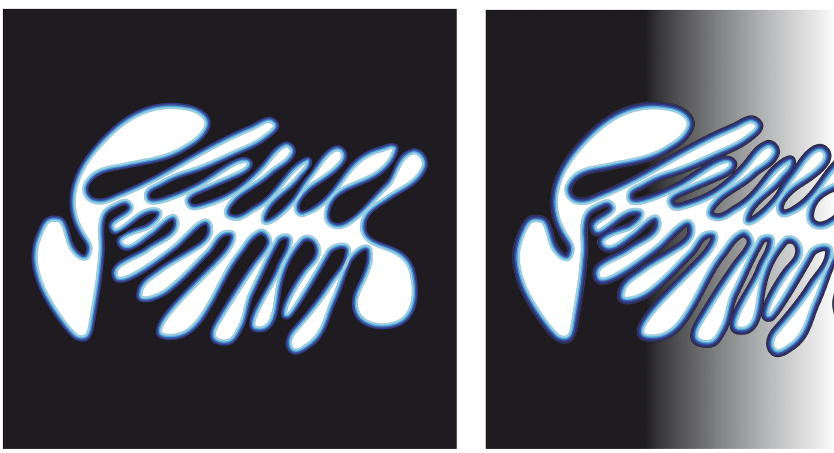

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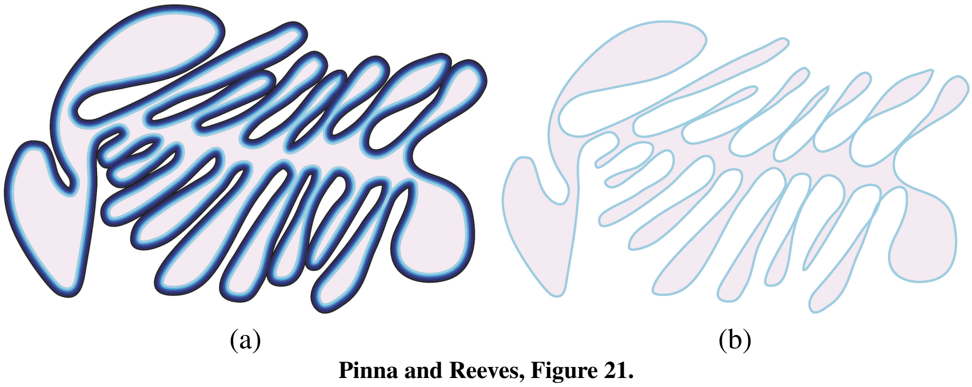

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