# Perceptual organization reconsidered in the light of the watercolor illusion: The problem of perception of holes and the object-hole effect

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The watercolor illusion is a long-range color assimilation (coloration effect) imparting a figure-ground segregation (figural effect) across large enclosed areas (B. Pinna, 1987; B. Pinna, G. Brelstaff, & L. Spillmann, 2001; B. Pinna, L. Spillmann, & J. S. Werner, 2003; B. Pinna, J. S. Werner, & L. Spillmann, 2003). The watercolored figure has a very poorly reversible or univocal figure-ground segregation and strongly enhances the unilateral belongingness of the boundaries (E. Rubin, 1915), a principle stating that the boundaries belong only to the figure and not to the background. The figural effect determines grouping and figure-ground segregation more strongly than the well-known Gestalt principles. Under watercolor conditions both the figure and the background assume new properties becoming respectively bulging object and hole both with a 3-D volumetric appearance (object-hole effect). Our purposes were: (i) to demonstrate that the hole induced by the watercolor illusion has unique figural properties comparable to those of the object and not present in the background induced by the known figure-ground principles; (ii) to demonstrate a dissociation of the object-hole effect from the coloration one; (iii) to demonstrate that the object-hole effect depends on a new principle. This was psychophysically tested by weakening (ungrouping) the whole figural organization of the watercolor illusion, i.e. by imparting motion to only some components of a stimulus, while other components remain stationary. The results showed that (i) subjects perceived moving holes more strongly than moving figures or objects enlarging and shrinking. (ii) Paradoxically, moving holes appear more as figures than the bulging surfaces. (iii) When motion was imparted to components that while stationary were perceived as objects, their figurality is further enhanced (summation effect). (iv) When object-hole and coloration effects were dissociated no significant difference compared to illusory colored conditions was reported. Coloration can be considered independent from the object-hole effect of the watercolor illusion. The object-hole effect may depend on the "asymmetric luminance contrast principle" (B. Pinna, 2005).

Keywords: color vision, perceptual organization, watercolor illusion, figure-ground segregation, object-hole effect, figurality, hole perception

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## Introduction

### From the boundaries to the watercolor illusion

In Figure 1, an irregular wiggly purple contour going from right to left several times is mostly perceived like «two peninsulas going from left to right with a mainland at the bottom or alternatively like two peninsulas going from right to left with the mainland at the top».[1] These two results can be easily reversed by switching the visual attention from left to right or right to left directions.

They depend on perceptual organization. The problem of perceptual organization is one of the central topics of visual perception. Wertheimer (1912a, 1912b, 1922, 1923) approached the problem of perceptual organization in terms of grouping. Through a set of phenomenological experiments, he suggested some 'grouping principles' that answer the following questions: how do the elements in the visual field 'go together' to form an integrated, holistic percept (Gestalt)?

Figure 1 shows the peninsulas as a form of grouping depending on the relative proximity among contours (proximity principle). Also the "good continuation" of the contours contributes to the perception of the peninsulas and particularly to the separation between the two sets of peninsulas going from left to right and from right to left.

The perceptual organization includes not only the problem of grouping but also the problem of figure-ground segregation. According to Rubin (1915, 1921), a figure—and then each of the phenomenal results perceived in Figure 1—shows the following properties. (i) It

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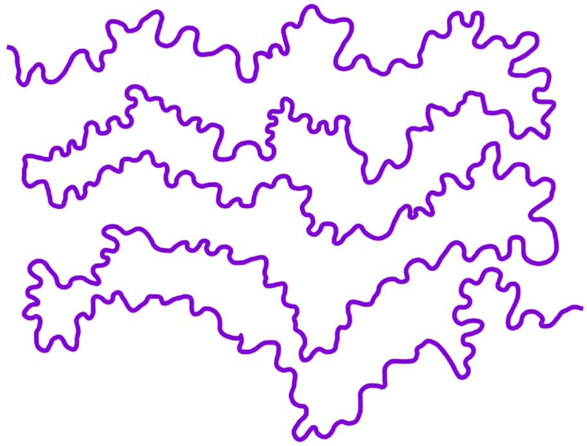


Figure 1. An irregular wiggly purple contour going from right to left several times is mostly perceived like two peninsulas going from left to right with a mainland at the bottom or alternatively like two peninsulas going from right to left with the mainland at the top.

appears closer to the observer than the ground that lies behind. This property suggests that figure-ground segregation is related to depth perception. (ii) The color of a figure appears denser (surface color) than the same color on the ground that appears instead empty and transparent. (iii) A figure assumes the shape traced by the contour. This property implies that the contour belongs only to the figure, but not the ground on the other side of the contour and is called "unilateral belongingness (*Zusammmengehörigkeit*) of the boundaries", also termed "border ownership" by Nakayama and Shimojo (1990). Rubin (1915, 1921) suggested several principles of figure-ground segregation: surroundedness, size, orientation, symmetry, convexity, and parallelism. All of them synergistically contribute to the perceptual results of Figure 1. The reversibility between the two results is due to the instable equilibrium of the principles of grouping and figure-ground segregation applied to the complementary regions (peninsulas) of Figure 1.

The purple contours of Figure 1 are symmetrical in the luminance profile on both sides. However, as it was first noticed by Rubin, the process of figure-ground segregation induces a *phenomenal* asymmetry in the properties of figurality, i.e. depth, color and unilateral belongingness of the boundaries. This asymmetry depends uniquely on the figure-ground principles. In Figure 2, the luminance profile on both sides of the boundary contours is *physically* asymmetrical: the thick purple contour of Figure 1 is split in two juxtaposed contours, purple and orange, of different luminance. This asymmetrical luminance and chromatic profile strongly enhances the figure-ground properties of Figure 1 and shows the Watercolor illusion (Devinck, Delahunt, Hardy, Spillmann, & Werner, 2005; Pinna, 1987, 2005; Pinna, Brelstaff, & Spillmann, 2001; Pinna & Grossberg, 2005; Pinna, Werner, & Spillmann, 2003; Spillmann, Pinna, & Werner, 2004; Von der Heydt & Pierson, 2006; Werner, Pinna, & Spillmann, 2007; Wollschläger, Rodriguez, & Hoffman, 2002).

In Figure 2, the purple undulated contour flanked by the orange edge is perceived as «two peninsulas going from left to right connected to the mainland on the bottom evenly colored by an opaque light veil of orange tint with a clear surface color property» (*Erscheinungweise,* Katz, 1930) spreading from the orange edges. This is what we called "coloration effect" of the watercolor illusion (Pinna, 2005). «The peninsulas appear like rounded surfaces segregated in depth extending out from the flat surface and with a solid figural appearance comparable to a bas-relief illuminated from the top». «The complementary regions appear as empty spaces with phenomenal figurality properties comparable to holes». This is the "object-hole effect" of the watercolor illusion (Pinna, 2005), phenomenally related to shape-from-shading (Pinna, Werner et al., 2003; Spillmann et al., 2004) and Renaissance Chiaroscuro (Pinna, 2005; Pinna & Reeves, 2006), and, given the simple limiting conditions of this effect, preceding them.

By reversing purple and orange contours of Figure 2, the figure-ground segregation is reversed: «two peninsulas going from right to left connected to the mainland at the top» (Figure 3). It is worthwhile noticing that the two sets of peninsulas of Figures 2 and 3 appear unrecognizable as derived from the same contour illustrated in Figure 1. This is due to the peculiar phenomenal properties of the "figurality", induced by the watercolor illusion, which refer to the 3-D 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.

By comparing Figures 1, 2, and 3, several properties useful to understand both grouping and figure-ground

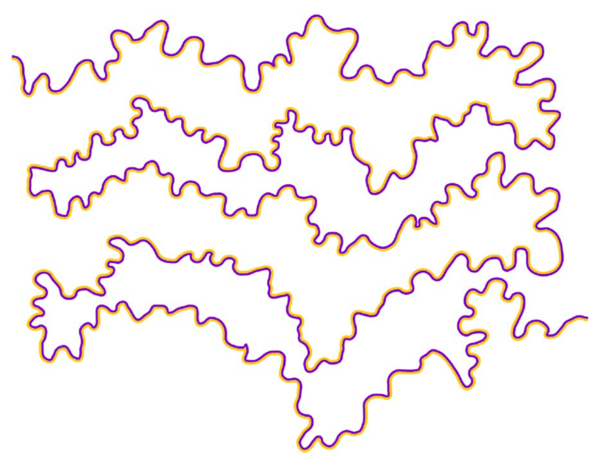


Figure 2. *The watercolor illusion*: The purple undulated contour flanked by the orange edge is perceived as two peninsulas going from left to right connected to the mainland on the bottom evenly colored by an opaque light veil of orange tint with a clear surface color property.

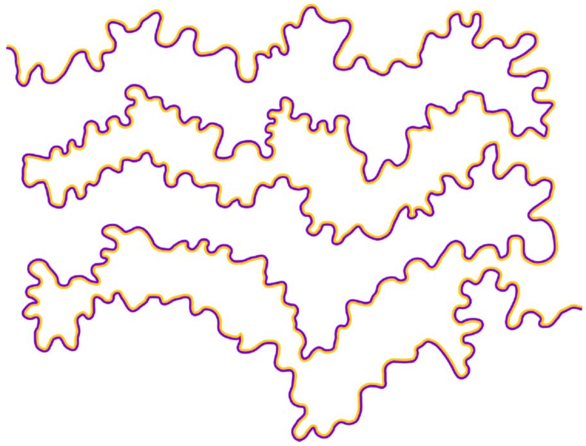


Figure 3. By reversing purple and orange contours of Figure 2, the figure-ground segregation is reversed: two peninsulas going from right to left connected to the mainland at the top. It is worthwhile noticing that the two sets of peninsulas of Figure 2 and this figure appear unrecognizable as derived from the same contour illustrated in Figure 1.

segregation emerge. In Figure 1, the figure-ground organization can be easily reversed, the figural properties identified by Rubin can be perceived and both the coloration and the volumetric figural effects distinctive of the watercolor illusion are almost absent. These results reveal clearly a phenomenal distinction between figure-ground and object-hole segregation. While the former is referred to the classical Rubin's figures as illustrated in Figure 1 having a flat 2-D appearance, the latter is defined by the emergence of the figure as a solid 3-D object and of the empty space comparable to a hole (see Pinna & Reeves, 2006). In summary, by creating an asymmetrical luminance and chromatic profile on the two sides of a contour, Rubin's figurality strongly increases and the object-hole and coloration effects emerge. The main properties of the two effects are described in detail in previous works (Pinna, 1987, 2005, 2008; Pinna et al., 2001; Pinna & Grossberg, 2005; Pinna & Reeves, 2006; Pinna, Spillmann, & Werner, 2003).

## Different kinds of principles of perceptual organization

The phenomenal properties of the coloration and the object-hole effects raise some remarks useful to better understand the problem of perceptual organization. The gestalt principles of grouping and figure-ground segregation do not depend on the same local or global conditions, but can be shared in different sets. Principles like proximity, surroundedness, size, convexity, symmetry, and parallelism put together and favor the figure-ground segregation of elements placed at a certain distance on the basis of these properties. The principle of common fate affects perceptual organization through motion imparted among the elements that group when they move in the same direction. Somehow the previous principles can all be included within the similarity principle, but similarity gets over their limits to consider more subtle properties like differences in color, size, orientation and more. Prägnanz handles whole properties of the shape like singularity, symmetry, order, and simplicity. Past experience considers the elements to be grouped by virtue of a totally new perspective closer to cognitive and meaningful properties.

By comparing and pitting the watercolor illusion against these principles, it was suggested that the watercolor illusion can be considered as the result of a new principle of grouping and figure-ground segregation (Pinna, 1987, 2005; Pinna et al., 2001; Pinna, Spillmann et al., 2003). This principle was called "asymmetric luminance contrast principle" (Pinna, 2005) and states that, all else being equal, given an asymmetric luminance contrast on both sides of a boundary, the region, whose luminance gradient is less abrupt, is perceived as a figure relative to the complementary more abrupt region perceived as a background. This figure-ground principle can also be expressed in terms of grouping.

On the basis of this principle, another property, never considered by gestalt psychologists—the luminance asymmetry on the boundaries—is introduced and appears to be decisive to determine grouping and figure-ground segregation. The high strength of this principle relative to all the gestalt ones demonstrates that most of the necessary information needed to define the figurality properties is placed on the boundaries and, more specifically, on the gradient surrounding and defining a perceptual object. This strong result can be understood in the light of Rubin's claims about the properties of figurality and, more particularly, on the basis of the unilateral belongingness of the boundaries. In fact, going back to Figure 1 we have seen that even where there is not a physical asymmetry on both sides of the boundaries, it is phenomenally created in any case. We can also say conversely that, any time the properties of figurality are perceived, a boundary asymmetry related to these properties is also perceived.

This asymmetry underlies and provides a depth cue that elicits the bulging effect similar to those of the luminance gradients that govern shape-from-shading (Pinna, Werner et al., 2003; Spillmann et al., 2004) and Renaissance Chiaroscuro (Pinna, 2005; Pinna & Reeves, 2006).

## The problem of perceiving a hole

The figurality on the boundaries related to the asymmetrical luminance profile can solve the problem of perception of holes that are special stimuli useful to study the perception of shape, and, particularly, border ownership. In fact, they can be considered as visual objects in between figure and background.

Palmer (1999) and others (Casati & Varzi, 1994; Feldman & Singh, 2005; Peterson, 2003; Subirana-Vilanova & Richards, 1996) demonstrated that holes imply quasi-figural properties, i.e. the inner region of the hole is perceived as a background, but it appears to have a shape through which the background can be seen. Palmer (1999) suggested the hole paradox: if holes are background, they should be shapeless, so how do we recognize the shape of a hole? If the contour is assigned to the surrounding object, the subjects shouldn't remember the shape of the hole. Palmer showed that observers are just as good at remembering the shape of a hole as at remembering the shape of a figure. This result goes against the unilateral belongingness of the boundaries. To solve the paradox Palmer suggested that, when an observer perceives a hole, he remembers a description of a shape that is similar to that of its solid complement but with a label that indicates that it is an empty surface. Therefore the shape of the hole is encoded with the shape of the object but with a "missing" or "empty" label that signals the absence of surface.

Bertamini (2006) suggested two solutions that could explain why people perceive the shape of a hole. The first solution is that the visual system could use different strategies to analyze figure-ground organization. But this does not seem to apply to holes because when we perceive holes we do not experience multistability, as we do with Rubin's Face/Vase. The other possibility is that when the visual system analyses the contour curvature of a shape, it registers the sign of both sides of the shape as being completely opposite, thus implying that the two sides analyzed are complementary. This would explain how people remember the lock-and-key match of two shapes.

One important critique to the previous results is that they are not directly related to the unilateral belongingness of the boundaries but emerge from a memory task (Bertamini, 2006). We think that the best way to demonstrate the figural properties of the holes is through clear visual phenomena and in the pure phenomenological domain.

Other findings suggest that holes behave like the other background regions (Bertamini, 2006; Bertamini & Croucher, 2003; Bertamini & Hulleman, 2006; Bertamini & Mosca, 2004; Hulleman & Humphreys, 2005). Bertamini and Croucher (2003) and Bertamini and Mosca (2004) starting from Gibson's claim that it is easier to judge the position of convex vertices than that of concave ones. They used two shapes called barrel and hourglass. The task was to look at the vertices on the outside and decide whether the left or the right vertex is lower. Responses were faster when the barrel is a figure and slower when the barrel is part of the background. Conversely, responses were faster when the hourglass is part of the background than when it is a figure. Bertamini and Croucher concluded that the contour belongs to the object and not to the hole, and that the object determines the shape of the hole. Hulleman and Humphreys (2005) reported similar results. By using a visual search task, they found that searching among objects was easier than searching among holes. They concluded that the hole is not immediately encoded as a figure with its own shape, and that the contour is assigned to the object rather than to the hole. In other experiments Bertamini and Hulleman (2006) imparted motion to circular objects and holes independently. Their results support the claim that the contour of a hole belongs to the object that surrounds it and that the hole is part of the object-with-hole. They suggest that contour ownership is incompatible with accretion/deletion on the figural side of the contour. It seems that observers introduced an owner of the contour (a lens or a spotlight) that moves with it, and that the hole cannot be the owner of the contour. If the contour belongs to the hole, the observers should perceive a hole that moves independently from the object with hole, but they perceive a lens because there is accretion/deletion in the non-owned side of the contour. The lens explains the problem of independent motion of the "hole." In fact, a lens, unlike the hole, is not a feature of the object with hole; therefore, if it is in front, the foreground should be visible behind it.

The appearance of surfaces seen through visual holes is a special case of amodal completion in which contour information is absent. Bertamini and Hulleman (2006) found no support for the idea that the surface behind a hole takes on the shape of the complement of the hole. Observers found it difficult to judge the extension of the surface for which there was no contour information.

All these results are based on conditions different from the watercolor illusion. We suggest that the object-hole effect of the watercolor illusion, where both the figure and the background assume new properties becoming respectively bulging object and hole both with a 3-D volumetric appearance, can cast a new light useful to solve the problem of holes. The hole induced by the watercolor illusion is more than something in between figure and background. To clarify this distinction, in Figure 4a the perception of the hole depends on the presence of the outer square surrounding it and appearing as the surface that contains the hole. The boundaries belong to the hole and at the same time to the complementary region. By removing the outer square, the hole becomes a «wiggly square» (see Figure 4b). It loses the phenomenal property of being a hole.

Under watercolor conditions even a hole alone can assume a figure status. In fact, unlike the purple-only condition of Figure 4, the purple-orange one can elicit a hole without surrounding object (Figure 5a), where the subjects perceived «a hole having the shape of a wiggly square». The surrounding surface without external boundaries is created by the perception of the hole whose shape surrounds an empty space. In other words, the hole creates the surface and the boundaries of the hole are like the perimeter of an empty space. Therefore, the phenomenology of a "hole" differs from the "figure status of a hole"

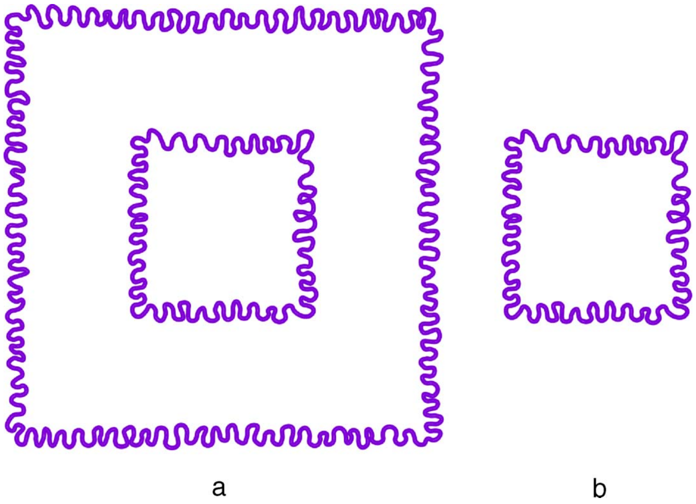



Figure 4. The perception of the hole depends on the presence of the outer square surrounding it and appearing as the surface that contains the hole (a). By removing the outer square, the hole becomes a wiggly square (b).

emerging from the watercolor illusion. The inner component of Figure 4a can be considered as "hole without figure status." The notion, here introduced, of "figure status of a hole" goes beyond the main definition of a hole, where a closed surrounding object is required and suggests that the boundaries delimit the hole that can be perceived as an empty space with a shape.

This phenomenal result is not in contradiction with the unilateral belongingness of the boundaries. In fact, in Figure 5a, the perception of the hole shows clearly that the boundaries belong to the outer region, but, meanwhile, the same boundary contours define the hole as an object and, conversely, that specific object as a hole. In other words, the same contours define two complementary objects at the same time. There is a complementary and reciprocal formation and belongingness: the perception of the hole induces the perception of the surrounding region that determines its inner edges to appear like an empty space perceived through a hole. (Compare these results with Figure 5b.)

It follows that the strong object-hole effects related to the watercolor illusion contain a paradox and can create other extreme and consequent paradoxical phenomena. In the light of the watercolor illusion, the hole paradox can be rephrased in these terms: if the hole appears as an empty space with a shape, where the boundaries belong to the hole and, at the same time, to the complementary region, then the hole can be perceived as a background that is a "figure" emerging from a surrounding figure behaving as a "background." If this is true, then several paradoxical phenomena can be created where the holes behave both like figures and backgrounds at the same time (see Figure 6).

In Figure 6a, «the wiggly square appears clearly in front of the circle» that completes amodally behind it. This result is similar to the one obtained without the watercolor illusion, i.e. in a condition where both the two adjacent contours are purple (not illustrated). In Figure 6b, the square appears as «a hole» and the circle as «a circular sector». The amodal completion of shape is now totally absent despite the presence of the T-junctions responsible for the amodal completion of shape. In other words, the figural effect of the watercolor illusion annuls the role of T-junctions and wins against the amodal completion of shape. If the perception of the hole and of its boundaries annuls the amodal completion, then the boundaries belong to the hole. In Figure 6c, «a circular hole, upon a larger square hole», completing amodally «behind a solid square» is perceived. The watercolor elicits this special result totally in favor of its figural effect and against the one of the amodal completion of shape. It is worthwhile noticing that an inner hole is perceived on a large hole. In Figure 6d, a paradoxical effect is perceived: «a hole» completing amodally behind another hole». In Figure 6e, a more complex paradoxical effect can be perceived: «A circular hole, upon a larger squared hole, completing amodally behind a squared hole upon a circular hole and a squared hole».

These effects are reminiscent of Penrose's impossible figures. However, our phenomena depend on the fact that holes behave both like figures and backgrounds at the same time. Therefore, if the holes under watercolor illusion behave like objects with a figure status, then the previous conditions are only apparent paradoxes.

The figural property and figure status of the hole seems to be fully demonstrated through the effects on the amodal completion of shape. They also show that (i) the hole paradox considered in the watercolor acceptation can be perceived and it does not need to be solved, (ii) the figural effect of the watercolor illusion is independent from and stronger than the amodal completion of shape, and (iii) a

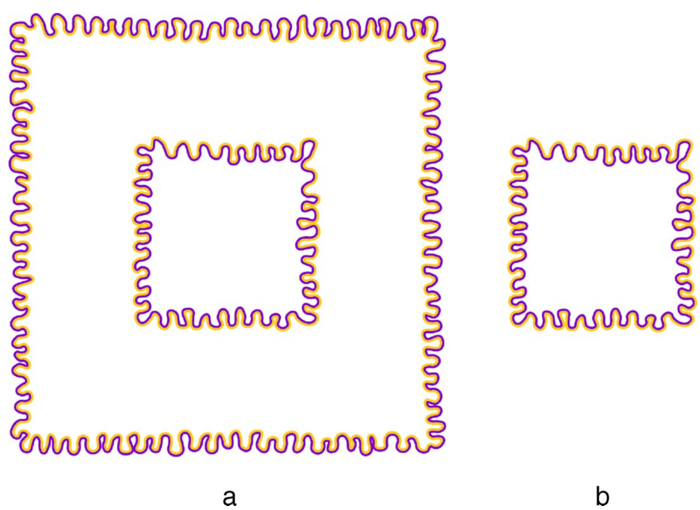



Figure 5. Under watercolor conditions even a hole alone can assume a figure status: A hole having the shape of a wiggly square (a). A control (b).

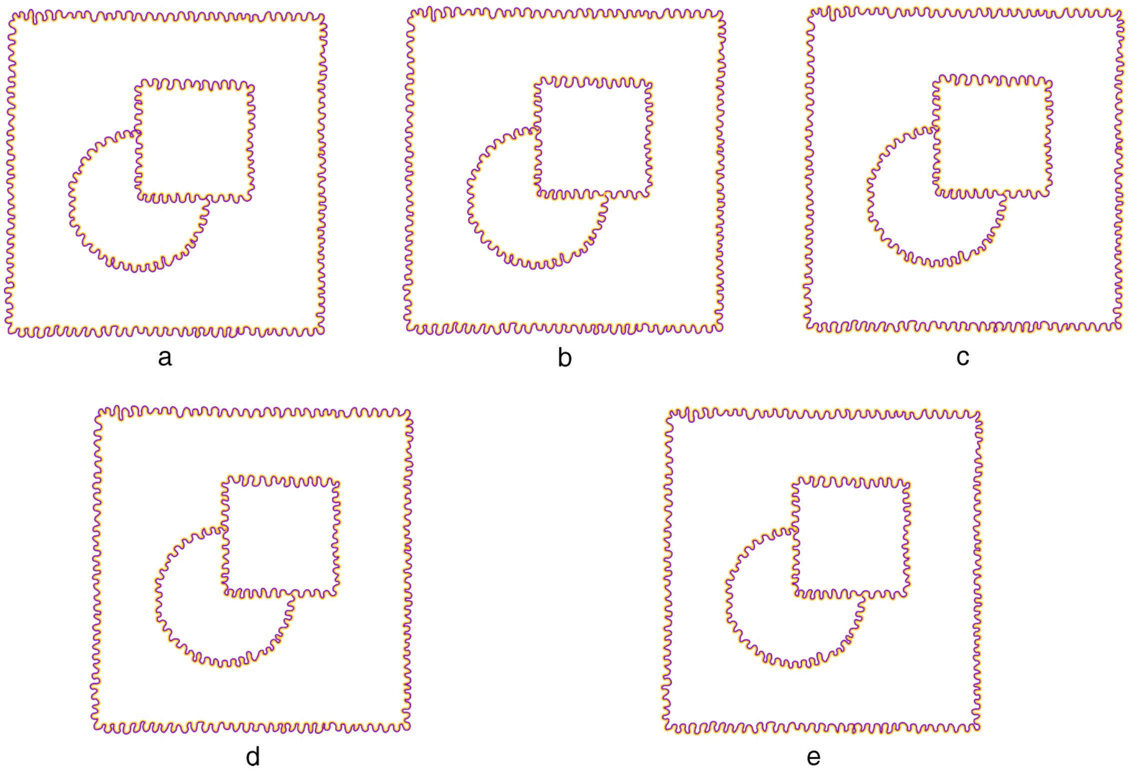



Figure 6. Through the watercolor illusion, several paradoxical phenomena can be created where the holes behave both like figures and backgrounds at the same time (see the text for more details).

hole takes on the shape of the complement of the hole, or, in other words, a hole behaves very similarly to the object-with-hole. These results also support the notion of amodal completion of color (Pinna, 2008).

There is also another way of demonstrating the figural appearance of a hole. Under watercolor conditions, if both the bulging object and the hole have a shape, then they compete to be perceived. Going back to Figure 5b, the main question is: is the perceptual result an object (i.e. a frame) without a hole, or a hole on an object (i.e. a square)? The belongingness of the boundaries of the frame is different from the one of the hole. In fact there is a specific size of the inner square of Figure 5b relative to the larger surrounding square that reveals the transition from the perception of the frame to the perception of the hole. This phenomenal switch is also accompanied by a more global phenomenal change involving the shape of the large square. More precisely, if the phenomenal result is “a frame” then the large square is not a square but the outer perimeter of the frame. The square loses its status becoming a frame. If the result is “a hole” then the large square is now perceived as a large square surface that in some way completes amodally behind the hole. In other words, the phenomenal description of “a square with a hole” shows that a square is amodally perceived even if there is not a square, and shows also a hole that is part of the square but, at the same time, something else eliciting the completion of the square. (This kind of amodal completion is called “amodal wholeness”. See Pinna, 2008). To conclude this argument: while the perception of the frame reveals the perception of only one object (the frame), the perception of a square with a hole reveals the perception of two objects or “things”: the square and the hole. Therefore, a hole takes over figural status. This phenomenological argument can be further strengthened by the following one.

It was already shown that the watercolor illusion and its underlying principle win against all the classical gestalt principles of grouping and figure-ground segregation. However, there is another property, moving vs. stationary, never considered as an independent principle of organization, but that can be considered as such. On one hand, it can be conceived as a special case of the common fate principle but it is not necessarily the same. The common fate principle states that, all else being equal, elements moving in the same way tend to be grouped together. It clearly emerges that the common fate principle is a grouping principle, while the moving vs. stationary is a figure-ground property. This is the main reason why they cannot be reduced to one. The moving vs. stationary figure-ground principle can be enunciated as follows: “all else being equal, moving elements appear as a figure, while the static elements appear as a background”. In other words, given a static condition with specific figure-ground organization, motion imparted to the figure or to the background can induce a figure status to it independently from the way it appears under static organization. In everyday life it is common that something that in a static condition appears as part of the background, becomes or emerges as a figure when it starts to move. This result is evident during camouflage, where a piece of surrounding environment through its motion pops out immediately as a visible organism. The motion vs. stationary principle is related to the primary kind of camouflage occurring when a prey animal stands stock-still to avoid predators. The same camouflage is used by predators to be able to sneak up on a prey. If camouflage is a form of deception, the moving vs. stationary principle is exactly the opposite. Camouflage contains this principle in the sense that one is the opposite of the other. Therefore, if the stationary condition elicits the camouflage, then the motion instills figurality.

The moving vs. stationary figure-ground principle is a very intuitive idea of figure-ground segregation. However, it was never mentioned as such in the theoretical context of the perceptual organization principles. Furthermore, it was never considered as independent from the common fate principle. Finally, it was never pitted against other principles like we will do in this work (see next Section). For these reasons we consider it as a new principle of figure-ground segregation with the same status of the classical ones.

By imparting motion to the outer or inner squares of Figure 4a, the figural organization, eliciting either the frame or the hole, is expected to be broken: the moving component segregates from the static ones to appear more strongly as a figure. In other words, if, under static conditions, the inner element is perceived as a frame, a hole or a background, by moving it (translating, rotating, appearing and disappearing randomly in different spatial locations), the perception of both the frame and the hole should be strongly weakened, and the inner element should acquire figure status becoming a moving inner small square upon a large square (to see the phenomenal outcome click Movie 1 but first of all, under static conditions, force your attention to perceive a hole). The subjects reported that «by moving the inner hole it becomes immediately a square moving within a larger square» (see the Results and discussion section for more details).

The main questions are: If the watercolor illusion induces a strong figural property to the holes, are they still perceived when motion is imparted to them? Does the watercolor win against the motion vs. stationary principle of figure-ground segregation? The answer to these questions can make clear the strength of the moving vs. stationary principle compared to the one of the watercolor illusion and its principle of asymmetric luminance contrast. Is the object-hole effect still perceived when the surrounding frame and the inner hole are ungrouped by imparting to the components of the stimulus different motion status? By answering this question the role of both common fate and asymmetric luminance contrast principles are compared. Under watercolor conditions and in the light of the object-hole effect, does the hole have figural properties? Other more general questions are: In what sense does a hole differ from a background? In what sense has a hole the object status? Can objects and holes be independent? Can the object-hole effect of the watercolor illusion be dissociated from the coloration effect?

The purpose of the next experiment was:

1. to demonstrate that the hole induced by the watercolor illusion has unique figural properties not comparable to those induced by the known figure-ground principles and those of the moving vs. stationary figure-ground principle;
2. to demonstrate a dissociation of the object-hole effect from the coloration one;
3. to demonstrate the role played by the new principle of motion vs. stationary in figure-ground segregation.

# Methods

## Subjects

Fourteen (male and female) undergraduate students participated to the experiment. Subjects were naive as to the purpose and all had normal or corrected-to-normal acuity with normal color vision as assessed by the Ishihara pseudoisochromatic plates.

## Stimuli

The stimuli were composed of figures like those illustrated in Figures 7a–7d and varied as follows. *Condition (i)—Figure-ground (control)*: both the two juxtaposed contours are purple like in Figures 1 and 4. This condition represents the control for the watercolor one ruled only by the classical gestalt principles of organization. *Condition (ii)—Watercolor illusion*: both contours are purple and orange like in Figure 7 with the inner components perceived as empty spaces or holes. *Condition (iii)—Watercolor illusion reversed*: both contours are orange and purple with the inner components perceived as volumetric objects. The conditions of Figure 7e were the same as before—conditions (i), (ii), and (iii)—but instead of one orange fringe, four different kinds of colored fringes were used within the same component (star or cross): orange, red, blue and green.

In Figure 7a, the frame vs. hole can be alternatively perceived and switched through attention. By imparting motion to different components of this stimulus, the square-hole and frame-empty space organizations can be broken. A variation of this stimulus was also tested: the inner square alone. In Figure 7b, the perception of holes is easier than in Figure 7a, furthermore, motion can split the inner component organization and change the phenomenal appearance. The inner components without the outer rectangle were also tested. In Figure 7c, the different shapes and arrangements of the inner components is

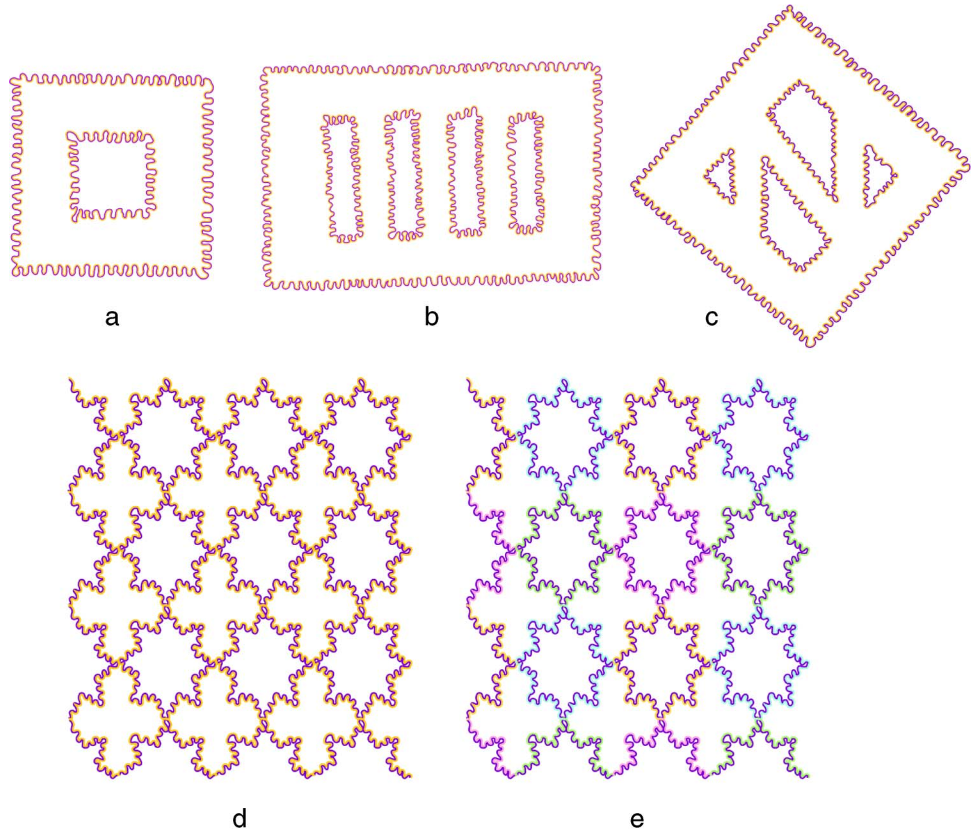



Figure 7. Experimental stimuli.

useful to increase the perception of holes, to further vary the motion imparted to different components and to evaluate the role played by past experience in organizing the holes: the inner region appears like a N cut out in a rhombic shape and connected to the large diamond. The stimulus was also reduced to only the inner trapezoid elements and tested independently from the outer square. Figure 7d was used for two main reasons: (i) to study elements where the organization in objects (crosses or stars) and in empty spaces can be broken by imparting motion to only half of their area, and (ii) to compare this figure where both coloration and figural effects are present at the same time with the figure illustrated in Figure 7e, where figural effect without coloration can be perceived. In Figure 7e, 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 achromatic color, denser and brighter than the one within each star but not completely opaque. By comparing Figures 7d and 7e, a dissociation of the object-hole effect from the coloration one can be demonstrated under motion conditions. This kind of dissociation was first reported under different conditions by Pinna (2005), Pinna and Reeves (2006), and Von der Heydt and Pierson (2006).

Stimuli were presented on a computer screen with ambient illumination from an Osram Daylight fluorescent light (250 lux, 5600°K). The mean overall size of the stimuli was about 13 × 11 deg of visual angle. The contour width was approx. 6.3 arcmin. The luminance of the white background was 85.5 cd/m2. The CIE *x, y* chromaticity coordinates of the chromatic components of the patterns were: (orange) 0.57, 0.42; (red) 0.30, 0.23; blue (0.201, 0.277); green (0.3, 0.5). The luminance contrasts of the purple contours were (0.85). Luminance contrast for any stimulus component (Lx) was defined by the ratio $(L_{\text{white background}} - L_{\text{x}}) / L_{\text{white background}}$.

The item elements (inner or outer components or both at the same in each stimulus) were moved with a speed of ~1.5°/s. They were subjected to several kinds of motion: translation, anticlockwise rotation, appearing and disappearing randomly in different spatial locations, other kind of motions described more precisely in the Results and discussion section. The modulation of appearing and disappearing of the item was respectively 1200 and 1800 milliseconds.

Stimuli, for all experimental conditions, were presented randomly in a frontoparallel plane at a distance of 50 cm from the observer and viewed binocularly. A chin rest stabilized the head position of the observers.

## Procedure

The subjects' task was to describe freely what they perceived by giving an exhaustive description of the main visual properties of the stimulus both under static and motion conditions, and to scale the relative strength or salience (in percent) of the perceived results.

The stimulus sequence started with the item stationary for the time needed to the subject to describe the stimulus and rate the perceived properties, then the specific item (outer or inner component or both) started to move with a speed of ~1.5°/s until the subject completed the description and the rate of the new condition. Each stimulus was presented once, in a different random order for each observer. Observation time was unlimited. The sequences, static and dynamic stimuli, were presented in the same order to all the subjects.

## Results and discussion

The results will be described referred to one figure at a time. Some resulting movies related to all the figures can be seen by clicking the corresponding hyperlinks within the text.

A schematic representation of the main outcomes is illustrated in Table 1. This can help the reader to summarize the following results.

Figure 7a. *Condition (i)—Static*: The inner component was perceived as «a square included in a larger square» (mean rating 35.3%, i.e. mean of the relative strength or salience of this result expressed in percent by all the subjects), «as a frame» (33.2) or «as a hole on a large square» (31.5). The difference was not statistically significant. *Condition (i)—Dynamic*: When the inner square started moving in the three kinds of motion (translation—Movie 1—anticlockwise rotation, appearing and disappearing randomly in different spatial locations), the three previous results were reduced to one: «a small square moving within a large square. The small square appears more solid and closer to the observer than the large one» (100).

The imparted motion induces a clear figural property. By rotating the outer square while the inner one is stationary, the two components appear as «two segregated squares with the moving one closer in depth than the other (100)». When both squares were rotated, the result was «two moving squares placed at the same depth (100)». These results demonstrate that the motion vs. stationary principle is stronger than the figure-ground principles involved in Figure 7a.

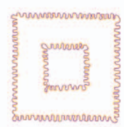
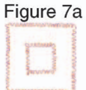
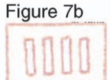
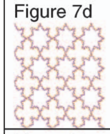
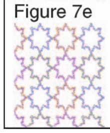
| | | Figure-ground control  | Watercolor illusion  | Watercolor illusion reversed  |
|---|---|---|---|---|
| Figure 7a  | Static | Double square-35.3<br>Frame-33.2<br>Hole on square-31.5 | Frame-93.5<br>Square with a hole-6.5 | Square surrounded by empty space-100 |
| | Dynamic | Small square moving-100 | A moving hole-99 | Moving solid square-100 |
| Figure 7b  | Static | 4 holes on a rectangle-49.6<br>4 biscuit-like figures within a rectangle-50.4 | 4 holes on a rectangle-100 | Solid biscuits-100 |
| | Dynamic | Moving biscuit-like shapes-100 | Moving holes-100 | Moving 3D biscuits-100 |
| Figure 7c  | Static | 4 inner figures-48.6<br>4 holes creating a N letter-51.4 | Holes within a diamond-100 | 4 figures in a empty space-100 |
| | Dynamic | Moving figures-100 | Moving holes-100 | Moving objects-100 |
| Figure 7d  | Static | Reversible crosses or stars-100 | Crosses-100 | Stars-100 |
| | Dynamic | Stars-100 | Crosses-100 | Stars-100 |
| Figure 7e  | Static | Reversible crosses or stars-100 | Crosses-100 | Stars-100 |
| | Dynamic | Stars-100 | Crosses-100 | Stars-100 |

Table 1. A schematic representation of the main results, where short descriptions are followed by the means of the relative strength or salience of each result expressed in percent by all the subjects. Compare the outcomes (descriptions and corresponding means) of the static presentations with the dynamic ones. This will show the role of the motion vs. stationary principle. Take the two kinds of presentations (static, dynamic) of each condition (Figure-ground control, Watercolor illusion, and Watercolor illusion reversed) and compare them with the two presentations of the other conditions. This multiple comparison shows the role of the watercolor illusion against the control condition with only purple lines. Within the text more results are described.

*Condition (ii)—Static*: The global figure was perceived as «a frame and both the inner and the outer regions as empty spaces» (93.5) or alternatively as «a square with a hole» (6.5). *Condition (ii)—Dynamic*: The three kinds of motion imparted to the small square remodeled the previous result in favor of «a large square and a moving—Movie 2—(99), rotating (98) and appearing and disappearing (99) inner hole. The inner square was perceived as a figural hole or as a 3-D hole closer to the observer than the large square».

The inner square was very poorly perceived as «a square under translation (0.1), rotation (0.2) or appearing and disappearing (0.1)». These results demonstrate that the motion vs. stationary principle instill figurality to the results obtained first by the watercolor illusion and, more precisely, by the asymmetric luminance contrast principle. They also lead to the following logical implication: if motion instills figurality, by imparting motion to a background (the empty space within the frame), then it appears as a hole. In other words, the empty space does not become a figure, because the asymmetrical luminance principle of the watercolor illusion determines primarily the object-hole direction. But it becomes a hole that, on the basis of the previous implication, is a background appearing as a figure. From this argument, it follows that a hole has figural properties or a figure status. A further demonstration of this result is obtained by removing the outer square and by moving the inner component alone (Movie 3). Under these conditions the square appears as a moving 3-D hole (100).

By rotating only the outer square, it appears as a solid rotating square placed closer than the inner strong figural hole (100). By rotating both the inner and outer squares, both the outer solid square and inner figural hole appear at the same depth plane (100). These results corroborate the figural status of the hole: given the watercolor conditions, the hole appears more as a figure than as a background. Furthermore, they show that the object-hole status is induced primarily by the asymmetric luminance contrast principle, on which the motion vs. stationary principle can add further figurality. This hypothesis suggests that, under our conditions, the figurality due to the motion vs. stationary principle is instilled to a hole, but to receive the figurality the hole should have some *a priori* figurality properties instilled primarily by the watercolor effect. If this is not true then the most expected results by imparting motion should have been the switch of the background or of the hole in a figure, as we saw in the stationary condition.

*Condition (iii)—Static*: The results revealed a small solid square surrounded by an empty space (100). *Condition (iii)—Dynamic*: The small solid square—Movie 4—pops out more strongly and is perceived closer to the observer than the outer square and more vivid in its 3-D appearance (100).

By rotating only the outer square or both the outer and inner square, the results go in the same summation direction although the rotation of the outer square alone places it closer than the inner square, but when both squares rotate they appear at the same depth (100). The imparted motion sums figurality instilled to the one induced by the watercolor illusion.

We introduced only for Figure 7a one variation of motion for each of the three conditions: the inner or the outer components were translated and rotated one on the boundaries of the other. In *Condition (i),* the results showed that by moving only the inner square, it appears as a square that becomes as the perimeter of a square (not a surface) or as a transparent square when it intersects the boundaries of the large square. During the intersection it appears closer to the observer than the large square (100). A similar result was also obtained when only the large square or when both squares at the same time were moved. The different depth segregation was reported when only one square is moved appearing closer to the observer than the stationary one. In *Condition (ii),* by moving the small square, it appears as a figural hole also when it intersects the large square: a moving transparent hole—Movie 5—showing a static large and solid square placed behind (100).

The variations of the apparent coloration during the dynamic intersection are in agreement with the perception of transparency. When only the large square is moved, it appears transparent and closer in depth when it intersects the stationary small square that is clearly perceived as a hole (100). By moving both squares, a hole and a large square are perceived. Both appear transparent and one in front of the other. The depth segregation can reverse (the hole in front of the large square or vice versa), but the hole is more easily seen closer to the observer (85,3). This result is likely related to Petter's (1956) rule. In *Condition (iii),* the motion of the small square increases its figural appearance that becomes transparent during the intersection of the large square perceived as a hole. By moving the large square, a moving transparent large hole is perceived in front of a solid small square (100). When both squares are moved, the results are the same as before and the depth segregation between the large hole and the small square can be reversed even if the small square tends to be perceived closer (79). These results show once more that a hole manifests figural properties by moving and by becoming transparent.

Figure 7b. *Condition (i)—Static*: The inner small rectangles were perceived as four holes on a large rectangular surface (49.6) or as four biscuit-like figures within a rectangular surface (50.4). The difference is not statistically significant. *Condition (i)—Dynamic*: We chose three kinds of motion for the inner elements (horizontal motion in opposite directions to the two couples of elements, anticlockwise rotation of the four elements, each element moves by itself and intersects the other components), one kind for the outer rectangle alone (clockwise rotation) and one for both the rectangle and the inner elements together (horizontal motion of the rectangle and of the inner elements in opposite directions). By moving the inner elements, they lose their hole status and appear strongly as biscuit-like shapes moving in the described directions and closer to the observer than the outer stationary rectangle (100). When an element intersects another one, it becomes transparent and appears in front of the element perceived through it (100). By rotating the outer rectangle, the inner elements appear as biscuits segregated and slightly more distant than the rectangle (100). By moving all the components, one differently from the other, the figural status of the inner biscuits is strong and all the elements are placed on the same depth plane (100). These results demonstrate that the motion vs. stationary principle instills figurality and it is stronger than the classical gestalt principles involved in these conditions.

*Condition (ii)—Static*: The watercolor illusion elicits the perception of holes: a large rectangular shape with four holes having a rectangular shape (100). *Condition (ii)—Dynamic*: When moved in the ways previously described, the holes enhance their strength appearing more as holes. They become "figural" holes, i.e. moving holes (100). When they moved one independently from the other and intersected other components, they appeared like moving transparent holes (100). Also their boundaries are perceived transparent and not only the inner empty space that is transparent by default (97). They are holes that appear like figures floating within and partially outside the entire pattern (96). The same result is also obtained when the outer rectangle is removed and the holes alone are moved one independently from the other. By rotating the outer rectangle, the inner elements are perceived like holes and, by moving both the large rectangle and inner elements, the perception of holes acquires a stronger figural status (92).

*Condition (iii)—Static*: Under this condition, the inner elements appear like solid biscuits (100). When they are moved, they increase their figurality even more: 3-D biscuits moving in a large rectangular empty space (100). When they intersect other components, they become transparent. By rotating the outer rectangle, it appears like a large rectangular hole rotating around four solid biscuits. When both rectangle and biscuits move, they enhance their appearance as rectangular holes and solid biscuits. The results are in agreement with those of Figure 7a.

Figure 7c. *Condition (i)—Static*: The subjects reported four inner figures—two trapeziums and two triangles—on a diamond surface (48.6) or four holes arranged to create a N letter cut out in a rhombic shape and connected to the large diamond (51.4). This difference is not statistically significant. *Condition (i)—Dynamic*: The inner components were moved two at a time in three different ways and the distance among them was reduced and expanded. Under these conditions, the moving elements and also the inner stationary ones assumed a figural status: the inner shapes appear as moving figures; the organization among the stationary elements is broken and they appear like independent figures.

*Condition (ii)—Static*: The figure is perceived like a diamond with inner holes arranged to create a virtual square surrounding an "N" letter. *Condition (ii)—Dynamic*: The animation of two out of four elements breaks the previous arrangement and the shapes appear like moving holes. The holes appear as figural holes breaking also the inner N that is hardly perceived as a deforming N (5.5). In other words, under these conditions, it is easier to perceive moving holes than deforming objects. This is again in favor of the figural status of the holes that, instead of becoming weaker thus appearing as figures, enhance their status as holes appearing like figural holes, i.e. moving holes with strong figural properties. This is not a phenomenal contradiction but a property of these kinds of holes induced by the watercolor illusion and by the imparted motion. The same results are obtained when only the holes are illustrated while the outer diamond is removed. Only during the dynamic reduction and expansion of the distance among the inner shapes, the N can be perceived but not as strong as in the static condition (i): Four holes moving closer and away (65.4) vs. a shrinking and stretching N (34.6). Under watercolor conditions, the imparted motion enhances the perception of holes that appear like figural holes.

*Condition (iii)—Static*: The four shapes are judged like four figures within the empty space of a diamond shaped hole or within an empty space perceived through a window (100). *Condition (iii)—Dynamic*: In all the dynamic conditions the inner elements appeared like solid moving objects within an empty space perceived through a diamond shape-like window (100).

Figure 7d. *Condition (i)—Static*: crosses or stars appear easily reversible (100). *Condition (i)—Dynamic*: Horizontal motions were added separating the stars from the crosses in columns and vice versa. Before the end of their ride, the divided columns were tilted clockwise. This dynamic separation immediately segregates as figures the stars—Movie 6—or the crosses while the complementary regions (crosses or stars) disappear becoming background (100).

*Condition (ii)—Static*: Being the orange contour within the crosses, on the basis of watercolor illusion the crosses appear as figures (100). The stars were invisible becoming a uniform background. *Condition (ii)—Dynamic*: Under these conditions, if the splitting motion is perceived within the crosses, the crosses get deformed—Movie 7—by stretching and shrinking their surface but, during their dynamic stretching and tilting, star-shaped holes emerge (100).

This result due to the imparted motion is in favor of the figural effect induced by the watercolor illusion. The stretching effect is related to the figural appearance of the space within the watercolored crosses. The imparted motion stretches and enhances the figural effect of this expanding space. The perception of star-shaped holes depends also on the summation effect between the watercolor illusion and the imparted motion. What emerges very clearly is the shape of the holes. Tautologically, only elements having a shape can be perceived with a shape. This means that the boundaries belong to the holes. If the splitting motion is perceived within the stars, then crosses moving away or close and tilting (100) are perceived. The stars were totally invisible. They were not mentioned.

*Condition (iii)—Static*: When the orange fringe is within the stars, they emerge as figures (100). The crosses are now invisible becoming a uniform background. *Condition (iii)—Dynamic*: The results are the same as *Condition (ii)—Dynamic,* but now referred to the complementary figure: stars or crosses (see previous results).

Figure 7e. *Condition (i)—Static and Dynamic*: The results are the same as those of Figure 7d. *Condition (ii)—Static*: The crosses emerge as rounded solid figures (100) but 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. The white within the stars is on the contrary completely empty and transparent (see also Pinna & Reeves, 2006). This is an example of figure-ground effect without coloration. For all the other *Conditions,* the results are the same (Movie 8) as those of the corresponding condition of Figure 7d.

They demonstrate that under dynamic conditions the object-hole effect can be dissociated by the coloration effect.

## Conclusions

The watercolor illusion was shown with the two main effects: object-hole and coloration. The object-hole effect manifests phenomenal properties stronger than the figure-ground segregation and the perceptual grouping studied by Gestalt psychologists. The object-hole effect can be considered as the emergence of the figure as a volumetric object and of the empty space as a solid 3-D hole. This effect can be brought back to a general principle of object-hole segregation, based on the physical property of the watercolor illusion, the luminance asymmetry on the two sides of a boundary, called "asymmetric luminance contrast principle" (Pinna, 2005). Under these conditions, the perception of the hole becomes an important problem useful to understand the more general problem of object perception and shape formation. The perception of the hole was previously studied by many authors (Bertamini, 2006; Bertamini & Croucher, 2003; Bertamini & Hulleman, 2006; Feldman & Singh, 2005; Hulleman & Humphreys, 2005; Nelson & Palmer, 2001; Palmer, 1999; Peterson, 2003; Subirana-Vilanova & Richards, 1996) in experimental conditions different from the watercolor illusion demonstrating two alternative hypotheses in favor or against the figural properties of a perceptual hole. The issue, "who owns the contour of a visual hole? (see Bertamini, 2006)," is still open.

Given that the classical organization principles are not effective against the watercolor illusion, to understand the problem of figurality and of the perception of the hole, a new principle of figure-ground segregation was introduced: the motion vs. stationary principle. This principle was pitted both against the classical gestalt principles and the asymmetric luminance contrast principle underlying the watercolor illusion. The results showed that the motion vs. stationary principle wins against the classical gestalt ones under the conditions here considered. But, under the watercolor conditions, moving holes appear, paradoxically, more as figures than the watercolor objects. In other words, given that the motion vs. stationary principle is pitted against the watercolor illusion, we should have expected that watercolored holes had become objects or figures or at least that they had weakened their perception as holes. The results revealed on the contrary that the imparted motion operates synergistically with the watercolor figurality, i.e. the holes appear much more as holes when motion is imparted to them. This means that the holes assume also the figural status imparted by motion, but this can happen only if the watercolored holes possess figural and not background properties. Then, the watercolor holes and those emerging after motion is imparted to them behave like figures having a shape, i.e. they move, intersect, complete amodally and become transparent like objects and figures. The object and the holes own the contours in a very similar way. This is what we saw in the previous section.

From these results it follows that the asymmetric luminance contrast principle operates primarily and then the motion vs. stationary principle imparts further figurality to the holes or to the objects previously segregated and manifesting clear figurality properties through the watercolor illusion. The motion vs. stationary principle operates by summing the figurality it instills to the object-hole segregation induced by the watercolor illusion. Further experiments are needed to test if the asymmetric luminance contrast principle operates earlier in the visual pathways than the motion vs. stationary principle.

The results showed also that within the watercolor illusion the object-hole effect can be dissociated from the coloration one. The use of the motion vs. stationary principle is an effective way to deepen this problem.

The difference between these results and those obtained in previous studies depend on the different boundary conditions of the stimuli, symmetrical vs. asymmetrical luminance profiles, and, consequently, on the different effects obtained: respectively, figure-ground and object-hole segregation.

The dissociation between the coloration and object-hole effects suggests the existence of parallel mechanisms. The FACADE model (Grossberg, 1994, 1997) posits that boundary grouping and surface filling-in processes can explain the two effects in the watercolor illusion (Pinna & Grossberg, 2005). 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), (Grossberg & Mingolla, 1985a, 1985b; Grossberg & Todorović, 1988).

These results suggest that most of the basic information about the figurality resides in the boundaries and, more specifically, in the luminance gradient peculiar to the watercolor illusion. A similar kind of asymmetry can be related to the motion vs. stationary principle. Some findings (Friedman, Zhou, & von der Heydt, 2003; von der Heydt, Zhou, & Friedman, 2003; Zhou, Friedman, & von der Heydt, 2000) 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. Figure-ground segregation may be processed in areas V1 and V2 (Friedman et al., 2003; von der Heydt et al., 2003; Zhou et al., 2000), in inferotemporal cortex (Baylis & Driver, 2001) and the human lateral occipital complex (Kourtzi & 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) suggested 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. Further neurophysiological studies are necessary to understand the object-hole effect and the problem of figure-ground segregation related to the holes. The results obtained with watercolored visual holes under motion conditions can be a good theoretical point that deserves to be studied in their neural correlates. In fact, given the figure status of the watercolored holes, they depict the problem of shape perception and figure-ground segregation in a new light that can challenge the previous neural findings.

Recently it was suggested that the object-hole effect is part of the more general problem of "figurality" (Pinna & Reeves, 2006) including the phenomenal appearance of what is perceived as a figure within the three dimensional space and under a perceived illumination. It concerns the color and the 3-D appearance and the volume of an object with light and shaded regions, and the direction and the color of the light emerging from the object. Some "principles of figurality", similar to the Gestalt ones were extracted from different luminance gradient profiles across boundary contours defining the phenomenal roles of the juxtaposed contours and as a consequence the phenomenal appearance of the figure—its color and spatial volume, perceived under an apparent illumination. These principles determine more analytically the more general principle of asymmetric luminance contrast of the watercolor illusion.

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## Footnote

[1]The descriptions reported in angle quotes (*guillemets*—«») through the paper used similar phrases and words as those provided by the spontaneous descriptions of no less than 11 out of 14 subjects but edited for brevity and representativeness. There were some individual differences, but we report only those descriptions generated by at least 11 of the 14 subjects in each group. The edited descriptions were judged by five graduate students, who were naive as to the purposes of the present research, to provide a fair representation of those provided by the observers. The descriptions are incorporated within the text without separations to make easier the understanding of the treated arguments. The subject's task was to report freely what they perceived by giving an exhaustive description of the main visual properties. Unless otherwise stated, different groups of fourteen naive observers each described only one stimulus. This was done to avoid interactions and contaminations among stimuli.

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