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Material properties from contours: New insights on object perception

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ABSTRACT

In this work we explored phenomenologically the visual complexity of the material attributes on the basis of the contours that define the boundaries of a visual object. The starting point is the rich and pioneering work done by Gestalt psychologists and, more in detail, by Rubin, who first demonstrated that contours contain most of the information related to object perception, like the shape, the color and the depth. In fact, by investigating simple conditions like those used by Gestalt psychologists, mostly consisting of contours only, we demonstrated that the phenomenal complexity of the material attributes emerges through appropriate manipulation of the contours. A phenomenological approach, analogous to the one used by Gestalt psychologists, was used to answer the following questions. What are contours? Which attributes can be phenomenally defined by contours? Are material properties determined only by contours? What is the visual syntactic organization of object attributes? The results of this work support the idea of a visual syntactic organization as a new kind of object formation process useful to understand the language of vision that creates well-formed attribute organizations. The syntax of visual attributes can be considered as a new way to investigate the modular coding and, more generally, the binding among attributes, i.e., the issue of how the brain represents the pairing of shape and material properties.

1. On the question "what is a visual object?"

The question "What is a visual object?" is an intriguing starting issue, based on the most famous Koffka's question "Why do things look as they do?," especially useful to understand the full set of perceptual attributes bound and subsumed within the term "object." This term can be phenomenally considered like a structured holder (Koffka, 1935; Metzger, 1963, 1975a, 1975b, 1982; Palmer, 1999; Pomerantz & Kubovy, 1986), an organized set of multiple properties, some of which are explicit, some other implicit, some become explicit or, on the contrary, implicit or invisible after a while (see Pinna, 2012a). Just by asking this question, it emerges that the meaning of the term object is phenomenologically not well defined and not completely immediate at first sight. Moreover, not all the possible object properties define with equal strength the phenomenology of the "object." It follows that not all its properties pop up perceptually with the same salience but some are more prominent and in the foreground than others.

It is quite spontaneous to consider the shape as the object itself or the object par excellence, i.e., the attribute that more than others represents the object (Johnston & Passmore, 1994; Koenderink, van Doorn, & Kappers, 1992; Rogers & Cagenello, 1989). Indeed, the shape immediately emerges when we refer to an object. In fact, when somebody asks "what is this object?", it is spontaneous to answer by describing only or mostly referring to its shape (Bülthoff & Mallor, 1988; Stevens & Brookes, 1987). In truth, it is much less frequent to start the description from its color and even less from other attributes like the volume, the material quality and so on (Dorsey, Rushmeier, & Sillion, 2008).

This entails that not all the visual attributes are placed at the same phenomenal plane of visibility but the full set of them are usually arranged along a complex gradient of visibility (Koffka, 1935; Pinna, 2010a) and according to some kind of visual syntax (Pinna, 2012b). In reality, the gradient and the syntax of the object attributes are strongly interrelated, as we will deepen in the final section, although these properties could be sometimes in open competition. In some circumstances shape and color can match to be in the foreground as, for example, in the case of different kinds of mature fruits within the same plant or among different meadow flowers, but this competition is usually implicit or immediately solved under more general circumstances and according to the full set of properties which tend to be perceived as nested one

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within the other or phenomenally arranged and organized in a manner that deserves to be scientifically studied with deeper attention. A similar sort of competition occurs, above all, if we think and compare the complexity and prominency of visual attributes like shape, material, color, volume, mostly placed in the foreground with respect to other properties like illumination or other expressive/tertiary qualities mostly located in the background of the object distribution of attributes along the gradient of visibility.

Given these general statements, it is phenomenally immediate to think of the contemporary emergence of more than one visual property from the same physical-geometrical attribute. For example, not only does the color show chromatic but also volumetric, material and expressive properties (Brainard & Maloney, 2004; Giesel & Gegenfurtner, 2010; Giesel, Hansen, & Gegenfurtner, 2009; Hansen, Giesel, & Gegenfurtner, 2008; Kingdom, 2008; Shevell & Kingdom, 2008). As a matter of fact, in history of Art, the multiple functions of color and, more generally, the way of seeing the world in terms of coloring, differentiates the Florentine and Venetian paintings during the Renaissance. In Florence, the "disegno" (drawing) was conceived as the essential beginning and ending of artistic work, the primary and final means for making art describe nature. In Venice, the "colorito/colorismo" (coloring) was instead the primary and final mean. In addition, in Venetian artists the process of layering and blending colors was aimed to achieve a glowing richness of perceptual attributes like volumes, material, depth and expressive properties. These antagonistic artistic approaches evolved more recently in a plethora of diverging tendencies aimed at exploring, from many point of views, the complexity of the "object" Art and, in particular, the world of colors.

A possible stronger demonstration of the multiple role of a physical/geometrical attribute in terms of visual properties is represented by the contours, which can easily appear as boundaries of a shape, as volume (depending for example on their concavity or convexity, (Spröte & Fleming, 2013) or expressive, tertiary or physiognomic qualities (Koffka, 1935). Phenomenologically, the perception of a shape involves more attributes than the mere detection of different positions in space or of other local surface properties. Absolutely, in the case of the well-known "Maluma-Takete" (Köhler, 1929, 1947; Ramachandran & Hubbard, 2001), two different shapes are perceived as having opposite contours attributes, curviness and pointedness, and as manifesting a large set of further opposite properties – smoothness and sharpness, jaggedness and roundedness.

Starting from these introductory phenomenal notes, to be deepened in the next sections, the general purpose of this work is to explore the notion of the gradient of visibility and the organization of attributes that more generally define a visual object. Within the multiplicity of attributes, we will focus our attention mostly on the syntactical organization of shape and material properties. This kind of organization has never been studied uniquely on the base of the contours. Only few studies (cf. Kanizsa, 1979; Michotte, 1963; Pentland, 1986; Spröte & Fleming, 2013) have investigated some partial effects of contour attributes on shape perception and material properties.

The basic assumption of this work can be synthesized as follows: shape and material attributes from contours. Shortly, our purpose is to reduce the complexity of these properties to the perceptual organization of different kinds of contours. In the next sections the following questions will be answered according to a phenomenological approach analogous to the one adopted by Gestalt psychologists. What are contours? Which attributes can be phenomenally defined by contours? Are material properties determined only by contours? What is the place of the material properties within the gradient of visibility in relation to other visual attributes? What is the visual syntactic organization of object attributes?

2. General methods

2.1. Subjects

Different groups of 12 naive subjects each ranging from 19 to 25 years of age participated in each experiment described in the next sections. All experiments were conducted in respect of the Declaration of Helsinki and with previous consent of all subjects who participated in the experiments voluntarily. Subjects were about 50% male and 50% female and all had normal or corrected to normal vision.

2.2. Stimuli

The stimuli were the figures shown in the next sections. The stroke width was ~6 arcmin. The luminance of the white background was $\sim$122.3 cd/m^2. Black contours had a luminance value of $\sim$2.6 cd/m^2). The stimuli were displayed on a 33 cm color CRT monitor (Sony GDM-F520 1600 $\times$ 1200 pixels, refresh rate 100 Hz), driven by a MacBook computer with an NVIDIA GeForce 8600 M GT, in an ambient illuminated by a Osram Daylight fluorescent light (250 lux, 5600° K). They were viewed binocularly and in the frontoparallel plane at a distance of 50 cm from the monitor.

2.3. Procedure

The subjects' task was to report spontaneously what they perceived for each stimulus by giving, as much as possible, an exhaustive description and, if necessary, to answer the questions asked by the experimenter. Subjects were also instructed to scale the relative strength and salience (in percent, where 100 is the maximal salience and 0 the minimal) of the perceived alternatives, if there were any, and the relative confidence and appropriateness of the responses.

In the next sections, the descriptions are included within the main text to aid the reader in the stream of argumentations. The edited descriptions were judged by three graduate students of linguistics, naive as to the hypotheses, to provide a fair representation of those provided by the observers. If not specified, the descriptions reported in the next sections were those spontaneously communicated by ten out of twelve subjects and judged highly appropriate (more than 90%).

During the experiments subjects were allowed: to make free comparisons, confrontations, afterthoughts, to see in different ways, to match one stimulus with others, to make variations and comparisons in the observation distance, etc. The subjects could also receive suggestions/questions from the experimenter as reported in the next sections. All the variations and possible comparisons occurring during the free exploration were noted down.

Subjects were tested individually. No time limit was set to the descriptions and their scaling, which occurred spontaneously and fast. The stimuli were shown continuously during the description task. Details and variations among experiments related to the subjects, the stimuli and the procedure will be reported more in details in the next sections together with the results of each phenomenological experiment and a theoretical discussion.

3. On the visual object: From contours to material properties

3.1. Implicitness and explicitness of the object properties

In Fig. 1a the shape emerges as the first and the only visual attribute (cf. the notion of "shape bias" by Landau, Smith, & Jones, 1988, 1992, 1998). No other object qualities are spontaneously reported, nor the color, nor the volume/depth. All these

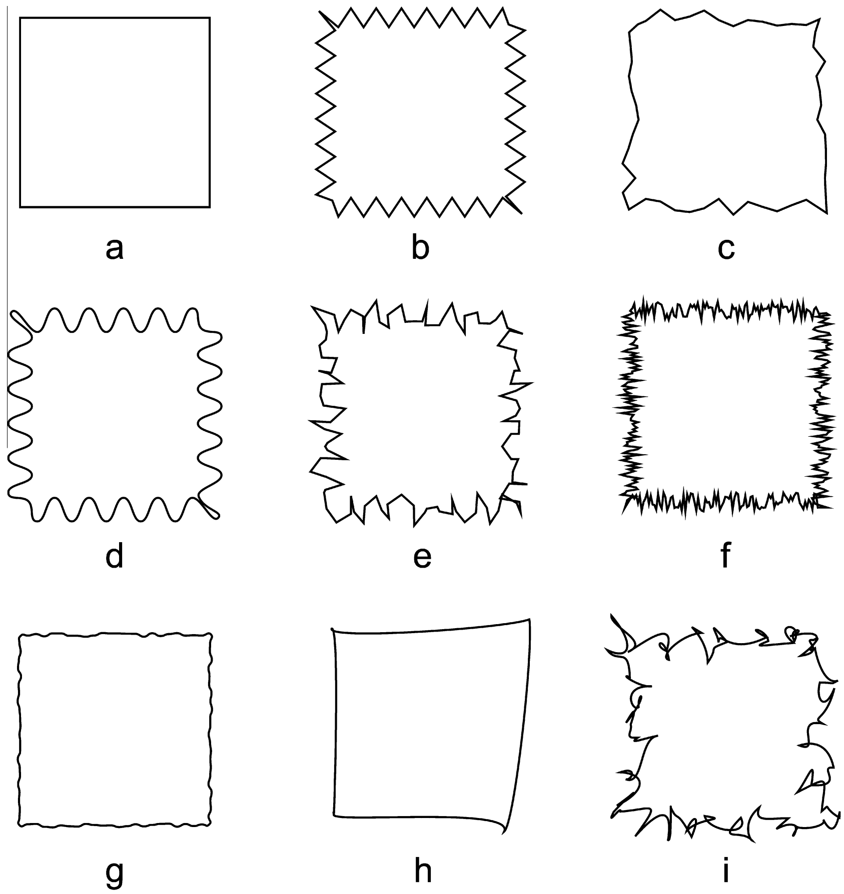

Fig. 1. Squares made up of different materials.

further attributes and many others not mentioned seem invisible or absent, but only the square, i.e., the shape, becomes the object tout court, the word that represents the object.

Secondly, none of the subjects spontaneously mentioned the background that remains totally implicit and invisible. Indeed, the background is implicit similarly to the color of the square that emerged only after the direct question, "What is the color of the square?" The most common answer (10 out of 12 subjects, 90% appropriateness) was: "White". Only 4 out of 12 (7%) said "transparent" and only 2 out of 12 (3%) reported "black." By suggesting: "can you see the square as black?" Most (9 out of 12, 85%) of the observers answered: "No, the square is not black but white." Only 3 out of 12 (15%) agreed with our clue. To deepen the meaning of the color assignment to the square, when only the contours are depicted, and to know more also about the syntactic organization of shape and color see Pinna's work (2012a) and other relevant literature in the field (Boyaci, Doerschner, & Maloney, 2004; Boyaci, Maloney, & Hersh, 2003; Doerschner, Boyaci, & Maloney, 2004; Khang & Zaidi, 2004; Landau, Smith, & Jones, 1988, 1992, 1998; Pinna & Ehrenstein, 2013; Ripamonti et al., 2004; Yang & Maloney, 2001).

On the basis of these findings, an antinomic phenomenal attribute should be highlighted: implicitness vs. explicitness of the object properties. The figure-ground segregation manifests a clear asymmetry in terms of visibility between the two complementary components: being the figure means being perceived in the foreground, i.e., explicitly; while, being the background means being perceived as tacit, implicit and, then, unexpressed in words. This has a strong adaptive fitness value within the biological domain. The possibility to remain implicit and tacit can sometimes be the only way to survive against a predator. Organisms evolved many visual strategies to be visible or invisible, to be and not to be perceived, to be perceived in some essential periods by the conspecific (e.g., during the mating season) and to be invisible or implicit, at the same time, to potential predators (Pinna & Reeves, 2013).

Within a phenomenological approach, a second remark, mostly methodological, declares that what is written down by the experimenter is mainly what emerges spontaneously and what is immediately described by the subjects, i.e., what is explicit and, thus, what is at the top of the gradient of visibility. Instead, what is implicit, given for granted and not described, is considered less important and sometimes not phenomenally relevant in the same scientific acceptation as the main prominent result.

Differently, the distinction between explicitness and implicitness in this work is considered necessary to understand the gradient of visibility and the hierarchical organization of the object attributes (Pinna, 2010a). As a matter of fact, not only does the gradient of visibility reveal, what is perceived at first sight and more saliently, but also it highlights what is seen as secondary, what is in the background and also what is totally invisible. Absolutely, Being implicit does not mean being "nothing" or less important. On the contrary, what is implicit can be even more important for the understanding of the object organization than what is immediately perceived. The phenomenal significance of this term will be appreciated in the next sections.

3.2. The implicitness of material properties

In addition to the background and the color, Fig. 1a contains other attributes that remain implicit. In fact, none of the subjects mentioned any material property of the square. When, it was asked: "what is the square made of?" The subjects' most frequent and immediate answer was: "paper (65%) or white plastic (25%)". To better conceive these results, it can be useful trying to perceive the same square as made of something unlikely, as for example stone, liquid material or something else much more different from paper or plastic. Under these conditions the asymmetry of the match in favor of our results emerges even more distinctly.

The perception of material properties in such a simple stimulus pattern is scientifically interesting. In fact, these properties are not related to a specific kind of information different from the contours that define the object shape. Both shape and material depend on the same source. This implies that both attributes are of the same kind. Therefore, the immediate questions are the following: are there different components in the contours that can explain the shape and the material attributes? If this is the case, which component of the contours defines the shape and which determines the perception of the material?

Before answering these questions, it can be argued that, as an alternative to this hypothesis, the material attributes could be rather related to the surface quality of the figure or to its depth segregation. In fact, the matter of the figure seems qualitatively more similar to the surface and to the volumetric qualities than to the contours segregation and boundaries of a shape. This is also plausible on the basis of Rubin's (1915, 1921) phenomenal descriptions of the surface color and of the volume/depth.

Nevertheless, if what just stated were true, we should have expected that the material properties do not change by changing the form and the shape of the contours as we will demonstrate in the next sections. Moreover, if this were true, the material properties should not be as implicit as they are but, on the contrary they should be much more prominent within the gradient of visibility and much more immediate and precise in the definition of the specific kinds of materials. In fact, a matter defines a figure very clearly without the phenomenal ambiguity of its surface color and epiphanous qualities. The fact that Rubin (1921) never mentioned the material qualities of his stimuli based on simple contours is in favor of this argument. Another evidence in favor of our hypothesis is that in English language the material attributes are mostly related and then collocated close as adjectives to the shape, which represents the noun. We will argue and discuss this important issue at the end of the last section.

While the surface appearance, as described by Rubin, belongs to the chromatic domain of the figure in relation to the background, we alternatively propose that, under the conditions here investigated, the material properties can be considered as a secondary product of the square, namely a shape attribute. Nevertheless, both shape and materials depend on the contours. In fact, the contours define the shape and, at the same time, with their different sub-attributes (e.g., global vs. local, first vs. second order), the material property of the square. Concisely, we can state: shape and materials from contours. This is the main motto of this work. This entails that, under our conditions, shape and materials belong to the contour domain (Duvelleroy-Hommet et al., 1997; Goodale & Milner, 2004; Heywood, Gaffan, & Cowey, 1995; Humphrey et al., 1994; James et al., 2003; Milner et al., 1991). The full demonstration of this assumption is based on the phenomenal outcomes reported in the next sections.

This hypothesis does not deny other conditions where the materials appear more related to the inner surface and depth/volumetric qualities (Anderson & Kim, 2009; Koenderink, 1999; Motoyoshi, Nishida, Sharan, & Adelson, 2007; Robilotto & Zaidi, 2004; Sharan, Li, Motoyoshi, Nishida, & Adelson, 2008; Xiao & Brainard, 2008). Our hypothesis follows from the specific simple conditions used in this work.

4. On the assumption "shape and materials from contours"

4.1. The case of the single square

To study and demonstrate the assumption "shape and materials from contours", Fig. 1a was changed as illustrated in Fig. 1b–i. A new group of 12 subjects participated in the experiment. All the stimuli of Fig. 1 were shown all at once and in a different random order for each observer. This kind of presentation makes all the figures more similar to a single stimulus with different instances. Under these conditions, a possible main tendency is to compare all the instances to find a phenomenal effect that at once describes and "explains" the variations occurring among the instances. Therefore, in short, the expected tendency is to extract the invariant component and the phenomenal "explanation" of the perceived differences. The meaning of the term "explanation" will be defined in the next sections.

The first immediate and common subjects' description (45% of the subjects) was "a square made up of some materials different from one square to another". The use of the term "square" entails that subjects described first what is common, invariant and more salient, i.e., the shape, and secondly what "explains" the differences and the variations, the matters. After the first general description, subjects reported more in details the specific material of each square: plastic (a); paper or fabric (b); paper or cardboard (c); soft goods (d); aluminum (e); fabric or wool (f); concrete (g); tissue-paper (h); brittle metal (i).

The second kind of answer (35%) was described as "squares with the shapes deformed or distorted in different ways". Again, the general description of the invariant component (the square) was followed by the general description of the variations (i.e., deformations/distortions). Then, the specific deformations/distortions of each single square were added at the end of the previous description as follows: straight (a); zigzagged (b); scrunched up (c); undulated (d); folded up (e); frayed (f); flayed (g); swelled (h); twisted out (i).

The third kind of outcome (20%) was the one reporting "a square made in different ways or with different peculiar shapes or characteristics of the shape" that were respectively described in great accuracy as in the second kind of outcome.

This threefold result suggests that, when defined through the contours, the material properties are strongly connected to what are also perceived as deformations and shape characteristics. This is an important relation that will be taken into further consideration through the next experiments. For the time being, we can bring back these results to the distinction between first and second order variations in a stimulus pattern (Cavanagh & Mather, 1989; Chubb & Sperling, 1988). The second order component of each figure, portraying variations in stimulus attributes other than luminance, i.e., contrast and texture information (Yoshizawa, Mullen, & Baker, 2000), is likely related to the invariant and common square, while the variations in the local luminances refer to the first order stimulus component related to the local variations that define the matter, the deformation/distortion or the specific characteristics. The fact that a stimulus can be perceived as made of a certain matter, as deformed/distorted or with peculiar shape characteristics represents a threefold way to view the same kind of information. Therefore, the same information conveys different properties and visual meanings.

The visual system handles very commonly the same source of information in many different ways and as related to different visual qualities. This occurs first of all during the "phenomenal scission" (Spaltung) of the figure-ground segregation, as described by Gestalt psychologists (Koffka, 1935; Metzger, 1963, 1975a, 1975b). Under these conditions, the common invariant set of

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attributes is subsumed into the background, while the variant one is embodied in the figure. The figure is what emerges, varies or differentiates the homogeneous background, which can thus appear invariant. The variation supported and incorporated within the emerging figure reinforces and supports the invariant qualities of the background and *vice versa* (Pinna, 2010b, 2012c). By generalizing to our conditions, what is described by the observers can be considered as some kind of further level of figure-ground organization where the matter/deformation/characteristic is the variant component that emerges from the invariant square that occurs in the previous segregation of the figure from the background.

Since the previous results can be considered as dependent on the kind of presentation making all the stimuli like instances of the same figure (the square), the same stimuli were now shown one at a time and in a random order to each subject belonging to a new group.

Subjects described the stimuli as follows: "a square with the sides deformed or distorted" (46%). The detailed descriptions of the precise kind of distortion of each stimulus were similar to those reported in the previous experiment. The second set of common results (35%) reported "a square made of some kind of matter" followed by a precise description of the matter, similarly to the previous experiment. Finally, the third set reported "a square with a specific shape" (19%), similarly to the previous presentation. In the two types of presentations, what is important to underline is not the exact description of the material, of the deformation and of the characteristics but the general description that reflects the perceived structure and organization of the objects.

These results support the previous ones and further highlight the multiple source of information carried by the contours. More in detail, the shape of the contours splits into global and local constituents, that represent the building block that determine the whole shape of the object and the specific kind of deformation or material property.

In the next section, the global shape (the second order information) is further weakened and cleaned up to study in more details the opening assumption: shape and materials from contours.

4.2. The case of the bisected square

Given a square, like the one illustrated in Fig. 1a, by bisecting it with a single straight line (see Fig. 2a), several possible outcomes could be perceived: a square bisected; two rectangles juxtaposed; a window showing a straight line continuing behind the boundaries of the window; a window showing two regions one perceived as a figure and the other as an empty background. All these possible results reflect the spontaneous self-organization of each single stimulus in four phenomenal patterns. The elements of Fig. 2 were showed to a new group of subjects one at a time in random order. The task was to judge in percent the visual strength and salience of the four possible results suggested by the experimenter.

The results of Fig. 2a revealed slightly differences among the suggestions, although the square bisected and the two figure-ground regions appeared more salient than the others: 32% and 35% respectively, against the other possible results all below the 20%. These changes reflect the shape of the phenomenal gradient of visibility. In addition, the two complementary regions segregated by the straight contour were perceived by the subjects, with similar strength, either as a figure or as a background. The segregation appeared reversible, as expected on the base of Rubin's principles of proximity and relative size (the two regions have the same area). Furthermore, none of the subjects spontaneously mentioned the matter of the region perceived as a figure.

By changing the kind of contour of the bisecting element (Fig. 2b), the shape of the phenomenal gradient changes accordingly. The strongest result (80%) was now the segregation in terms of figure and background of the two facing regions. The bisection of the square with a wavy line was judged very low (15%). The other outcomes were barely perceived.

More importantly for our purposes, the region that appeared as a figure was spontaneously described as made of a soft undulated rubbery matter. Finally, differently from the results of the previous experiment, where the undulated contours of the square were perceived as a deformed square, none of the subjects perceived the wavy line as a deformation of a straight one. This entails that, as expected, in this stimulus variation the global vs. local phenomenal scission within the contours does not occur in the same acceptation of Fig. 1. However, the straight bisecting segment, not showing any inner and local variation is not informative in terms of material attributes. This also points out that indeed these inner and local components of the contours are the basic information responsible for the perception of the matter.

In Fig. 2c–f, the shape of the contours was further changed and the results varied mostly in favor of the material properties that are more and more clearly perceived in the figural region segregated from the background and seen through the window. The percents of the suggested outcomes do not change significantly from

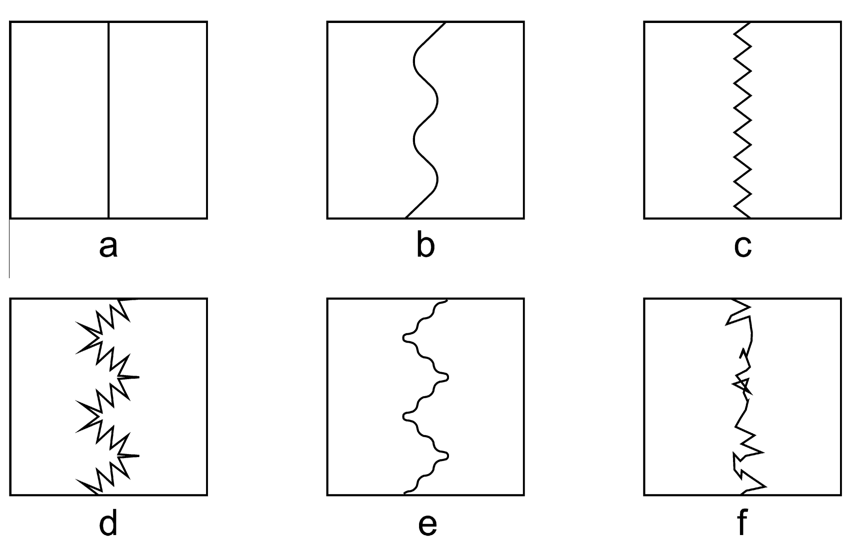

Fig. 2. Bisected squares showing different materials properties in the region perceived as a figure.

the results of Fig. 2b. The matters of the figural regions of the stimuli shown in Fig. 2c–e were respectively described as: concrete, fabric, wood (c); ice, metal (d); rubber, plastic (e); metal, wool, ink (f).

These results corroborated those previously discussed. However, the weakening of the global information, related to the shape of the object elicited by the contours (the squares of Fig. 1), suggests the following question: what happens if all the stimuli are now presented all at once like instances of the same figure?

On the basis of the previous outcomes, we expect the strengthening and reinforcement of the perception of the material properties and of the set of deformations of the bisecting contours. However, since the whole information is weakened, the deformations could be not as strong as the material properties. As a matter of fact, given that a deformation is always referred to something (i.e., a shape) and since the whole shape is absent in this kind of figures, it follows that the perception of the deformation should appear very weak or different.

A new group of subjects judged all the stimuli of Fig. 2 at once and in a different random order for each subject. The results corroborated our predictions. The material properties of the regions perceived as a figure were perceived much more saliently and the differences in terms of matters among instances were more demarcated. These outcomes were supported by the subjects' answers that were faster than before and by the lower percents of the confidence and appropriateness of the responses.

These results suggest the following step described in the next section, where the salience of the material properties was studied by manipulating the proximity and relative size of the two complementary regions within the square.

4.3. Bisected squares and figure-ground segregation

In Fig. 3, the area of one of the two regions of Fig. 2 has been reduced, therefore, on the basis of the proximity and size principles of figure-ground segregation, the figure-ground reversibility of the previous conditions is expected to be reduced in favor of the smallest area that should now appear more likely as a figure. Moreover, if the figure-ground segregation and the material properties are related, then, by changing the strength of the figure also the salience of its perceived material attributes is assumed to change accordingly.

As previously, the stimuli of Fig. 3 could be presented in two ways: one at the time or all at once. The results of both presentations confirmed our predictions: as one (the figure) increases its strength, the material properties increase their salience at the same rate (direct proportionality). Moreover, the answers were faster and the percent values of the confidence and appropriateness of the responses were higher of about 10% than in the previous conditions (Fig. 2).

On the basis of the arguments based on the global and local contour attributes, it can now be argued that the interactions between global and local information within the contours in the bisecting line is not really annulled. Indeed, in Fig. 1, it is referred to the global perception of the square and to the local contours variations but just transferred from one component of the stimulus (the perimeter of the whole square shape) to the ratio between inner bisecting line and the outer square. In other words, while in Fig. 1 all the contours of the figure are of the same kinds, in Figs. 2 and 3 they are different. Therefore, this can now be the new source of the global and local information used by the visual system.

4.4. Reversing the contour in bisected squares

To resolve this issue, four different kinds of contours (see Fig. 4) among the two components of each stimulus (namely, the outer square and the inner bisecting contour) are reversed with respect to the previous experiment. Four different conditions were combined in every possible way involving either the inner and the outer contours, as illustrated in Fig. 4. They were: straight, zigzagged, undulated and irregular. The stimuli were presented randomly one by one.

The conditions of the first row (on the top) of the matrix corroborated the previous results. By changing the contours of the element $a_{1,1}$, both the figure-ground segregation and the material attributes increased their salience (of about 30%) with respect to the weaker conditions illustrated in the element $a_{1,1}$ of the matrix. However, by reversing the kinds of contours (zigzagged, undulated and irregular vs. straight), as illustrated in the first column, the perception of the figure-ground segregation and of the material attributes did not confirm the prediction of the previous argument, but new phenomenal results emerged. The surrounding zigzagged, undulated and irregular contours are now perceived as holes or breaches, having a square shape, on the white paper showing the

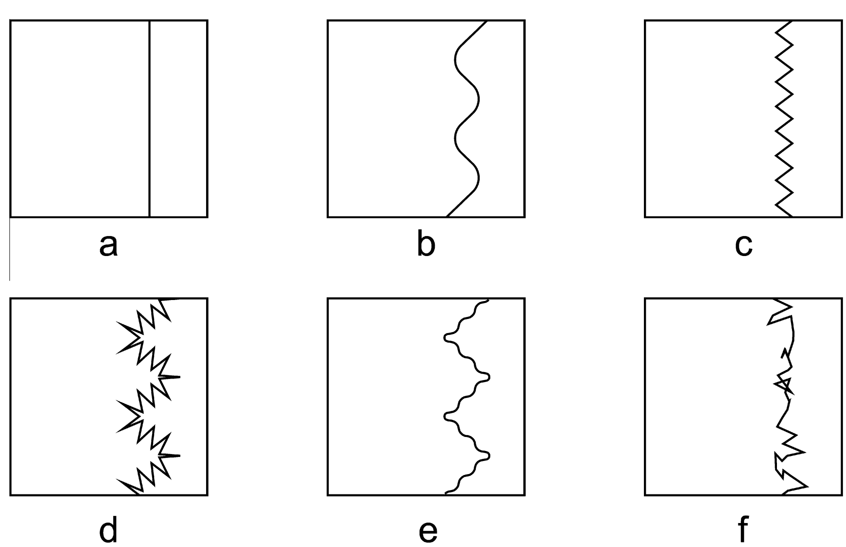

Fig. 3. By increasing the strength of the region perceived as a figure also the salience of the material properties increases accordingly.

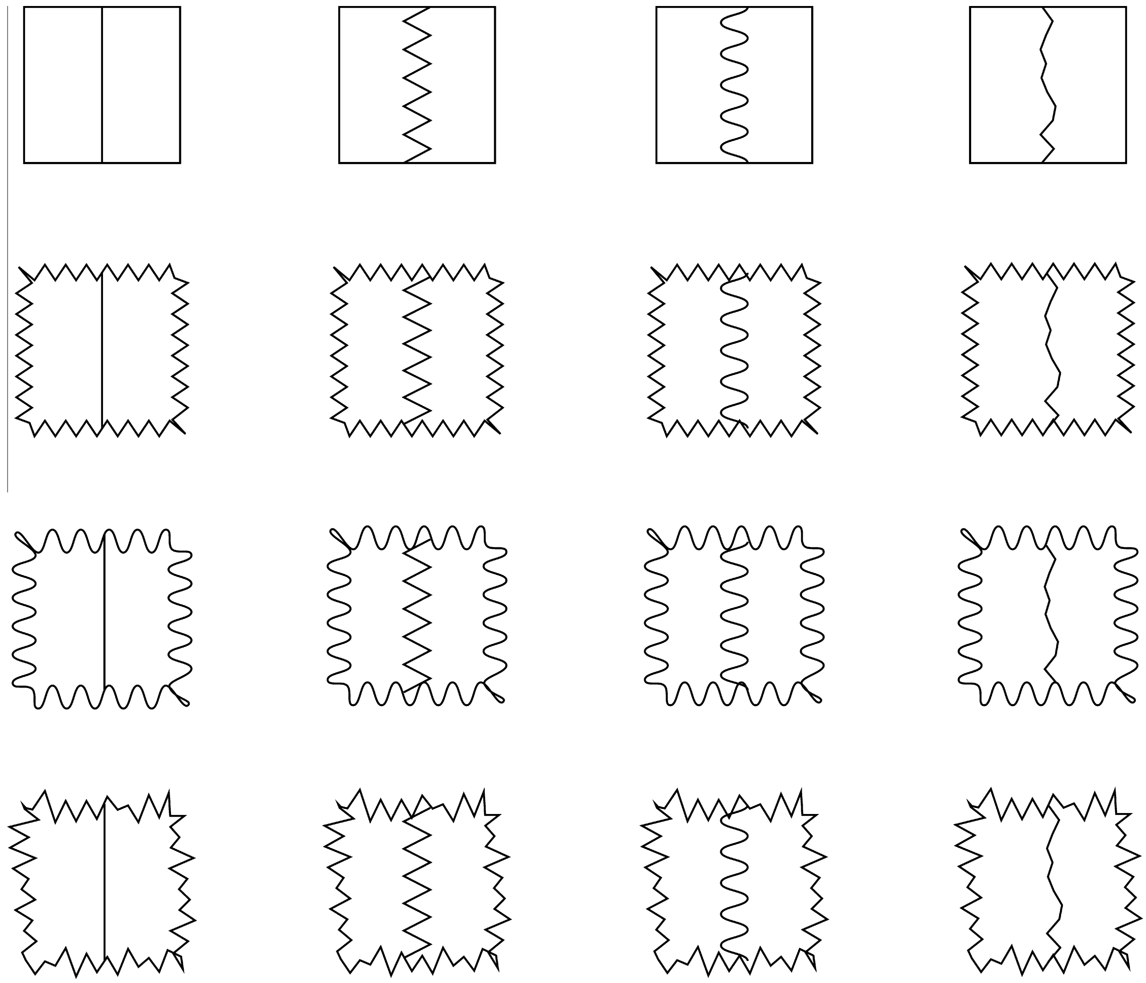

Fig. 4. By combining different kinds of contours of the bisecting element and of the surrounding square, different effects of the figure-ground and of the material attributes emerge.

void behind them and a segment completing amodally behind the boundaries of the hole. In greater details, the figure-ground segregation in two halves of the element $a_{1,1}$ of the matrix, one perceived as a background and the other as a figure like flat surface, is now absent.

The results of the sub-matrix $A_{i,j}$ with $i,j \geqslant 2$ confirmed those of the first row and of the first column. Nevertheless, if compared to the previous ones, these results were weaker, confused and ambiguous, swinging from the results perceived in the first row and to those of the first column.

Altogether, these results suggest the role of the interactions between global and local information within the contours and the clear difference between the straight contours, on one side, and the zigzagged, undulated and irregular one, on the other. While zigzagged, undulated and irregular contours manifest phenomenal properties related to two different object qualities (shape ad materials), a straight contour is mostly devoted to demonstrate only the shape attribute.

These results and the issue of the global perception of the square related to the local contours variations are further investigated in the next conditions.

4.5. Reversing the contours in inset squares

The same four variations of the contours (straight, zigzagged, undulated and irregular) of Fig. 4 are now combined using two inset square shapes combined in all the possible ways, as illustrated in Fig. 5. The stimuli were presented randomly one at a time.

On the basis of Rubin's principles (relative size, proximity and surroundedness) the element $a_{1,1}$ (the one placed on the top-left corner) of the matrix A can be perceived mostly as a frame but also as a small square superimposed to a larger square. This result was confirmed by the percents (70% vs. 30%). As expected on the basis of results of Fig. 2a, none of the subjects reported the material properties of the frame or of the inner square. The elements $a_{1,i}$ of the first row, although subjected to the same Rubin's principles of relative size, proximity and surroundedness, manifest a new interesting result. The inner component was mostly perceived as a hole or a breach on a square or on a wall that could be made up of concrete, wood, fabrics, cardboard or glass with different strength for each condition. The perceived hole (breach) is not a background like the one perceived in the frame of the element $a_{1,1}$, but it appears as a background with figural properties comparable to those of the object. Briefly, the hole is a figure on a background (the square) showing the background (empty space) behind the square.

Similarly, these conditions cannot be defined as frames but as "complete" shapes with holes. The term "complete" is here considered in the "amodal completion" or "amodal wholeness" acceptation (Pinna, 2010b; Pinna & Albertazzi, 2011). As a matter of fact, the empty space of the frame is a background, the one of the hole is something, the square. Therefore, the hole is a figure within another figure (the square). Conversely, the hole is background

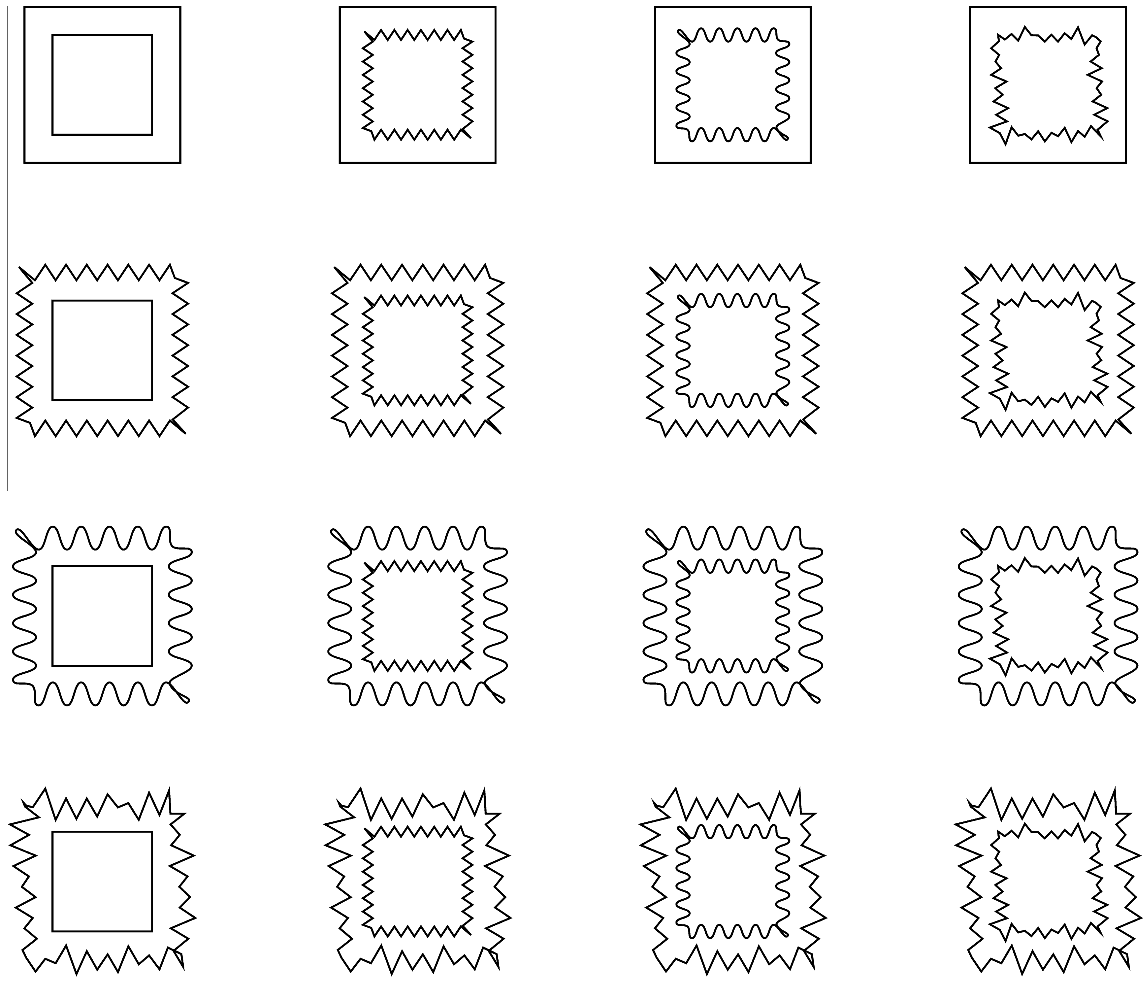

Fig. 5. The combination of different kinds of contours of inset squares reveals new effects of figure-ground segregation and material attributes.

because it is nothing similarly to the empty background, whose boundary contours, according to Rubin's principle, belong unilaterally to the figure. Besides, the hole reveals paradoxical effects related to the belongingness of its boundaries. In fact, they belong to the hole (a hole shows its boundaries) and, at the same time, to the surrounding square, which appears as the background of the hole and as the object on which the hole is made.

In summary, the hole is a background that behaves paradoxically like a figure (Bertamini, 2006; Bertamini & Croucher, 2003; Bertamini & Helmy, 2012; Nelson & Palmer, 2001; Nelson, Thierman, & Palmer, 2009; Palmer et al., 2008; Pinna & Tanca, 2008). What is more important for our purposes is that the paradoxical characteristics of the hole make it as the main responsible for the perception of the material attributes of the surrounding square/wall that, *ipso facto*, can be considered as a paradoxical figure, i.e., a figure with the properties of a background.

The results of the elements of the first column ($a_{i,1}$, with $i \geqslant 2$) demonstrate even more clearly the role of the contours in inducing figure-ground segregation, but it also shows the paradoxical properties of both the figure and the background and, finally, the role of the contours in inducing the material attributes. In reality, subjects perceived the inner square as if it were a solid block made of some kind of concrete floating in the empty space seen through a hole or a breach. The inner square does not appear as the inner boundary of a frame and does not group with the surrounding shape in any way. To better appreciate the floating and unstable effect of the square compare the elements of the first column with those of the first row, where, instead, the reciprocal belongingness and grouping is stable and clear in terms of a square with a hole.

The sub-matrix $A_{i,j}$ with $i,j \geqslant 2$ shows conditions with effects that can be mostly assimilated to frames (in a range going from 65% to 90%). A 40% of subjects perceived a square annulus instead of a frame. In spite of these differences, these outcomes can be considered as equivalent in phenomenal and structural terms. The other possible result, the inner small square-like shape placed on the large one, was a weak phenomenal possibility as rated by the subjects (only 15%).

The material of the perceived frame was described spontaneously and more clearly by the observers along the main diagonal of the sub-matrix $A_{i,j}$, where the inner and outer components of each stimulus are equal and much less clear in the stimuli where the components are different. The dissimilarity between the components weakens their grouping as a frame and, as a consequence, it also weakens their material attributes.

The previous results were tested through the variation illustrated in Fig. 6. In addition to Rubin's principles, Morinaga (1941) studied the parallelism or non-parallelism of inset contours demonstrating that it can be considered as a further and strong principle of figure-ground segregation. By rotating in Fig. 5 the inset square of $a_{1,1}$ by 10° (the two conditions are now reported in Fig. 6, first column, for a direct phenomenal comparison), the perception of the frame is much weaker and the inset square is perceived as a segregated rotated figure superimposed to the surrounding large square. This result was confirmed by our observers.

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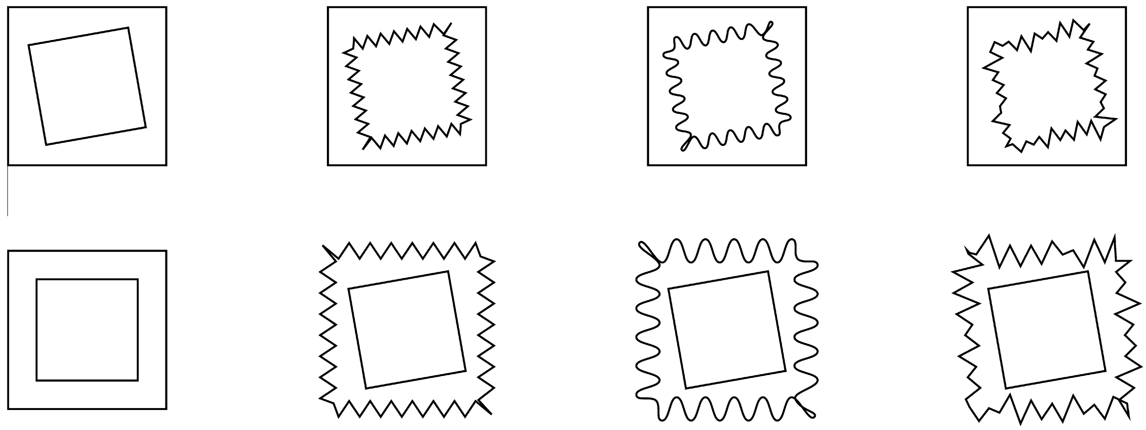

Fig. 6. The loss of parallelism strengthens the paradoxical effect of the hole and the material properties of the square.

The rationale of the variations illustrated in Fig. 6 is, then, the following. If the loss of parallelism significantly strengthens the figural appearance of the inset component and, at the same time, strongly reduces the perception of the frame, than, under similar conditions, the perception of the hole and of the breach of the elements $a_{1,j}$ with $j \geqslant 2$ of the first row of Fig. 5 is expected to be significantly weakened or totally annulled, given all the more reason that the two inset contours are different and therefore not parallel (parallels are the global or send order contours of the square not the first order ones). Besides, the results showed, on the contrary, a slight increasing in the strength of the hole and the breach built on a squared surface made of some matter (the same as in the previous results). This suggests that the loss of parallelism enhances the role of the contours differentiation in inducing figure-ground segregation and material properties. To a larger extent, this enhancement can be explained as referred to the paradoxical figural attributes of the hole, previously described.

Analogous results were obtained by comparing the second row of Fig. 6 with the elements $a_{i,1}$ with $i \geqslant 2$ of the first column of Fig. 5. The increasing of the figural emergence of the inner square affects by slightly increasing the main outcome of the previous experiment: the inner square perceived like a solid block made of something floating in the empty space seen through a hole or a breach.

These results altogether imply that the material attributes are dependent on the kinds of contours, from their similarity and dissimilarity and from contours organization in terms of figure-ground segregation and paradoxical figure-ground. Moreover, the principle of dissimilarity among contours can be considered as a new principle of figure-ground segregation and of extraction of material properties. It is in fact, the main source of information through which the visual system picks up the matter attribute of an object. The strength and salience of the figural organization is directly proportional to the material properties (as one amount increases, the other amount increases at similar rate).

It is worthwhile to note that most of the subjects of the two last experiments reported a further interesting result not mentioned before and mostly related to the conditions where the object-hole effect was much more convincing. For example, the previous conditions, not only did they show the figure as a hole on a wall made up of some kind of matter, but also they emerge as a hole created by something or in some way: "the square made of concrete is seen as violently broken by a heavy punch or by a big bullet". These sorts of outcomes suggest that the perception of the figure-ground segregation, of the material properties and of the causes and effects are strongly related to one another. Moreover, the same kind of information that carries figural and matter attributes can also convey information about the perception of the causality (Michotte, 1963). Indeed, in the previous conditions, the perception of the causality occurred in the stimuli where the object-hole effect and the material attributes were more intense.

The extension of the object complexity, based on the contours and going from the shape to the material attributes to the causality, will be more deeply investigated in the next sections.

5. Shape, material properties and casualty from contours

5.1. The case of the square

In the previous sections we presented stimuli where the whole shape and each element of the whole organization manifests only one kind of contour. The only exception was made for the frame and the square annuli, which could show two types of contours in the inner or outer boundaries. Nevertheless, the inner and outer boundaries are in these cases two different boundaries and within each of them the contours do not change at all.

At this stage the question is: What is the kind of perceptual organization in terms of figure-ground segregation and material properties when the same shape has different kind of contours?

The first stimulus on the left of Fig. 7 shows a condition where the figure manifests contours that differ in the horizontal-vertical and oblique directions. Here, the stimulus was described as "a beveled (50%) or a cut (45%) square made up of paper and cut with scissors". A further weak result obtained was "a pentagon" (5%). In short, this description entails that the grouping between the horizontal and vertical sides is related to the perception of the square, while the oblique side is responsible for the beveling/cut and as a consequence for the material attributes and cause based on the scissors.

The complexity of this description can be phenomenologically defined through the Gestalt dynamics described by Rubin and Wertheimer, without invoking cognitive processes. First of all, the perception of the square is phenomenally the whole invariant component, while the beveling or cut represents the local inner variation within the wholeness. Moreover, the resulting perceptual object is related to Wertheimer's (1922, 1923) grouping and unification in a whole and unique shape of different kinds of contours, mostly on the basis of the closure principle. This principle puts together and forces all the components (the segments that become sides) to assume a common visual meaning that could "explain" what is invariant and what is the variation, namely what is similar and what is different (the horizontal and vertical sides vs. the oblique one). This implies that, not only does the closure play a role but

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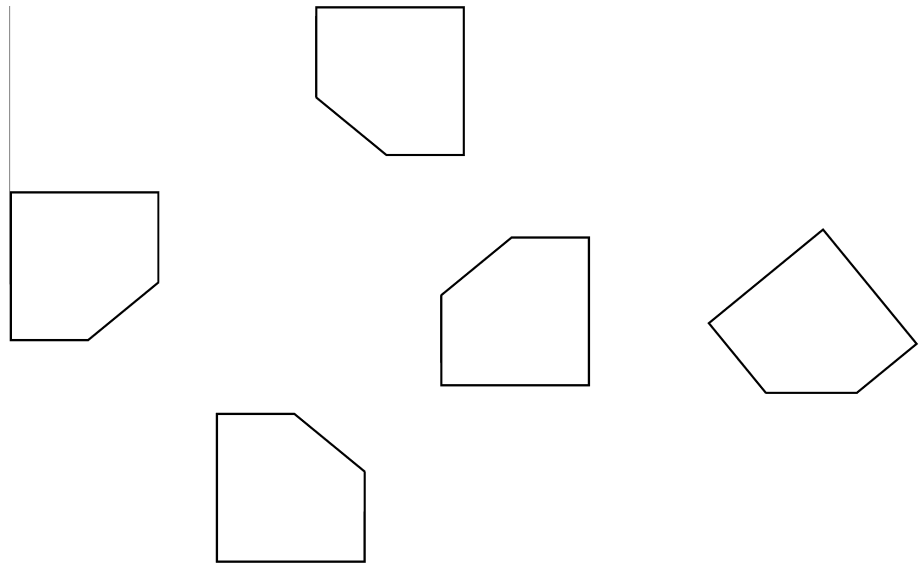

Fig. 7. Different instances of a bevelled square and a pentagon/diamond.

also the similarity could play some role within the same set of elements. As a result, it creates a distinction between similar and dissimilar components that group and emerge as parts or components of a whole. These inner forces are not discounted but they are taken into account by differentiating the whole object in visual meaning that qualifies the final percept.

In spite of these attempts, the Gestalt dynamics just described cannot fully explain the complexity of the outcomes, although they can be useful to understand the structure due to the interaction among the single geometrical components. A full explanation of conditions like these can be found in Pinna (2010b), Pinna & Albertazzi (2011). What is basic for our purposes is to explore the phenomenal connections among figure-ground segregation, material attributes and causality or other tertiary qualities.

The same beveling occurring in different angles of the same square is perceived as such but with different strengths (cf. all the instances of Fig. 7 are here placed in a random order to minimize or reduce the grouping and interaction among them, which can influence the strength of the described effects). The most outstanding result was perceived when the beveling is placed on the bottom angles and on the horizontal side that defines the base of the square. When the beveled/cut becomes the base of the shape (see the last stimulus on the left of Fig. 7), the perception of the square as the whole figure is remarkably reduced and "a pentagon" or "a diamond" was now perceived.

Further and more complex conditions, where these qualities appear strongly interrelated, are illustrated in Fig. 8. In Fig. 8a, the spontaneous descriptions of the subjects were a square made up of a wire with a missing or cut angle (90%). This suggests that missing elements or absences can contribute to elicit the perception of both material attributes and causality (Leyton, 1989, 1992). In Fig. 8b, the square made up of glass appears violently broken in a corner (93%). In Fig. 8c, the square is perceived partially gnawed or nibbled from the bottom by some kind of animal (a mouse). The contour variations within the same figure make explicit the variant and invariant components. More importantly, these descriptions reveal the close connection between contour changes, matter and causality.

In Fig. 8d, the square made up of soft material like wax or plastic appears burning out and wearing out (90%). In Fig. 8e, the square of paper was said to be deformed by a scorch (81%). The deformation elicited the perception of the square and qualifies its matter. In Fig. 8f, the contour variations defined the square as made of a crystalline matter that grows spontaneously like a crystal (88%). The square of Fig. 8g was perceived as a holder diffusing or bleeding a dense liquid (77%). The square of Fig. 8h was perceived like a soft rubber deformed by the heat (83%). In Fig. 8i, the square appeared as made up of a non-rigid cable tangled up (85%). In Fig. 8j, the square was now seen as made up of a rigid steel cable mixed and intertwined (79%). In Fig. 8k, the square appeared as erupting some kind of liquid and light material (82%).

All the stimuli of Fig. 8 clearly demonstrate that the inner contour changes influence the material attributes and the cause of the changes. More generally, the phenomenal steps and dynamics could be the following. Whenever something perceived as a whole shape, amodally completed, is also perceived as broken, it reveals its material properties and the cause of the breaks. As a matter of fact, something made up of glass appears broken differently from a square made up of pottery or fabrics. It is the specific shape of the broken part that defines the matter. Furthermore, each contour change is related to some kind of variation that defines a kind of break and, thus, a specific verb that describes appropriately the perceived meaning of the happening (Pinna, 2010a) occurring on a shape made up of a certain material. The term "beveled" indicates only a small number of material attributes (paper, metal, etc.) and, at the same time excludes many others. Moreover, by defining the matter, the shape of the broken part also discloses useful information on how that matter was broken and the maker or cause of the break.

5.2. Simplicity vs. complexity of properties emergence of organization

The array of the previous emerging attributes can be also perceived in the next conditions (Fig. 9), where more systematic and geometrically organized changes of the contours are illustrated. By presenting the stimuli all at once, a new group of subjects reported to perceive "a soft fishing net with a square shape distorted and deformed by the wind or by other invisible causes that impart a pressure on it."

Again, the shape of the net, perceived as having a square shape, is related to the invariant components, while the material properties and causality depend on the local contour variations (Leyton, 1989, 1992). The material attributes emerge together with the

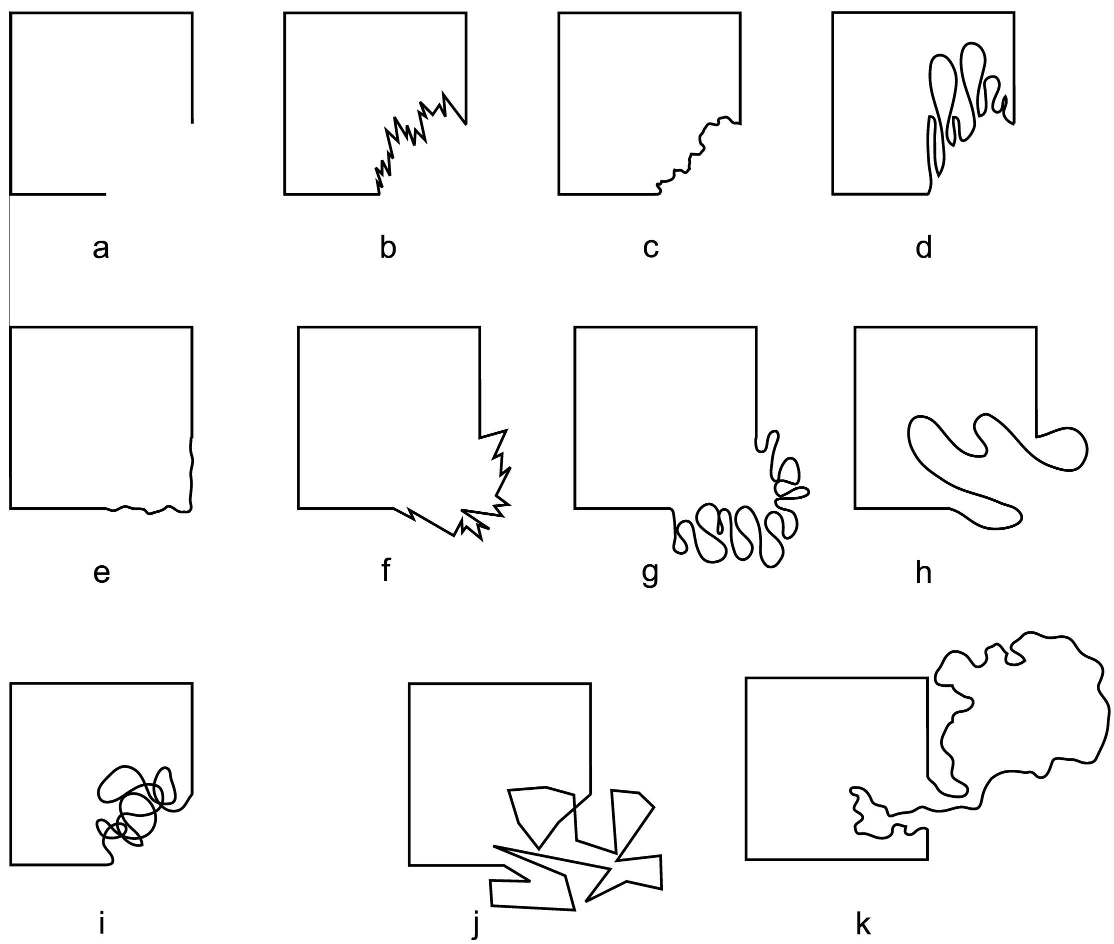

Fig. 8. Shape, material properties and causality related to different contour changes.

whole shape. Without the shape the matter cannot be seen. The same argument can be addressed to the causality.

These results, taken together with those of the previous experiments, show the following inner phenomenal logic implicit to the whole organization of emerging qualities. According to this logic, the contours and their inner variations of first and second order elicit the formation of the whole shape (invariant) and of the material properties that, in their turn, elicit the formation of the changes and deformations within the shape that all together elicit the perception of the causes, which circularly "explain" both the deformations of the shape made up of a certain matter. Deformations and changes become the variant components that emerge and explain what remains invariant, namely the whole shape and its matter.

The term "explain" is here used not in the cognitive acceptation (Gregory, 1987; Metzger, 1963, 1975a; Pomerantz, 2003) but as a synonym of putting together, complement and elicit the best phenomenal results among all the possible ones given certain basic stimulus conditions. In this sense, it can be considered as an extension of the notion of perceptual organization as used by Gestalt psychologists (cf. Pinna, 2010a).

This is reminiscent of the simplicity-Prägnanz principle, according to which the visual system, similarly to each physical system, is considered as aimed at finding the simplest and the most stable organization consistent with the sensory input (Koffka, 1935; Köhler, 1920). In computational terms, the visual system chooses the simplest interpretation, the one defined by the least amount of information in terms of descriptive parameters due to regularities (Attneave, 1954; Hochberg & McAlister, 1953). Therefore, the preferred perceptual organization is the one which elicits the briefest perceptual encoding (Atick & Redlich, 1990; Barlow, Kaushal, & Mitchison, 1989; Blakemore, 1990). This entails that a visual result, like the soft net of Fig. 9, conveys information about the regularities of the stimulus and the briefest perceptual encoding.

In spite of these similarities with the simplicity-Prägnanz principle, there are also clear differences depending on the complexity of the emerging qualities and outcomes that "explain" the array of contour variations. In other words, to elicit simple conditions the visual system creates emergent and complex new qualities and objects, like the material properties and the causes that, by deforming the objects, reveal their shape and their matter. Simplicity and complexity are the two complementary poles that on the basis of our results deserve to be discussed and studied more deeply. The next conditions go in this direction.

As a matter of fact, the major contribution of the contour changes in terms of simplicity and complexity was demonstrated by showing to a new group of observers a squared lattice not deformed like the ones shown in Fig. 10. The most common description was "a squared structure like a checkerboard without black and white alternated components or a squared or ruled square." Subjects did not mentioned spontaneously the matter of the figure that remains placed on the low levels of the gradient of visibility. Only after a direct question, they answered "a rigid and solid checkerboard made up of plastic or wood" and "a squared sheet of paper."

These results suggest that the material attributes emerge mostly when contour changes are introduced within a figure. Moreover, the outcomes could also be based on past experience,

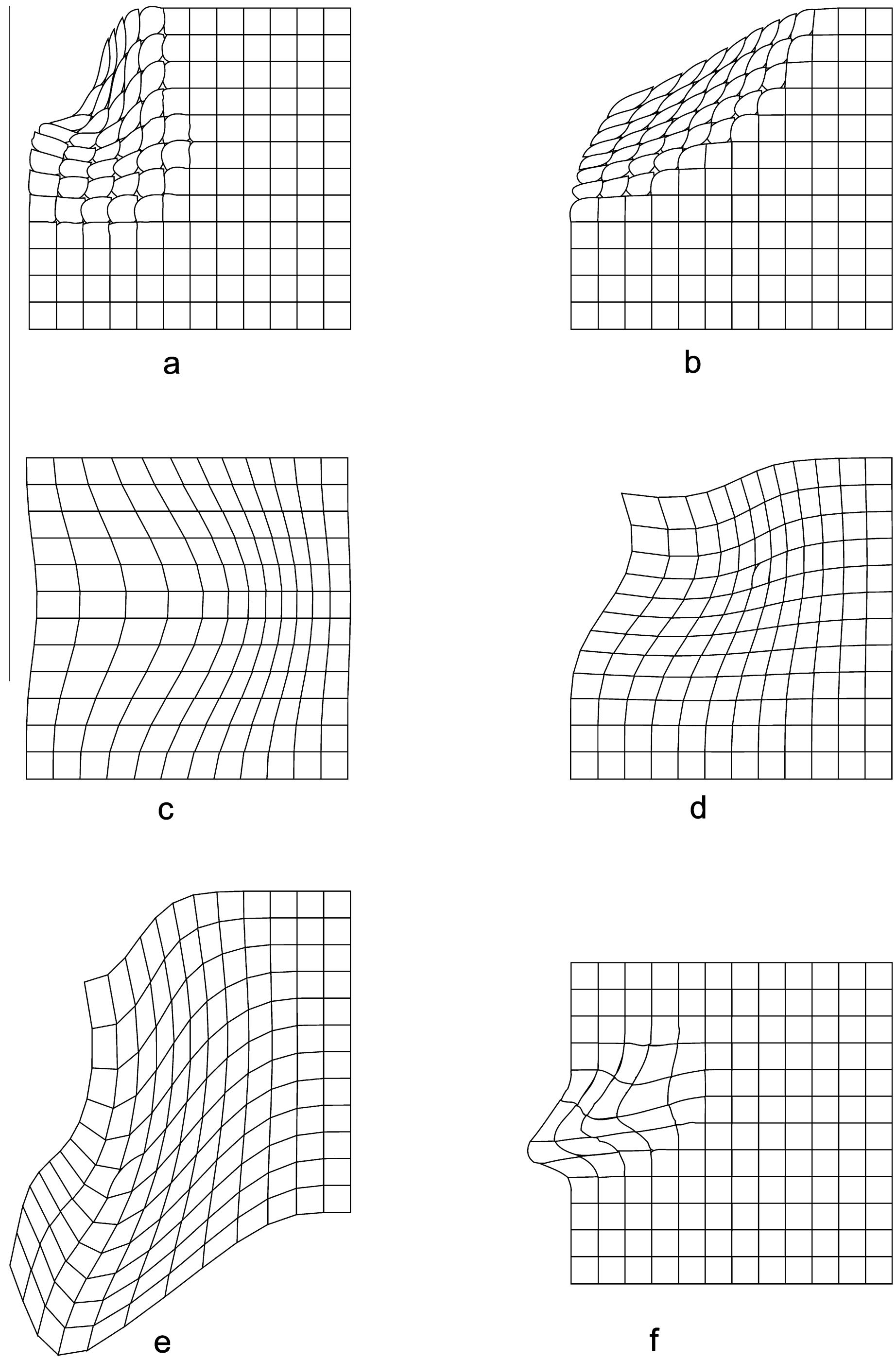

Fig. 9. A soft fishing net with a square shape distorted and deformed by different invisible forces.

for example in the case of the squared sheet of paper. However, this is only one possible result among others, that not necessarily depends on past experience. In the final section, in reality, we will analyze these results in terms of perception as inference as opposite to the simplicity approach suggested by Gestalt psychologists. The phenomenal logic, based on the contour variations that defines the material attributes, the deformations and the possible causes of this deformations can be better appreciated in Fig. 11.

A new group of subjects reported more complex and richer sets of attributes. Under these conditions the question "what is the object?" is very appropriate and not immediate as before. The same zigzagged contour, placed near and in different spatial positions with respect to the contour changes, appeared as if it were different causes operating with different strength on different materials. Although the descriptions (here not reported) where all very different from one subject to another (some of which very bizarre although shareable), the main structure and phenomenal logic previously described remains unchanged and common to all the subjects: a square shape made of some material deformed by something with a certain strength. Only the set of details and the specific appearance related to the forces causing the deformations of the shape changed on the base of the contour variations that elicit also a specific matter. Finally, by changing the orientation, the spatial position, the width or other parameters like the shape

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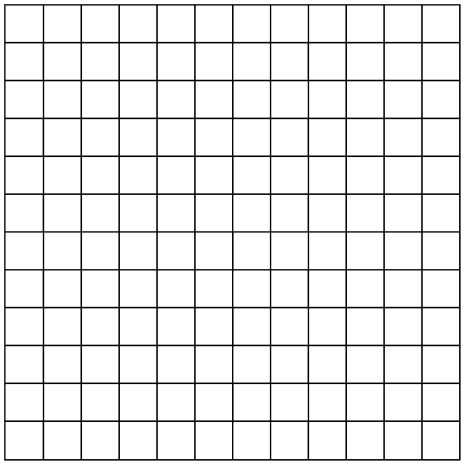

Fig. 10. A ruled square.

(curved) of the zigzagged contour the main structure of the perceived results was the same, while the details of the perceived meanings notably involved changes.

These results also demonstrated that the changes in a single portion of the whole set of components spread and fill the entire shape with the same kind of material attributes perceived in that portion. It means that the material properties, when attributed, tend to remain invariant everywhere within the same object. These results are tested in the next section, where the components are not contiguous and adjacent but work as distinct objects.

5.3. The case of distinct squares

At this stage, the main question is: What is the kind of perceptual organization, object formation and material attributes when separated elements manifest different kinds of contours?

To answer this question we studied conditions like those illustrated in Fig. 12. To clarify the rationale of this section, it is useful to compare Fig. 12a–c. In Fig. 12a, the array of small squares groups together creating a large square. Subjects described this condition as "a square made up of squares" (cf. with Fig. 10). When the question asked was "what is the square made of?", the observers answered "a rigid matter composed of blocks of concrete or plastic cards." The sense of rigidity was the main characteristic of each single component as well as of the whole assemblage. When it was asked "how can the figure be split into pieces?" Subjects reported that each small square could be removed or alternately the array could be broken in parts as shown, for example, in Fig. 12b and c, i.e., by considering the whole array as a rigid set made up of rigid subarrays. Shortly the same forces that group together each square to create a larger square could be applied to the subarrays. Moreover, a regular array tends to be perceived as made up of regular subarrays, not as a set or subarrays having different shapes from the square, e.g., irregular.

Fig. 12b and c were shown to a new group of observers. They perceived a broken subarray moved away from the whole. None of them described the opposite possible solution, namely a large portion of squares arranged in horizontal and vertical directions creating an L-shape moved away from a small grid of squares. This last outcome sounds strange and semantically wrong, although it is logically equivalent to the other solution. Furthermore, other conditions showing a one way direction of the visual assignment of meaning will be described in the next stimuli. These results are useful to understand the matter of the grouping. In fact, the kind of grouping elicits the matter of the array and, *vice versa*, the kind of matter perceived through the grouping elicits specific and different possible ways to split up and break the wholeness. Finally, none of the subjects reported that the shape of each small square could be broken by splitting its sides. This suggests that, through the grouping, each square is like "glued" by local forces and all the squares are glued through long range forces that maintain the perceived qualities of the elements, the whole and the parts invariant and constant.

In Fig. 12d, the small squares are replaced with irregular shapes. A new group of subjects described this condition as a square arrangement of distorted squares made up of a soft matter like tissue-paper. This description corroborated previous results by demonstrating the intimate connection between contour distortions and matter. The distortions suggest and are related to the matter and *vice versa*.

This outcome is further supported by the variations of Fig. 12e–i, where not all the small squares of the whole object are involved in the contour changes and deformations. Under these conditions, the deformed squares become part of a global structure, where all the components are assumed to have the same material characteristics.

It is worth noticing the relevant asymmetry between the deformed and not-deformed components. The results demonstrate that it is more likely that the "deformed squares" determine the material attributes of the non-deformed ones and not *vice versa*. This is a simple implication, not a double, meaning that the material attributes are perceived mostly through the deformations than through the regular squares with straight parallel sides. This unidirectional way is required and necessary to put together all the variations within the small squares.

On the contrary, the perceived direction of the changes goes from the regular to the irregular squares, not the other way round (unidirectional entropic perception). In other words, it is much easier to perceive an array of regular squares gradually changing or deforming their shape and not an array of deformed squares that become gradually regular and rigid (Pinna, 2010a). At the same time, the matter of the components is defined by the deformations and proceed in the opposite direction. A further unidirectional phenomenal tendency is the perceptual causality, which proceed from the deformations and material attributes to the regular components of the grouping. Both matters and causes are visible through the irregularities and spread in the direction of the regularities and invariant components. The irregularities are needed to perceive the regularities and their matter. It further implies that the irregularities of the contours are much more informative of the regular ones, thus favoring the possibilities to put together and "explain" the shape and attributes of the whole object.

These remarks were further tested through the stimuli illustrated in Fig. 12j–m, where a large square is included in between the two separated groups of elements (regular and irregular). Under these new conditions, the perceived changes are "annulled" or "discounted" and incorporated in the large square that subsumes all the qualities and becomes "a thick kind of glass that deforms the square behind it". The large square is perceived as the agent, the cause of the deformation. Furthermore, the contour changes of the elements, perceived through the superimposed transparent glass, determine the material attributes of the glass. This result reveals a tendency to assign a change or a certain property to only one component instead of two. As a matter of fact, if the source of deformation eliciting the matter is assigned to the squared glass, it is discounted from the small squares underneath, which are, as a consequence, perceived as regular. On the other hand, if the deformations belong to the squares, then the large square is perceived as the perimeter of a square, i.e., empty inside. This is some kind of law (or principle) of the excluded third (*principium tertii exclusi* or *tertium non datur*: Subjects' reports corroborated this basic tendency.

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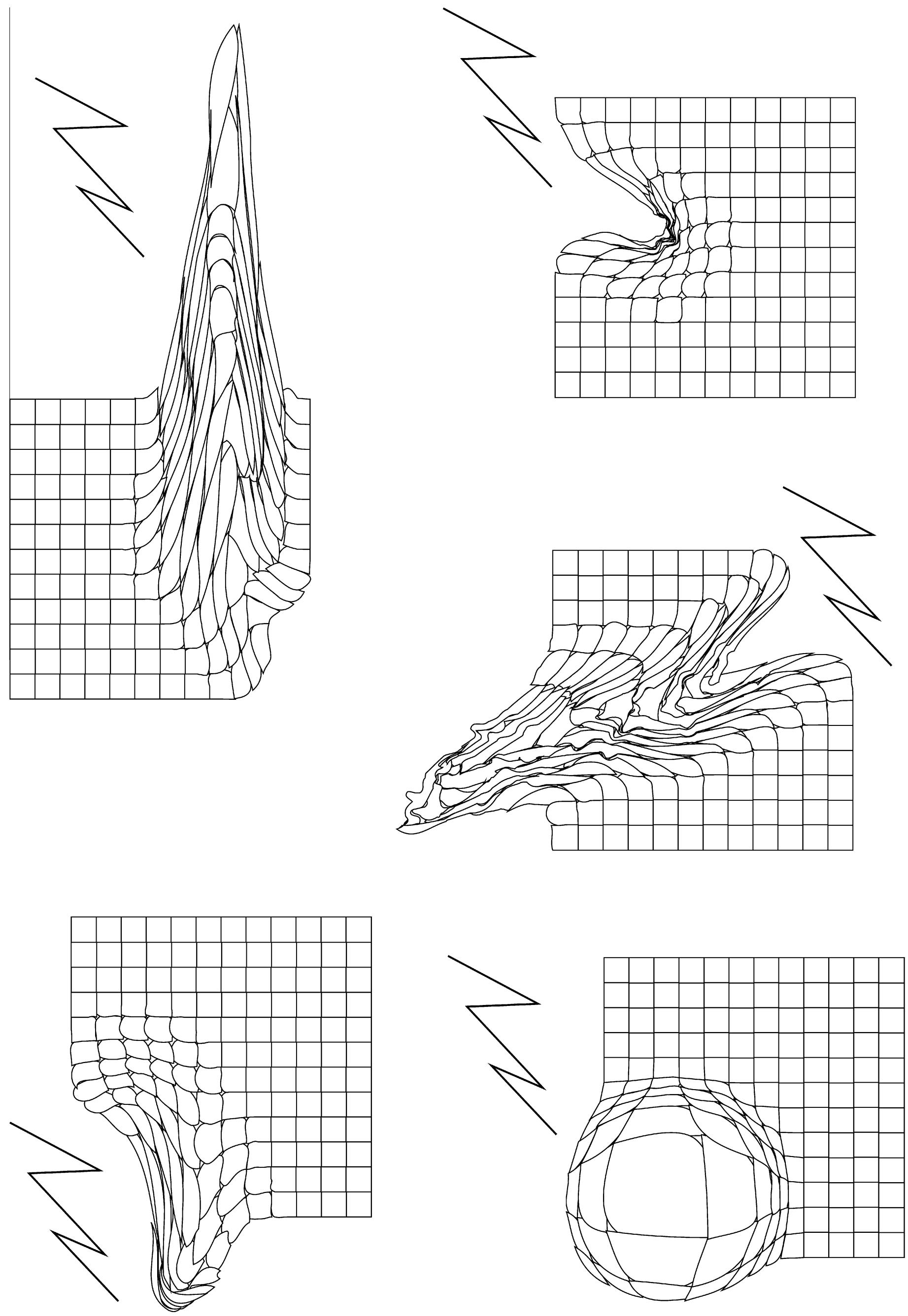

Fig. 11. A square shape made of some material deformed by something.

It is worth noticing that none of the subjects reported to perceive three juxtaposed different groups of elements segregated on the base of the similarity principle: the regular squares, the irregular shapes and the larger square. This solution, theoretically but not phenomenally strong enough, cannot put together and cannot explain the multiplicity of elements and, above all, of changes (variations) and invariants. On the contrary, the whole visual meaning previously described makes simpler and, at the same time, more complex (Pinna, 2010a) the sets of components, putting them together, explaining all the differences and subsuming all of them within the glass that, as a consequence, appears superimposed.

In summary, the larger square perceived as made up of some kind of glass, due to its material attributes, becomes the cause of changes and deformations. Besides, the changes affect the specific and "visible" cause and, thus, the whole arrangement and meaning of components, their shape and material properties.

Not always, the causes incorporate the material attributes. In reality, as shown in Fig. 12n–q, the causes can just determine the changes in the contours of some elements of the array, thus revealing their material properties. In other words, the causes favor the emergence of the matters and are influenced by them in terms of strength and other attributes related to their being causes of those changes.

All the observers perceived these conditions as a coherent set of elements synergistically arranged to create a full and clear visual meaning. None of them noticed that the so-called "cause", that, indeed does not touch the part of the array which is changed or influenced by them. In fact, the causes do not really affect the elements, due to their distance from the targets. Fig. 12r–s

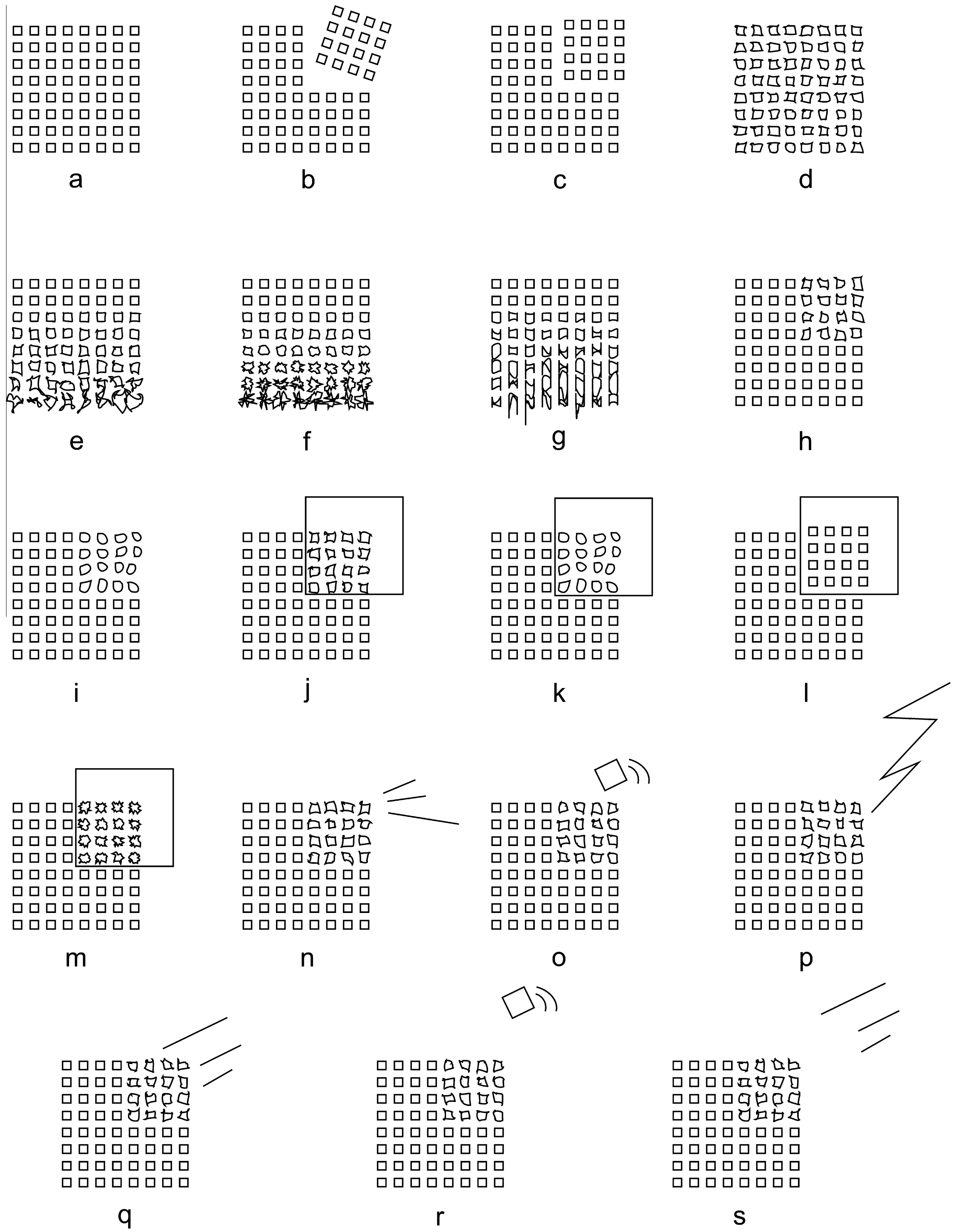

Fig. 12. Different conditions showing shape, material properties and causality from contour changes.

demonstrated that although the distance is very large the close relation between cause, material attributes and shape were still perceived.

All the kinds of additions to the square array can be perceived as "cause". These outcomes suggest a further and more complex kind of perceptual organization that puts together (explains) the different elements, which otherwise i.e., only on the base of the Gestalt grouping principles (mostly the similarity) should appear as different separated groups. We wish to underline that the terms "put together" and "explain" are here used in the acceptation of minimization of the information load. Namely, by putting together many elements, the number of the final components is reduced in number, from many to one or to just a few. This is the side of simplicity related to this kind of organization. The other side is the complexity that favors the emergence of complex new meaning. Phenomenally, it is by virtue of the emergence of the complex

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meaning (maximization of the meanings) that the information load can be minimized. Therefore, the differences and changes can be put together and explained in terms of sets and subsets of invariant emergent qualities.

As a general statement, all kinds of changes within the contours, rather than ungrouping in many different components, activate their self-organization, their staying together in a new emerging way that takes into account the multiplicity and complexity of the changes and, at the same time, the similarities among them. Within this hypothesis, the material attributes can be considered as properties emerging from this contour organization aimed to explain or minimize the complexity of the information load. The phenomenal causes reinforce this process by revealing with the full set of attributes the notion of "object" that was the incipit of this work.

These theoretical remarks will be discussed and extended in the next final section.

6. Discussion and conclusion

In this work we explored phenomenologically the visual complexity of the material attributes on the basis of the contours that define the boundaries of a visual object. The starting point is the rich and pioneering work done by Gestalt psychologists and, in particular, that carried out by Rubin (1921), who first demonstrated that contours contain most of the information related to object perception, like the shape, the color and the depth (Pinna, 2012a; Pinna & Reeves, 2006). By investigating simple conditions like those used by Gestalt psychologists, mostly consisting of contours only, we demonstrated that the phenomenal complexity of the material attributes emerge through appropriate manipulation of the contours.

A phenomenological approach, analogous to the one used by Gestalt psychologists, was chosen to answer the following questions. What are contours? Which attributes can be phenomenally defined by contours? Are material properties determined only by contours? What is the visual syntactic organization of object attributes?

Our results can be summarized with the following simple assumption: shape and material properties from contours. We also demonstrated that shape and material are closely related to the perception of causality. These three properties contribute to define what a perceptual object is within the stimulus conditions given in this work. On this base and through a large number of figures and phenomenological experiments we showed that the answer to the question "what is a visual object?", as proposed by Gestalt psychologists in terms of figure-ground segregation and grouping, is insufficient to show the complexity and, at the same time, the simplicity (discussed in the previous sections) of the inner organization of properties that depend on contour changes. Fig. 13 summarizes the main results shown in the previous sections.

More precisely, this figure clearly defines the complexity/simplicity of the notion of object perception and the direct link among contours, shape and material properties. In fact, marks, spots, stains, blots, smudges are good examples of how contours can define the nature of each object, and above all, its material properties and what causes them. Although also other properties, like for example color and density, contribute to define the nature of these objects, contours play here the basic role.

This is related to the fact that they are structurally similar to the holes. In fact, stains are figures that segregate from the background but behave like something not required, something extra that disturbs, that should not stay there and that stains the object on which they are applied. Therefore, they are figures and not figures at the same time. For example, a stain on a jacket is in some way similar to a hole. However, differently from the hole, the stain reveals through its contours, not only its matter but also the matter of the jacket. Instead, the hole shows mostly the matter of the jacket. Similarly to the hole, through its contours, the stain shows the cause, the strength and much more information related to it. In general, as demonstrated in the previous sections, the contours contain and reveal a great deal of visual information that goes much beyond the simple shape.

There is also information related not only to the secondary qualities, but also to the tertiary or physiognomic attributes (Koffka, 1935) that pop out and emerge together with the materials. Indeed, tertiary properties also refer to more complex Gestalt qualities that apparently are not part of the physical (sensory) stimulus itself. The beauty, the energy, the artistic value of a stain, a spot and other kinds of patches are tertiary qualities that cannot be denied. Jackson Pollock's dripping paintings and the abstract expressionist movement are good examples of the emergence of such physiognomic qualities that became Art.

None of these qualities are contained in the sensory stimulus. However, this is only a phenomenal result, in the sense that it is what appears to be. Phenomenally, some qualities are perceived as being more related to the physical object than others. The tertiary qualities seem to be more subjective than objective. However, from an epistemological and theoretical point of view the problem of belongingness is more complex, as demonstrated by the debate elicited by ecological approach (Gibson, 1950, 1966, 1979) to visual perception. Gibson's direct perception, considers the optical information available in the retina of a moving organism as sufficient to convey visual perception without any mediating processes or internal representations. Such an idea denies that perception is the result of unconscious inferences that go beyond the information strictly given by sensory stimulation.

Going back to our results, it is not easy to say which qualities belong to the sensory stimulus and which do not belong to it. More generally, we can say that none of the results of the perceptual organization are part of the sensory stimulus and, conversely (in Gibsonian terms), that all the results are part of the sensory stimulus. For example the square of Fig. 1a is the result of the organization of the segments that become "sides" only after or when the square is perceived. In this sense, a square is not part of the sensory stimulus, but the result of a process of perceptual organization. At the same time, the square is phenomenally perceived as something belonging to the physical world. The bevelled square of Fig. 7 is not fully considered as part of the physical stimulus but mostly as the consequence of the perceptual organization. Nevertheless, it can also be considered as a secondary or primary quality and thus part of the sensory stimulus. The beveling is also a visual meaning that can be judged as a tertiary quality, revealing a special kind of perceptual organization that goes beyond the Gestalt grouping. The same arguments can be applied to the material attributes related to the contour variations and to the perception of the causes and effects and so on. They can be and cannot be considered, at the same time, as part of the sensory stimuli. In spite of these philosophical issues, what is here important is the phenomenology of the objects and of the properties we explored. Phenomenally they all appear "real" like the pictures of Fig. 13, and like every physical object, they also appear independently from the observer. However, there are conditions demonstrating that this issue is more complex.

Fig. 14 illustrates a further extension of the contour attributes in showing primary, secondary and tertiary attributes all reciprocally related to one other and all difficult to be categorized as belonging to one or to another domain (primary, secondary or tertiary). The different kinds of comic balloons show different ways of talking, thinking and communicating. The kinds of balloons depend on variations placed on the contours and demonstrate the "material attributes" of the expressions of the subjects. Some of these

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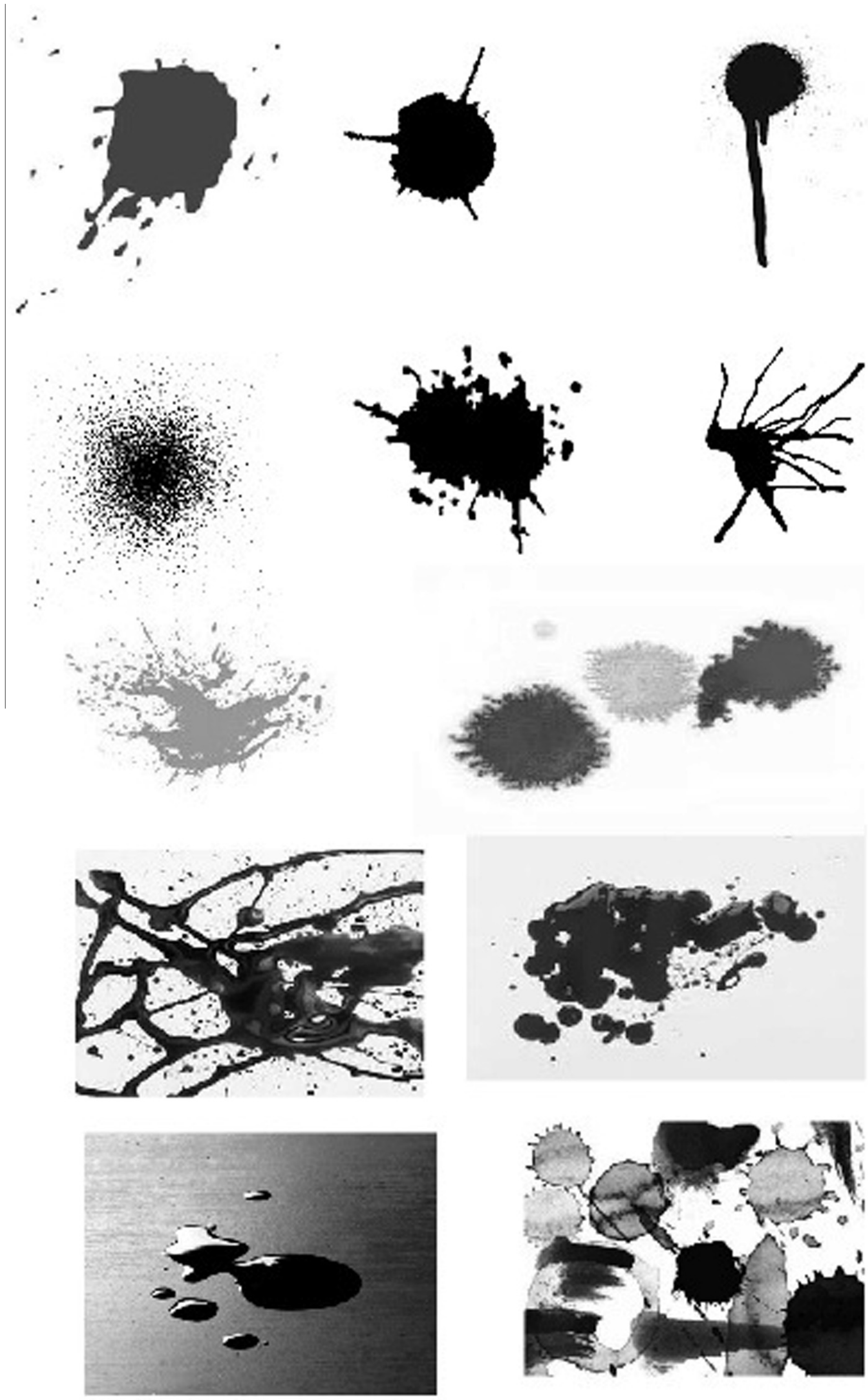

Fig. 13. Marks, spots, stains, blots, smudges are examples of how the contours define the material properties.

expressions are, in fact, like materials, i.e., light, soft, hard and so on. The contours seem to define the material attributes of the balloons, each strictly linked to a specific kind of comic expression. In the upper part of Fig. 14, the expressions of the balloons mean respectively: normal speaking, whispering, screaming, thinking, dreaming about, speaking nervously, speaking with anger. At the bottom part of Fig. 14, many other gradations of expressions are perceived as directly related to the kind of contours.

Although always related to the material attributes, the kind of contour becomes pure expressivity in artistic drawings as demonstrated in Fig. 15, where Matisse's, Picasso's and Giacometti's portraits are illustrated. The contours are clearly related not only to the content and to what is represented but mostly to its expressivity. They show not only a pure shape but mostly its expressivity and tertiary qualities. These portraits exhibit different sort of beauties, different styles of drawing, different personalities, different kinds of Arts, different abilities, different meanings. Rivers of ink have been spilled during the centuries to explain the expressiveness of the contours, of the strokes and of the outlines typical of a certain artist or to different artistic

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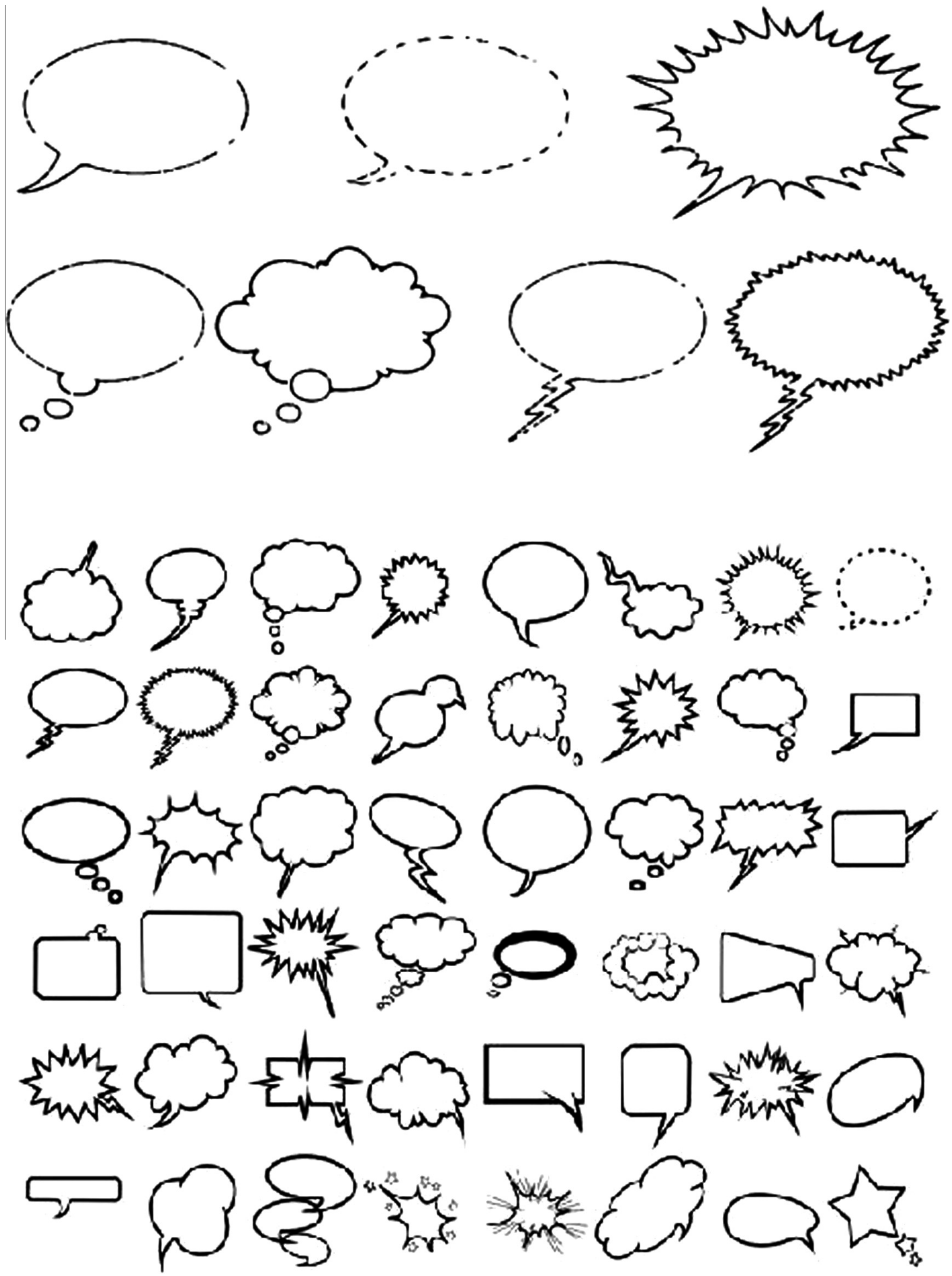

Fig. 14. The contours of the comic balloons demonstrate different ways of talking, thinking and communicating.

movements. This demonstrates the strength of the contours in expressing and showing so interesting and complex qualities, which emerge from the basic material attributes.

Last but not least, there is a final aspect already mentioned but never discussed. It is the syntax of vision emerging from our results. In the previous sections, we have demonstrated that the contours define the shape as a first object property and, then, the material attributes are defined.

Linguistically, the matter is an adjective that describes the noun, which is mostly the shape. Phenomenally, the matter is what the shape is made of. The phenomenal asymmetry in terms of visual meanings between "the matter of a shape" and "the shape of a matter" demonstrates the primary role of the shape against the matter. Clearly the shape comes before the matter. The phenomenal hierarchical organization between shape and matter can be considered as the perceptual basis of the linguistic syntactic

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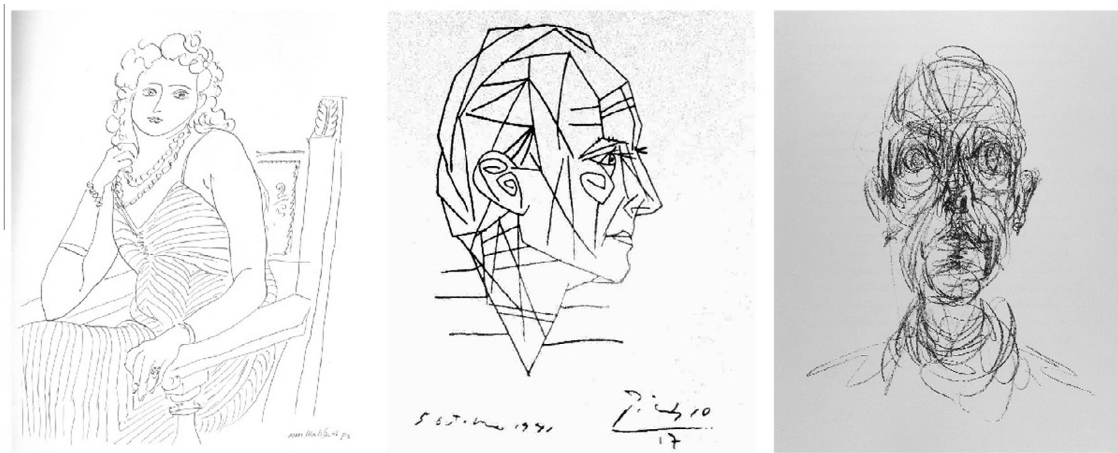

Fig. 15. Matisse's, Picasso's and Giacometti's portraits demonstrating the role of contours in the defining expressive qualities.

organization of the word classes and, more in detail, the different roles/classes within a language between noun and adjective. The shape is the noun, while the matter is the adjective. The matter is the 'describing' word that qualifies the shape, i.e. the noun, which is the 'content' word.

In other words, the shape is primary, earlier in time and order than the matter. The matter can be implicit, the shape cannot. In fact, it tends to be always explicit. Therefore, the shape is the noun. As such, the shape is like "a thing", which can appear in many different ways, and the matter is one of his ways of being, i.e. the attribute of that specific thing.

Previously (Pinna, 2012a, 2012b), the syntax of visual attributes was already demonstrated for shape, color, volume and illumination. In this work, we extend preceding data to the material attributes and expressive qualities. Further works are necessary to set up the syntax arrangement of attributes in series. Our data suggest that the material attributes are closely related to the shape, not to the color or to the surface qualities. Given that the shape is the primary property, the material attributes are presumably the closest among adjectives to the shape, the noun. If we assume that the spoken language reflects or is isomorphic to the visual language and to its syntax (Pinna, 2012b), than in our languages we can find the proofs and the reflexes of the visual syntax or of a syntax behind or beyond both domains (visual and cognitive). The object naming has been shown to interact with contour shape and material properties in a number of many interesting ways related to our hypotheses in subjects of different ages (see Subrahmanyam, Landau, & Gelman, 1999).

Indeed, in English language (an extension to other languages is required) adjectives nearly always appear immediately before the noun or noun phrase that they modify. Sometimes they appear in a string of adjectives, and when they do, they appear in a set order according to category. Now, we suggest a possible explanation, limited to shape material properties and color, about why we say "red metallic square" and not "metallic red square" or "square metallic red" or "square red metallic" and so on for all the possible combinations. The order in which adjectives in a series sort themselves out is sometimes perplexing but perhaps coherent with the visual language. Indeed, most languages dictate a similar order. (About the long set of adjectives related to many different categories further and more systematic investigation are required). In general, we suggest that this order is not arbitrary or capricious but well defined on the basis of the visual syntax. For example, it is worth underlining that in English language the order of the adjectives, which are studied here and in previous works, reflects our results, i.e., color, material, qualifier (mostly the shape). As suggested from our data, the matter is in between the color and the qualifier. This corroborates the isomorphic syntax assumption. More results are needed to further support this assumption and extend it to other visual properties.

In conclusion, the phenomenological results of this work support the idea of a visual syntactic organization as a new kind of object formation process useful to understand the language of vision that creates well-formed attribute organizations. The syntax of visual attributes can be considered as a new way to investigate the modular coding and, more generally, the binding among attributes, i.e., the issue of how the brain represents the pairing of shape, matter and color.

This approach, only apparently, can be considered as an alternative, in the terms discussed in the previous sections, to the simplicity-Prägnanz principle, according to which the visual system, similarly to each physical system, is considered as aimed at finding the simplest and the most stable organization consistent with the sensory input (Koffka, 1935; Köhler, 1920).

Similarly, our approach cannot be considered as alternative to the one based on Helmholtz's likelihood and to the Bayesian statistical decision theory, which formalizes the idea of perception as inference (Bülthoff & Yuille, 1991; Feldman, 2000; Jaynes, 1983; Knill & Richards, 1996; Landy et al., 1995; Liu, Knill, & Kersten, 1995; Mamassian & Landy, 1998; Nakayama & Shimojo, 1992; Weiss & Adelson, 1998). Bayes' theory can be considered very valuable in explaining conditions like ours showing how information is combined with prior knowledge in perceptual inference (Kersten, Mamassian, & Yuille, 2004; Kersten & Yuille, 2003; Maloney, 2002; Mamassian, Landy, & Maloney, 2002).

Moreover, our approach, based on the syntax organization, subsumes aspects of both when assumes that the visual syntax is isomorphic to the syntax of the spoken language. None of them is considered as primary in relation to the other but both reflect the way the brain codes the information that is beyond the visual and the cognitive domains (cf. Subrahmanyam et al., 1999).

The main conclusion of this work, namely, material properties from contours, leaves open important phenomenal issues and suggests the following theoretical critiques. First of all, it seems that too much stress is assumed and placed on the influence of contours *per se*. Second, the nature of the stimuli used suggests the obtained conclusions in a possible circular way, i.e., the conclusions are those obtained because the stimuli are made as they are and *vice versa*. In more specific terms, the results could be considered as side-effects of the restricted class of stimuli used. Third, the stimuli

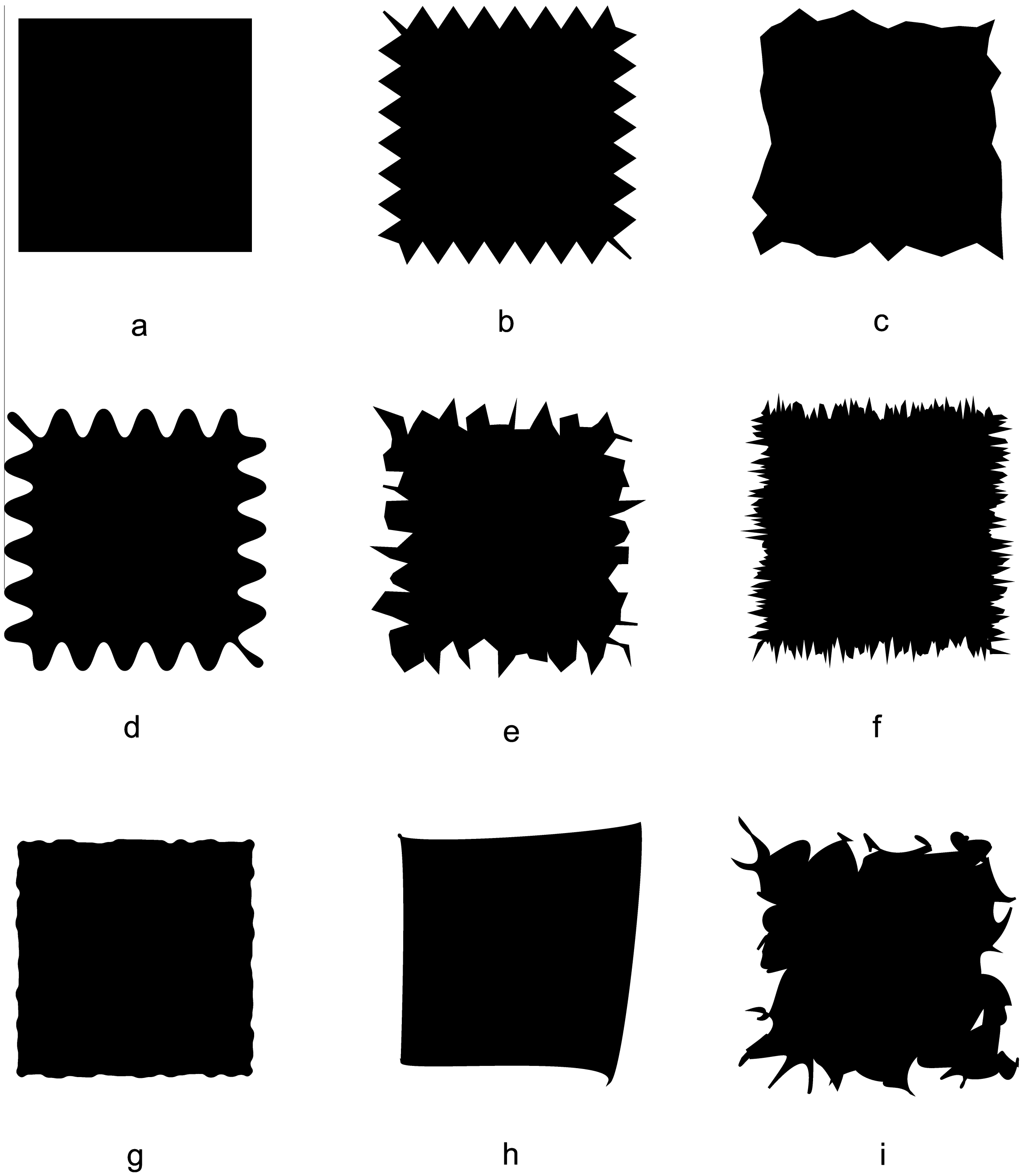

Fig. 16. The same squares of Fig. 1 filled with black appear more clearly as made up of different materials.

used are fully outlined, otherwise empty forms and the outline tends to be in uniform thickness black line. Therefore, the stimuli could be "too simple" to explain the complexity of the material properties. As such, they stand as representative only for a very minor part of pictorial art and photography.

What previously stated is not necessarily a weakness point for our work, but a strong one. As a matter of fact, the line-drawing displays can be seen either as depictions of solid objects, as well as black wire-frame objects. However, this creates opposite and conflictual effects in terms of material properties. Therefore, the simplicity of the stimuli, rather than strengthening the assignment of the material attributes, as suggested in the previous arguments, on the contrary, weakens this assignments as shown in Fig. 16, where the same shapes of Fig. 1 are now filled with black. These conditions, when shown to a new group of subjects, were judged more saliently to show material properties and as belonging to different materials than those illustrated in Fig. 1.

On the base of these results the material assignment is expected to be even stronger when more and more shading, volumetric and 3-D cues are added. These predictions can be clearly appreciated in Fig. 17 (although shown under not controlled conditions). Going from the outlined drawing of the columns, where different contours manifest different materials, the assignment of these attributes become stronger and stronger as the columns become more and more realistic and photographic. We expect that in the real scene the role of the contours could be even stronger.

To conclude, from our result it does not follow that contours provide the only, or even the primary source of information about

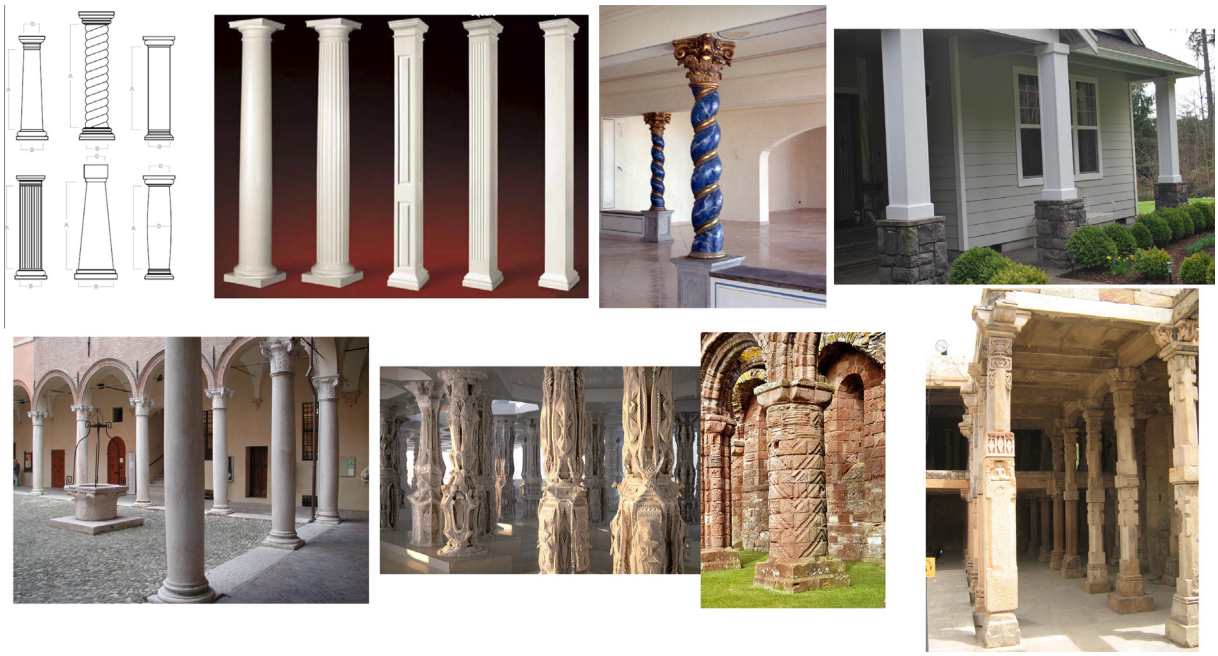

Fig. 17. The perception of the material properties become stronger when more and more shading, volumetric and 3-D cues are added.

material properties. Not any comparison has been made within this work among different sources of information. Although, these results cannot be generalized and absolutized in relation to richer classes of stimuli, they alone are sufficient to highlight the role of contours and the fact that they can be a strong and clear (a true sufficient condition) source of information useful for the assignment of material properties.

References

Anderson, B. L., & Kim, J. (2009). Image statistics do not explain the perception of gloss and lightness. *Journal of Vision, 9*(11), 1–17. http://dx.doi.org/10.1167/9.11.10. http://www.journalofvision. org/content/9/11/10.

Atick, J. J., & Redlich, A. N. (1990). Towards a theory of early visual processing. *Neural Computation, 2*, 308–320.

Attneave, F. (1954). Some informational aspects of visual perception. *Psychological Review, 61*, 184–193.

Barlow, H. B., Kaushal, T. P., & Mitchison, G. J. (1989). Finding minimum entropy codes. *Neural Computation, 1*, 412–423.

Bertamini, M. (2006). Who owns the contour of a visual hole? *Perception, 35*(7), 883–894. http://dx.doi.org/10.1068/p5496.

Bertamini, M., & Croucher, C. J. (2003). The shape of holes. *Cognition, 87*, 33–54. 10.1016 S0010-0277(02)00183-X.

Bertamini, M., & Helmy, M. S. (2012). The shape of a hole and that of the surface-with-hole cannot be analyzed separately. *Psychonomic Bulletin & Review, 19*(4), 608–616. http://dx.doi.org/10.3758/s13423-012-0265-3.

Blakemore, C. (Ed.). (1990). *Vision: Coding and efficiency*. Cambridge, England: Cambridge University Press.

Boyaci, H., Maloney, L. T., & Hersh, S. (2003). The effect of perceived surface orientation on perceived surface albedo in binocularly viewed scenes. *Journal of Vision, 3*(8), 541–553. http://dx.doi.org/10.1167/3.8.2. http://www.journalofvision. org/content/3/8/2.

Boyaci, H., Doerschner, K., & Maloney, L. T. (2004). Perceived surface color in binocularly viewed scenes with two light sources differing in chromaticity. *Journal of Vision, 4*(9), 664–679. http://dx.doi.org/10.1167/4.9.1. http://www.journalofvision.org/content/4/9/1.

Brainard, D. H., & Maloney, L. T. (2004). Perception of color and material properties in complex scenes. *Journal of Vision, 4*(9), 1–3. http://dx.doi.org/10.1167/4.9.i. http://www.journalofvision.org/ content/4/9/i.

Bülthoff, H. H., & Mallor, H. (1988). Integration of depth modules: Stereo and shading. *Journal of Optical Society of America, 5*(10), 1749–1758.

Bülthoff, H. H., & Yuille, A. L. (1991). Bayesian models for seeing shapes and depth. *Comments on Theoretical Biology, 2*(4), 283–314.

Cavanagh, P., & Mather, G. (1989). Motion: The long and short of it. *Spatial Vision, 4*, 103–129.

Chubb, C., & Sperling, G. (1988). Drift-balanced random stimuli: A general basis for studying non-Fourier motion perception. *Journal of Optical Society of America, 5*, 1986–2007.

Doerschner, K., Boyaci, H., & Maloney, L. T. (2004). Human observers compensate for secondary illumina-tion originating in nearby chromatic surfaces. *Journal of Vision, 4*(2), 92–105. http://dx.doi.org/10.1167/4.2.3. http://www. journalofvision. org/content/4/2/3.

Dorsey, J., Rushmeier, H., & Sillion, F. (2008). *Digital modeling of material appearance*. Boston: Morgan Kaufmann/Elsevier.

Duvelleroy-Hommet, C., Gillet, P., Cottier, J. P., de Toffol, B., Saudeau, D., & Corcia, P. (1997). Cerebral achromatopsia without prosopagnosia, alexia, object agnosia. *Revue Neurologique, (Paris), 153*, 554–560.

Feldman, J. (2000). Bias toward regular form in mental shape spaces. *Journal of Experimental Psychology: Human Perception and Performance, 26*(1), 1–14.

Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton Mifflin.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Giesel, M., & Gegenfurtner, K. R. (2010). Color appearance of real objects varying in material, hue, and shape. *Journal of Vision, 10*(9), 1–21. http://dx.doi.org/10.1167/10.9.10. http://www. journalofvision.org/content/10/9/10.

Giesel, M., Hansen, T., & Gegenfurtner, K. R. (2009). The discrimination of chromatic textures. *Journal of Vision, 9*(9), 1–28. http://dx.doi.org/10.1167/9.9.11. http://www.journalofvision. org/content/9/9/11.

Goodale, M. A., & Milner, A. D. (2004). *Sight unseen: An exploration of conscious and unconscious vision*. Oxford: UK, Oxford University Press.

Gregory, R. L. (1987). Illusory Contours and Occluding Surfaces. In S. Petry & G. E. Meyer (Eds.), *The perception of illusory contours* (pp. 81–89). New York Berlin Heidelberg: Springer-Verlag.

Hansen, T., Giesel, M., & Gegenfurtner, K. R. (2008). Chromatic discrimination of natural objects. *Journal of Vision, 8*(1), 1–19. http://dx.doi.org/10.1167/8.1.2. http://www.journalofvision. org/content/8/1/2.

Heywood, C. A., Gaffan, D., & Cowey, A. (1995). Cerebral achromatopsia in monkeys. *European Journal of Neuroscience, 7*, 1064–1073.

Hochberg, J. E., & McAlister, E. (1953). A quantitative approach to figural "goodness". *Journal of Experimental Psychology, 46*, 361–364.

Humphrey, G. K., Goodale, M. A., Jakobson, L. S., & Servos, P. (1994). The role of surface information in object recognition: Studies of a visual form agnosic and normal subjects. *Perception, 23*, 1457–1481.

James, T. W., Culham, J., Humphrey, G. K., Milner, A. D., & Goodale, M. A. (2003). Ventral occipital lesions impair object recognition but not object- directed grasping: An fMRI study. *Brain, 126*, 2463–2475.

Jaynes, E. T. (1983). E. T. Jaynes: Papers on probability, statistics and statistical physics. (R. D. Rosenkrantz,. Dordrecht, D. Reidel. ed.)

Johnston, A., & Passmore, P. J. (1994). Independent encoding of surface orientation and surface curvature. *Vision Research, 34*(22), 3005–3012.

Kanizsa, G. (1979). *Organization in vision: Essays on Gestalt perception*. New York, NY: Praeger.

Kersten, D., Mamassian, P., & Yuille, A. (2004). Object perception as Bayesian inference. *Annual Review of Psychology, 55*, 271–304.

Kersten, D., & Yuille, A. (2003). Bayesian models of object perception. *Current Opinion in Neurobiology, 13*, 150–158.

Khang, B.-G., & Zaidi, Q. (2004). Illuminant color perception of spectrally filtered spotlights. *Journal of Vision, 4*(9), 680–692. http://dx.doi.org/10.1167/4.9.2. http://www.journalofvision. org/content/4/9/2.
Kingdom, F. A. A. (2008). Perceiving light versus material. *Vision Research, 48*, 2090–2105.
Knill, D. K., & Richards, W. (Eds.). (1996). *Perception as Bayesian inference*. MA, Cambridge, University Press: Cambridge.
Koenderink, J. J. (1999). Virtual psychophysics. *Perception, 28*, 669–674.
Koenderink, J. J., van Doorn, A. J., & Kappers, A. M. L. (1992). Surface perception in pictures. *Perception & Psychophysics, 52*(5), 487–496.
Koffka, K. (1935). Principles of Gestalt psychology. New York, NY, Harcourt, Brace & World.
Köhler, W. (1920). *Die physischen Gestalten in Ruhe und im stationären Zustand*. Braunschweig, Vieweg: Eine naturphilosophische Untersuchung.
Köhler, W. (1929). *Gestalt Psychology*. New York: Liveright.
Köhler, W. (1947). *Gestalt Psychology* (2nd ed.). New York: Liveright.
Landau, B., Smith, L., & Jones, S. (1988). The importance of shape in early lexical learning. *Cognitive Development, 3*, 299–321.
Landau, B., Smith, L., & Jones, S. (1992). Syntactic context and shape bias in children's and adults' lexical learning. *The Journal of Memory and Language, 31*, 807–825.
Landau, B., Smith, L., & Jones, S. (1998). Object shape, object function, and object name. *The Journal of Memory and Language, 38*, 1–27.
Landy, M. S., Maloney, L. T., Johnston, E. B., & Young, M. (1995). Measurement and modeling of depth cue combination: in defense of weak fusion. *Vision Research, 35*, 389–412.
Leyton, M. (1989). Inferring causal history from shape. *Cognitive Science, 13*, 357–387.
Leyton, M. (1992). *Simmetry, casuality, mind*. Cambridge: The MIT Press.
Liu, Z., Knill, D. C., & Kersten, D. (1995). Object classification for human and ideal observers. *Vision Research, 35*(4), 549–568.
Maloney, L. T. (2002). Statistical decision theory and biological vision. In D. Heyer & R. Mausfield (Eds.), *Perception and the physical world: Psychological and philosophical issues in perception* (pp. 145–189). New York: Wiley.
Mamassian, P., & Landy, M. S. (1998). Observer biases in the 3d interpretation of line drawings. *Vision Research, 38*, 2817–2832.
Mamassian, P., Landy, M., & Maloney, L. T. (2002). Bayesian modelling of visual perception. In R. N. P. Rao, B. A. Olshausen, & M. S. Lewicki (Eds.), *Probabilistic models of the brain: Perception and neural function* (pp. 13–36). Cambridge: MA, MIT Press.
Metzger, W. (1963). *Psychologie*. Darmstadt: Steinkopff Verlag.
Metzger, W. (1975a). *Gesetze des Sehens*. Krankfurt-am-Main: Kramer.
Metzger, W. (1975b). Die Entdeckung der Prägnanztendenz. Die Anfänge einer nicht-atomistischen.Wahrnehmungslehre. In: Flores D'Arcais, G.B (ed.): Studies in Perception. Festschrift for Fabio Metelli, Milano/Firenze: Giunti-Martello, pp 3–47.
Metzger, W. (1982). Möglichkeiten der Verallgemeinerung des Prägnanzprinzips. *Gestalt Theory, 4*, 3–22.
Michotte, A. (1963). In T. R Miles & E. Miles (Eds.). *The perception of causality*. New York, NY: Basic Books.
Milner, A. D., Perrett, D. I., Johnston, R. S., Benson, P. J., Jordan, T. R., Heeley, D. W., et al. (1991). Perception and action in 'visual form agnosia'. *Brain, 114*, 405–428.
Morinaga, S. (1941). Beobachtungen über Grundlagen und Wirkungen anschaulich gleichmäßiger Breite. *Archiv für die gesamte Psychologie, 110*, 309–348.
Motoyoshi, I., Nishida, S., Sharan, L., & Adelson, E. H. (2007). Image statistics and the perception of surface qualities. *Nature, 447*, 206–209.
Nakayama, K., Shimojo, S. (1992). Experiencing and perceiving visual surfaces. Science, 257, 1357–1363, A. (1986a). Parts: Structured descriptions of shape. In: Proceedings of the 5th National Conference on Artificial Intelligence, 1, 695–701.
Nelson, R., & Palmer, S. (2001). Of holes and wholes: the perception of surrounded regions. *Perception, 30*(10). http://dx.doi.org/10.1068/p3148. 1213-2.
Nelson, R., Thierman, J., & Palmer, S. (2009). Shape memory for intrinsic versus accidental holes. *Attention, Perception, & Psychophysics, 71*(1), 200–206. http://dx.doi.org/10.3758/APP.71.1.200.
Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, Massachusetts/London: The MIT press.
Palmer, S., Davis, J., Nelson, R., & Rock, I. (2008). Figure-ground effects on shape memory for objects versus holes. *Perception, 37*(10), 1569–1586. http://dx.doi.org/10.1068/p5838.
Pentland, A. (1986). Perceptual organization and the representation of natural form. *Artificial Intelligence, 28*(3), 293–331.
Pinna, B. (2010a). What comes before psychophysics? The problem of "what we perceive" and the phenomenological exploration of new effects. *Seeing & Perceiving, 23*, 463–481.
Pinna, B. (2010b). New Gestalt principles of perceptual organization: An extension from grouping to shape and meaning. *Gestalt Theory, 32*, 1–67.
Pinna, B. (2012a). Perceptual organization of shape, color, shade and lighting in visual and pictorial objects. *i-Perception, 3*, 257–281.
Pinna, B. (2012b). The organization of shape and color in vision and art. *Frontiers in Human Neuroscience, 5*. http://dx.doi.org/10.3389/fnhum.2011.00104.
Pinna, B. (2012c). On the Meaning of Visual Meanings. *Gestalt Theory, 34*, 237–258.
Pinna, B., & Albertazzi, L. (2011). From grouping to visual meanings: A new theory of perceptual organization. In L. Albertazzi, G. van Tonder, & D. Vishwanath (Eds.). *Information in Perception* (pp. 288–344). MIT Press.
Pinna, B., & Ehrenstein, W. (2013). On the syntactic organization of shape and color. In B. Eiglsperger, M. Greenlee, P. Jansen, A. Zimmer, & S. Jörg (Eds.). *Spaces: Perspectives from Art and Science. Series Art and Science*. Regensburg University Press.
Pinna, B., & Tanca, M. (2008). Perceptual organization reconsidered in the light of the watercolor illusion: The problem of perception of holes and the object-hole effect. *Journal of Vision, 8*(7), 1–15. http://dx.doi.org/10.1167/8.7.8. http://journalofvision.org/8/7/8/.
Pinna, B., & Reeves, A. (2006). Lighting, backlighting and watercolor illusions and the laws of figurality. *Spatial Vision, 19*, 341–373.
Pinna, B., & Reeves, A. (2013). What is the purpose of color for living beings? Toward a theory of color organization. *Psychological Research*. http://dx.doi.org/10.1007/s00426-013-0536-2.
Pomerantz, J. R. (2003). Wholes, holes, and basic features in vision. *Trends in Cognitive Sciences, 7*(11), 471–473.
Pomerantz, J., Kubovy, M. (1986) Theoretical approaches to perceptual organization: Simplicity and likelihood principles. In: Boff, K.R., Kaufman, L. Thomas. J.P. (Eds.): Cognitive processes and performance.
Ramachandran, V. S., & Hubbard, E. M. (2001). Synaesthesia: A window into perception, thought and language. *Journal of Consciousness Studies, 8*(12), 3–34.
Ripamonti, C., Bloj, M., Hauck, R., Greenwald, S., Maloney, S. I., & Brainard, D. H. (2004). Measurements of the effect of surface slant on perceived lightness. *Journal of Vision, 4*(9), 747–763. http://dx.doi.org/10.1167/4.9.7. http://www.journalofvision.org/content/4/9/7.
Robilotto, R., & Zaidi, Q. (2004). Limits of lightness identification for real objects under natural viewing conditions. *Journal of Vision, 4*(9), 779–797. http://dx.doi.org/10.1167/4.9.9. http://www.journalofvision.org/content/4/9/9.
Rogers, B., & Cagenello, R. (1989). Disparity curvature and the perception of three-dimensional surfaces. *Nature, 339*, 135–137.
Rubin, E. (1915). *Synsoplevede Figurer*. Glydendalske Boghandel: Kobenhavn.
Rubin, E. (1921). *Visuell wahrgenommene Figuren*. Gyldendalske Boghandel: Kobenhavn.
Sharan, L., Li, Y., Motoyoshi, I., Nishida, S., & Adelson, E. H. (2008). Image statistics for surface reflectance perception. *Journal of Optical Society of America, A, 25*, 846–865.
Shevell, S. K., & Kingdom, F. A. A. (2008). Color in complex scenes. *Annual Review of Psychology, 59*, 143–166.
Spröte, P., & Fleming, R. W. (2013). Concavities, negative parts, and the perception that shapes are complete. *Journal of Vision, 13*(14), 1–23.
Stevens, K. A., & Brookes, A. (1987). Probing depth in monocular images. *Biological Cybernetics, 56*, 355–366.
Subrahmanyam, K., Landau, B., & Gelman, R. (1999). Shape, material, and syntax: Interacting forces in children's learning in novel words for objects and substances. *Language and Cognition Processes, 14*(3), 249–281. http://dx.doi.org/10.1080/016909699386301.
Weiss, Y., Adelson, E.H. (1998). Slow and smooth: a Bayesian theory for the combination of local motion signals in human vision (A.I. Memo No. 1624). Massachusetts Institute of Technology Intelligence Laboratory.
Wertheimer, M. (1922). Untersuchungen zur Lehre von der Gestalt I. *Psychologische Forschung, 1*, 47–58.
Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt II. *Psychologische Forschung, 4*, 301–350.
Xiao, B., & Brainard, D. H. (2008). Surface gloss and color perception of 3d objects. *Visual Neuroscience, 25*, 371–385.
Yang, J. N., & Maloney, L. T. (2001). Illuminant cues in surface color perception: Tests of three candidate cues. *Vision Research, 41*, 2581–2600.
Yoshizawa, T., Mullen, K. T., & Baker, C. L. J. (2000). Quasi- linear and nonlinear motion mechanisms for chromatic and luminance stimuli in foveal vision. *Vision Research, 40*, 1993–2010.

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