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The science and craft of autostereograms

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Abstract—Autostereograms or SIRDS (Single Image Random-Dot Stereograms) are camouflaged stereograms which combine the Julesz random-dot stereogram principle with the wallpaper effect. They can represent any 3D shape on a single image having a quasi-periodic appearance. Rather large SIRDS can be interpreted in depth with unaided eyes. In the hands of computer graphic designers, SIRDS spread all over the world in 1992–1994, and these images, it was claimed, opened a new era of stereoscopic art. Some scientific, algorithmic and artistic aspects of these images are reviewed here. Scientifically, these images provide interesting cues on stereoscopic memory, and on the roles of monocular regions and texture boundaries in stereopsis. Algorithmically, problems arising with early SIRDS, such as internal texture repeats or ghost images are evoked. Algorithmic recommendations are made for gaining a better control on the construction of SIRDS. Problems of graphic quality (smoothness of the represented surfaces, or elimination of internal texture repeats) are discussed and possible solutions are proposed. Artistically, it is proposed that SIRDS should become less anecdotal, and more oriented towards simple geometric effects, which could be implemented on large panels in natural surrounds.

Keywords: RDS; SIRDS; autostereograms; algorithms.

1. RANDOM-DOT STEREOGRAMS AND THE PUBLIC

In the 1960s and the 1970s, the random-dot stereograms (RDS) of Bela Julesz struck the imagination of the scientists interested in visual perception and brain mechanisms, and possibly attracted many talented young researchers into cognitive sciences (see e.g. Papathomas, 2005; Shimojo, 1994). The RDS were presented on several occasions in popular science magazines (e.g. Julesz, 1965) yet they failed to catch the attention of lay audiences. These computer-generated stereograms represented a shape in depth which emerged only under binocular viewing of the two images constituting the stereo couple. The shape could not be guessed from a monocular inspection of the images. The RDS appeared to be filled with purely

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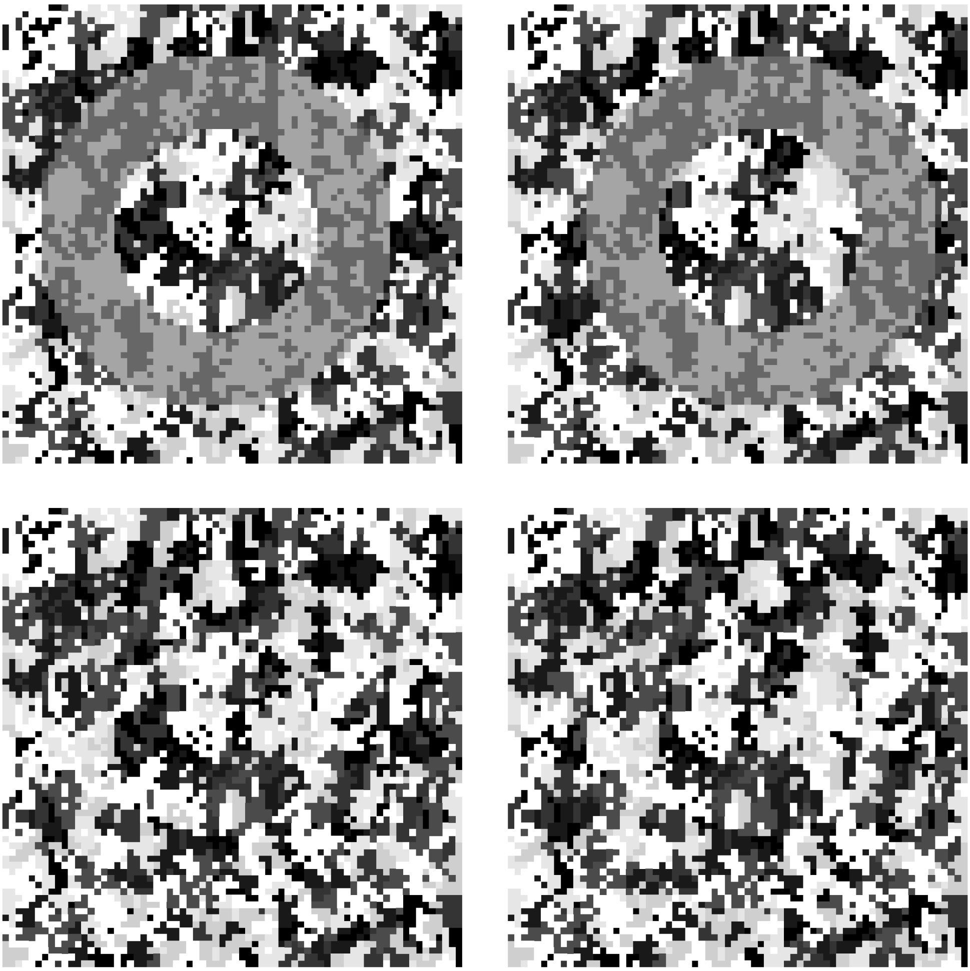

Figure 1. Explicit and camouflaged stereograms in two images. The top stereogram represents a fronto-parallel circular band above background in crossed eyes viewing mode, or below background in uncrossed eyes viewing mode. The band and the ground are represented with distinguishable textures. The geometrical layout of the band and the ground is unchanged in the bottom stereogram, but now the ring has the same texture as the ground and becomes monocularly invisible.

random texture. (Compare, for instance in Fig. 1, the explicit stereogram at the top, with the RDS at the bottom.)

About thirty years later, stereograms in a single image, known as autostereograms (Tyler, 1983) or as 'single image random-dot stereograms' (SIRDS) swept over the planet, first launched in Japan and Korea by Thomas Baccei in 1992 (Thing Enterprises, 1992) then in the USA in 1993 (Thing Enterprises, 1993) and the movement rapidly extended to most other countries. Thanks to these images, millions of people experienced for the first time in their lives the emergence of a 3D percept from images that did not contain any obvious clue about the encoded shape. Most lay people felt that there was something almost magical in the effect produced by these images, and 'magic eye' was the generic title of one of the most successful book series devoted to these images (e.g. Thing Enterprises, 1992, 1993).

Many uninformed people made erroneous assumptions about the SIRDS. They assumed for instance (i) that the shape revealed in 3D was explicitly present in the SIRDS as a subset of the points of the SIRDS, carefully dispersed and hidden among the other points of the image, or (ii) that the highly repetitive aspect of the image was essential to the creation of depth or (iii) that one could transform any photographic picture into a SIRDS conveying a 3D interpretation of the picture.

As far as understanding stereoscopy was concerned, the SIRDS brought essentially the same message as their less glamorous ancestors, the RDS: namely that a 3D shape could be computed from the geometric relationships between two views of a scene even when the shape is entirely camouflaged in the 2D views. There are though a number of peculiarities of the SIRDS which are relevant to stereoscopic theory (see Section 4). What made the SIRDS so appealing to the public? This came from a conjunction of two factors: (i) the technical invention, which allowed large stereoscopic images to be interpreted in depth without any instrumental aid (see Section 3); and (ii) the creativity of graphic designers who used camouflaging or distracting textures taken from photographs, or from paintings. In rare cases, imaginative textures were also designed (mostly, in Japan).

After giving a brief historical sketch on RDS and SIRDS (Section 2), I will discuss the relationship between the two types of images, and some algorithmic aspects of their construction (Section 3). This will lead me to make a few comments on the scientific implications of these images (Section 4), and on some technical problems encountered in their construction that impinge on their graphic quality (Section 5). Finally, I will comment on the artistic future of these images (Section 6).

2. BRIEF HISTORICAL SKETCH

One of the first camouflaged stereograms of which I am aware was designed by the Swiss ophthalmologist Emil Hegg. Hegg produced a set of over 60 pairs of images, conceived as exercises for ocular reeducation of people suffering from bad eye movement coordination (e.g. Hegg, 1905). In one member of the set (reproduced in Ninio, 1994, p. 6) there were 21 small black disks in each image, scattered without obvious order. Under binocular vision, these disks segregate into three different layers. This pair is reminiscent of another stereo couple, published earlier by Georg Hirth (Hirth, 1892) which looks like a stereo pair of stars in the sky, containing a large central star, and 30 smaller stars. Among the RDS forerunners, Kompaneysky (1939) and Aschenbrenner (1954) are the most frequently quoted authors. Kompaneysky, a member of the Russian Academy of Fine Arts, published a lengthy article on binocular correspondence in an ophthalmology journal which included, as Tyler (1994) explains, 'a stereogram of the face of Venus hidden in a field of blobs designed to effectively conceal the face when viewing with one eye'.

Aschenbrenner (1954) was interested in the topic of how to get information out of air photographs taken from a high altitude. He devised a random texture made by 'scattering a mixture of an equal number of black and white paper disks over an area until it was entirely covered' and created camouflaged stereograms with this texture (see for instance the reproduction in Shipley, 1971). He concluded that 'seemingly random and meaningless distributions of density specks are valuable for the stereoscopic definition of a surface in photogrammetry' and that 'they may contain information which cannot be made visible except by the use of a stereoscope'.

Much earlier, Ramón y Cajal had described a method to generate random-dot stereograms (Ramón y Cajal, 1901; see Bergua and Skrandies, 2000); but he did not publish, it seems, stereograms generated according to his proposal. The method, involving taking photographs of a portion of a random texture in front of a background of the same texture, was rediscovered by Papert (1961). Papert proved with his RDS of a Müller-Lyer pattern that the illusion could be produced after the stage of retinal processing.

Concerning SIRDS, one path to these images (see Tyler, 1983, 1994) begins with Brewster's observations on spurious depth effects arising upon gazing at wallpapers, and more recent observations on RDS representing sinusoidal gratings. The concept, as expounded by Tyler, was based on three points: (i) if there are vertical stripes of texture which repeat in the horizontal direction, and the repeats are imperfect, such that there are relative horizontal displacements between corresponding elements in neighbouring stripes, then a pair of stripes acts as a stereogram, in which the (accidental) displacements play the role of horizontal disparities. (ii) if there are N successive stripes numbered $1, 2, 3, \ldots, m$, etc. from left to right, each couple of successive stripes constitutes a stereogram encoding a portion of a surface in depth. Stripe number m constitutes the left image of an $(m, m+1)$ stereo pair, and at the same time the right image of an $(m-1, m)$ stereo pair. A whole surface may be encoded in depth by assembling the surface patches encoded by the successive and overlapping couples of stripes. (iii) The texture filling the patches may be random, as in the RDS of Julesz.

In his history of the SIRDS, Itsuo Sakane (1994) shows an early SIRDS by the Japanese graphic designer Masayuki Ito, which was contributed as an illustration for one of Sakane's articles, published in a December 1970 issue of Graphic Design. The same illustration was also reproduced in Sakane (1973). Alphons Schilling, Austrian artist and explorer of visual effects, also conceived the principle of creation of a whole stereoscopic surface from quasi-repeating images, and presented his large-sized images in the Ariadne art gallery in New York (see Schilling, 1975).

The early computer algorithms for generating the single image stereograms from quasi-repeating stripes (e.g. Stork and Rocca, 1989) raised a number of technical problems which are expounded in Tyler and Clarke (1990). According to Thimbleby and Neesham (1993), the first-generation algorithms placed some of the dots in a way which caused the appearance of undesirable 'echoes and ghost images'. Naturally, several designers developed ways of circumventing the difficulties. One useful principle is described by Thimbleby and Neesham (1993): Instead of propagating the disparities from stripe to stripe, the computer program should start by 'identifying all the dots that must be the same color as each other'. Yet, the authors must have encountered serious difficulties, for they also wrote that 'it is virtually impossible to use dots of more than two colors, as this would lead to complete mayhem with pink dots appearing where the other eye expects to see orange, and so on'. However, at the time of this writing, splendid full color SIRDS were already produced in Japan, among others by the great graphic designer Shiro Nakayama, and included in various 'magic eye' and 'CG stereogram' albums.

In my view, while it is undoubtedly true that the wallpaper effect and periodic patterns were milestones in the elaboration of the SIRDS concept, it is now possible to forget for a moment this historical path, and start to reason backwards, from what the SIRDS achieve. I do not know whether the approach described in the next section is original or not. Successful SIRDS designers have often claimed that they were the inventors of new methods, but are quite silent on the tricks they really use.

3. FROM TWO IMAGES TO SINGLE IMAGE STEREOGRAMS

I now explain a way to transform a stereoscopic couple into an RDS (Fig. 2). The random character of the stereogram (the 'RD' in RDS and SIRDS) is of secondary importance here. All the conceptual difficulty is in the transformation of a pair of images into a single one. Let us take a stereoscopic couple and slide the left image behind the right image. They are represented for convenience one above the other in Fig. 2. In a SIRDS, it is as though the two images were physically occupying exactly the same portion of space, but each eye viewed only one of the two images. (See also the 'overlapping cats' figure in Thimbleby and Neesham, 1993.)

Since the texture used in one image may be taken arbitrarily (the independence of shape and texture is at the root of the RDS), is there a particular choice of texture, for the left image, which makes the left and right images identical? The answer is 'yes'. When this constraint is satisfied (see how further below), the overlapping left and right images can be printed as a single image.

In order to satisfy the constraints, let us consider any abstract point S_1 in the final image. It must have a well defined color (or grey level), let us call it c, represented by a black disk in Fig. 2 (step 1, SIRDS line). This abstract point coincides with a point M_{L} of the contributing left image of the stereoscopic couple (represented by a square), and a point N_{R} of the contributing right image (represented by a cross). So, we must assign the same color c to both M_{L} and N_{R} even though, initially, they may have had different colors (Fig. 2, step 2). Now, M_{L} has in general a stereoscopic partner belonging to the same surface in the right image, let us call it M_{R}, and N_{R} has in general a stereoscopic partner belonging to the same surface in the left image, let us call it N_{L}. As M_{L} and M_{R} are matching points, they must have the same color, and N_{L} and N_{R} must also be of the same color (Fig. 2, step 3). Now N_{L}

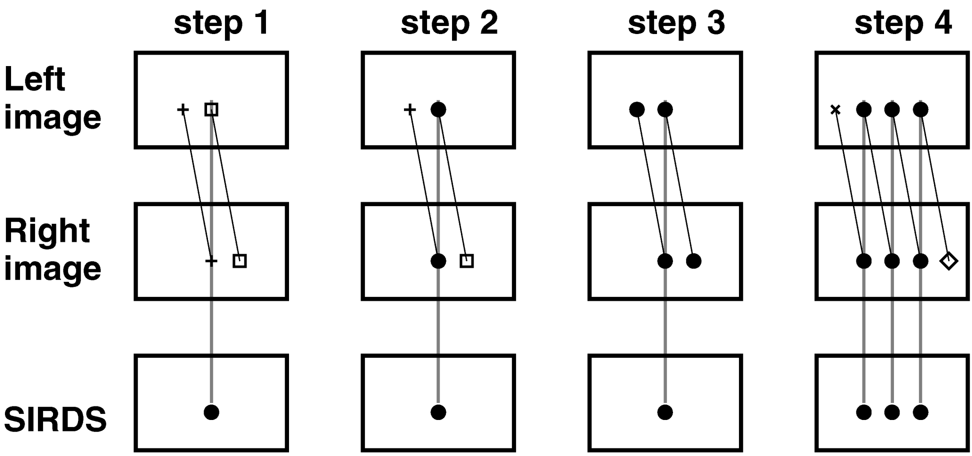

Figure 2. Intermediate stages in the construction of a SIRDS. The two top rectangles in the first column represent the two members of a legal stereoscopic couple. They are shown here one above the other, instead of the usual side-by-side presentation. Corresponding points in the stereoscopic couple are joined by an oblique line. The grey vertical lines indicate points which physically coincide. The graphic symbols (crosses, squares, circles) represent different colors (or different grey levels). Coinciding points must be of a same color. The color may be any of the starting colors (represented here by a square and a cross), or a color taken from an arbitrary texture (represented here by a black disk). Once the color of a point of the SIRDS is chosen, it spreads vertically to satisfy the constraint that coinciding points must be of the same color (from step 1 to step 2, and from step 3 to step 4) and horizontally to satisfy the constraint that stereoscopically matching points must also be of the same color (from step 2 to step 3).

in the left image and M_R in the right image coincide with abstract points S_2 and S_3 respectively in the SIRDS being constructed, so both S_2 and S_3 must be of the same color c (Fig. 2, step 4). So once a color is assigned to a given point in the SIRDS, it spreads to the left and to the right to satisfy the matching and the coincidence constraints.

Applying this protocol, the two initial rings of Fig. 1 are now overlapping in Fig. 3 (top). The texture used for the rings is now spreading to the sides where it encodes part of the background. Notice also the presence of portions of texture (mainly in the overlap region), which are found both on the right and left sides of the rings. Both features are a consequence of the spreading of the constraints in the SIRDS construction process.

When similar textures are used for the figure and the ground, one gets the perfectly camouflaged SIRDS in the middle and the bottom of Fig. 3. Making partially uncamouflaged SIRDS, as in the top of Fig. 3 allows the designer to check that all the constraints are satisfied correctly, and to detect programming errors. To the best of my knowledge no such SIRDS have been published outside my own work (e.g. Ninio, 1994, 1999).

Geometrically, SIRDS such as those of Fig. 3 are fully equivalent to a stereoscopic couple such as those of Fig. 1. So, the images in Fig. 3 may be viewed with classical

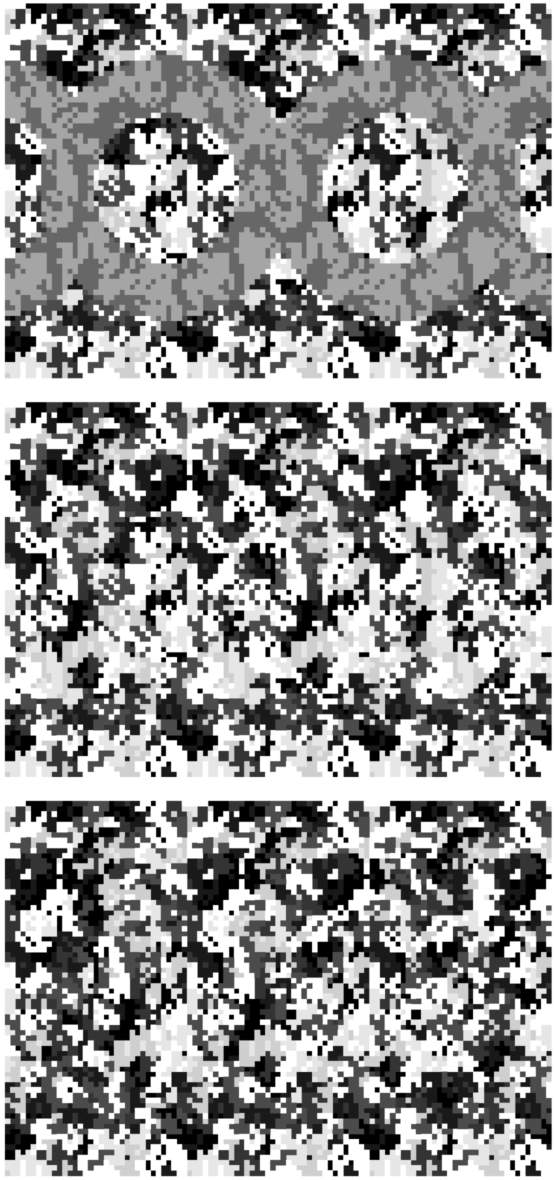

Figure 3. Partially uncamouflaged and regular SIRDS. The two circular bands of the stereoscopic couple of Fig. 2 are now represented on a single image (top). The texture of the bands now extends on the two sides, giving the appearance of additional bands. Actually, these added portions of texture are encoding the background. One can check that the horizontal shifts between corresponding texture elements on the rings are here larger than the horizontal shifts between corresponding texture elements of the ground. When the bands are presented with the same texture as the ground, one obtains the fully camouflaged SIRDS shown in the middle. The circular band should be seen above background with the crossed eyes viewing mode. The SIRDS at the bottom represents the same shape, to be viewed with uncrossed eyes.

stereoscopic devices such as mirror or prism stereoscopes, they can be converted into anaglyphs, etc. However, their main advantage over classical stereograms is that they can extend over large surfaces, yet be interpretable under free viewing conditions. The separation between a couple of points which correspond to a same point in space is roughly equal to the width of a stripe (plus or minus the disparity when the encoded point does not belong to the background plane).

A SIRDS with stripes slightly narrower than the separation of the eyes is convenient for free viewing with both the crossed eyes and the uncrossed eyes viewing modes. A stripe width of 4.5 cm (6.4 degrees of visual angle at 40 cm) is, in my experience, convenient for most viewers. Narrower stripes in the 2 cm range (2.9 degrees of visual angle at 40 cm) require rather precise coordinations of gaze landing. Many observers have difficulties with SIRDS constructed with narrow stripes. Very often, commercial SIRDS found in book illustrations, or sold as postcards, are reductions of larger SIRDS, created in poster format, and their stripes become too narrow after reduction. Viewers who use the crossed eyes viewing mode are often able to deal with stripes that are larger than the separation of their eyes.

Most commercial SIRDS are designed for the uncrossed eyes viewing mode. This could be due to the fact that in this mode, a more extended surface can be encoded. The rings in the top SIRDS of Fig. 3 are rather well separated. In this arrangement, they correspond to a frontoparallel ring above background in the crossed eyes viewing mode. The disparity shifts go to the left in the ‘left’ image (more precisely, they go to the left for the ring to be viewed with the right eye) and to the right for the ‘right’ image. So, the disparity shifts pull apart the two rings. If one wishes to represent a ring above background to be viewed with uncrossed eyes, one must use disparity shifts of the opposite sign, and there will be more overlap between the two rings. Consequently, more space is available in the SIRDS for representing surfaces above background. Since the disparity fields create inward shifts for surfaces above background in the uncrossed eyes viewing mode, there is a texture compression effect which goes in the wrong direction, in relation to perspective clues.

4. SCIENTIFIC ISSUES

4.1. Depth sensations and stereoscopic memory

Depth and relief can be deduced from many cues, such as perspective cues, interposition or shading (see, e.g. Koenderink *et al.*, 1996). Vivid depth sensations can be obtained from still images viewed monocularly under particular conditions: see for instance the discussions on paradoxical monocular stereoscopy (e.g. Ames, 1925; Claparède, 1904; Koenderink *et al.*, 1994). In the kinetic depth effect (Musatti, 1924), successive images of a moving object (in particular, a slowly rotating object), viewed with a single eye, convey a vivid sensation of depth.

The kinetic depth effect works equally well with random-dot images (Lappin *et al.*, 1980). Depth interpretation develops in this case without lag, from the comparison of the very first frames. In contrast, depth perception with RDS comes after a lag, which varies from subject to subject. According to Julesz (1964), the minimum processing time for RDS is around 50 ms. In practice, an inexperienced observer may take several seconds or more to develop an interpretation, and this comes all of a sudden, as described for instance by Shinsuke Shimojo (1994): ‘I still remember vividly what happened to me (or what happened to my eyes, perhaps I should say) in the following several seconds. “Gosh!” I yelled (...). It may sound absurd, but my first perceptual experience was somehow ‘super real’ — even more real than real objects. It looked more than merely three-dimensional to me’. SIRDS seem to be interpreted with about the same temporal characteristics as RDS. For instance, Reimann *et al.* (1995) write: “At first glimpse, these so-called autostereograms appear as structured but meaningless patterns. After a certain period of observation, a 3D pattern emerges in an impressive way”.

This sudden appearance of the 3D percept, described for both RDS and SIRDS is experienced when a simple surface is represented, for instance a square above or below background. Typically, in forced-choice psychophysical tests, subjects choose among a very restricted set of alternatives. What happens when they must perceive a complex surface or a complex scene? In this case they acquire local depth information which must then be assembled into short-term visual memory.

A few facts are known about stereoscopic memory, including the possibility of developing a stereoscopic interpretation from a couple of images which are sent to the two eyes with an inter-ocular delay of about 60 ms (e.g. Ogle, 1963; Guttmann and Spatz, 1985) and the possibility, for some subjects, of maintaining the depth interpretation of a stereogram after closing one eye (Ronchi and Mariani, 1972). On the other hand, I am not aware of investigations on the issue of how the local depth information is assembled and maintained in memory. Tyler (1983) writes that “Once stereopsis is achieved, the observer is free to inspect the entire field of the autostereogram without losing the depth percept”. And he states that there is no size limit to SIRDS: “An entire wall may be covered if desired, giving cyclopean vision over the full vision field”.

4.2. Monocular regions

When a stereogram represents a surface separated in depth from the ground, there are, flanking the surface in each member of the stereoscopic couple, portions of background with no match in the other member of the couple. These monocular regions are not necessarily detrimental to stereoscopic interpretation. They create disparity discontinuities along the horizontal lines, which facilitate depth interpretation (Gillam and Borsting, 1988). Monocular regions can be filled with a texture unrelated to those used in the binocular regions. Upon binocular reconstruction, the monocular regions may (i) be suppressed (ii) be used to extend laterally the overhanging surfaces (iii) slope down, connecting the overhanging surface to the ground (iv) be interpreted as transparent surfaces, or surfaces viewed by transparency (see, e.g. Erkelens and van Ee, 1997; Grove *et al.*, 2006; Ninio, 1987).

Many people thought that SIRDS would be ideal cryptographic tools, and thought that complex messages could be encoded in the SIRDS. Actually, the messages found in SIRDS are simple ones, with very few letters along a same horizontal line — for instance the word ‘bingo’ is encoded in a 27 cm wide SIRDS produced by Benedikt Taschen (Riemschneider, 1994). The reason is that every overhanging letter of the message generates monocular regions. If the letters are thick, and there is not sufficient space between them, most of the texture between the letters will be recruited by the monocular regions. Then, there is little stereoscopic information in the horizontal band containing the letters.

In order to reduce the space occupied by monocular regions, there are two, not mutually exclusive possibilities. First, one can use a small depth separation between the message and the ground. This, in my experience, works well and leads to the paradoxical observation that with SIRDS containing written text, depth sensation *improves* when disparity (i.e. theoretical depth) is decreased. A second strategy would be to use very thin letters. However, this will work only for very good stereoscopists.

In single image stereograms, a surface cannot be completely differentiated from the ground on the basis of texture. If one decides that all the points of a surface must be represented with a certain texture, this texture is repeated leftwards and rightwards on successive stripes where it will at one point or another begin to encode ground regions. Thus, textures get mixed at the end, and this limitation becomes more and more severe as the number of stripes increases. This brings about a paradox. A text is easy to represent in a classical (two images) stereogram, provided the letters can be distinguished monocularly (for instance, on the basis of texture) from the ground. In single image stereograms, a complete differentiation is not possible, and the textures get mixed at the end. This feature may explain why camouflaged SIRDS (such as those in the middle and the bottom of Fig. 3) often turn out to be easier to interpret in 3D than their partially uncamouflaged counterparts (top of Fig. 3). This could be due to the presence, in the latter, of texture clusters which belong in part to the encoded surface and in part to the ground. The brain would be reluctant to dissociate the clusters into two components at two different depths.

4.3. Transparencies

In my experience, transparencies work as well with SIRDS as with RDS. An example of a surface viewed through a 3D wire screen is shown in Fig. 4. I am not aware of other such SIRDS outside my own work (e.g. Ninio, 1994).

4.4. Random-needle textures

Random-needle textures were found to be very well suited for stereoscopic interpretations (Herbomel and Ninio, 1993). Two examples of colored random-needle SIRDS were provided in Ninio (1994). In my experience, SIRDS with random needles of a single color give rather disappointing results, for unknown reasons.

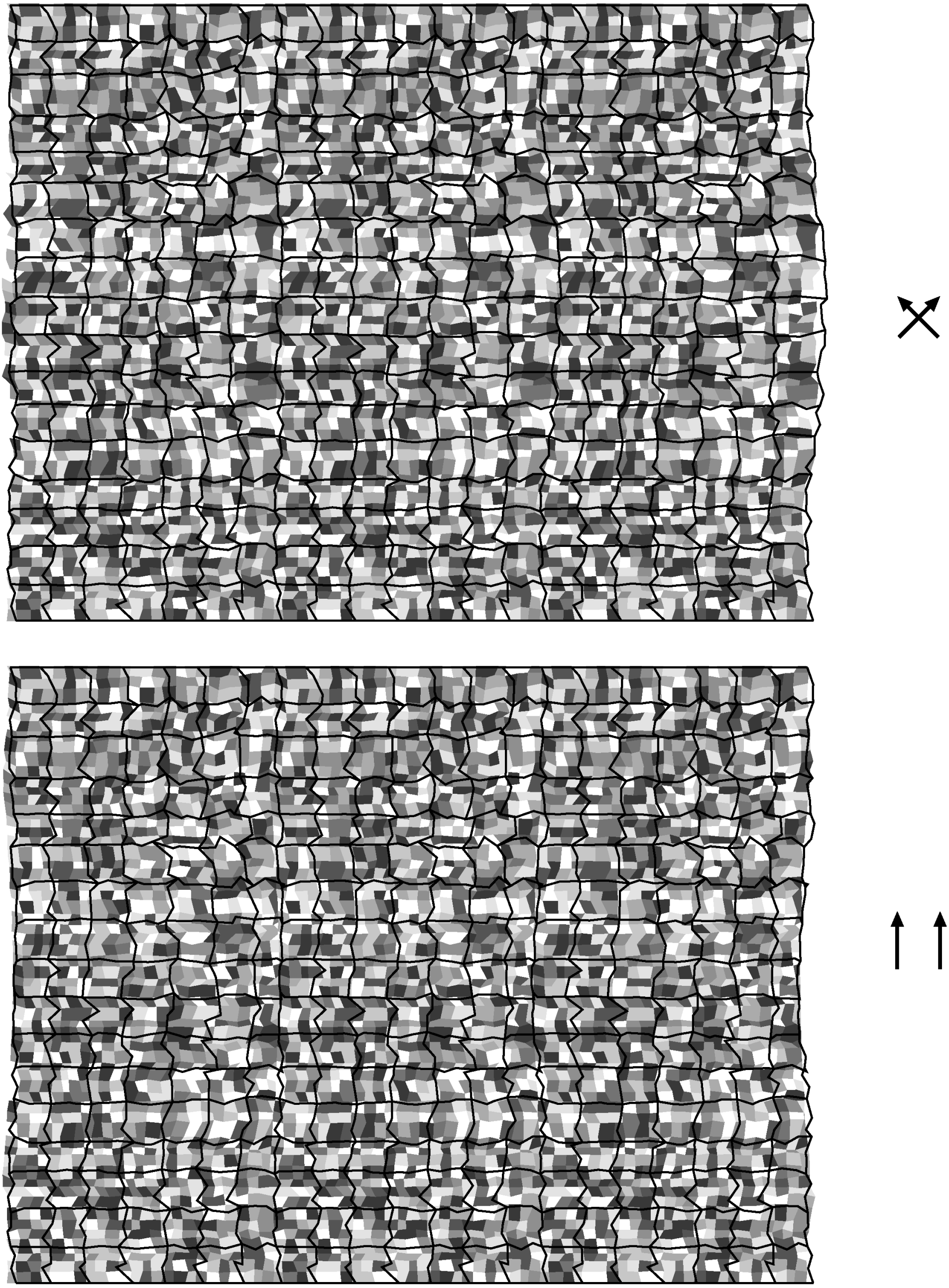

Figure 4. Transparency. The filled texture represents a Mexican hat shape: there is a protruding dome at the center of the top SIRDS (assuming crossed eyes viewing) surrounded by a circular depression. The black net espouses the shape of the dome in the central region, but remains at ground level over the depression. The depression is then seen by transparency through the net. The same shape is shown in the bottom SIRDS, prepared for uncrossed eyes viewing.

5. GRAPHIC QUALITY

5.1. 3D models' sophistication

Previously, the RDS were representing geometrical surfaces — e.g. a fronto-parallel rectangle, or at best a complex geometrical surface, the undisputed masterpiece being the 'hyperbolic paraboloid with torus' RDS of Julesz (Fig. 4.5-3 in Julesz, 1971). The 3D surfaces could be defined by a set of equations borrowed from the toolkit of analytical geometry. Now with the SIRDS, the designers represented complex 3D shapes which could be identified with real world objects, such as faces, tools, toys, animals, or even complex scenes. These shapes were not defined by equations. They could be taken from 'virtual reality' computer graphic models, or they could be obtained by 3D laser scanning and digitization of real objects. The 3D models were then expressed as discrete xyz maps, in which a depth value z was assigned to a set of discrete x, y coordinates covering a section of the plane.

Another route to the xyz map was to create a white plaster model of the object to represent (or cover a model with white paint), illuminate the model frontally, and take a photographic picture of it. On the picture, there would be variations in luminance, the most remote parts of the object being the darkest. In this way, when the picture is scanned, the grey level which is assigned to a particular x, y pixel in the image can be converted into a z depth value. Many commercial books of SIRDS used this rather crude method for generating xyz maps. Photographs of the plaster models were usually shown at the end of the books to explain what the observer should see in depth.

5.2. Discretization problems

Most of the early SIRDS (e.g. Tyler and Clarke, 1990) were constructed from 'cellular' stripes in which the basic texture was a square lattice of randomly drawn white or black squares, horizontally and vertically aligned. A typical stripe had about 30 squares on a cross-section of about 2 cm. Viewed at a distance of 40 cm, a unit square then subtends an angle of about 6 min of arc. Disparity varies, in such a SIRDS, by integer multiples of the unit square width. The encoded surface is then perceived as stratified into a number of layers corresponding to the discrete disparity values.

Even when the subsequent commercial SIRDS started to use fine-grained textures, many good stereoscopists were still sensitive to the stratified character of the encoded surface. Assume that an image is printed at a printer resolution of 300 dots per inch, and assume that the image is viewed at 40 cm from the eyes. Then, the visual angle between two consecutive dots is about 43 sec of arc, and such an angle produces a detectable disparity (e.g. McKee, 1983).

There is therefore a need for methods which permit a better encoding of smooth surfaces. Cosmetic computer graphic techniques (such as anti-aliasing) may be used to alleviate the rugged appearance of the shape. More frontal strategies are also conceivable. Actually, it is not necessary to initiate the calculations with a discretized texture. The starting points may be drawn at random on continuous intervals. According to his artist's profile (p. 95 in Horibuchi, 1994), Shiro Nakayama 'developed a technique for producing smoothly curving surfaces in stereograms in 1992'. Considering the outstanding quality of his SIRDS, he can be credited for this achievement, although I have no idea of the exact nature of his invention.

In my case, I developed a vector graphic method, inspired from the 'random-curve stereograms' (Ninio, 1981). In this method, the initial texture is a kind of deformable grid using nearly horizontal and vertical lines. The intersections are free to move on continuous intervals. The two endpoints of a horizontal line on a stripe are subject to the constraint that they must correspond to a single point of the shape to be represented. Therefore, the generating stripe has an elastic character; it is deformed to be applied on the encoded surface. The method is well suited for the representation of continuous surfaces (Fig. 4, and most SIRDS in Ninio, 1994), but it becomes rather delicate when there are discontinuous disparities to deal with.

5.3. Stuttering

Many SIRDS have a recognizable defect: thin portions of texture form internal repeats within stripes, in addition to their natural periodicity. Internal repeats are due to the presence of monocular regions in the SIRDS. In practice, when programmers do not pay special attention to the fate of the monocular regions, they maintain without change the original background texture in these regions. Since such regions are also, by construction, part of the overhanging surface, the result is a kind of stuttering.

6. ARTISTIC FUTURE

Many designers of SIRDS were convinced that they were creating a new form of art. For instance Susan Schutz writes, in Schutz and Schutz, 1993: "In the true spirit of innovation and inventiveness, our book utilizes a phenomenal art form created by Stephen Schultz: the 5-D$_{\text{TM}}$ stereogram. Stephen's sensitive graphics, with meaningful hidden images, bring the craft of the stereogram to a new level of aesthetic beauty". On the cover of *3-D Planet*, a book by Kunoh and Takaoki (1994) one reads that "state-of-the-art computer graphics technology brings to you a uniquely artistic view of the world". In the Introduction to *Hidden Dimensions*, Dan Dyckman (1994) writes: "Since 1989, I've been working at bringing these images into the realm of art ... and I've consistently been pushing the forefront of the field, producing curved and rounded depth designs, adding colored, swirled patterns — and this book". Sagawa (1993) explored the range of visual effects (such as stereoscopic lustre) which could be incorporated into SIRDS.

Other designers sought to make a bridge with art by using as supporting texture the reproduction of a portion of painting. Alternatively, the SIRDS were produced as collaborations between a painter who supplied the supporting texture, and computer programmers (e.g. Godon and Mortagne, 1994). There were also painters who produced SIRDS as oil paintings on canvas (e.g. see Cornette de Saint-Cyr and Molinier, 1997).

However, one feature that contributed to the enormous commercial success of the SIRDS in 1992–1994 may also have been the cause of their lack of success in promoting stereoscopic art. Most books of SIRDS were planned to be attractive for children and teenagers. They proposed anecdotal images, which worked like brain teasers: "Here you see an explicit scene. Can you discover what is hidden behind the scene?". For instance, people would look at a picture suggesting a desert surface — then a dinosaur would jump to their eyes.

In a more mature and artistic mode of reasoning it would have been preferable to design images which said: "Here is a pleasant 2D pattern or a pleasant 2D texture. Now, looking at this pattern or this texture, you may see it take three-dimensionality, and form an interesting complex shape". I believe that there is a future in fact for large sized displays, which could be painted on the walls of buildings, or erected in public gardens. The displays would be decorative by themselves. But due to the geometric constraints, they would also induce, for some observers, simple shapes in 3D. I have designed several SIRDS in this spirit (Ninio, 1994) but they were not implemented in natural surrounds. The wallpaper pattern shown in Fig. 5 could be used in this way. The oblique bands could be erected separately as panels, and some viewers would be able to fuse two neighbouring panels and see pleated sheets in

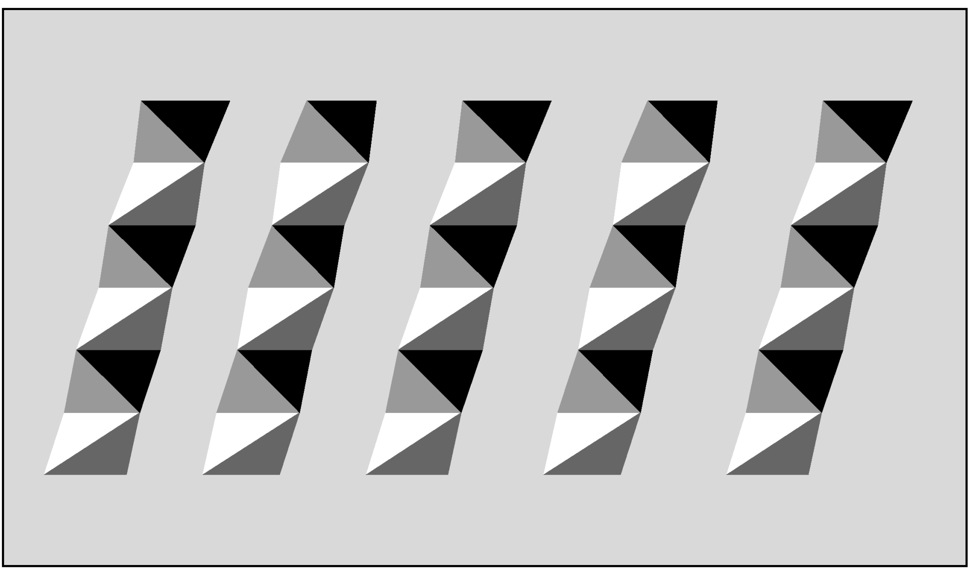

Figure 5. From 2D to 3D geometrical patterns. A simple geometrical wallpaper motif (Ninio, 1994) in which quasi-repeating stripes are subdivided into triangles of four different levels of grey. When two neighbouring stripes are stereoscopically fused, they form a rather complex pleated sheet in 3D. A disparity gradient from bottom to top, and a separation gradient from left to right were introduced to allow viewers with different stereoscopic biases to be able to form depth in one part or another of the display.

3D. Naturally, an artist could start with the pattern, and replace any grey level with a color of his choice, make the pattern more complex by adding points, or making new connections between preexisting points, etc. In other words, the scientist would create a basic geometric pattern and the artist would use his imagination and his artistic sensitivity to choose the best visual renderings or invent startling variations on the pattern.

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