CONTRIBUTIONS TO STEREOSCOPIC VISION

Jacques Ninio

Contents

1 OVERVIEW

(Included in the web site http://www.lps.ens.fr/∼ninio) Updated May 26th 2016.
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Among the twelve or so different fields to which I contributed, stereo vision is the one in which I have the greatest diversity of contributions: a purely theoretical one (on the correspondence problem), many experimental ones (e.g., on orientations in stereo, on stereoscopic memory...) and a huge investment in the design of both ludic and scientific stimuli (e.g., my book of autostereograms). I have the feeling of having produced stimuli that lead to inescapable conclusions, and established many important results that are, it seems, ahead of their time.

2 BIOGRAPHICAL NOTES

2.1 First encounter in 1971 with Bela Julesz, and his random-dot stereograms

My first contact with Bela Julesz and his work was memorable. In 1971, I was a young molecular biologist, interested in the genetic code and the origin of life. One day, Boris Ephrussi, a founding father of molecular genetics who was heading the molecular genetics institute in which I was working told me about a forthcoming meeting in Versailles entitled "From theoretical physics to biology". He wrote a letter to the organizer, Maurice Marois, and I was accepted without difficulty. I found myself in a prestige mundane meeting, with dozens of Nobel laureates from all scientific disciplines, many of them being historical figures extracted from their formalin bottle, and a good dozen of would-be laureates, detected early in their carreer. There were also a few participants like me who had been pushed there by a prestigious invited speaker who did not wish to attend the meeting. Much later, I learnt that Hugh R. Wilson, now an authority in neurophysiological modelling was among the young substitutes. Some of the talks were enlightening, others were standard nonsense of the type "how quantum mechanics explains consciousness". After one such talk, a man stood up in the audience. He said that such speeches were completely obsolete because now the workings of the mind could be studied with scientific tools. This man was Bela Julesz and in the afternoon he gave a talk in which he initiated the audience to his random-dot stereograms and random-dot cinematograms. Everyone in the audience was looking at Bela's anaglyphs with red-green spectacles. I watched the audience looking at these seemingly meaningless pictures, then beginning to shout once the encoded 3D shape had started to emerge. I was unable to see anything in depth but I immediately understood what was at stake (I had a rather good background in geometry, so I understood the nature of the stereoscopic matching problem).

2.2 From errors in molecular processes to errors in perception

At that time however, my priority was working on the genetic code and the origins of life. Leslie Orgel, one of the world's leading specialists in the origins of life, and the closest to me by his molecular biology background was a speaker at the meeting, so I talked to him and he invited me to join him for a postdoctoral period at the Salk Institute in La Jolla, California. There, while working on “prebiotic” RNA replication (see the website chapter on “contributions to the origins of life”) and on molecular accuracy (see the website chapter “contributions to the kinetic theory of accuracy”), I had access to the multidisciplinary library of the Salk Institute, and found there the just published seminal book of Bela Julesz [1]. I went through the book, but still I could not see the stereograms in depth. I was back in Paris in April 74. My theoretical 1974-1975 papers on the accuracy of molecular processes stemmed in part from puzzling observations made by the geneticists on errors in DNA replication and errors in translation. In my (kinetic) treatments, the errors were not treated as aberrations, but as the normal outcome of molecular processes, designed to work rather accurately. Such a philosophy was of course familiar in the field of psychology. For instance, contrast illusions had been understood since the early times of Ernst Mach as signatures of normal processes designed to extract contours, or to make corrections according to the local environment. Freud’s work showing that in mental processes normal processes were at the root of pathological ones, was also rather well known. I thought that I could transfer my expertise on errors and accuracy in molecular biology to a subfield of psychology, that of geometrical visual illusions. I bought Robinson’s book on visual illusions [2] and devoted the best of my time to try to work out the geometric principles underlying geometrical illusions. In particular, I was looking for data leading to an objective classification of the illusions (see the web chapter on geometrical illusions). In this domain, a very important result had been obtained by Seymour Papert [3]. He had used camouflaged stereograms, independently of Julesz, and had shown that when a Müller-Lyer pattern was encoded into a camouflaged stereogram, it could be seen in depth with its usual distorsion. From there, it could be inferred that the Müller-Lyer illusion was not of retinal origin, since the pattern could not have arisen prior to the stage of stereoscopic matching. Later, Julesz showed that many geometrical illusions still existed when camouflaged as random-dot stereograms (RDS), but there was an exception: the Zöllner illusion which was cancelled when represented as an RDS.

2.3 How I recovered from stereo blindness

The RDS technique then appeared to be a perfect tool to produce an objective classification of geometrical illusions, and this is the reason which made me start working on stereo vision. My first step was to try to see depth in the anaglyphs of Julesz’ book. I spent perhaps half an hour or an hour every day during three whole months looking at the stereograms in the book, and waiting in vain for the appearance of the 3D shape. I had also started producing steregograms myself, and I tried also to see depth in these stereograms. One night I shut down the light in my room, but there was still some light coming from the buildings outside, and I looked at my stereograms lying flat on the floor, my eyes looking ahead, so the stereograms were observed mainly through the retinal bottom hemifields, and there, for the first time I experienced the emergence of a stereoscopic interpretation. Subsequent progress was rapid, but I never achieved a good level of stereoscopic acuity. Recently, there has been much publicity on “Sue’s story”, an American case of recovery from stereo blindness, (e.g., [4, 5]). It took me a long time to understand why I had recovered from stereoblindness. I thought that my stereo vision had been restricted to a part of the viual field. But I learnt later from Russian colleagues that I had, unknowlingly, used a principle that was well-known to Russian orthoptists. The foundations were laid down by Alexander Cogan, a Russian specialist of visual perception who emigrated to the Unites States in 1974, and worked at the Smith-Kettlewell Institute in San Francisco. Cogan reasoned that a person with two valid eyes, but who would no longer see in stereo, would suppresses all the time the information coming through one of the two eyes, otherwise this person would see everything in double. This suppression would be due to an inhibition process occurring in neuronal circuits, and it would be implemented only for the usual positions of the eyes [6]. Thus, in order to see in stereo, these people should try unusual positions of the body and the eyes, topple the head in all directions, until, by chance, they find a position for which inhibition would not operate, and they would thus experience double vision. They must then try to maintain this double vision, this would be the first step in the recovery process. It would be followed by fusion of disparate images in a stereogram, then depth interpretation. I take all this from Professor Igor Rabitchev who drew my attention to Cogan's concept, and derived from it a procedure that he applied to his strabismic patients [7]. It is sad that this Cogan-Rabitchev technique is unknown outside Russia, and that top scientists in visual perception are loosing their time on the subject, using inadequate stimuli and protocols [8].

2.4 Working on the correspondence problem

When we look at a scene, we receive on the two eyes two slightly different perspective views of the scene. When sets of parallel lines, in the real world are not in a fronto-parallel plane, they give sets of converging lines in projection. This is a major effect of perspective. It might be exploited in stereo vision. If there were, somewhere in the brain, neuronal assemblies sensitive to sets of parallel or nearly parallel lines, and if some measure was made of the relative convergence of the sets of lines on the two projections, these measures could be used to deduce the orientation in 3d space of the sets of lines. (The words "tilt" or "slant" are currently used in visual science to describe orientations that are not fronto-parallel. The two terms are equivalent in current language, but Kent Stevens introduced a distinction, in which slant designated "an angle measured perpendicular to the image plane", and tilt designated "an angle measured in the image plane" [9]).Then one could understand why there was something special about the Zöllner illusion in stereoscopic vision. In nature, plant stems or tree trunks form, owing to their verticality, sets of parallel lines. Some module in the stereoscopic interpretation system might look for such parallel lines, and might apply different distorsions on the left and the right inputs to achieve a good match between the two projections. I thus became interested in the problem of the geometrical relations between two perspective projections, and the matching algorithms applicable to stereo vision. So, my first publication in stereo vision was, in 1977, about the geometry of the correspondence between two retinal projections [10].

While most investigators in the field of stereo vision were aware of Hubel and Wiesel's work and so accepted the concept that much of early visual processing has to do with detecting edges and determining their orientations, most of the work that was carried out by Bela Julesz, and most psychophysicists with him and after him used stimuli - the random dot stereograms – constructed in such a way that edge-like features were, by design, almost totally eliminated. Yet the authors often interpreted their results in terms of orientation-tuned receptive fields. This schizophrenic attitude lasted several decades. Ultimately however, an even more unphysiological class of stimuli was invented – the so-called Gabor patches (see comment on Gabor patches at the end) and, very logically, these stimuli became the new standard in the field.

In my case, I considered that Hubel and Wiesel were essentially right, and considered that a good deal of stereo vision had to deal, not with point-like elements as in RDS, but with edge-like elements. I thus designed a new kind of random stereograms. Their appearance was that of random lines filling a square, and they represented various continuous surfaces in 3d. Thus, my second publication in stereo vision was about the design and some properties of such “random-curve stereograms” [11]. Subsequently, most of my experimental work in stereo vision aimed at characterizing how stereo vision deals with edge-like elements. (A good deal of my published work in this domain was carried out while I was still in a molecular biology laboratory, heading a team performing enzymological experiments on DNA polymerase mechanisms, and also involved in bioinformatics (see the corresponding chapters in the website). After my institutional switch to cognitive sciences in 1992, I could have made an entire carreer in stereo vision.

2.5 Miraculous collaboration with a Russian ophthalmologist

One day of 2006, I received a message from a Russian ophthalmologist working in the city of Irkoutsk, in Siberia. She was working in a clinic, and was greatly interested in the recovery of stereo vision in strabismic children, after corrective surgery. My name was given to her by Olivier Cahen, an active member of the French stereo club, an association of people mostly interested in stereoscopic photography. She had to attend an ophthalmology congress in Paris, and paid a visit to my lab on this occasion. There, she explained why she was in need of scientific advice. She had observed, with some of her strabismic patients an almost unbelievable capacity. They could fuse two images with a single strabismic eye! Nobody in her environment took her seriously, and people were trying to explain her observations with various possible artefacts, mainly that the strabismic eye was rapidly alternating between the two images. I thought that her observations were compatible with neurophysiology, taking into account the utrocular issue (the brain may not know from which eye it receves an input), and the fact that each eye sends information to both hemispheres. This was the beginning of a fruitful collaboration, leading us to studies on stereopsis under alternating presentation conditions, allowing us to clarify the role of memory in stereoscopic processing. Our initial work on stereopsis with a single strabismic eye was published in Vision Research [12].

2.6 Popular stereo and the scientific decline of stereo vision studies

Autostereograms have been viewed by millions of people around the world, and this can be considered as a large-scale experiment in cognitive sciences. One remarkable thing about autostereograms is that they can be displayed on large posters, and the people looking at these posters can form a complete 3d interpretation of the encoded shape. Yet, a substantial fraction of the psychophysicists still believe that stereo vision is a phenomenon occurring within one degree of visual angle, with the chin immobilized on a chin-rest; and they only have one regret, which is that they cannot immobilize with curare the eyes of their human subjects. Several years later, stereo vision made a second popular invasion, with the 3d movies. Here again, this wide scale experiment in stereo vision did not inspire the specialists in the field.

Unfortunately, this was also a time of collapse for the whole field of stereo vision. After the death of Bela Julesz (december 2003), many of the leaders in the field of stereo vision reached retirement age, or pulled out. There were less and less contributions to stereo vision sessions at ECVPs, and most of the researchers in the field have remained glued to conceptual aberrations. In particular, stereo vision studies suffer from acute "orientation blindness" or "orientation neglect". As I said, scientific stereo studies ignored autostereograms and 3d movies, from which there would have been a lot to learn. And it became almost impossible to find competent reviewers for our scientific articles.

3 GRAPHICAL DESIGN OF STEREOSCOPIC STIMULI

3.1 Random curve and random needle stereograms

Although many important results had been established with the random-dot stereograms, I had the feeling that they were not suitable for making the connection with the neurophysiological work, which showed the importance of orientational analysis. Contradistinctively, neurophysiology did not have anything to say about dots, and still does not say anything about dots. I thus started to produce stereograms that looked random, yet contained oriented elements. I called them “random-curve stereograms”. The article describing them was published in “Perception” [11]. In practice, I took a point within a square or a rectangle, and made it move according to a random-walk in two dimensions. This generated a random curve in the plane. I also defined a surface S that I wished to represent. To each point M of coordinates x and y in the initial random-curve, I assigned a depth z giving the height of the point P on the surface S that projects vertically onto M. The points P ran on a 3d random-curve in space. I then computed the left and right projections of P, and drew the corresponding left and right projections. One such random-curve stereogram is shown in Figure 1.
Note that one perceives a complete surface, rather than just a curve in space.

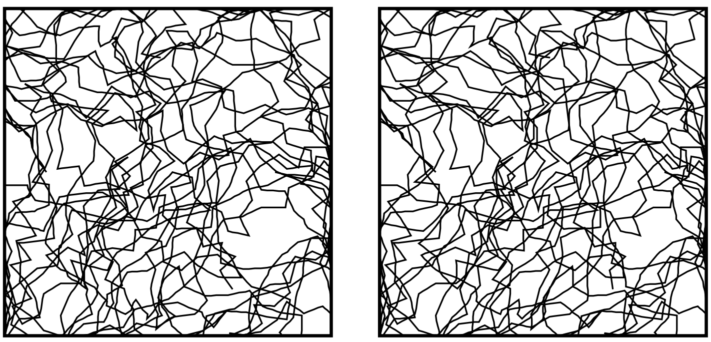

Figure 1: Random-curve stereogram representing a dome, with a central depression, for crossed-eye viewing or the opposite shape for parallel viewing.

In some way, it is a case of “modal surface completion”, or subjective surface in 3d (as pointed out to me by Ken Nakayama). The effect is not felt as paradoxical as in the case of the paradoxical surfaces of Harris and Gregory [13] or Idesawa and Zhang [14], but its “normality” is in itself interesting. When the represented surface can be generated by suitably folding a plane (for instance, the surface is a torus, a cone or a cylinder) one can use another strategy: the initial random-curve is generated on a plane, the plane is then folded to form the surface one wishes to represent, then the two projections of the random-curve are computed. In the “Perception” article, I included an example representing two conical surfaces, shown here in Figure 2.

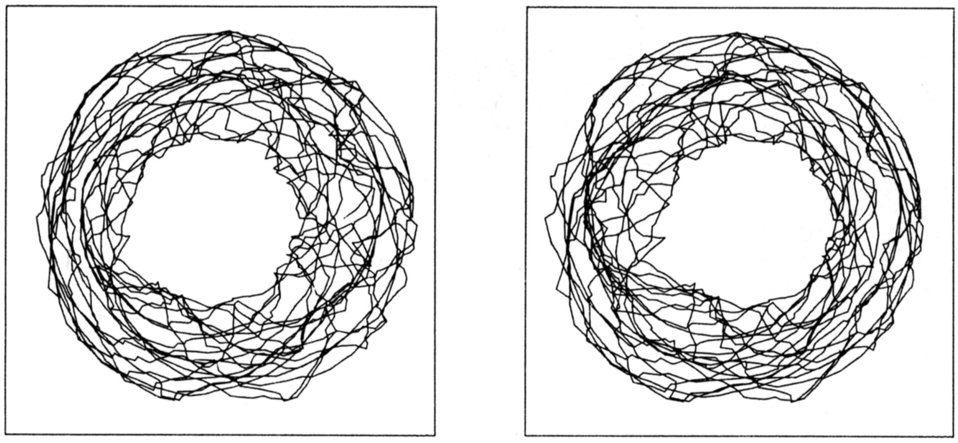

Figure 2: Two conical nets, one inside the other. First published as Figure 3b of [11].

This Perception figure proved to be of high practical value. When people who were visiting my lab wished to know about their stereoscopic capacities, I used to show them this stereogram in the first place. They could adjust the stereoscope to get a correctly fused image – which is easy in this case, because there are circular shapes with clear boundaries to fuse, and I explained to them that they should see the image within a square frame, which should not be squeezed, and that they could also see parts of the phantom squares on the left and right sides. So, fusion could already be optimized at this stage before going to the more delicate stage of stereoscopic interpretation (Note however that simple stereograms may be easier to fuse than old-fashioned tests for fusion, that involved pairs of images having different extensions on the left and the right). The visitors were then asked to form a 3d interpretation of the shape. A few could just see it as a kind of bump. Others went further and saw clearly a wire net forming a cone or a cylinder. Some others immediately saw that there were two surfaces one inside the other. Usually, those who just saw a single surface could discern after a variable amount of time the existence of two distinct surfaces. I have witnessed this for 35 years now, and in general, I can say that whenever I test people for their stereo vision, I find that people interpret the images to various levels of detail. So, the standard psychophysical tests that reduce stereoscopic aptitudes to a single parameter on a scale based upon a single type of test, are tragic oversimplifications.

I also generated random-curves on spherical surfaces. The difficulty here is to cover the sphere in a visually homogeneous manner, which requires some skill (see here Figure 12, page 23 in Section 4.4). Then the random-curve could be remapped on another surface, for instance a bucket, to generate a stereogram representing this surface. Last but not least, if the random-curves are drawn in dashed style one obtains a “random-needle” stereogram (see Figure 3). This type of stereograms turns out to be most suitable for stereoscopic interpretations (see section below on optimal textures for stereo vision). The needles carry both orientational information, and positional information at their two ends.

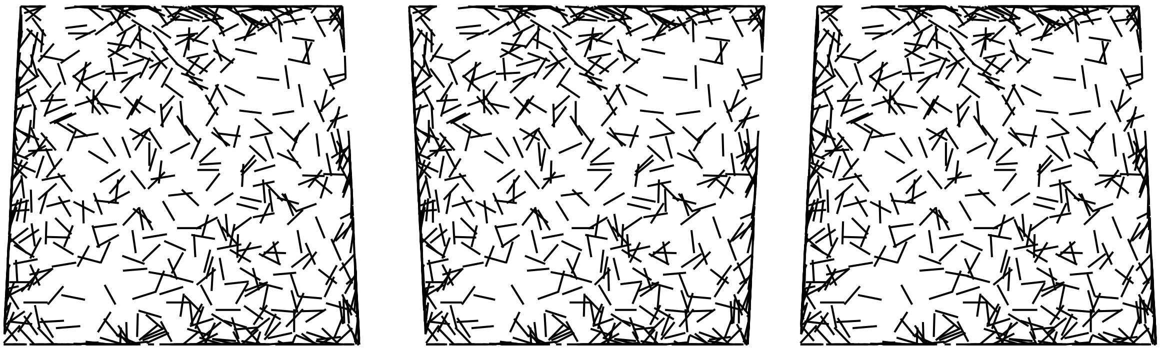

Figure 3: Random-needle stereograms representing a folded sheet, with a fold along the descending diagonal.

3.2 “Elastic” autostereograms in random-curve style

At the end of 1991, I left my molecular biology laboratory, and joined a team of physicists at Ecole Normale Supérieure, interested in neural network theory and cognitive sciences. There, I started an activity of designing textures manually. The idea was to create camouflaged stereograms without using the computer (see textures in[15], and some stereograms in [16, 17]). However my stereoscopic activities were soon to take an unexpected turn. In April 1993, I attended "Art Futura", a most agreeable annual symposium in Barcelona on computer art and related topics. The theme of the year was “artificial life”, and I was invited there as a molecular biology specialist, for the concluding discussion session [18]. I met there many famous people. During informal discussions with some of the participants, I had an opportunity to show in anaglyph form my random-curve and random-needle stereograms. At that time, autostereograms had started their carreer in Japan. They were unknown to me. One of the participants, Erkki Huhtamo from Turku, Finland had a copy of a marvelous autostereogram by the Great Master Shiro Nakayama, which he gave me. (I found later this image on the cardboard cover of "CG stereogram 2"). My stereo vision was not good enough to see depth in it, but I understood the principle of deriving depth from distorted wallpaper patterns. Earlier this year, I think, I had received a telephone call from Japan. Itsuo Sakane (then Editor in Chief of the art and science journal Leonardo) was writing a hisstory of camouflaged stereograms, and was asking the permission to reproduce some random-curve stereograms from the Perception article [11], as part of the history of camouflaged stereograms. He did mention on that occasion the existence of a single image stereogram technique, but I did not realize at the time of his call what was going on. Sakane included three of my figures in a chapter of a Japanese autostereogram book, "CG stereogram 2" containing a superb collection of autostereograms by Japanese designers [19]. However, my figures were removed from the American edition of the book [20]. Incidentally, the very first autostereogram was made by the Japanese graphic deisgner Masayuki Ito, and included in a 1970 article (see [19] and a 1973 book by Sakane “Coordinates of beauty”, Misuzu Shobo, Tokyo - I thank Kotaro Suzuki for providing the information).

My son Julien was working in Japan. I wrote to him about autostereograms after the Barcelonal meeting, and he sent me, month after month, plenty of autostereogram books, I understood how they worked, and what was at stake. I was soon in correspondence with Cristopher Tyler, author of the seminal articles introducing these single image stereograms [21, 22]. Instead of assimilating Tyler's method, I immediately attempted to construct autostereograms my own way, as random-curve autostereograms. I found a way to do that, which is very convenient for continuous surfaces (see, e.g., Fig. 4).

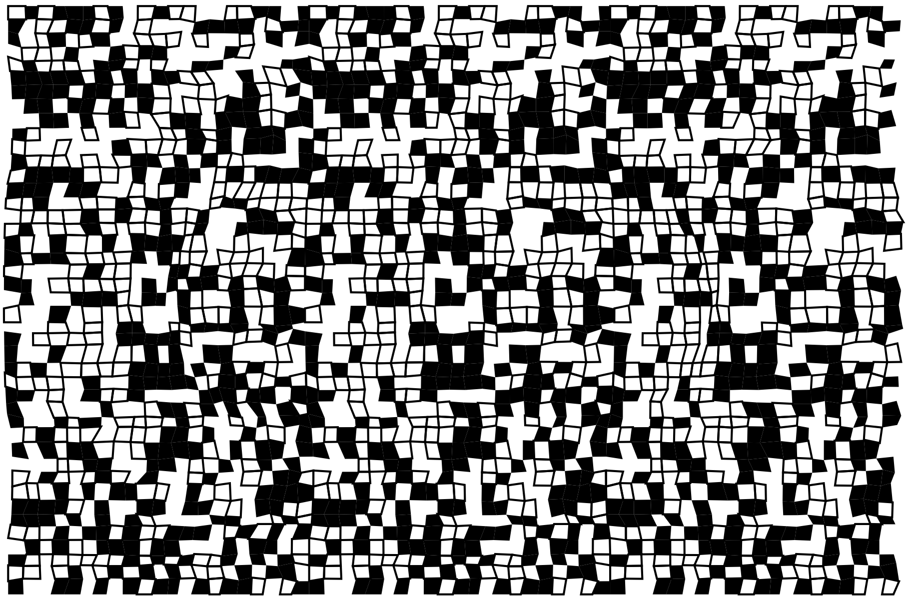

Figure 4: Three-band autostereogram or SIRD, using an "elastic" distorted grid, in the author's style. Here, the texture contains both filled and outlined black cells. The shape, for cross-eyed viewing is a dome at the center, surrounded by a circular depression or the opposite for the parallel viewing mode. This image pas published as Figure 3, page 566 of reference [23].

Contrary to most commercial autostereograms, in which the whole surface of the image is covered with compact texture, here we have the elegance of outline drawings. This property allows one to represent two surfaces simultaneously, one seen by transparency through the other. Discontinuous surfaces could also be represented. This required complex programs. I produced a few examples, but did not develop the needed technology until I fully mastered the correct algorithm for producing autostereograms, as described in [23] - see also Figure 5, here.

The autostereograms struck the layman's imaginations, not because the stereograms were in a single image (so they are often called "single image random-dot stereograms" or sirds), but because the represented shape was camouflaged. Many scientific journalists entertained the confusion between the two properties of the sirds. As a matter of fact, it is nearly impossible to represent the encoded shape in a sird in a monocularly visible way. This property follows from the need to repeat again and again the same textural motifs. So, I paid attention to which part of the texture was covering which part of the surface,

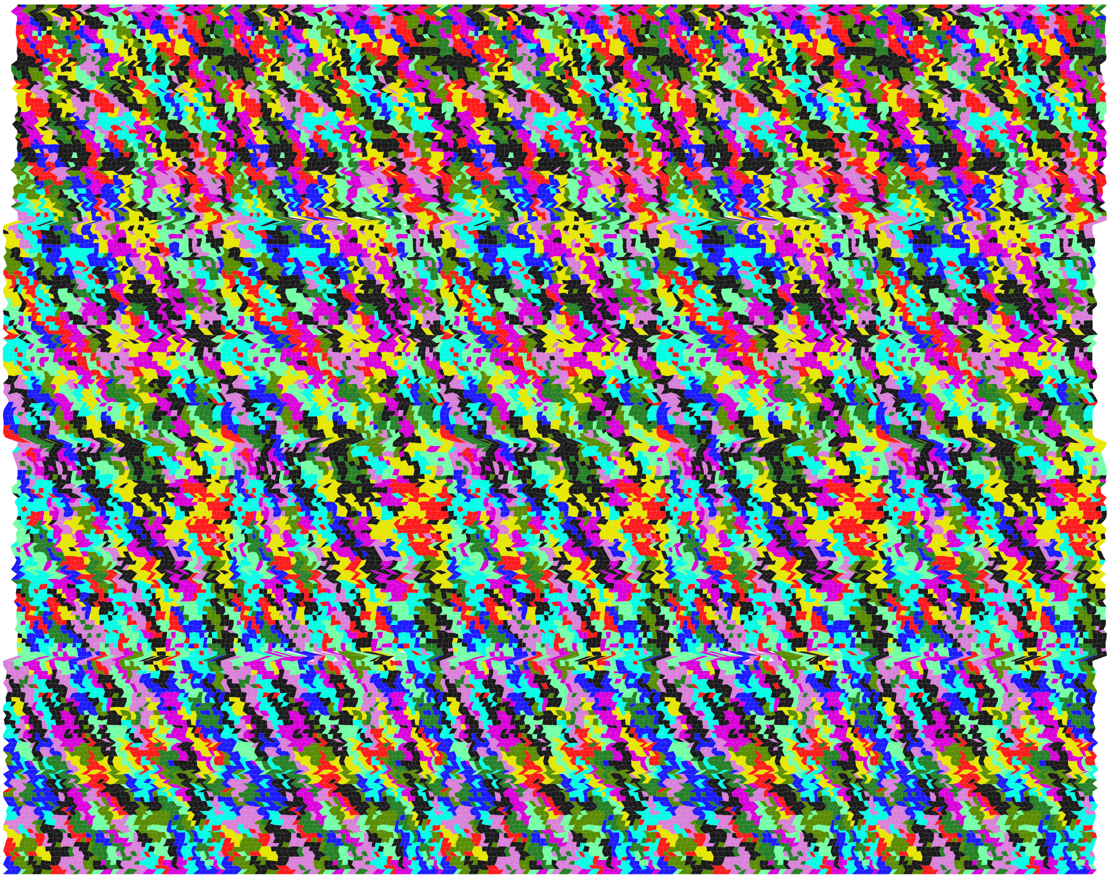

Figure 5: Autoseterogram representing 4 parallel sinusoidal bands, alternating in their phases

and produced autostereograms in which there was some congruence between shape and texture, as examplified in pages 32 and 33 of my stereo book [16].

I also devoted time to the creation of wallpaper patterns producing geometrical volumes in space. Fig. 6 is perhaps my most successful creation in this line. I wonder how many fundamentally distinct 3d patterns one will be able to design? In my opinion, if there is a future in stereoscopic art, it is in this type of work. Artists could use the geometric canvas provided by the computer as a starting point, and choose colours of their own, and add a number of effects and variations according to their inspiration.

Within one year, I had produced a considerable amount of material. I had worked on these new images with intensity, to a point which normally would have caused a nervous breakdown. About ten years later, having changed my computer graphics technology, and having to rewrite almost everything from scratch, I am surprised at how fast I generated so many different images, requiring widely different computer programs. Yet, I did not work fast enough to become rich with the sirds in the French context (see Note 1 at the end). There were several obstacles to the publication of my work. My book came one month too late to become a best-seller. It contained plenty of interesting things that could have been used later in academic review articles. In fact, I gave a talk on the scientific lessons to be derived from the autostereograms at ECVP 1995 in Göttingen [23a], and wrote little pieces here and there, but did not dive into the subject again. Abstract

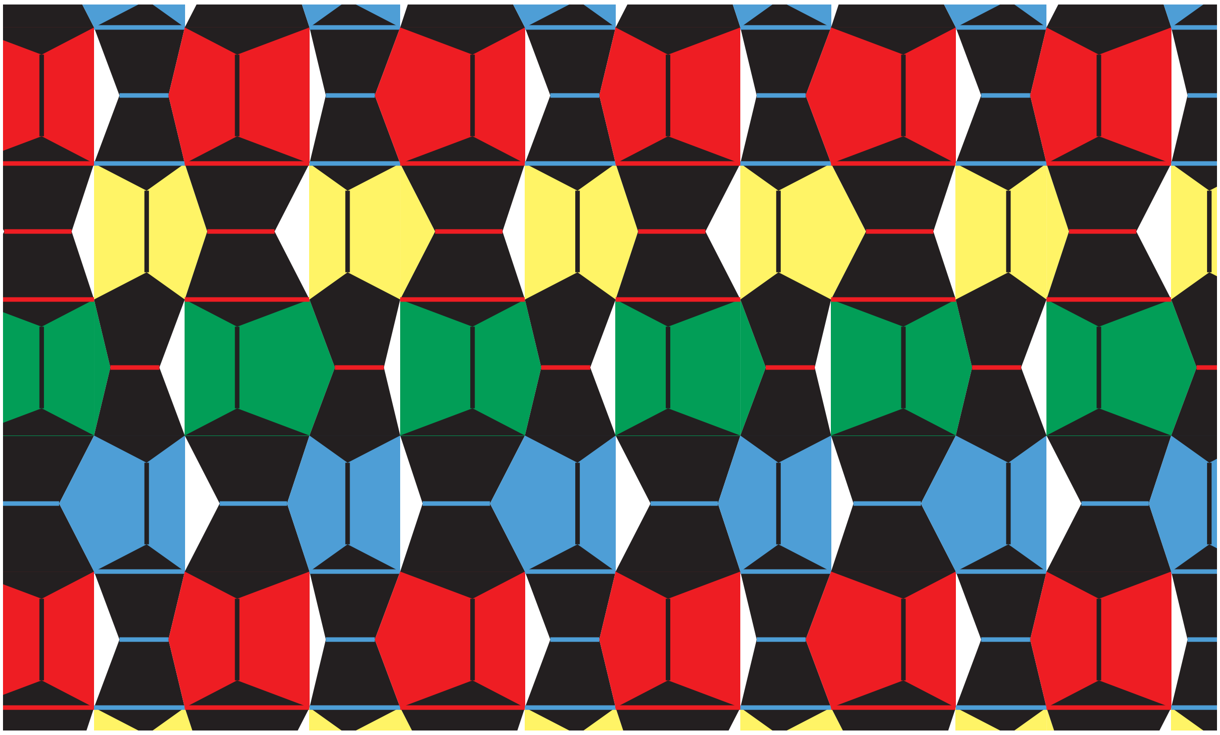

Figure 6: A complex geometrical motif encoded as a "wall-paper" autostereogram. It is made of cells with planar sides, each explicit line is a frontier between planar sections with different orientations in 3d space.

of the 2007 review published in “Spatial Vision” [23]:

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 anecdotical, and more oriented towards simple geometric effects which could be implemented on large panels in natural surrounds.

3.3 Paradoxical stereoscopic stimuli

Paradoxical anaglyphs. Assume that you are looking at anaglyphs with, say, the red filter in front of you right eye, and the blue or green filter in front of your left eye. If there are in the anaglyph red or green lines over a white background, the red lines will be stopped by the green filter, and give rise to black lines in the left eye. The blue or green lines will be stopped by the red filter and give rise to black lines in the right eye. So, the left eye receives the signal from the red lines, and the right eye receives the signal from the blue or green lines. Over a black background, it is the opposite. The black is stopped by both filters. The red lines then give a red signal which goes through the red filter and is received by the right eye, and the blue or green lines give a signal which is received by the left eye.

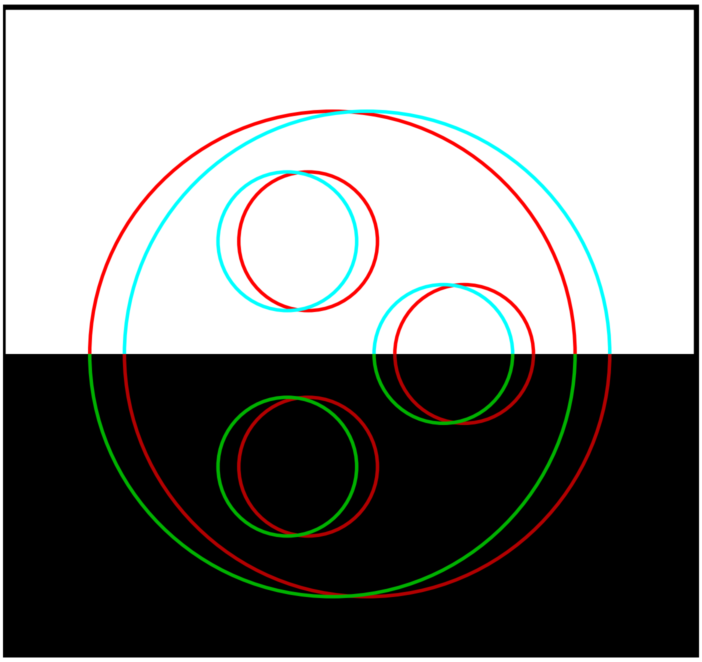

Figure 7: A paradoxical anaglyph. Due to the various encoding of colours by the computer monitor, and the colour printer, this anaglyph may not work. The principle here is to demonstrate that anaglyphs work differently over white or black backgrounds. The sign of the disparity in an anaglyph is shown to depend upon the grey level of the background. The color that goes to the left eye in the black region, goes to the right eye in the white region. The disparities, and therefore the depth values are inverted. If the color balance is well reflected, the two large circles should be seen as continuous, although each circle is made of two half circles of opposite colours. Upon stereoscopic viewing: (i) the small red and green circles on the right become two half-circles at different depths (ii) the complete small circles on the left appear at two different depths although the red circles are, in both cases shifted by a same amount to the right with respect to the blue or green circles (iii) Although the big circles are constructed with half circles of different colours, they give rise to a single circle in depth.

Therefore, the sign of the disparity in an anaglyph, for a same set of lines, depends upon the background. This fact should in principle be detrimental to anaglyphs using hihgly contrasted pictures. The paradox is illustrated in Fig. 7. I made the point in the

French Stereo-Club magazine [24], but there was, in the next issue, a rebuttal by an idiot who thought that I did not understand how anaglyphs work.

Stereoscopic Dissection of continuous lines. Most experimental studies in stereo vision use stimuli that involve flat and fronto-parallel surfaces above or below the ground surface. Then, unless the top surface is transparent, there are regions of the top surface that hide a portion of the background in the right projection, and other regions that hide part of the background in the left projection. Such "half occlusions" thus generate regions in one image of a stereo pair that have no conterpart in the other image So, when a stereogram represents a surface above or below background, there are so-called "monocular regions" (see Note 2 at the end). Gillam and Borsting, 1988, reasoned that the existence of such monocular regions in a stereogram might be a powerful clue to depth, because they clearly indicate where the brain has to look for the beginning of the matching regions [25]. They used stimuli with random dots, and the monocular regions were blank, so they formed very clear boundaries. At about the same time, I designed random-curve stereograms that presented a much greater difficulty. The curves used in both the left and the right images had to look continuous as usual, yet they had to encode a depth discontinuity.

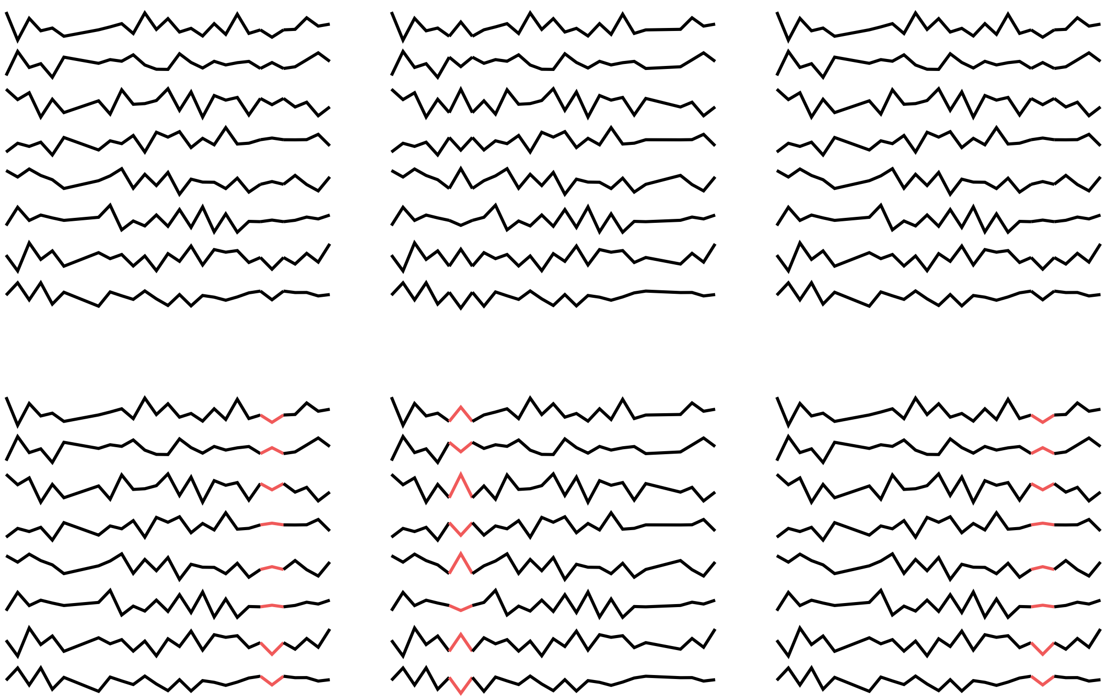

Figure 8: Stereoscopic splicing, or the most difficult stereogram in the world! The top stereograms represent a vertical rectangle above or below background. The geometry is the same as in standard Julesz stereograms. A rectangular area, extending to the top and the bottom of an image is shifted by a constant value, to the left or the right of the other image. This generates half-occluded regions that are present in one of the two images. They are shown in red in the bottom images. How 20 able subjects perceived 16 similar stereograms was reported in [26].

I produced stereograms having this property which represented a rectangle elongated in the vertical direction, above or below ground level. Such stereograms are rather difficult to interpret, and although many subjects do dissociate the two depth levels, they do not suppress the monocular parts of the lines, and have them run as sides connecting the two surfaces. The work was presented at a congress in 1987, and published in the proceedings of the congress [26]. The summary ran as follows:

ABSTRACT. Given a continuous line in a stereogram, is the brain able to cut it into two or more pieces to which different depths would be assigned ? Sixteen stereograms representing a rectangle above or below the picture plane were constructed, with random textures composed of continuous or discontinuous lines. Twenty able stereoscopists to whom these stereograms were given to analyze provided various interpretations: (a) rectangle above or below background (b) same figure, but with visible sides (c) same as a) or b) but with curved surfaces d) same as a), b) or c) but with depth inversion.

I did not attempt to publish the work in a regular journal. It would have been suited, as a demo, for inclusion in a review article. See examples in Figure 8.

Other paradoxical stereograms

As part of a work with Philippe Herbomel on the effect of illusory patterns in stereograms, I designed the stereograms shown in Figure [9]. They incorporate Müller-Lyer patterns, the figure with the ingoing finns being in one image of the stereo pair, and the figure with the outgoing finns being in the other image. In the Mülle-Lyer illusion, the shaft with the outgoing finns seems to be longer than the shaft with the ingoing finns although they have by construction the same length. So, there may be illusory disparities between the left and right versions of the shaft, and we wondered whether or not the apparent length difference would create a slant effect as would occurr in stereo pairs involving horizontal segments with real length differences between the left and right images. There was indeed a slant effect, but in the opposite of the expected direction! Actually, what we observed was consistent with observations published by Anna Stein in 1947 [27]. The whole figure seems to have rotated in depth, so as to minimize the occupation in depth of the figure. As far as I know, Anna Stein's result has not yet been incorporated into stereoscopic orthodoxy. Two of my stimuli were included in a chapter on stereo in an Italian book on perception [28].

4 EXPERIMENTAL CONTRIBUTIONS

4.1 Orientational disparity

If orientation matching is important in stereopsis, as suggested by neurophysiological studies, then one should logically expect that stereoscopic interpretations take advantage of the orientation differences between the left and right projections of a linear segment to assign to this element an orientation in depth (slant). I thus designed a number of stereograms to determine whether or not orientational disparity was used in stereopsis. My work, published in Perception [29] was summarized as follows:

Abstract. Twenty stereograms with needles either plunging in depth or untilted were constructed. When the geometry of the needles was unbiased, the tilt of the needles was correctly and rapidly appreciated. When the needles were biased so as to remove either

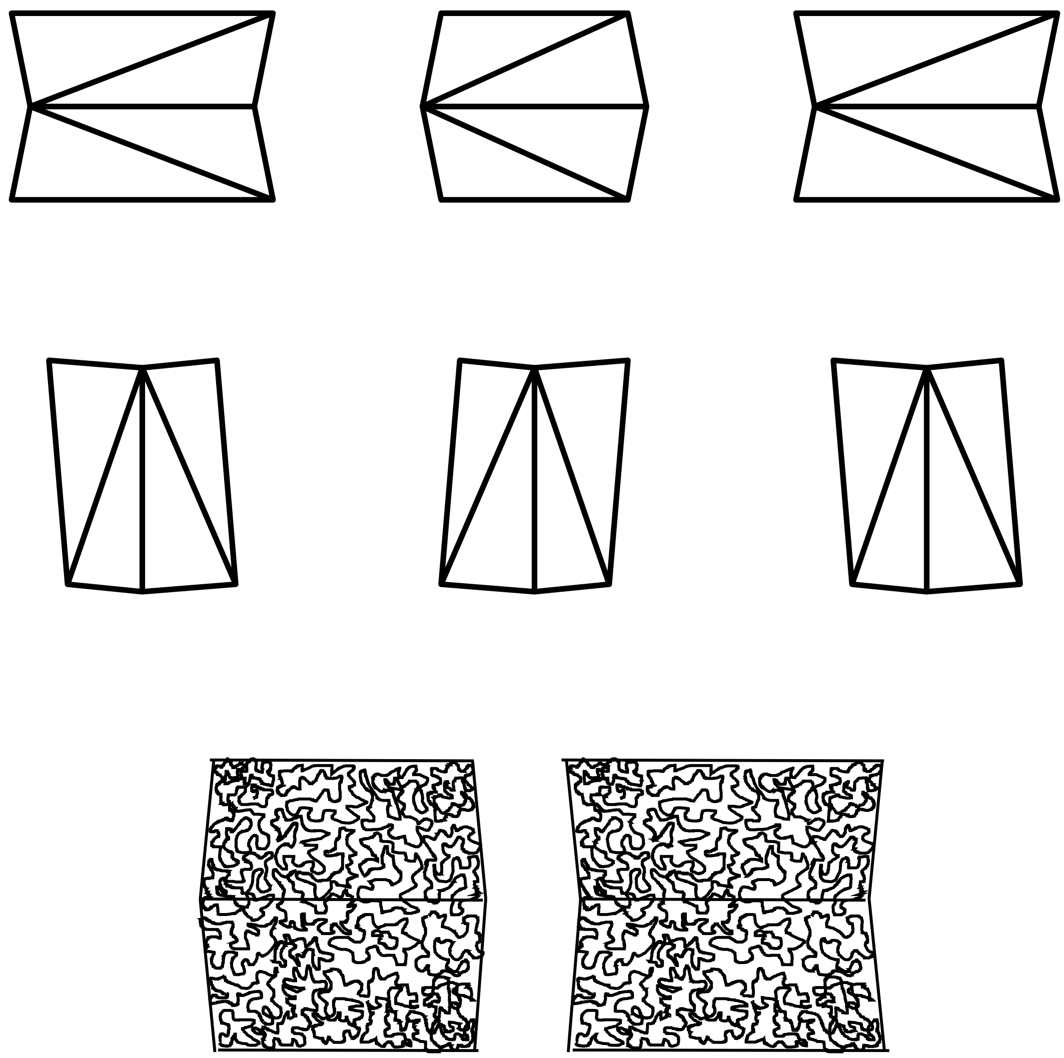

Figure 9: stereograms with illusory disparities. In the top patterns, the central horizontal lines are shortened or lengthened due to a Müller-Lyer effect. Under stereoscopic viewing, the central line is perceived with a slant which is opposite to that predicted by the illusory disparities. It seems that the whole figure is rotated in depth about a a vertical axis, in a way which minimizes the in-depth span of the figure. There is no illusory disparity in the bottom stereogram, but a similar rotation effect is observed. This time, the whole figure is slanted around a horizontal axis so as to minimize the depth span.Published in [28] and [72]. The sterogram in the bottom has the same geometry as those in the top, except that its is filled with texture. It folds exactly as that in the top, yet, according to stereoscopic orthodoxy, there is no folding clue!

their orientational disparity, or the difference in horizontal disparities at the tips, they could be seen, depending on the subject and the nature of the bias, either with or without slant. Orientational disparity proved to be, with two different testing methods, clearly more effective than horizontal disparity in conveying the information of slant. Biased needles at -45 degrees were more often rejected as untilted than biased needles at +45 degrees.

The orientational disparity information was ineffective with crosses that combined +45 and -45 degrees needles. The reaction time and the nature of the percept were correlated, the tilted percept taking longer to mature than the untilted one in biased stereograms. Of the seventy tested subjects, one appeared to make no use at all of horizontal disparity in the stereoscopic appreciation of slant

This work did not have the impact it deserved. Some of the reasons why it may have been neglected are given below. But before listing them, I show in Fig. 10 a very striking stereoscopic demo, which I have constantly used with visitors, after the demo of Fig. 2. When people look at these two sterereograms representing pyramids, there are several types of reactions. Some people found it difficult to fuse the apexes of the pyramids, due to excessive disparities. But most people could fuse the edges. However some people did not realize that the cross-like elements must also be viewed in depth. In their first interpretation, they use the edges to form pyramids, and the crosses remain at ground level (or they do not pay attention to their positions). After being told that the crosses belong to the pyramids, they manage to perceive the edges and the crosses in a coherent manner. But they do not see the difference between the two pyramids (or they mistakenly say that one is higher than the other). Others find the main difference between the two pyramids as soon as they look at them through the stereoscope. In one of the stereograms, the crosses lay on the faces of the pyramids, so it is a pyramid with smooth faces. In the other pyramid, the crosses are parallel to the base so the pyramid is stratified. Those who did not find the difference by themselves were told to pay attention to the orientation of the cross-like elements with respect to the faces of the pyramids, and in most cases they did ultimately find correctly the difference. The very good stereoscopists were able to detect almost at once another difference: In the stratified pyramids, most of the apparent crosses are made of a pair of needles which do not intersect in 3d. A substantial fraction of the other stereoscopists did detect correctly the difference once asked to focus their attention on whether or not the two needles forming a cross touched each other in space. With this test, one gets a finer evaluation of stereoscopic aptitudes than was possible with the stereogram of Figure 2. It shows once again that stereoscopic interpretation does not reduce to a binary closer/farther judgement. A most curious feature that deserves further investigation is the nature of the percept one has when one sees the crosses in depth without being aware of their quite different arrangement (slanted and stuck to the faces of the pyramid in one case, fronto-parallel and sticking out of the faces in the other case).

Beyond this demo, which was included in [29], I studied a number of related stereograms in which the geometry of the projection was biased so as to remove either the orientational disparity information or the positional disparity information at the end-points of the needles. So there were pairs of biased stereograms using crosses or needles, one with each type of bias. One subject could see the first pyramid with the elements glued to the faces, and the other pyramid with the elements sticking out, and another subject would see the opposite. About half of the subjects appeared to rely on orientational, rather than positional disparity for the appreciation of slant, and another half seemed to have the opposite preference. A single subject out of 70 subjects answered all the tests as though she relied exclusively on orientational disparity for the appreciation of slant. Several months after the publication of the article, I had the opportunity to test again the subject, and this time the answers corresponded to a more balanced use

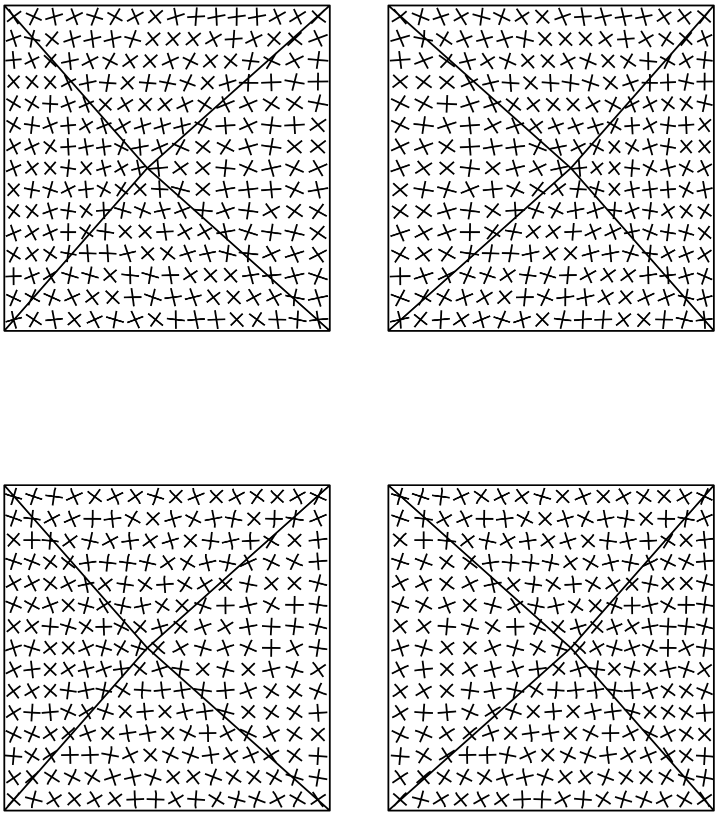

Figure 10: Find the differences between the two pyramids. Some people have difficulties fusing the edges because there might be for them excessive disparity at the apexes of the pyramids. This can happen with very good stereoscopists who are sensitive to very small disparities and intolerant to larger ones. The top pyramid is smooth, the crosses are lying flat on the faces. The bottom pyramid has steps and looks bristly. In the bottom pyramid, the crosses are made up of two needles that do not necessarily touch each other. This example is a less dense version of that published in [29]. Similar pairs of stereograms, but with needles instead of crosses were also published in [29]. One of them was reproduced in [45], Figure 6.19.

of the two types of information. It appeared that at the time of the first testing she was pregnant, so there could have been here an interaction between a peculiar hormonal state, and the preferential use of a visual area. I did not investigate the subject further, and it is a topic that I prefer to leave to others, although it could lead to the kind of sensational publications of which the editors of “Nature” or other fashion science journals are fond of.

Despite the rather demonstrative character of my results, they did not impress other workers in the field. The reason is that the field of stereoscopic vision was still in a state of acute schizophrenia, the psychophysicists still believing that only stimuli with dots were worth studying. As a result there were several studies on the role of orientation disparity in stereo vision (e.g., [30, 31]) most of them concluding that orientational disparity did not play any role. However, the stimuli used there to test for orientation disparity in these studies were dot stimuli that did not contain oriented elements!!! To make the situation worse, there was concomitantly a conceptual regression in the community of neurophysiologists. While in the early studies of Blakemore, Bishop and others (e.g., [32, 33]) there was room for binocular neurons sensitive to orientation disparity, and therefore detecting slanted orientations, slant sensitivity has nearly disappeared from more recent publications. De Angelis, Ohzawa and Freeman published in 1991 a famous article in "Nature" in which they introduced a new technology to map the receptive fields of neurons of the visual cortex [34]. In their protocol, they used patchy random-square type stimuli, and they extracted by a mathematical analysis of the neuronal responses a kind of point by point representation of the studied neuron's receptive field. For binocular neurons, they carried out the mathematical analysis by treating as noise all the orientational disparity information. Fortunately, not all neurophysiologists (see, e.g. [35, 36]) equated orientation disparity with noise. To pursue on the topic of neurophysiological ideology, it must be emphasized that many articles that claim to say something on stereoscopic mechanisms use in fact experimental setups that do not distinguish between binocular fusion and stereoscopic interpretation (e.g., [37]). My subsequent work suggested that the brain was a bit slower when using orientational rather than position disparity (see Section below on "optimal textures for stereo vision"), but the information derived from orientational disparity might be more resistant to decay (see section below on "stereoscopic memory").

4.2 Texture segregation

If you have a stereogram containing two types of elements on which stereoscopic interpretations may proceed, will the interpretation be carried out homogeneously on the figure, or will elements belonging to different textures be handled by different units, thus generating discordant interpretations? During a visit in my laboratory by Eduardo Mizraji, a biophysicist from Uruguay, we generated a large number of stereograms representing hemispheres carrying on their surface two related or different linear textures. The studied textures included random curves, and regular lattices of lines at two orthogonal orientations (horizontal and vertical, or ± 45 degrees). Our results, published in Perception [38] were summarized as follows:

Abstract. Stereograms containing two similar or dissimilar linear textures, either on the same surface or at two different depths, were tested on seventy subjects. Whereas random textures usually produced correct percepts, regular textures consistently led to errors of stereoscopic interpretations, including reversals of hollows into bumps, dissociation of single surfaces into two layers, and errors in relative positioning of two surfaces. Horizontal-vertical textures tended to be seen closer than discontinuous ones. In the interpretation of the results, the possibility is raised that different textures are processed independently and that the brain has no reliable method for combining the conclusions into a rigorous global percept.

I believe today that some of the stereoscopic errors originated from local matching ambiguities. Although the stereograms were globally unambiguous, there is the definite possibility that many subjects relied on local interpretations, neglecting the inconsistencies that might arise at the global level. Incidentally, the most aberrant percepts were contributed by the best stereoscopists as though they were systematically relying on very fine analyzes of spatially restricted regions. For the importance of proximity effects in stereoscopic interpretations, see e.g. [39, 40]. On the whole, the main conclusion – that different textures can be processed independently and that the brain has no reliable method for combining the conclusions into a rigorous global percept is probably correct.

4.3 Optimal textures for stereo vision

In 1983 I had for the first time an opportunity to start building a team on visual perception. A young and brilliant mathematician from Ecole Normale Supérieure, Isabelle Herlin, joined my lab (which was mostly devoted to wet biochemistry and bioinformatics) to work with me on stereoscopic vision. The project was about orientation preferences in stereo vision. Assume a surface is represented with lines running horizontally, or vertically, or at any other orientation. Are there orientations at which stereoscopic interpretation will work better than others? Herlin found that continuous, nearly horizontal lines were poor carriers of stereoscopic information, but most orientations from plus or minus 22.5 degrees to the vertical were equally good. The findings were published in the proceedings of a 1985 congress [41a]. She left the laboratory after one year, to join an institute of research in informatics, and I completed the psychophysical testings, including various kinds of textures in the comparisons. I tested the subjects, and Herlin performed the statistical analyzes. The results, published in Vision Research [41b], were summarized as follows:

Abstract. Stereograms belonging to 10 different textural types were constructed. Each stereogram represented five hemi-ellipsoids, either as bumps or hollows (+, -) and elongated either along the horizontal, or the vertical direction (H, V). The ease with which these stereograms could be interpreted was tested on 70 subjects. The two criteria of speed and accuracy were correlated. The main factors contributing to the ease of interpretation, in the case of the+ or - character were: (i) diversity in the orientations of the matching stimuli; (ii) other factors reducing matching ambiguity; (iii) the presence of discontinuous elements; and, to a much lesser extent (iv) the presence of monocular cues. The last two factors exerted a stronger influence on the appreciation of the H-V character. Of the four kinds of objects, the H- and the V+ hemi-ellipsoids appeared to be the least and the most error-prone ones respectively. The results further suggest that: (i) stereoscopic interpretation does not proceed from small to large disparities; (ii) the edge detectors of the visual cortex, when activated, speed up interpretation, but are easily saturated; (iii) large surtaces are reconstructed by correlation of horizontal rather than vertical patches.

In 1989, I published a book to popularize cognitive sciences in France [42], and this brought to my laboratory a molecular biologist from the Pasteur Institute who had performed a small research project with me as a student [43]. He was also curious about cognitive sciences, and wished to have a closer look at the field. I oriented him on two subjects: the link between geometrical illusions and stereo vision (see the next section), and the continuation of Herlin's work. My prejudice, at the initiation of this second textural work was that the capacity of a texture to provide orientational disparity information was a main determinant of the texture efficiency for conveying stereoscopic information. The studies focused this time on textures with needles or with crosses. The results were clearcut and invalidated my starting assumption. Orientational disparity did not play any role in the speed or accuracy of stereoscopic interpretation. On the other hand, "orientational distinctiveness" was proven to play a major role. This is subtle, but understandable. We are used to think of the stereoscopic calculation tasks as occurring in the spatial domain. The problem then is to match spatial positions on the left and the right images. The task is facilitated when the figures do not look homogeneous – the space is filled with landmarks which are easily detected and are then used to anchor the matching process. In the case of a random dot texture, local inhomogeneities in dot density may play this role. What our study showed is that, as far as oriented elements are concerned, we have to reason differently. The landmark character of an oriented element is in large measure due, not to a local positional inhomogeneity, but to the fact that its orientation makes it distinct from other oriented elements. Our study provided rather convincing evidence on the dual character of stereoscopic processing, showing that after an initial stage, stereoscopic processing could take two alternative routes, depending on the presence or absence of oriented elements. Our conclusions were summarized as follows, in a Vision Research article [44]:

ABSTRACT. The stereoscopic processing of small linear elements is probed through the comparative analysis of stereograms containing needles or crosses, differing in the local spatial arrangement and orientation of the elements, and the presence or absence of slant. Depending upon the details of textural design, depth analysis may proceed faster with crosses than with needles, or the reverse. It proceeds faster with vertical than with horizontal needles, except in the case of unslanted regularly-spaced needles. On the whole the data suggest that the elements to be matched in a stereogram are first processed along a common pathway, in which positional regularity has a detrimental effect. In the presence of small linear elements, orientation-tuned neurons would be recruited and their participation would lead either to an inhibition effect when the elements are all similarly oriented, or to a facilitation effect when there is sufficient orientational diversity among the elements. Here, slant plays an indirect role, by widening the orientation spectrum in otherwise regularly oriented textures. Positional irregularity is useful to suppress false matches, while orientational diversity helps to stabilize the perceived surfaces.

Our conclusions, if correct, seem to be rather important. Yet, to the best of my knowledge, the two articles on how stereopsis worked with different types of textures [41, 44] were neither challenged, nor in any way incorporated into the current stereoscopic doctrines [45, 46].

4.4 Illusory disparities, and other illusory effects in stereo vision

The Zöllner illusion in stereopsis. The starting point of all my work on stereoscopic vision had been the observation made by Julesz that the Zöllner illusion was cancelled when camouflaged in a random-dot stereogram. From my preceding work showing the importance of oriented elements in stereopsis, the significance of Julesz' observation could be questioned. The RDS used by Julesz did not contain oriented elements. What would happen with stereograms containing in a visible way the oriented bars of a Zöllner pattern? I designed a number of stimuli in which the oriented bars were monocularly visible, but the full Zöllner pattern could emerge in isolation only under stereoscopic viewing. We found that the illusion exists in stereo "only when monocular edges (e.g., separating two different random textures) are visible, even if the Zöllner pattern as a whole is not seen monocularly". We concluded provisionally that contrary to Julesz' claim, "the Zöllner illusion is formed at a late stage of visual processing, provided that the lines or edges of the bars have been identified at an early stage". Our conclusions were presented at the 1990 ECVP congress organized by Andrei Gorea in Paris [47], but we did not attempt to transform the abstract into a full-sized publication. Our stimuli were not easy to see in depth. I propose here a new stimulus which I believe should make our point rather clear. The stimulus is based upon a "half-Zöllner" pattern in which there are two colinear Zöllner stacks that seem to be misaligned. A single mechanism is at work in both the standard and the half-Zöllner illusions [48]. By superimposing two half-Zöllner patterns of opposite polarities, we get aligned stacks of crosses, and there is then no misalignment illusion. However, in the stereoscopic display of Figure 11, the half-Zöllners stacks of different polarity segregate in depth. Then, misalignement of the stacks is clearly visible in each depth layer.

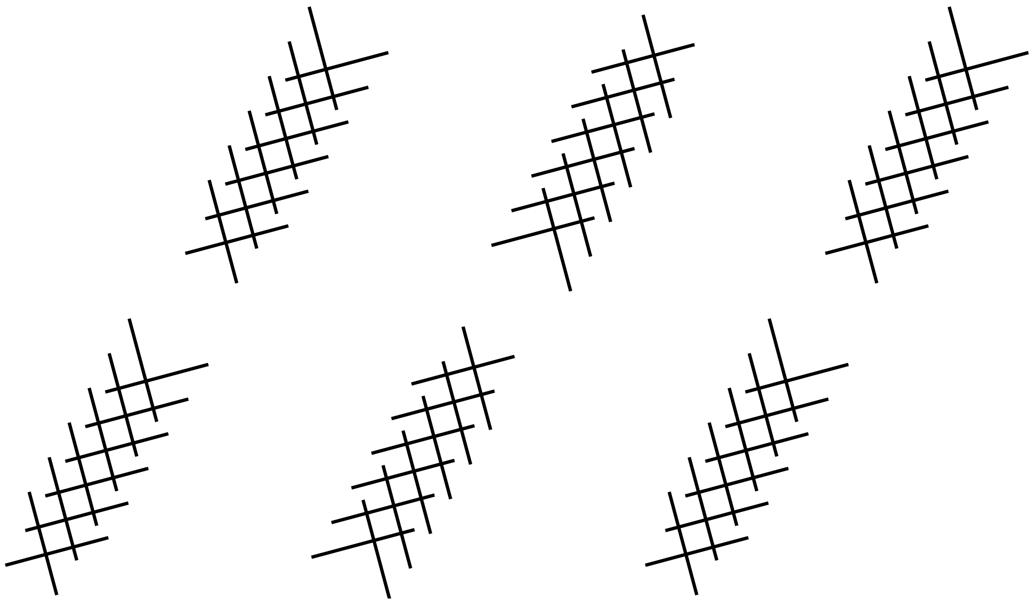

Figure 11: Camouflaged half-Zöllner illusion in stereo. The stacks contain two sets of parallel segments at two orientations. When viewed in stereo, the sets of segments oriented in one direction (say, + 30 degrees) segregate in depth from the sets of segments oriented in the other direction (say, +120 degrees). When stacks involving a same direction of the segments are aligned two by two, but in the plane, they appear misaligned, in conformity with the classical Zöllner illusion [48]. Here, there is no illusion before fusion, but under stereoscopic viewing, when the segments with different orientations segregate, the illusion is perceived on pairs of aligned stacks with segments of a single orientation.

There is however a problem in the perception of the Zöllner patterns: One of the stacks has a tendency to rotate, so as to appear in a vertical, rather than a horizontal plane. I leave it to the reader to decide whether or not a pair of stacks of opposite polarities one above the other in two depth layers appear to have aligned axes, or misaligned ones as required in the half-Zöllner illusion.

Illusory disparities. The demonstration that stereopsis could work on RDS had been of enormous importance in the field of stereopsis. Yet it did not rule out the possibility that when monocular cues were present, they would feed the normal stereoscopic process. The results on the different fate of the Zöllner pattern, depending on its mode of presentation were a clear indication that stereopsis could work on a feature basis, and was not restricted to abstract point by point correspondence. Now let us push to its limit the notion that there exists a stereoscopic interpretation pathway in which monocular interpretation comes before stereoscopic matching. What can be expected if there are figures in a left and a right images which give rise to monocular illusory effects? The figures can be arranged in such a way as to generate illusory disparities. So, would these illusory disparities give rise to illusory depth percepts? This is the question that Herbomel and I addressed in a very systematic study. Unknown to us at the beginning of this work was the fact that the problem had already been addressed by Lau, in 1925 [49] and Linschoten in 1956 [50] and had generated substantial controversy, until both Ogle [51] and Julesz [1] dismissed the phenomenon, on the grounds that they could not see the effect, and it must therefore be non-existent. The work performed by Herbomel and I is decribed in Note 4 at the end of the text. This work led me to reject the notion that illusory disparities could feed the stereocopic matching process and believe instead that a number of 2d patterns could influence depth judgements preceding the authentic stereoscpic calculations (see next section on 3d curvature biases).

3d curvature biases Several years later, I started doing extensive psychophysical work on many themes, including geometrical illusions, subjective contours, human memory. I had many volunteer subjects, and in order to make the tasks more agreeable, I varied the nature of the tests. So I thought of including stereoscopic tests. From the earlier work with Herbomel, I retained as most significant the finding that in-depth curvature could be observed on curved lines that were present in a single of the two images. But I knew that the theme of illusory disparities was taboo, so I chose not to use stimuli that generated monocular illusions. Instead I chose to study the perceived in-depth curvature of stimuli that were already curved in the plane. The results of this study were particularly interesting. They suggested that the brain makes guesses about depth relationships, prior to the authentic stereoscopic calculations. They also suggested that stereoscopic matching is unidirectional, it is initated from the nasal side. The article was submitted to Perception, and kindly handled by Susan McKee. Typical stimuli are shown in Fig. 12. The conclusions of the article were summarized as follows [52]:

ABSTRACT. The reliability of curvature judgements for linear elements was studied with stereograms that contained a binocular arc with curvature in depth, and either a binocular frontoparallel arc or a monocular one, on a background representing a hemiellipsoid. The subjects made about 15 per cent errors on binocular arcs with curvature in depth, and 60 to 80 per cent of these occurred when both the hemiellipsoid and the arc were convex, the arc being perceived as concave, by transparency through the hemiellipsoid. There were also about 15 to 30 per cent errors on frontoparallel arcs, but spread among all situations, with a small prevalence of concave judgements. Curvature in depth was assigned to the monocular stimuli in more than 60 per cent of the cases. There was a curvature bias when the monocular arcs were on the nasal side, and were viewed against a concave background. Assuming parallel viewing, nasal ingoing arcs were usually perceived as concave, and nasal outgoing arcs usually perceived as convex, in agreement with geometrical likelihood. Nasal-side elements captured by one eye are, in general, those with the highest likelihood of having matching elements in the other eye. Then the observed nasal bias effect suggests that the matching process in stereopsis could be driven from the nasal sides of the projections in the two cerebral hemispheres.

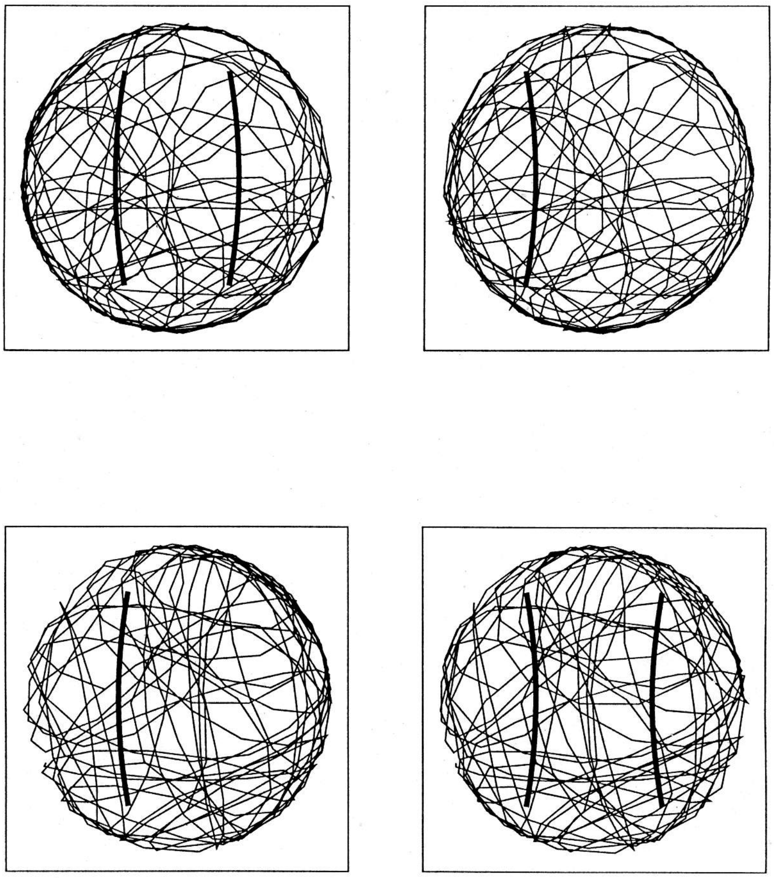

Figure 12: 3d curvature biases. Stereograms representing a hemiellipsoid, an arc curved in depth in the same direction, and a monocular arc. The top stereogram is intended for parallel viewing, and the bottom one for cross-eyed viewing. Against the concave background,the monocular arc is often appreciated as having curvature in depth, with a bias towards convexity in the top example, and concavity in the bottom one. Published as Figure 2 in [52].

4.5 Stereoscopic depth from two images captured by a single eye

Svetlana Rychkova, an ophthalmologist working in Irkoutsk (Siberia) came to me in 2006, to discuss her paradoxical observations with some strabismic patients. She had been involved in the recovery of normal vision after corrective surgery. She observed that a number of patients were able to fuse the two images of a standard fusion test, even under the control condition in which one of the two eyes was occluded by interposition of an opalescent screen. This seemed very strange, and the other ophthalmologists in the clinic where she was working suggested possible artefacts. It appeared in our discussion that a strabismic deviating eye may develop a sensitive zone, a second fovea so to speak, that would allow the patient to capture visual information straight ahead. A patient with inconstant strabismus might thus maintain in an active state both the natural and the second fovea. This explains how for some patients, the strabismic eye may capture two images from two different directions, giving rise in some cases, to monocular diplopia [53-54b]. What was not clear, at that time was how the two images could be compared and fused. I thought that this was not unconceivable. First, it is known that each eye sends visual information to both hemispheres. Second, it is suspected that the brain may not know for sure from which eye an information that is received on a given hemisphere is coming. Additional information must be taken into account to remove the ambiguity. This is the well-known "utrocular" or "eye of origin" issue, and several of my past experiments had shown cases of interpretation errors made by quite good stereoscopists, in which the depth sign of a reconstructed surface was the wrong one, as though they had interchanged the left and the right visual streams. Third, if the brain of a strabismic patient receives two images from the two foveas of a single strabismic eye, it may well deal with them as being contributed by the two eyes. Hence, fusion of two images sent by a single eye is compatible with the known neurological wiring conneting the retinas to the brain hemispheres. I thus proposed to Svetalana Rychkova to perform experiments in which, beyond fusion, the capacity to derive a 3d interpretation in stereo pairs could be detected. I designed a set of 20 different stereo pairs that probed many aspects of stereo vision. We submitted a manuscript describing the work to Vision Research. The Editor was Casper Erkelens, and the manuscript was accepted [12]. Here is its abstract:

ABSTRACT Some strabismic patients with inconstant squint can fuse two images in a single eye, and experience lustre and depth. One of these images is foveal and the other extrafoveal. Depth perception was tested on 30 such subjects. Relief was perceived mostly on the fixated image. Camouflaged continuous surfaces (hemispheres, cylinders) were perceived as bumps or hollows, without detail. Camouflaged rectangles could not be separated in depth from the background, while their explicit counterparts could. Slanted bars were mostly interpreted as frontoparallel near or remote bars. Depth responses were more frequent with stimuli involving inward rather than outward disparities, and were then heavily biased towards "near" judgements. All monocular fusion effects were markedly reduced after the recovery of normal stereoscopic vision following an orthoptic treatment. The depth effects reported here may provide clues on what stereoscopic pathways may or may not accomplish with incomplete retinal and misleading vergence information.

4.6 The resolving power of alternating presentations

The starting point of this work was again an observation made by Svetlana Rychkova. There is a common apparatus, in orthoptic clinics: the synoptophore. Two images designed as tests for fusion are sent to the two eyes of a patient, in alternation. Typically, at a 2 Hz alternation frequency, each image is presented for 250 milliseconds, and the patient with a lazy eye perceives two images in alternation, rather than a single stable or blinking image. The alternation frequency is then raised. With training, the patient becomes able to perceive the two images at increasingly high alternation frequencies, until he/she hopefully succeeds in fusing the two images. Svetlana Rychkova added my stereoscopic tests to the commonly used fusion tests. She soon found that patients who were able to interpret a certain stereoscopic pair in 3d at a certain alternation frequency on the synoptophore, could require a significantly higher alternation frequency for another stereo pair, independently of the disparity ranges used in the stereograms. Differences in minimal alternation frequencies were found between quite simple stereograms. Subsequently, differences in such thresholds of alternation frequencies were also observed with subjects who had normal vision. Whereas earlier comparative studies on stereogram perception often focused on complex images that required large latencies in order to be perceived, the synoptophore studies at several alternations per second seemed to be exquisitely sensitive to subtle differences between quite simple stereograms. I thought that a systematic study, made with normal subjects, on the alternation frequencies at which they would begin to interpret stereograms would reveal something about the nature of the difficulties arising in the stereoscopic processing mechanisms. We thus used a set of 20 stereograms shown, with a fex modifications, in Figure 13.

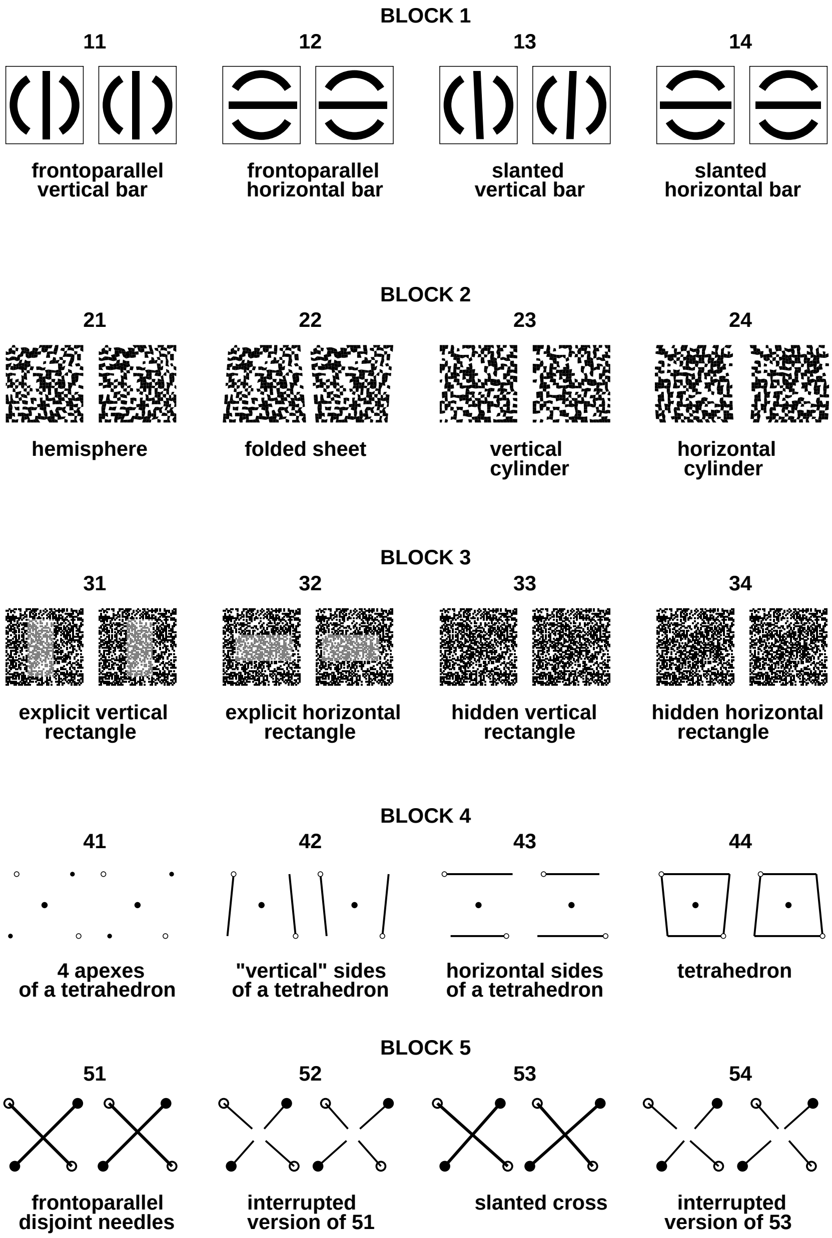

Figure 13: A set of twenty stereograms presenting various types of difficulties, suitable for probing the different pathways of stereoscoping processing in different subjects. *Enlarged versions of the stereograms are shown at the end, Section 6.6, Fig. 17-21.* This set of stereograms was used in [58], but there were some differences with the set used in [56]. Each stereogram was presented as shown here, as well as in the inverted depth variant, in which the left and the right images were switched.

Rychkova did the testing work, once with the synoptophore, and a second time with liquid crystal shutters. A main result, obvious or not, was that the more difficult a stereogram, the higher the needed alternation frequency. The general interpretation is that the information brought by each of the visual flows decays, so the more complex a stereogram, the more important it is to refresh the information by frequent alternations. Alternatively, it is the current 3d interpretation under construction that decays by parts, hence a need for frequent refreshes. Another important result is that even with extremely simple stereograms (compared with the traditional RDS) one could determine significant differences in the alternation frequencies requirements. Thus, we were able to quantify the impacts of slant, curvature, depth discontinuities, depth dissociations, camouflage, orientation disparity, information redundancy (Figure 14).

Abstract. When stereoscopic images are presented alternately to the two eyes, stereopsis occurs at $F \geqslant 1$ Hz full-cycle frequencies for very simple stimuli, and $F \geqslant 3$ Hz full-cycle frequencies for random-dot stereograms (e.g. Ludwig et al., 2007 Perception and Psychophysics 69, 92-102.) Using 20 different stereograms presented through liquid crystal shutters, we studied the transition to stereopsis with 15 subjects.The onset of stereopsis was observed during a stepwise increase of the alternation frequency, and its disappearance was observed during a stepwise decrease in frequency. The lowest F values (around 2.5 Hz) were observed with stimuli involving 2 to 4 simple disjoint elements (circles, arcs, rectangles). Higher F values were needed for stimuli containing slanted elements or curved surfaces (about 1 Hz increment), overlapping elements at two different depths (about 2.5 Hz increment) or camouflaged overlapping surfaces ($>$ 7 Hz increment). A textured cylindrical surface with a horizontal axis appeared easier to interpret (5.7 Hz) than a pair of slanted segments separated in depth but forming a cross in projection (8 Hz). Training effects were minimal, and F usually increased as disparities were reduced. The hierarchy of difficulties revealed in the study may shed light on various problems that the brain needs to solve during stereoscopic interpretation. During the construction of the 3d percept, the loss of information due to natural decay of the stimuli traces must be compensated by refreshes of visual input. In the Discussion, an attempt is made to link our results with recent advances in the comprehension of visual scene memory.

This article [56] was submitted to i-Perception, and excellently handled by John Frisby. One of the reviewers (presumably Patrick Cavanagh) made a favourable concise report. The report by the other reviewer was completely insane (see Note 6). It recommended rejection. Frisby attempted to give satisfaction to both parties. He rewrote sections of our article to make it look much less conclusive than it deserved to be, and he re-wrote the title in such a way that the take-home lesson should be lost to most potential readers. But he took the innocent authors out of the insane reviewer's claws, and essentially rescued our work. Thanks, John! The original title was "Alternation frequency thresholds for stereopsis reveal different types of stereoscopic difficulties. In hidsight, it is surprising how often in my carreer I had to change a striking title into an inocuous one under the pressure of reviewers or editors.

4.7 Stereoscopic memory

Here again, in this third opus of my collaboration with Svetlana Rychkova, and the one I am the most proud of, the starting point was in a set of observations made by a Russian ophthalmologist, a colleague of Rychkova: Igor Rabitchev. We encountered his name in

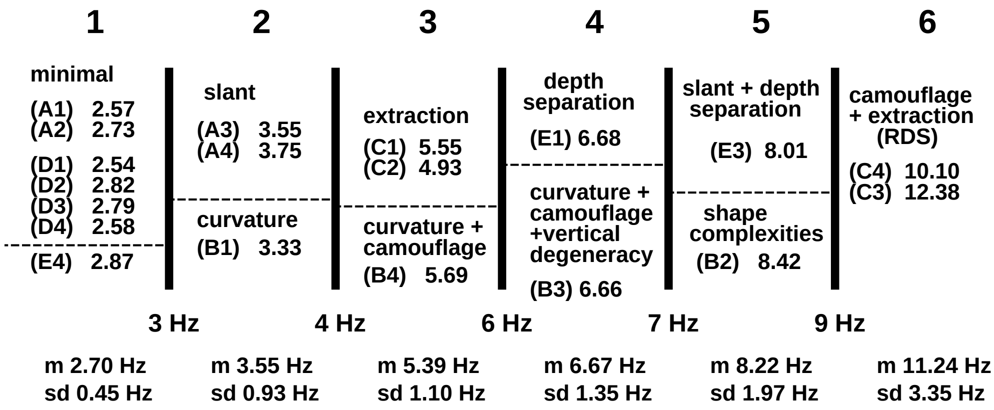

Figure 14: Hierarchy of stereoscopic difficulties, reproduced from [56]. Starting from a core of "basic" stereograms, the threshold frequencies are shown to increase when the following features are introduced: slant, curvature, extraction of monocular regions, depth separation, camouflage, absence of shear disparities. The A, C and D stimuli corespond to the block 1, 3 and 4 stimuli of Figure 13. The B3 and B4 stimuli are the same (23) and (24] of Figure 13, and B1 represented a hemisphere but without background. B2 represented a dome with a central depression as in Figure 1. In the last series, E1 was equivalent to (51), E2 was equivalent to (53), E3 represented disjoint slanted needles (rather difficult to interpret) and E4 represented an interrupted verion of E3, much easier to interpret. Average threshold frequencies and standard deviations are given for each class.

connection with the recovery from stereo blindness (see the "Biographical Notes" section 2.3 and [7]). Rabitchev had been in touch with a French designer of LCD shutters, Pierre Chaumont. The Chaumont shutters allowed one to vary independently the time of exposure to each eye, and also the duration of an interval during which both eyes were exposed simultaneously. Chaumont's idea was that a person with a lazy eye equipped with these shutters could find the suitable combination of exposure times to become quite comfortable, and eventually recover from stereo blindness. Rabitchev tested on himself the shutters with systematic variations of the parameters, and filled a chart indicating the combinations that allowed him to see binocularly in stereo, those for which he could see in stereo, but only during the limited time of the binocular presentations, and those that did not give rise to stereo percepts at all. The chart was communicated to me by Svetlana Rychkova, and I found in this chart a quite remarkable effect: When the "binocular interval" separating the two monocular exposures was increased by a certain amount – say, 20 ms, – the monocular exposures could be increased by a much larger amount, e.g., 50 ms, without disrupting stereopsis.

I thus encouraged Svetlana Rychkova to make a complete exploration of the domain, and proposed a change in technology, allowing the work to be carried out without LCD shutters. I wrote a computer program generating a set of 20 test stereograms see Figure 13 and the enlarged figures at the end, in Section 6.6. This set differed slightly from the sets used in previous work [12, 56]. The two images of a stereo pair appeared on the screen one above the other, and one could modify, by keyword presses the common duration of the two monocular exposure times, and independently the duration of the binocular interval. In addition, we also implemented an option to insert a void duration between the two monocular exposures, instead of a binocular interval (Figure 15). The images were viewed with the help of vertically deflecting prisms, in my case with a plastic "Nesh" viewing device, and in Rychkova's case, with the prisms mounted on standard metallic rims that are used by ophthalmologists to determine the most suitable correcting lenses or prisms for their patients. The prisms were then inserted in the rims, one with the base up for one eye, the other with the base down for the other.

For each selected value of the void, or the binocular interval, we increased the duration of the monocular intervals, and determined whether the subject experienced stable stereopsis, discontinuous (pulsating) stereopsis, or no stereopsis at all. The use of intercalated binocular intervals produced important, unexpected results. First, a modest increase in the duration of the binocular interval makes possible a much larger increase in the duration of the purely monocular presentations. This suggests that the information that is acquired during truly binocular presentations might be more reliable and less subject to decay than the information acquired during the persistence overlap periods. Second, as the binocular duration increases, we find three different phases, a phase in which there is a transition between stereopsis and no stereopsis, a later phase in which there is a transition from stable stereopsis to pulsating stereopsis, then from pulsating stereopsis to no stereopsis and an intermediate paradoxical phase in which, we propose, the pulsating character of stereopsis does not reach consciousness, and the subject reports stable stereopsis. Third, a pair of closely related stimuli that could be hardly differentiated in our previous work under strict monocular alternations (56) can now give rise, in some subjects, to strikingly different behaviours at large binocular intervals. The use of these intervals thus increases considerably the alternation presentation technique as a tool to reveal subtle processing differences between closely related stimuli.

We confirmed Rabitchev's initial observations on the "multiplicative" effect of small binocular intervals, and presented the results at ECVP 2010 in Lausanne [57]. But there were, on top of that, two important observations. First, whereas in the previous work [56] we had assigned one "alternation frequency threshold" for each stereoscopic pair, here we had a detailed description of the influence of the durations of the monocular exposure times, combined with either binocular or void intervals, making a kind of complete phase diagram (see Figure 16). It turns out that when the complete phase diagram is considered, one finds substantial differences between stereograms that could not be separated by the criterion of alternation frequency threshold. Their behaviour may turn out to be quite different at increasingly large monocular exposure times, such large exposure times becoming possible due to the intercalated binocular intervals.

The publication of the paper discribing the work was chaotic. It was first rejected by J.O.V., due to the deeply idiotic report of a reviewer whod did not seem to understand how science works. I could have managed to improve the situation through an exchange with the handling Editor, but I was very ill at that time and could not invest myself in the task. Then it was submitted to i-Perception. One of the reviewers was possibly drunk when he made his report, the other behaved as a psychopath, convinced that nothing could be achieved in the field outside his own work. The managing editor David Simmons rejected the MS in an exquisitely polite (according to British colonialists standards) but

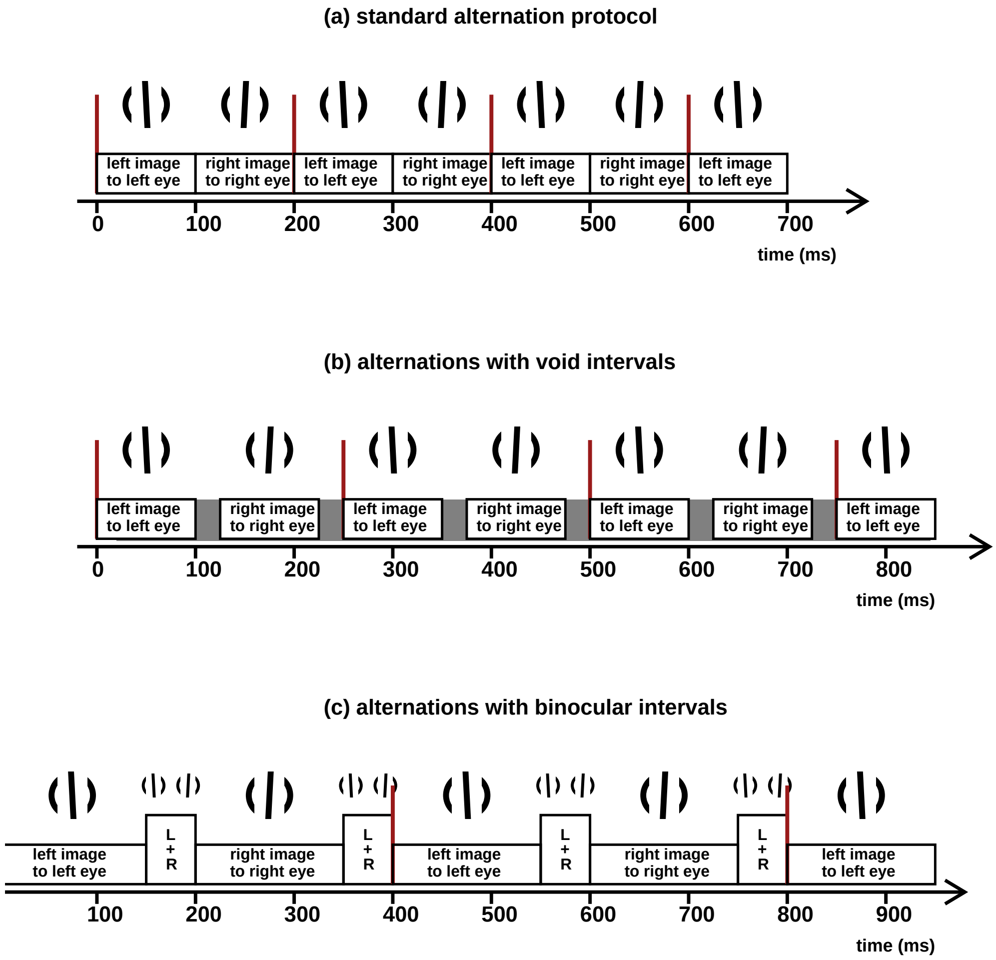

Figure 15: The alternating presentation protocols. (a) Standard alternation protocol. The two images composing a stereoscopic pair are presented in alternation to the two eyes. one above the other, over a uniformly grey screen. So one eye receives an image while the other receives a grey background. In this example, each image is presented for 100 ms, one complete cycle takes 200 ms, so the alternation frequency is 5 Hz. (b) Alternations with void intervals. Here, a 25 ms interval during which the screen is uniformly grey is intercalated between two consecutive 100 ms presentations of each of the two images. A complete cycle takes 250 ms, and the alternation frequency is 4 Hz. (c) Alternations with binocular intervals. Here, a binocular interval of 50 ms, in which both eyes receive their corresponding image is intercalated between the 150 ms monocular phases. One cycle then takes 400 ms, and the alternation frequency is 2.5 Hz.

insulting manner. In all likelihood, he did not even read the paper, otherwise he would have immediatedly detected the aberrations in the reviewer's reports. Unfortunately, his decision was supported, against all scientific rationality, by the whole editorial board of the journal (see note 6.5 at the end). Finally, the paper found space in a not too prestigious journal [58], but at least one review, in this paticular case was quite meticulous.

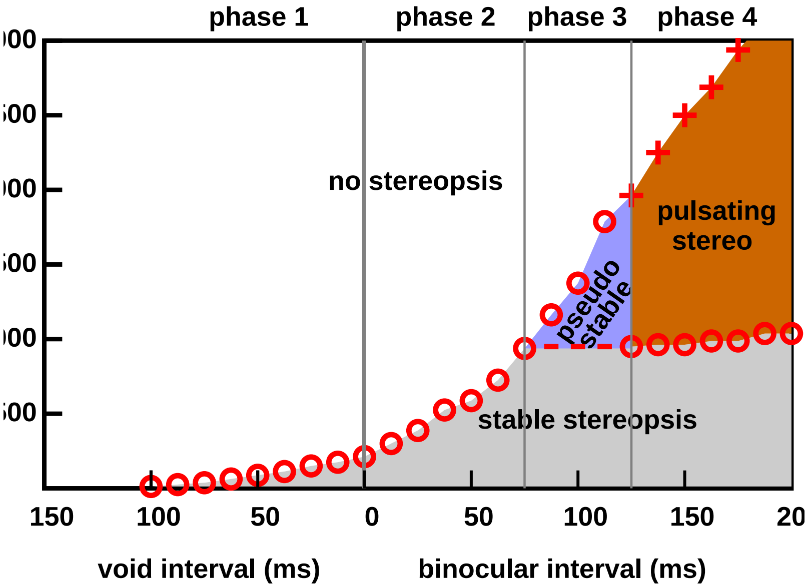

Figure 16: Phase diagram, as published in [58]. Selecting a fixed, particular void or binocular interval, shown in abscissa, one determines the longest monocular duration that allows the occurrence of stereopsis, shown in ordinate. An essential result of this study is that the intercalation of a moderate binocular interval between the left and right monocular presentation intervals (Phase 2) allows a much larger increase of their durations. At large binocular intervals (Phase 4), there is a first transition from stable stereopsis to pulsating stereopsis (lower curve) and a second transition from pulsating stereopsis to no stereopsis at all (upper curve). In Phase 3, the first transition is not observed experimentally, it is conjectured to occur in hidden form, as represented by the triangular blue domain. In this domain, the subjects actually report a single transition, from stable stereopsis to no stereopsis (upper curve). The continuity between the Phase 3 and Phase 4 upper curves suggests that stereopsis also has an interrupted character in the blue domain but the subjects are not conscious of the situation. Actually, the curve shown here is that of the raw data for one of the subjects, see [58].

5 THE CORRESPONDENCE PROBLEM IN STEREO VISION

The problem of how the brain computes 3d shape from the matching elements in a stereo pair has not received much attention, the interest of the theoreticians being focused on an "earlier" problem: how does the brain find out which part of the left image corresponds to which part of the right image? In other words, how is the correspondence between the two images established? Usually, people reason as though the two images to compare were parallel projections of a scene on a single plane. Things are not so simple. The two views of the outside world taken by the two eyes are, to a first approximation, point projections (through the pupils of the eyes) on the retinal surfaces. The retinas are not planar and the density of their photoreceptors varies considerably from the fovea to the periphery.

The non-planar character of the retinas, and the variable densities of the receptors are not insurmountable problems, because the pupil of each eye is in a nearly fixed position with respect to the retina, so the retinal data may be "re-formatted" in a suitable way, for instance it may be re-formatted as data on a plane homogeneously covered with photoreceptors. On the other hand, the fact that the eye may rotate around its axis introduces a permanent variability, and there is no simple mechanism for re-formatting the data to eliminate this source of variation. Most of these complexities were dismissed by Julesz [1]. Bela Julesz treated the problem as a problem of finding the correspondence between the two figures of his stereograms, as they were on paper, and not projected on the retinas. In his stereograms, the corresponding matching points in the left and right images lie exactly on a same horizontal line. So, in his view, the problem was that of finding for any point on, say, the left image, a corresponding point among the hundred or the thousand points that were at the same horizontal level on the right image. Repeating the reasoning for the N other points on the same horizontal line there would be NxN possible matches to consider on every pair of horizontal lines, hence an enormous ambiguity problem. There were at least two erroneous assumptions in this description of the correspondance problem. First, each of the two figures composing the stereogram reaches the retinas after receiving a perspective transformation (a point projection through the pupil of the eye). The brain has to deal with these distorted projections, and not with the idealized geometry of the stereograms displayed on paper. Next, the "false matches" problem is, in most cases, simply non-existent. Under the assumption that most of the surfaces that have to be reconstructed from the projections are essentially continuous, the ambiguity problem reduces to the necessity of making just a few strategic choices, and there can be only a few solutions that are globally consistent with the data. The erroneous description of the correspondence problem was reproduced almost everywhere, e.g. [59], and incorporated in most theoretical work on computer algorithms to solve the correspondence problem. On the other hand, Julesz minimized the correspondence problem, invoking a projective geometry argument based upon a misunderstanding of Cayley's theorem on imaginary points at infinity (chapter 9, Section 2 of [1]).

There is no evidence that the brain knows how his eyes were positioned when the two views were captured for the sake of stereoscopic analyzes. First, it seems that the brain does not know with certainty which input comes from the left eye, and which input comes from the right eye – this would be deduced from contextual information. Even if the eye of origins problem is solevd correctly, and the positions of the eyes were known to some extent, they could not be known with the needed precision. Measurements of stereoscopic acuity show that human stereovision is able to detect disparities as small as ten seconds of arc (see, e.g., [60]). This value is far smaller than the precision with which eye movements are generated and eye positions evaluated by the brain. Incidentally, this argument rules out theories of stereo depth perception from vergence information [37]. Then, if there is a matching algorithm it should be able to work without prior knowledge of the geometry of the projection systems under which the two members of the stereo pair had been generated. My first contribution to stereo vision was a theoretical paper on how to establish the potential geometrical correspondences between two projections [10].

I showed how classical theorems in projective geometry could be used for this purpose. Before projective geometry comes into play, the brain needs to determine, by trial and error, at least seven anchoring point to point correspondences. These being determined, it could determine, for any point on the left image, the line on the right image in which to locate all the potential matches. The two matching horizontal lines in the misleading Julesz-Marr description were thus replaced with the now commonly accepted "epipolar" matching lines. The seven anchoring pairs of points in my treatment could not be chosen arbitrarily, they had to obey a well-defined geometrical condition. Longuet-Higgins then proposed a more general method, using eight pairs of anchoring points and matrix algebra [62]. I also described in the same article [10] a method for relating the orientations on the two images, which is easily connected to the known rules of linear perspective on one hand, and to the neurophysiological properties of the orientation detectors of the visual cortex on the other hand. At that time, it was widely believed that the receptive fields were in strict topographical correspondence with regions on the retina. It was also believed that the binocular neurons of area V2 were organized in columns dedicated to a same orientation in space. I showed that these properties could not be simultaneously true. My proof of mathematical impossibility, (which proved that something was wrong with the set of current assumptions in the field) did not impress the workers in the field. I suggested that the receptive field of a neuron should vary with the surrounding input, and this is now part of current orthodoxy.

I also noted in [10] that "Many theoretical discusssions of binocular vision neglect the fact that stereopsis can be obtained with convergent visual axes, making an angle of 20 or even 40 degrees with each other, and implicitely assume the visual axes to be nearly parallel. This can be seen in the lack of concern for vertical disparities". Vertical disparities soon became a very fashionable topic, when Mayhew and Longuet-Higgins [63] showed how the pattern of vertical disparities between the two projections could inform the visual system about the geometrical parameters of the projection. I remained outside the debate. I knew that vertical disparities could not be used to encode local depth, and was sympathetic to the proposals of Mayhew and Longuet-Higgins (well supported by Porrill et al. [64]) but was much more interested in the issue of orientational disparities. More recently, my attention was drawn towards an insightful metaphor, found in one of Richard Gregory's books: If you deal with printed stereograms, which you copy on transparent sheets, you have a very simple way of finding the corresponding regions: move one transparent sheet over the other, until you find a domain which is recognizable by its higher contrast: it is a domain in which white is superimposed on white, and black is superimposed on black. Convolution algorithms, proposed by theoreticians often reduce to this principle. More interestingly, it could be the case that the signals to be matched in the brain are subject to physical displacements, using "shifter circuits" [65]. The idea can be reformulated as follows: "move, in order to match". I had proposed in fact a related strategy, but working in the orientation domain. The rules by which perspective distorts sets of parallel lines (making them converge, when they are not fronto-parallel) are well-known. My idea was that the brain could try to apply reverse transformations on the orientations of the left and the right images, to obtain an improved orientational match. Then, the differences between the orientations of matching elements (their "orientational disparity") would be crucial in stereovision. I proposed that the Zöllner illusion had to do with the application of reverse perspective transformation [10].

6 NOTES

6.1 Note 1 Comment on Gabor patches

Fourier transforms and Fourier analysis are well established and mathematically rigorous tools used in several areas of mathematical physics. Uni- or multi-dimensional signals are convoluted with sets of periodical functions extending to infinity, and the integration products can be used to recover the initial signals to any degree of precision. The method is ideal for signals extending to infinity, and becomes less and less practical as the signals are less and less extended. The recently developed "wavelet analysis" is now replacing Fourier analysis in a number of fields. It also uses sets of functions to convolute a signal and derive a hopefully more compact description of it. The wavelets are damped oscillating functions. Neurophysiologists now believe, possibly with reason, that most receptive fields of the neurons in the primary visual areas resemble wavelets. So the visual system would have the capacity to perform a wavelet analysis of the visual scene. From there, a habit has developed of presenting, in psychophysical experiments stimuli that are representations of the mathematical tool: representations of wavelets, under the more common name of Gabor patches. Replacing a real physical stimulus by a physical representation of the tool assumed to analyze a stimulus can hardly be justified scientifically. More concretely, when you look at a Gabor patch, the image is captured by thousands of neurons, each neuron having a receptive field covering a part of the image. There is perhaps, among the thousands and thousands of neurons who cover the Gabor patch in the image, one neuron the receptive field of that matches exactly the Gabor patch. So what? This unique neuron will contribute very little to the overall description of the scene, provided by all the other neurons, none of which has a receptive field which matches exactly the Gabor patch. Therefore the use of Gabor patches as "pure stimuli" in psychophysical studies is complete nonsense. Although no educated researcher in the field can ignore this fact, many researchers keep publishing studies involving Gabor patches – including Julesz himself in his late years (e.g., [66]). Note that in the new ideological framework, a point cannot be a simple feature. It is a highly complex blend of an enormous set of Gabor patches of all available spatial frequencies and orientations. For those who have not still understood the point, I give a simple analogy, taken from colour vision. On the human retina, there are three classes of colour sensitive cones. Although the cones are described as being sensitive to red, green and blue, they have in fact a broader sensitivity. Each cone responds to a substantial fraction of the visible spectrum. Assume now that you take the curve which describes the intensity of response of a cone to the visible wavelengths. Furthermore, assume now that you create a colour mixture in which the various wavelengths are blended exactly in the proportions given by the response function of the cone. Assume now that a researcher in colour vision claims that the only valid way of studying colour vision is to use stimuli with patches of these "cone-like" colour mixtures. What would you think of him? Would you not consider him as a complete imbecile? There are so many ongoing studies today in the philosophy or the history of science, dealing again and again with the same historical cases. Here, with the use of Gabor patches in psychophysical stimuli, we have a case of contemporary collective aberration, and this would be worth being discussed in the abovementioned fields.

6.2 Note 2 Autostereograms, and the difficulty to publish them in France

In 1992, before learning of the existence of sirds, I had started writing an article on stereoscopic vision for a French popular science monthly magazine, La Recherche. This article was initiated at the invitation of Olivier Dargouge, a young collaborator of this magazine. I worked very hard on this article, in which I hoped to include many striking illustrations. While the manuscript was under revision, I learnt about autostereograms, and so included at the end of the article an example from Shiro Nakayama (taken page 4 of [67]; this image also appeared -without any mention of its author's name, page 20 of [68]). My article would have introduced the autostereograms in France, where they were totally unknown at that time. The revised version was however rejected. A reviewer's report was produced to legitimate the rejection. The report was written by a complete imbecile, possibly a close co-worker of Michel Imbert. The editor of the journal, Stephane Khemis did not accept any negociation on the article, although it had been revised according to the requests of La Recherche. It seems that there had been a kind of conspiracy, within the editorial board to block the publication of my article. Note also that in November 1992, while my article was under revision, La Recherche had published an article on stereo vision propagating the idiotic thesis that stereoscopic interpretations were based upon vergence [69]. As a result, the first journal to speak of autostereograms in France was a scientific journal for the young: Science et Vie Junior. I had alerted their journalist Jean-Philippe Rémy, and they rushed to publish an imported autostereogram in an October 1993 special issue [70]. They came again on the subject in the November issue [71], including this time my earliest (colour) autostereograms. Fortunately, after the rejection of my stereo article by "La Recherche", Gérard Toulouse, the leader of my group at ENS talked to Philippe Boulanger, Editor in Chief of "Pour la Science", another high level French popular science journal, actually a kind of semi-autonomous clone of Scientific American. I reshaped my article to comply with the length requirements of Pour la Science. The article was accepted, and appeared in March 1994 [72]. In the meantime, I had contacted Nicolas Witkowski, the director of a collection of scientific essays within a very respectable publishing house, Le Seuil. He was immediately enthousiastic with the project of publishing a book of autosterograms, containing a susbstantial scientific introduction to the field of stereo vision. It took him, however quite a long time to convince Claude Cherki, the director of the publishing house, of the interest of publishing such a book. The contract being signed, I had to make a whole book with a wide variety of images in a rather short time, and under very tight technical constraints. It is amazing that I managed to do it. The commercial staff of the publishing house decided to release the book in November 1994 [16]. Two or three months before, France started being invaded with the "Magic Eye" books, translated from the American series launched by Thomas Baccei.

6.3 Note 3. On monocular regions in stereograms and autostereograms

In the early RDS, and in a large number of autostereograms there are often closely repeated vertical bands – a kind of "stuttering". For simplicity, consider the construction of an RDS representing a rectangle with horizontal and vertical sides, above or below background. An unskilled programmer would fill a square or rectangular "background" surface with random texture, then define a square or rectangular region within it, then displace this region once to the left, and once to the right to create the left and the right images of the stereo pair. When the inside region is displaced to the left, and the background texture is not changed, there will be a duplication of the portion of the background texture that has been uncovered, once on the background as in the starting image, and once on the right side of the displaced rectangle. This is the origin of the stuttering effect, and the same happens with autostereograms created by unskilled programmers (see discussion in [23]). In any event, monocular regions create a problem when they occupy a substantial fraction of a stereogram. This often occurs when the stereogram represents a text. Each letter that is represented generates monocular regions on its sides, and if each letter is close to the next, there is no space defined in 3d between the letters. This explains a paradox described and explained in [23]: to see in 3d a text represented in an autostereogram, it is sometimes advantageous to reduce the disparity thus reducing the surface occupied by the monocular regions. Gillam and Borsting claimed that the presence of monocular regions facilitated stereoscopic interpretations, but their conclusion is in doubt, because what they observed could have been a side-effect of another difference between test and control stereograms. Although the Gillam-Borsting idea [25] is seducing, my own results [26, 56] provide counter-examples to their thesis.

6.4 Note 4 The illusory disparity issue

Herbomel and I studied stereograms containing patterns of the Müller-Lyer type, for instance stereograms with say a horizontal shaft on the left with outgoing arrows and a matching horizontal shaft with ingoing arrows on the right. If the usual Müller-Lyer distorsions (illusory lengthening of the shaft with outgoing arrows, illusory shortening of the shaft with ingoing arrows) were feeding the stereoscopic calculations, then one could predict that the shaft would not be perceived as fronto parallel but slanted in a well-defined direction. We found that indeed the shafts were perceived as slanted, but with the opposite sign of that predicted from the illusory disparities. We studied patterns such as those shown in Fig. 9, and presented our results at ECVP 1992 in Pisa [74]. The work was presented as a poster, there was a reasonably small amount of posters at this meeting and they were well located, so the poster was attended by many congressees. One of the first person who came and discussed with us was Mario Zanforlin, and he informed us of Lau's early work on illusory disparities. Younger participants came later and reacted with great excitation. They saw a problem because they knew a young colleague, Andrew Glennerster, who had studied similar patterns and found just the opposite effect. Then came Brian Rogers, the supervisor of Glennerster, he looked at our stimuli and inquired about our experimental conditions and seemed satisfied with the fact that although they and us had obtained opposite results, the experimental conditions were sufficiently dissimilar, so the two pieces of work could be simultaneously correct. He also informed us that the manuscript describing the work was about to be submitted to "Perception". John P. Harris, then managing editor of Perception was at the meeting, so we talked to him and proposed to him to handle our forthcoming article, once Glennerster and Rogers would have published theirs. At this meeting there was also a kind of open forum, called "business meeting". Richard Gregory spoke about the spirit of the journal Perception, saying that he would maintain the journal open to philosophical and historical inquiries. He said, among other things that the journal was not a repository for tedious psychophysical work, and that it would be open to work carried out in the old style.

Back in Paris, Herbomel, who understood German looked into Lau's papers, then into Linschoten's lengthy thesis [50]. Lau had studied figures in which a straight line, crossing radiating lines away from their origin appeared illusorily curved. This is one of Hering's illusions, and in this particular design it was named Hofler's illusion. Lau studied stereograms, involving Hofler's patterns in the left and the right images. The straight lines crossing the radiating lines had unequal illusory curvatures on the left and the right. Lau reported that under stereoscopic viewing, the straight line appeared with illusory in-depth curvature, and the sign of this in-depth curvature agreed with that of the difference between the illusory curvatures of the lines in the left and the right images. However, subsequent work, in particular by Linschoten showed that the effect was not systematic, not all subjects were sensitive to the effect. When they were sensitive, they did not all perceive it in the same direction. Finally Lau was mistaken about the sign of the in-depth effect deduced from the illusory disparities. Herbomel, confident in Gregory's statement of editorial policy started to reinvestigate the subject in the ancient style, taking a few subjects, interviewing them at length, and following their reactions session after session. The subjects were tested extensively on a wide series of Lau's type stimuli plus a series of stimuli which I had designed, in which straight vertical lines were intersecting concentring ellipses that formed a conical surface in depth (e.g., Figure 5, top, in [72]).

The study confirmed the earlier observations: (i) only a fraction (about one half) of the subjects were sensitive to the effect (ii) the direction of the effect could not be predicted from the illusory disparities (iii) an effect was also present under dichoptic presentation, the straight line which was the target of illusory curvature being present in only one of the images of the stereo pair. This work confirmed the existence of perceived illusory in-depth curvature effects, but dismissed illusory disparities as the origin of these effects. An article was written, and submitted after the publication of the Glennerster-Rogers contribution [76]. It contained a substantial historical introduction, plus Herbomel's experiments on illusory in-depth curvature, and my own experiments on various illusory 3D effects with patterns related to Müller-Lyer's illusion or Judd's arrow bisection illusion. The MS received critical reports, that in my opinion should not have led to rejection. Bela Julesz was one of the reviewers, and it seemed that we could answer his requests for improvement. We submitted a revised version which we thought met the criticisms made by the reviewers, and the article was then vetoed by Julesz. Apparently, the fact that he was not sensitive to the effect was sufficient proof, in his eyes, of the non-existence of the effect. I was quite disgusted by this episode, and dropped the subject. Herbomel had been busy, during most of his two years in my lab writing a monumental molecular biology treatise [76], and he had devoted only a small fraction of his time to stereo vision. Furthermore, he had returned to the Pasteur Institute, deciding that after all, his place was in molecular biology. Some of our stimuli were included in various publications, for instance in the 1996 edition of [42], in a review on a stereoscopic mechanisms in a popular science journal [72], and in a book chapter on stereo vision [28b]. In this chapter, I showed that the apparent rotation in depth of Müller-Lyer type patterns could be understood in terms of a "minimal space occupation rule". A 3d shape would be somewhat perceptually rotated so as to minimize its extension in depth. This rule connects the 3d Müller-Lyer effect to more classical gestalt effects, described by Anna Stein [27], a collaborator of Ames.

6.5 Note 5 A reviewer's insane report/editorial frauds

To be documented later

6.6 Note 6 A canonical stereoscopic testing set

The set of 20 rather simple stereograms shown in Figure 13 appears to be remarkably suited to probe individual styles in the processing of stereoscopic information.

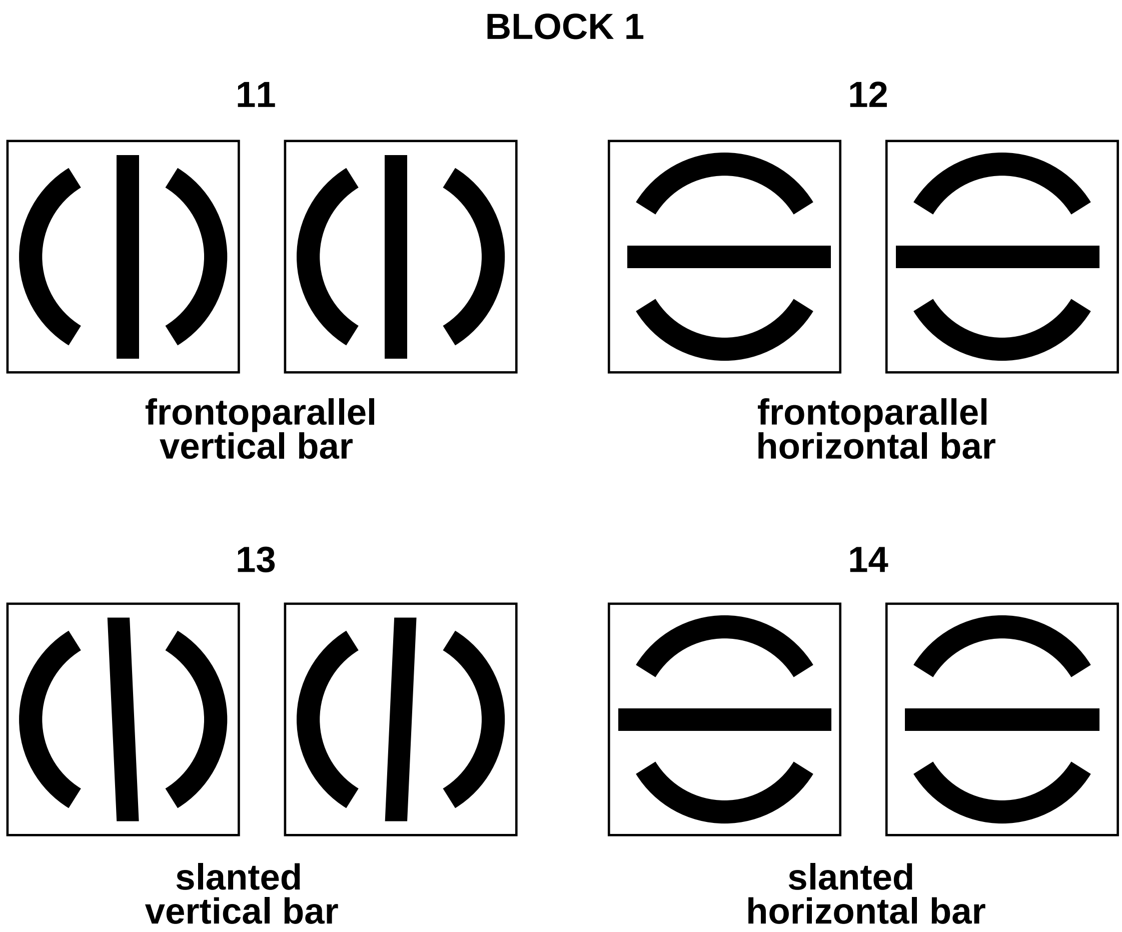

Figure 17: The four stereograms in this block represent a frontoparallel or a slanted rectangle enclosed by two arcs defining a zero disparity background. They were designed to be particularly easy to interpret. Stereograms 11-14, as numbered here, as well as in Figure 13 and in [58] are the same as A1-A4 of Figure 14 and [56]. If stereoscopic processing needs only to assign a depth to the four apexes of the rectangles, then all the stereograms in this block should be of nearly equal difficulty. This is not the case. The subjects have very similar responses to the horizontal (12) and the vertical (11) frontoparallel rectangles. This is expected. There is only position information at the rectangles' four corners. The subjects have clearly greater difficulty with the slanted rectangles (13) and (14) as judged by the increased alternation frequency threshold (see in Figure 14, A3 and A4, compared to A1 and A2). Under the conditions of testing with alternating presentations and intercalated binocular intervals, some subjects differentiate between 13 and 14. We showed in [58] data for one subject who was much more at ease with the slanted vertical rectangle, than with the slanted horizontal one. This can be explained. In the vertical case, the rectangles' projections appear with different orientations on the two views to be matched. This provides a strong cue (orientation disparity) to slant. In the horizontal case, there is no orientation cue to slant — the cue is provided by the length difference of the rectangle's projections along the horizontal. It thus seems that this subject has no difficulty maintaining orientation (or orientation disparity) information in memory, but that for her, length information quickly fades away.

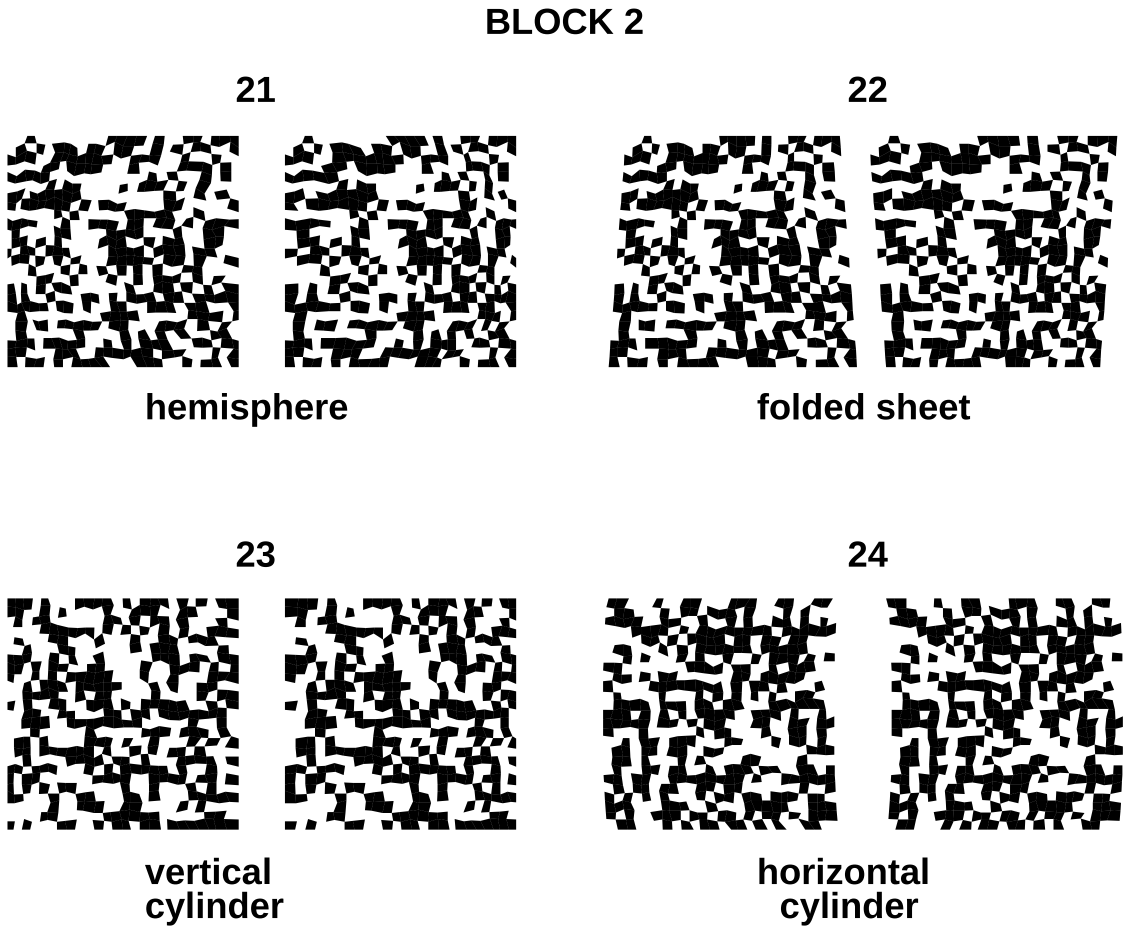

Figure 18: The four stereograms in this block use textured grids that form curved surfaces in three dimensions. Such stereograms were designed to provide a flexible alternative to RDS [11, 23]. They contain contours at various orientations, a feature that may activate a stereoscopic pathway mediated by the orientation edge detectors in V1 and V2. These distorted grid stereograms are usually easier to interpret than RDS. However, they are not suited to represent surfaces with depth discontinuities and they carry compresion cues that can be detcted under careful examination. Stereograms (23) and (24), as numbered here as well as in Figure 13 and [58] are the same as (B3) and (B4) of [56]. Stereogram (21), here and in [58] represents a hemisphere, as B1 of [56], but with a different background. Stereogram (22), here and in [58] involves two planar slanted sections. It has no equivalent in [56]. This stimulus, made of two planar elements, appears to be, for at least one subject in [58] easier to interpret than (21), involving a curved surface. In [56], it was noted that some subjects had difficulties with stimulus (23) that represents a vertical cylinder. In this stimulus, the disparity field does not change along the vertical direction. In contrast, shear disparities are present in the fourth stimulus (24), that represents a horizontal cylinder. This feature is known to facilitate stereoscopic interpretations [20].

BLOCK 3

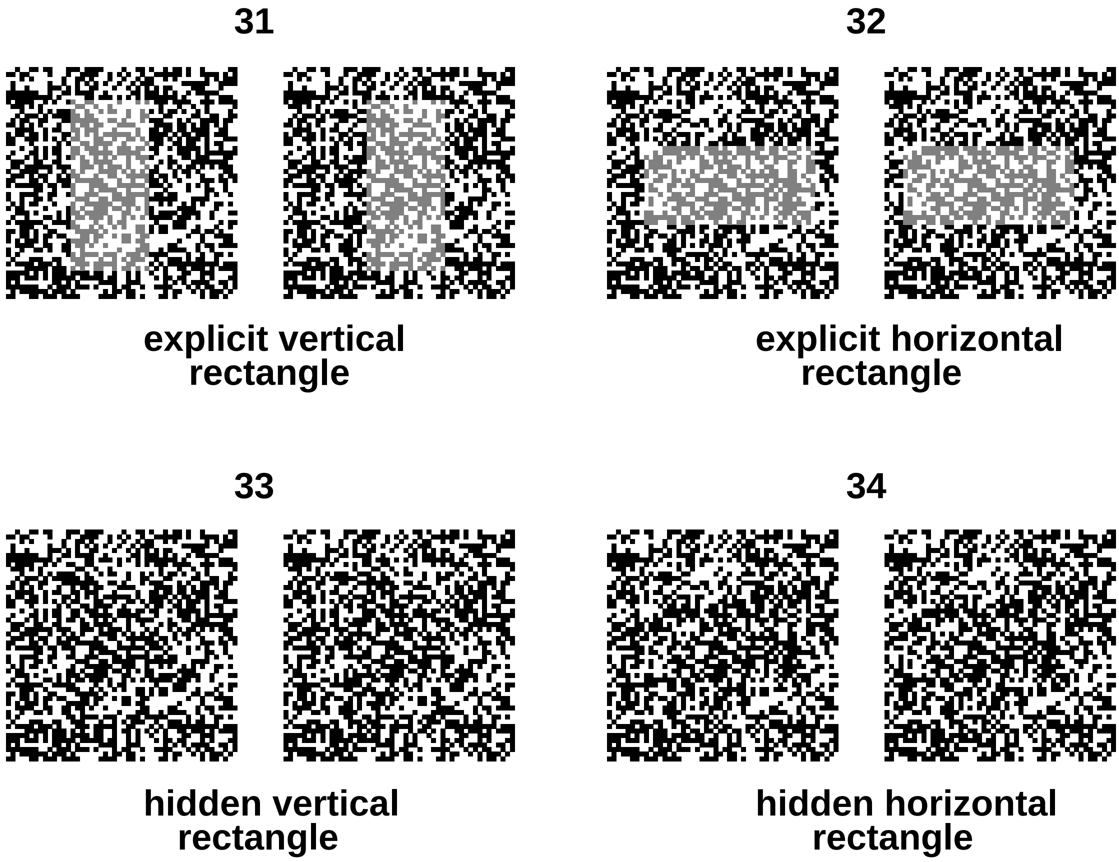

Figure 19: Here, (33) and (34] are classical Julesz type RDS, made by matrices of black or white squares drawn at random. They represent a vertical (33) or a horizontal (34) rectangle above or below background. In (31) and (32) the rectangles are represented explicitly by turning their black cells into grey cells. They serve as controls for (33) and (34). Here, stereograms (31-34) as well as in Figure 13 and [58] are the same as (C1-C4) of [56]. As expected, the explicit stereograms (31) and (32) are much easier to interpret than the camouflaged ones (33) and (34).

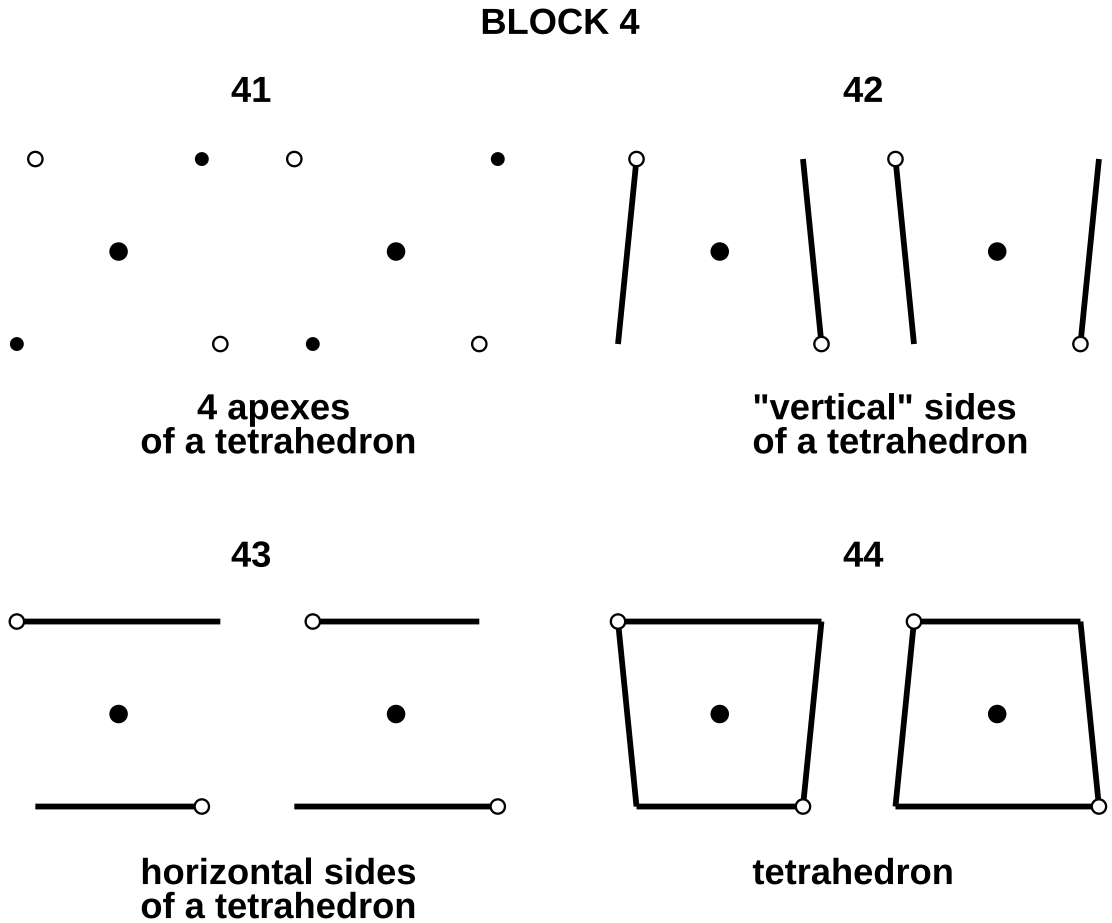

Figure 20: In this block, a set of 5 points occupy exactly the same positions in three-dimensional space in all four stereograms. There is a central disk that can be used as a reference and four circles at the apexes of a tetrahedron. The stereograms differ only in how the four apexes are connected. Stereograms (41-44) here and in Figure 13 as well, and in [58] are the same as (D1-D4) in Figure 14 and [56]). Small differences in alternation frequency thresholds were detcted between the stimuli in [56]. For one subject in [58], the results concerning the stimuli represented with a pair of horizontal (43) or vertical (42) edges are entirely in line with those shown for Block 1, in the case of slanted horizontal or vertical rectangles. Because the four apexes of the tetrahedrons are exactly the same, the implication is that point disparity information had been neglected in the horizontal case (43), the segment length attributes taking precedence.

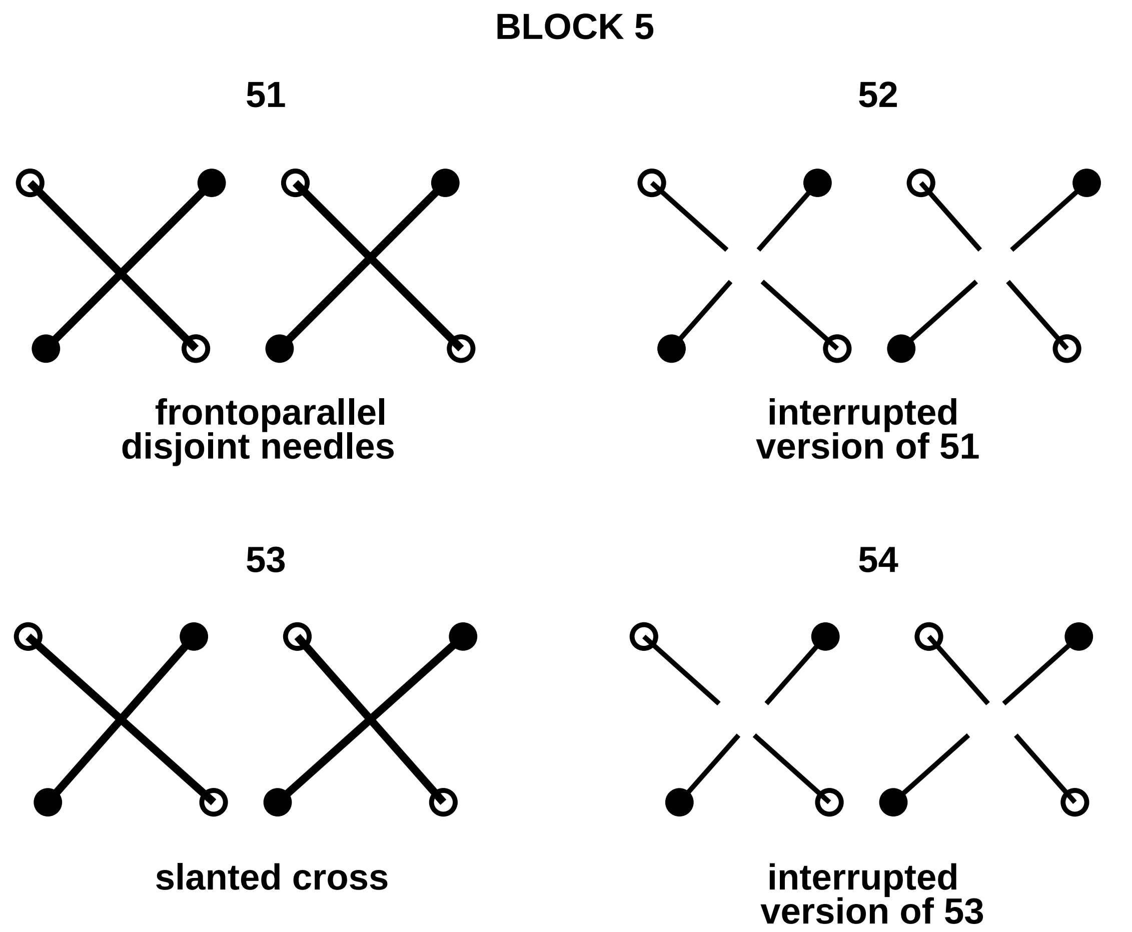

Figure 21: Here the stimuli are frontoparallel or slanted crosses, as well as their interrupted versions. The interrupted versions involve four segments in each figure instead of two, so there is more information related to the segments terminators. The two frontoparallel needles of (51) are at different depths. Therefore, although the four endpoints do match in the left and right figures, the intersections of the two segments in the two projections do not correspond to a real point in space, and they have a vertical disparity in the projections. We are thus exploring a blind spot of the current stereoscopic doctrine. The (51-54) set of stereograms also used in [58] was modified with respect to the earlier (E1-E4) set, used in [56]. In [58] the fronto-parallel needles were always easier to interpret than their uninterrupted counterparts, over the whole range of monocular and binocular intervals. On the other hand, the true slanted cross and its interrupted version were interpreted with about equal ease.

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