

Alternation frequency thresholds for stereopsis as a technique for exploring stereoscopic difficulties

Svetlana Rychkova[¶]

Moscow City Psychological and Pedagogical University, 29 Sretenka St, Moscow 127051, Russia;
e-mail: rych.sv@mail.ru

Jacques Ninio

Laboratoire de Physique Statistique, UMR 8550 of the CNRS associated with UPMC Université Paris 06 and Université Paris Diderot, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris cedex 05, France;
e-mail: jacques.ninio@lps.ens.fr

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Abstract. When stereoscopic images are presented alternately to the two eyes, stereopsis occurs at $F \geq 1$ Hz full-cycle frequencies for very simple stimuli, and $F \geq 3$ Hz full-cycle frequencies for random-dot stereograms (eg Ludwig I, Pieper W, Lachnit H, 2007 “Temporal integration of monocular images separated in time: stereopsis, stereoacuity, and binocular luster” *Perception & Psychophysics* **69** 92–102). Using twenty different stereograms presented through liquid crystal shutters, we studied the transition to stereopsis with fifteen 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 two to four 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 three-dimensional 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.

Keywords: stereopsis, temporal integration, slant, shear disparities, processing times, stereoscopic memory.

1 Introduction

1.1 Origin of the work

In clinical ophthalmology a classical treatment for reeducating patients with a lazy (amblyopic) eye uses pairs of images that can be fused. The idea is to present the images in alternation to the two eyes, with a specialized apparatus called a synoptophore. Typically, at a 2 Hz alternation frequency, each image is presented for 250 ms, 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. Up to 4 Hz the patient usually perceives two alternating images. Above 4 Hz the lazy eye’s image is perceived with a lag, and at around 6–7 Hz this image completely disappears (SR; data not shown). With training, the patient becomes able to perceive the two images at increasingly high alternation frequencies, until he or she hopefully succeeds in fusing the two images.

One of us (SR) was initially interested in monitoring the progress made by strabismic patients in the course of orthoptic treatments, and added stereoscopic tests to the commonly

[¶] Authors’ contributions to this work: SR performed the experimental work; JN handled the statistics and the graphics; SR and JN interpreted the results and wrote the paper.

used fusion tests. It was soon revealed that patients who were able to interpret a certain stereoscopic pair in three dimensions 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 were found between quite simple stereograms—for instance, between the first two and the last two stereograms in [figure 1](#), which had been designed for strabismic patients with inconstant squint (Rychkova and Ninio 2009). Subsequently, differences in 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 (see section 1.2 below), here our criterion seemed to be exquisitely sensitive to subtle differences between simple related stereograms.

In this paper we report our observations on alternating frequency thresholds involving a set of twenty different stereograms, organized in five blocks of four images each. The first three blocks had already been used in our previous study, and were found to provide a nicely graded range of difficulties (Rychkova and Ninio 2009). The stereograms that were perceived with the greatest difficulty under static viewing conditions in our earlier work turned out to be those that required the highest alternation frequencies in the present work. The last two blocks of images were included here to extend our exploration of stereograms based on very simple patterns. While it is tempting to advance, as a first approximation, that processing latencies in static displays measure the same properties as frequency thresholds in alternating presentations (see sections 1.2 and 1.3 below), this is an oversimplification (section 1.4 below). As will be stressed in section 4.3 of the discussion, our results on alternation frequency thresholds require a refining of the common conceptions of memory's role in stereoscopic processing.

1.2 Processing times in simultaneous presentations

So far, most comparative studies on stereoscopic difficulties in stereograms have used static stimuli that required large latencies to be interpreted in depth. For instance, in their study of slant perception and the primitives of stereopsis, Gillam et al (1988) used random-dot stereograms (RDS) and found response times ranging from about 7 s for twists about a vertical or a horizontal axis to 35–38 s for whole-field slants or hinges around a vertical axis. In their comparative studies on linear textures, for stereograms representing five hemiellipsoids, Ninio and Herlin (1988) found response times in the 10 s to 30 s range, depending on the texture. Interpretation times of < 3 s are more commonly reported, even on the first presentation of a RDS to naive subjects (Bradshaw et al 1995). Learning effects are important (eg Frisby and Clatworthy 1975; Ramachandran 1976). While it took about 1.5 min for an average subject to interpret the famous 'hyperbolic paraboloid' of Julesz (1971) the first time it was seen, the perception time was reduced to just 1–2 s after six or seven exposures to the same pattern (Ramachandran 1976).

Other experiments provide very different time scales for stereoscopic processing. Using an indirect argument, Julesz (1964) proposed a 50 ms processing time for an RDS. In more recent work, with dynamic RDS, values in the 130–290 ms range or the 50–80 ms range have been proposed, depending on the velocity of the moving patterns studied (Rosenzweig et al 2002; Wolf et al 1996). It would seem that, when a simple surface (a rectangle) is encoded in an RDS and the subjects merely have to state whether the surface is above or below background, the response time can be 100 ms or less, while, when a more complex surface must be perceived, appreciably larger response times are found. We wish to stress here a common but perhaps frail observation—that stereoscopic processing would be *slower* when stereograms use *larger disparities* (eg Goriyu and Kikuchi 1971).

1.3 Temporal processing in alternative presentations

Stereopsis can occur even when the two images are presented with a delay between the two eyes (Exner 1875). More precisely, Ogle (1963) found that exposure times of 18 ms could be separated by delay times of 100 ms. By using cyclic presentations (left eye exposure, delay, right image exposure, delay) he was able to study the time constraints in a flexible manner. He found that, when exposing the subjects to these repeated cycles for a total of one second, the delay time could be increased by about 50 ms at constant exposure times. The subject, he reported, did not need more than four or five cycles to develop a depth interpretation at 100 ms exposure times and 70 ms void interval. Thereafter, many studies using cyclic alternative presentations were carried out, focusing on the alternation frequency (the reciprocal of the total cycle duration) at which stereopsis occurred. For instance, Ludwig et al (2007) observed stereopsis at 1 Hz for stimuli composed of three vertical rods. With RDS they could not observe stereopsis below 3 Hz, while binocular luster could be observed only above 10 Hz. In agreement with Ogle (1963) or Herzau (1976), these authors found that *smaller disparities* require *higher* alternation frequencies.

1.4 Do latencies (in static presentations) and frequencies (in alternative presentations) measure the same properties?

It seems obvious that stereograms presenting difficulties for stereoscopic processing should take a long time to be interpreted in three dimensions. However, there would also be cases in which processing takes a long time because the establishment of a complete accurate interpretation is tedious, rather than caused by a difficult stereoscopic problem. In the case of alternating presentations, one is tempted to assume that the higher the required alternation frequency, the more difficult the underlying stereoscopic processing problem. The distinction between very simple line stimuli that may require only 1 Hz and RDSs that require 3 Hz or more point in the direction of this assumption as do the detailed results presented in this paper.

It is commonly argued (see Howard and Rogers 1997, page 186) that stereoscopic processing can occur under the alternating presentation modality because “signals from one eye persist long enough to interact with those from the other.” Note, however, that the three-dimensional interpretation builds up over several successive cycles. Therefore, what is typical of stereograms that require high alternation frequencies is the need for frequent *updating* of two-dimensional information—a notion that does not coincide with the common interpretation of latencies for statically presented stereograms just stated. This consideration draws attention to the potential of the alternation frequency threshold technique for complementing other methods customarily used for studying stereoscopic processing. The goal of this paper is to demonstrate this potential in an exploratory study using a wide range of different stereograms.

2 Materials and methods

2.1 Subjects

The twenty-seven subjects in our study (twelve males, fifteen females; average age = 27 years) had normal vision (1.0/1.0 acuities) in both eyes without correction (nineteen subjects) or after correction with refractive lenses (eight subjects). All had normal responses to standard clinical tests for binocular vision (Worth, Lang, and Fly tests).

2.2 Apparatus

A first part of the work, involving twelve subjects, was performed with a synoptophore, an apparatus classically used in clinical ophthalmology (see the supplementary material, part S1). We concentrate here on the data acquired on fifteen other subjects, using liquid crystal shutters designed by P Chaumont (Chaumont et al 1982), and produced in small series

in Russia. These shutters were designed for orthoptic work and are used for developing fusion in strabismic children (Rychkova et al 2001). A recent model was used, in which exposure times could be varied from 10 ms to 5 s in steps of 10 ms. The field of view is opalescent for the eye that does not receive an image. A normal cycle with these shutters involves alternative exposures to the two eyes, separated by *binocular* exposure intervals. In this work the binocular interval was set to its present minimum value of 10 ms. We also wrote an interactive graphics program for presenting our stereograms as anaglyphs on a computer screen, and running alternative presentation experiments. The source code and the instruction guide for this program are supplied in the supplementary material, parts S3 and S4.

2.3 Stimuli

The stereograms used for the tests were designed to probe various aspects of stereoscopic vision. They were grouped into five blocks, each block containing four stereograms representing different objects. The stereograms are shown in their standard version in figures 1–5. These were complemented by some variants with smaller or higher disparities. Furthermore, by exchanging the left and right images of each stereogram, variants with opposite depth signs were systematically studied.

For the LCD experiments, each image was printed with a width of 2.5 cm then pasted on a plastic holder mounted on a graduated slide. The subject's eyes were 25 cm away from the stimuli. The subtended angle was about 5.7 deg. The separation between the centres of the two images was chosen between 58 mm and 63 mm to suit best the natural viewing mode of the subject at the chosen viewing distance (25 cm). The two images were physically separated by cardboard affixed perpendicularly to the plane of the images so that each eye viewed a single image. Maximum disparities across the range of stereograms were roughly comparable but this factor was not precisely controlled in this exploratory study. The reader can judge their relative sizes by fusing the stereograms shown in the various figures reported here.

2.4 Procedures

All subjects first practised with an easy stereogram representing a small central disk in front or behind a larger disk (Rychkova and Ninio 2009, figure 2e). The instructions to subjects are given below when we describe the typical sequence of percepts from alternating left–right stereo image presentations and the criterion that subjects were required to use in making their threshold judgments. They were then tested on the twenty stereograms in both their standard form and their inverted depth form. The presentation order was randomized as follows: the stereograms were presented block by block, and the order of presentation of the blocks was drawn at random. Within each block the order of presentation of the four stereograms in the block was drawn at random, and the two depth forms of each stereogram were presented in random order. The alternation frequencies were varied in ascending mode from 2 Hz to 20 Hz until stable stereopsis was reached, and in descending mode until the two images were seen monocularly in alternation. For each stimulus both the ascending and the descending modes were used, in random order.

In both the synoptophore and the LCD work, each subject went through three complete series of tests, with different presentation orders, over three to six different days. At each frequency change there was a pause of a few seconds. To avoid visual fatigue the tests were divided into several 30–40 min sessions, interrupted by pauses of about 30 min to 60 min. In the case of the synoptophore studies, the tests included variants with lower or higher disparities of each of the four stereograms in blocks 1 and 3 (see the supplementary material).

2.5 Statistics

For each stereogram in this study and each subject we take the threshold frequency averaged over the twelve tests (ascending or descending frequency mode, normal or inverted depth, each condition tested three times) as a single result. For each stereogram we then have fifteen threshold frequencies—that is, one for each subject. The means (m) and standard deviations (sd) within this set of fifteen values are shown in figures 1–5. Assuming normally distributed variables (which is not strictly the case), the 95% confidence interval (see, for instance, Dixon and Massey 1957) corresponds to the mean \pm sd multiplied by 1.96 and divided by \sqrt{N} , the square root of the number of measures. Here, $N = 15$ when the mean is taken over a single stereogram, or kN when the mean is taken over k stereograms. For $N = 15$, the factor $1.96/\sqrt{N}$ equals 0.506, and the corresponding factor for the 99% confidence interval ($2.85/\sqrt{N}$) equals 0.666. We will therefore consider that a difference between two means taken over fifteen values is significant to the 95% level when it is larger than half the sum of the standard deviations. Similarly, the same difference is significant to the 99% level when it is larger than $2/3$ of the sum of the standard deviations. A referee has suggested that the design of our study makes it open to a repeated-measures statistical analysis as data were collected for all conditions from each subject. We prefer the approach we have just outlined which, we note, happens to be a more cautious approach by assuming that data collected across conditions from different subjects are independent rather than correlated in some ill-defined way.

3 Results

3.1 General observations

When stereograms are presented at low alternation frequencies, the subject perceives the left and the right images in alternation. When the alternation frequency increases, there is a point at which the two images fuse, and this can happen in two ways. A subject may perceive a flickering image which seems intermediate between the left and right images or he or she may experience a form of unstable stereopsis: the stereogram is interpreted in three dimensions, but the relative locations of parts of the image are alternately those of the left image and those of the right image, giving an apparent rocking motion effect. As the alternation frequency is raised, the apparent motion stops and the subject perceives a three-dimensional image (flickering or stable) with stable geometry. The measurements we report here relate to this transition to or from stable stereopsis. Specifically, subjects were instructed to state when stable stereopsis became established, and the threshold was the frequency at which this judgment occurred.

In these experiments, for each stereogram and each subject we collected twelve transition frequencies (ascending or descending frequency modes, standard or inverted disparities; three determinations for each of the four cases). The dispersion between the twelve values was rather small: training effects were minimal, and threshold frequencies slightly increased as disparities were reduced (for details, see the supplementary material, part S2). We will therefore discuss the averages of the twelve frequencies, first block by block (section 3.2), then in a more synthetic fashion (section 3.3).

In response to the comments of a referee, we wish to make clear that our primary focus in the discussion that follows is to argue that the results reveal the *potential* of the alternating frequency threshold technique for exploring what we will call for short ‘stereoscopic difficulty’. Our stimuli varied on a number of dimensions—the nature of the three-dimensional surface portrayed, the complexity of the texture carrying disparity cues, the presence or absence of monocular regions, etc. Hence we do not try to draw definitive conclusions from our study about what stimulus factors may or may not have caused the observed variations in alternation frequency thresholds for our various stimulus conditions.

Rather, we use the results discursively to debate possible factors that may have been picked up by the alternating frequency threshold technique. We hope others will use our study as a starting point for their own use of this technique, using precisely controlled stimulus variations to suit their own experimental objectives.

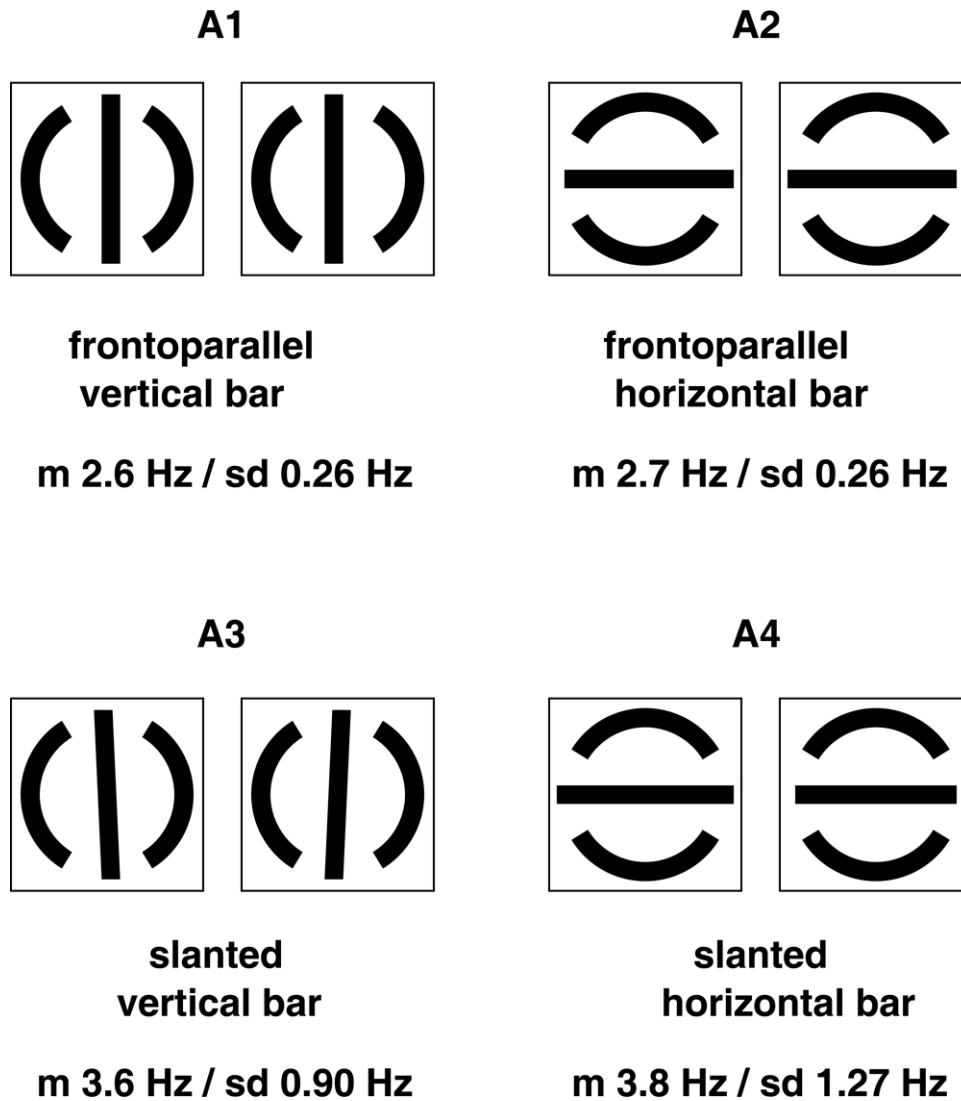


Figure 1. The four stereograms of block A represent a frontoparallel or a slanted rectangle enclosed by two arcs defining a zero disparity background. Each stereogram was presented as shown here, as well as in the inverted depth variant, in which the left and the right images were switched. The average threshold frequencies and standard deviations for the transition to stable stereopsis are given in Hz below each figure.

3.2 Results per block

Block A. These stereograms (figure 1) were designed to be particularly easy to interpret. Each pair contains three conspicuous shapes that are planar in three dimension: two thick arcs that form a zero disparity reference frame, and one rectangle. 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. The ‘vertical’ rectangle in stereogram A3 is in fact slanted about a horizontal axis: this can be deduced in monocular vision from the different orientations of the rectangles in the left and right images. The horizontal rectangle

in stereogram A4 is in fact slanted about a vertical axis, and this can be deduced in monocular vision from the length difference between the rectangles in the left and the right images. In stereograms A1 and A2 the rectangles are frontoparallel: these stereograms can be taken as controls for A3 and A4.

The four stereograms were used in our previous study on paradoxical fusion with a single eye (Rychkova and Ninio 2009). In this case there were clear-cut results. Most subjects (twenty six to twenty eight out of thirty) could detect depth in the case of the frontoparallel rectangles. About half (fourteen to seventeen out of thirty) could detect depth in the case of the slanted rectangles, but the slanted aspect was reported by only seven subjects and, even with these seven, not systematically.

Here, with our subjects (who all had normal vision), we observe a difference in average threshold frequencies between the frontoparallel rectangles (2.6 Hz and 2.7 Hz) and the slanted ones (3.6 Hz and 3.8 Hz). Before reaching the frequency at which they perceived the slant in A3 and A4, a few subjects perceived these rectangles as frontoparallel. The difference in threshold frequencies between the frontoparallel rectangles (A1 and A2) and the slanted ones (A3 and A4) is significant at the 99% confidence level.

Using complex stereograms of the random-dot kind, Gillam et al (1988) found a very significant difference between the latency for a hinge about a horizontal axis (13.8 s) and that for a hinge around a vertical axis (37.7 s). We find a very slight effect in the same direction with our simplified stimuli, but in our case it is not statistically significant.

Block B. The four stereograms in this block (see figure 2) use textured grids that form curved surfaces in three dimensions. Such stereograms were designed to provide a flexible alternative for RDS (Ninio 1981, 2007). They contain contours at all orientations, a feature that may activate a stereoscopic pathway mediated by the oriented edge detectors in V1 and V2. These distorted grid stereograms are usually easier to see than RDS. However, they are not suited to represent surfaces with depth discontinuities (by which we mean step changes in depth), and they carry compression cues that can be detected under careful examination. Stereogram B1 represents a hemisphere, and in monocular vision a reasonable guess can be made about its three-dimensional shape because the circular contour matches the rim of the hemisphere. Stereogram B2 also represents a hemisphere but with a convexity reversal added in the centre. A subject who perceives the global spherical shape may still fail to detect the slight depression at the centre. B2 therefore requires more precision in the subject's stereoscopic reconstruction than B1. Stereogram B3 represents a cylinder with a vertical axis, flanked with zero disparity extensions on both sides. These extensions were incorporated to create clear disparity signals at the edges of the cylinder. Stereogram B4 represents a cylinder with a horizontal axis. The cylinder's contours may provide clues to its shape, and the stereogram should be easy to interpret in depth, due to its simple shear disparity pattern.

The four stereograms in this series were used in our previous work (Rychkova and Ninio 2009). All patients could see a convex or concave shape in the B1 hemisphere, but only half of them (thirteen to fifteen out of twenty four) could detect convexity or concavity in the three other stimuli.

In the present work, like in our previous work, B1 emerges as the easiest stimulus in the block (3.3 Hz average threshold frequency). The other stimuli are well separated. Stimulus B2, which requires precise stereopsis, needed an 8.4 Hz threshold frequency. The vertical cylinder in B3 needed 6.7 Hz, and the horizontal cylinder in B4 needed 5.7 Hz. The difference in threshold frequencies between B3 and B4 is not significant at the 95% confidence level; all other pairwise comparisons are significant at the 99% confidence level.

There is no new theoretical observation to derive from this set, but there is a practical one: the distorted grid textures appear suitable for generating significant differences in threshold frequencies between stimuli that represent different shapes.

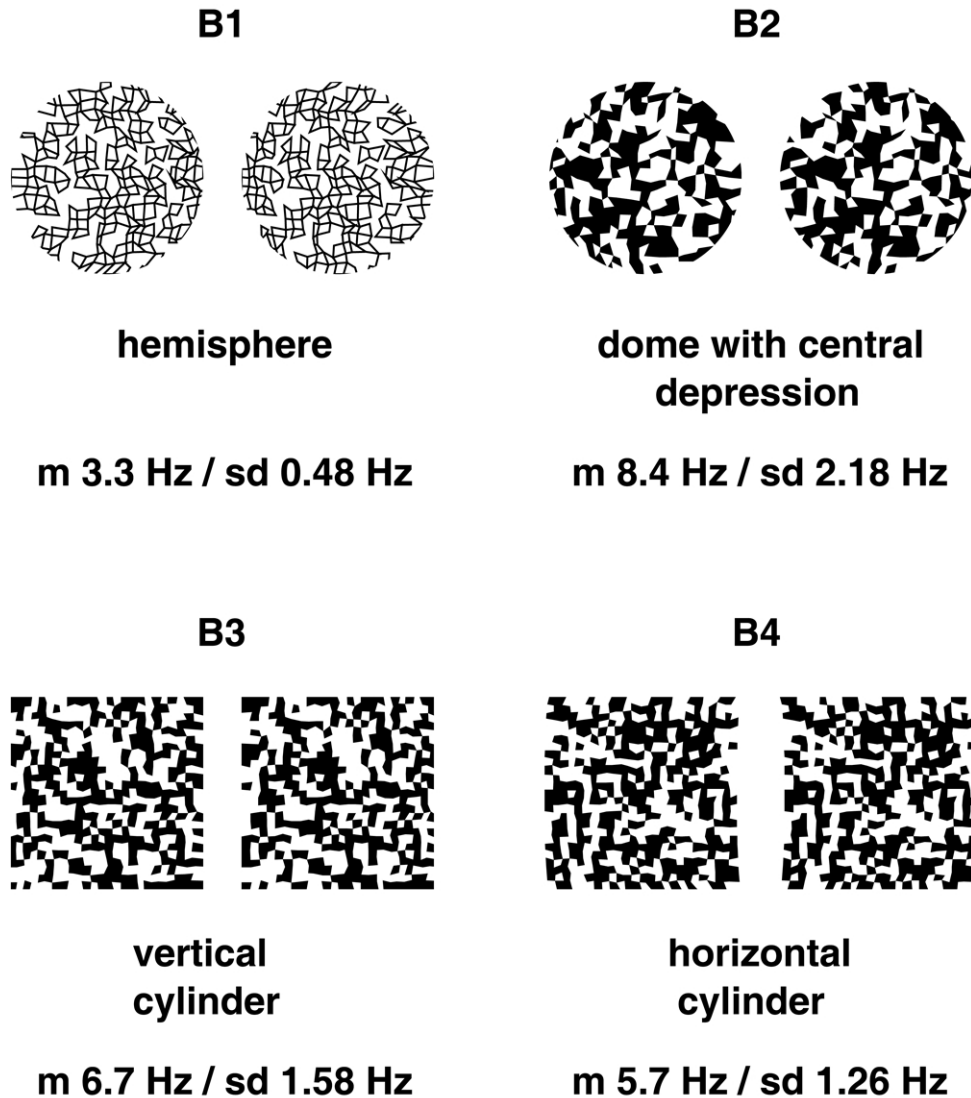


Figure 2. The four stereograms of block B represent continuous surfaces defined by a distorted grid texture. As in figure 1, threshold frequencies and standard deviations are shown.

Block C. Here, we have a more common class of stereograms (figure 3). C3 and C4 are Julesz-type stereograms—also commonly called RDS made by matrices of black or white squares drawn at random. Disparity takes discrete values determined by the side of an elementary square. Such stereograms are suitable for representing frontoparallel surfaces above or below background. With respect to monocular inspection, camouflaging is perfect (unless, due to unskilful programming, some monocular regions are revealed by internal repeats), but the shapes can easily be revealed using a physical procedure (representing the images on transparent sheets, and sliding one sheet horizontally over the other). These stereograms essentially test the capacity of stereopsis to defeat camouflage. C4 represents a horizontal and C3 a vertical rectangle, above or below background. Stereograms C1 and C2, in which horizontal or vertical rectangles are represented explicitly by turning the black cells into grey cells, serve as controls for C3 and C4.

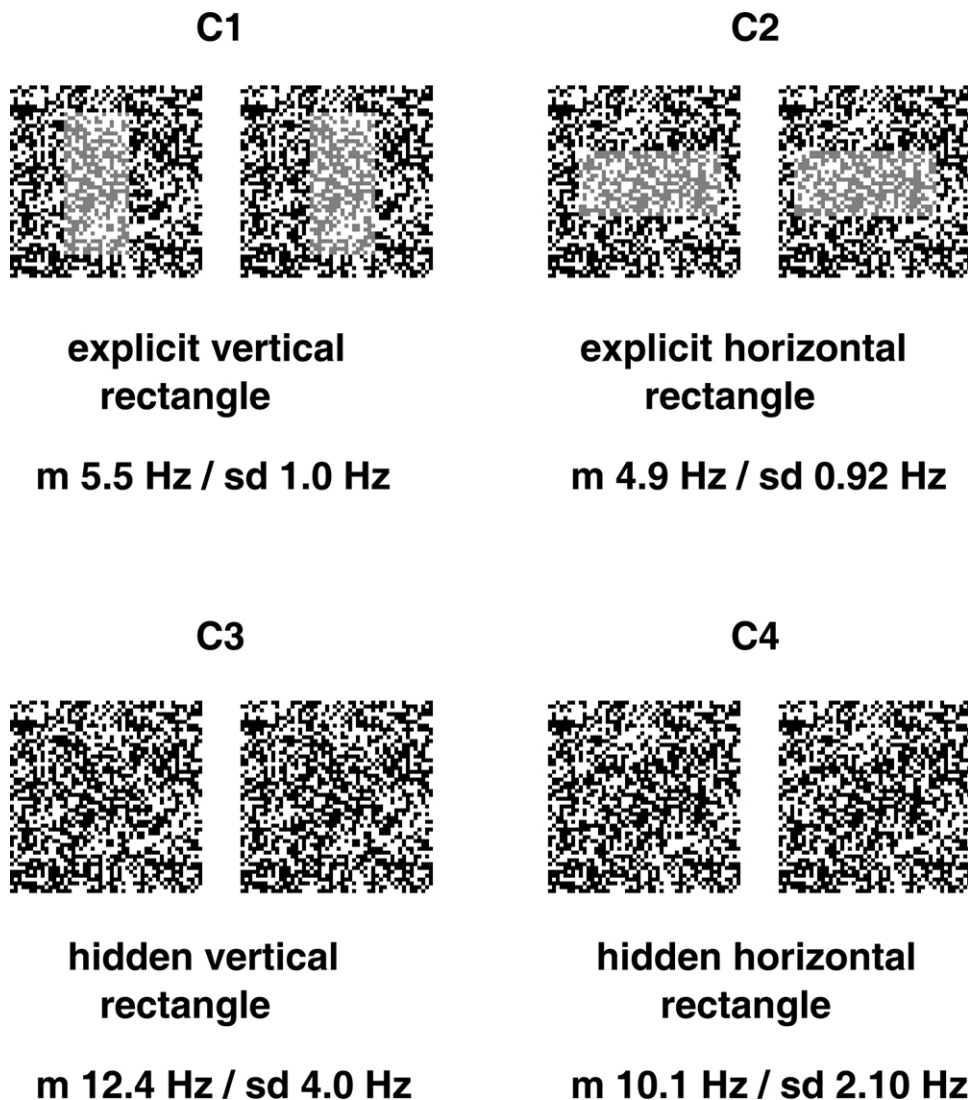


Figure 3. The four stereograms of block C represent a frontoparallel rectangle above or below background, using Julesz-type random square textures. C3 and C4 are camouflaged, using one of Julesz's RDS styles. The rectangles are made explicit in C1 and C2.

The four stereograms of this block were also used in our previous study, where they gave clear-cut results: only two out of twenty-four subjects could perceive depth with the camouflaged stereograms C3 and C4, while twenty-three out of twenty-four subjects could see depth with the explicit stereograms C1 and C2. In the present study our subjects with normal vision passed successfully the Lang's RDS test (section 2.1), yet their threshold frequencies were quite high with the camouflaged stereograms C3 and C4 (12.4 Hz and 10.1 Hz, respectively). The threshold frequencies were lower with the explicit stereograms C1 and C2 (5.6 Hz and 4.9 Hz, respectively). The difference in measured threshold for stereopsis between the horizontal and the vertical camouflaged rectangles is not significant at the 95% confidence level. The difference between the camouflaged and the explicit rectangles is significant at the 99% confidence level.

Block D. In blocks A, B, and C the stereograms represented different shapes, but there was some uniformity in visual appearance. In block D a set of five points occupy exactly the same positions in three-dimensional space in all four stereograms (figure 4). There is a central point—actually, a small black disk, centrally located—that can be used as a reference,

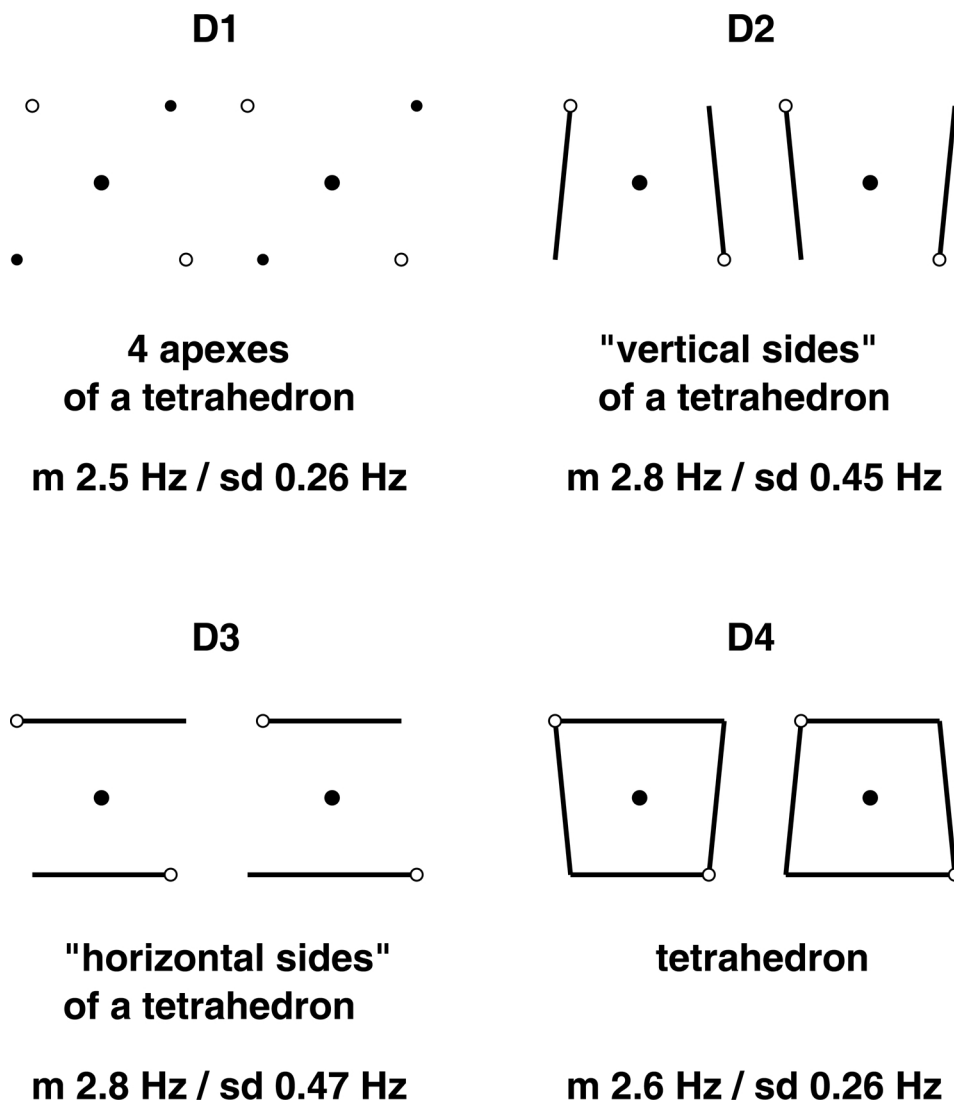


Figure 4. The four stereograms of block D contain four peripheral elements at the apexes of a tetrahedron, and a central reference element. The stereograms differ in the way the peripheral elements are connected.

and four circles at the apexes of a tetrahedron. The stereograms differ only in how the four apexes are connected. In D1 the apexes are unconnected, in D2 they are connected 2 by 2 with horizontal segments, in D3 they are connected 2 by 2 with vertical segments, and in D4 they are connected with both horizontal and vertical segments. This is similar in spirit to an earlier work in which textures were constructed by identical sets of points connected in different ways (Herbomel and Ninio 1993). In the present work all four stereograms turned out to be very easy to interpret (from 2.5–2.6 Hz for D1 and D4 to 2.8 Hz for D2 and D3).

Block E. The four stereograms in this series explore a blind spot of the current stereoscopic doctrine. The important stereogram is E3; the others serve as controls (figure 5). Stereogram E3 represents two slanted needles that cross in projection but do not touch in three dimensions. Upon monocular inspection, the fact that the needles do not touch can be deduced from the fact the crossing points on the left and on the right are at different horizontal levels, implying that these points should not be matched in the three-dimensional interpretation. The fact that the needles composing the apparent crosses are slanted is revealed, under monocular inspection, by their orientation disparity. According to the current

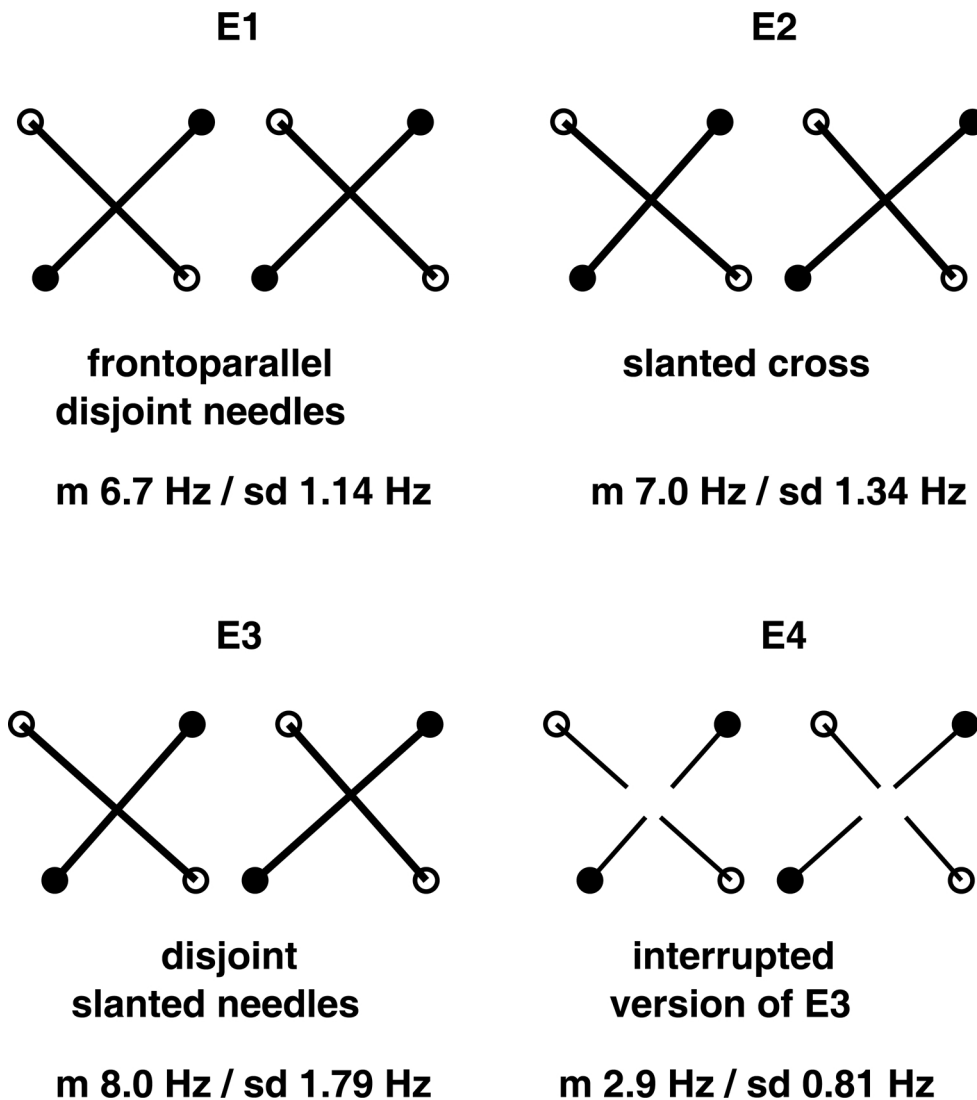


Figure 5. Stereograms E1 – E3 of block E contain crosses in two dimensions that define either a slanted cross or a pair of needles at different depths. E4 is an interrupted version of E3.

physiological doctrine about edge detection by neurons in V2, isolated needles should be appropriate stimuli for these neurons, but crosses should not. However, how V2 neurons should respond to needles that exist as needles only in the three-dimensional interpretation, but not in the two-dimensional stimuli, is not known. In E4 the central part of the E3 crosses were erased so that the images in E4 contain four smaller needles that do not intersect in two dimensions. In E2 there is a true slanted cross. In E1, like in E3, the segments that cross in two dimensions do not touch in three dimensions, but, while E3's needles are slanted, E1's needles are frontoparallel. The four stereograms have quite different thresholds for stereopsis. While a high 8 Hz frequency is needed for E3, 2.9 Hz are enough for the interrupted E4 variant. The real slanted cross (E2) needs a slightly higher frequency (7.0 Hz) than the dissociated frontoparallel needles E1 (6.7 Hz). Comparing E3 with E1 and E2, there is a penalty for slant, which affects E3 and E2 but not E1, and a penalty for separation in three dimensions which affects E3 and E1 but not E2. Both penalties would be at play in E3, making E3 one of the most difficult stereograms in the whole work in spite of its extreme simplicity in the two-dimensional projections. Statistically, the pairwise differences between E1, E2, and E3 are

not significant at the 95% confidence level, but all differences with E4 are significant at the 99% confidence level.

3.3 Across-block comparisons

The results for all five blocks are recapitulated in [figure 6](#). The stereograms can be organized into six classes according to their associated threshold frequencies ([figure 3](#)).

Class 1 contains the apparently easiest stereograms, with associated frequencies below 3 Hz. These stereograms represent explicit frontoparallel bars (A1, A2), a tetrahedron defined by four isolated or connected apexes (D1–D4) or four small isolated slanted needles (E4).

Class 2 contains three stereograms with associated frequencies between 3 Hz and 4 Hz. Stereograms A3 and A4 are slanted versions of A1 and A2. Stereogram B1 represents a textured curved surface. The matched circular contours give a strong cue about the three-dimensional shape.

Class 3 contains two stereograms that represent rectangles (C1 and C2), but this time three-dimensional interpretation requires handling monocular regions, either by extracting them or by adjoining them to the sides of the rectangles [as documented for instance by Collett (1985); recent review in Harris and Wilcox (2009)]. This factor may have contributed to the associated threshold frequencies being as high as around 5 Hz. The camouflaged stereogram B4 falls in the same frequency range.

In class 4 (6–7 Hz threshold frequency) we find two new types of difficulties. In stereogram E1 we have two frontoparallel needles that need to be separated in depth. The problem differs from that of extracting monocular regions, and may relate more to transparency issues. In stereogram B3, which represents a textured cylinder with a vertical axis, the disparity field repeats itself all along the vertical axis (we call this feature ‘vertical degeneracy’), so there are no shear disparities.

In class 5 (7–9 Hz threshold frequencies), the case of stereogram E3, representing two slanted needles forming an apparent cross, but separated in depth, is straightforward. The 1.3 Hz increase in frequency with respect to the unslanted counterpart E1 is in the same range as that observed between slanted and unslanted rectangles (A3 and A4 versus A1 and A2; average difference 0.9 Hz). Stereogram B2, whose ‘dimple in the sphere’ requires a detailed perception of shape, also falls into this frequency range.

Finally, the two stereograms C3 and C4 with average threshold frequencies of > 9 Hz take their place in class 6. These are RDS in the style of Julesz (1971), in which the extraction of monocular regions and the camouflaging difficulties are combined.

The only stimulus that does not find a natural place in this classification is the slanted cross E2. Its threshold frequency (7 Hz) is surprisingly high.

Statistically, the differences between threshold frequencies are significant at the 95% confidence level for the class 4 versus class 3 or class 5 comparisons, and at the 99% confidence level for all other comparisons.

In drawing up the summary table in [figure 6](#), it is useful to restate here the caveat made at the outset that we have used a wide variety of stereograms that differ on several dimensions simultaneously. Hence we are not proposing firm conclusions and instead offer the comments above as simply suggestive and, we hope, of interest to those considering the multifaceted concept of ‘stereoscopic difficulty’.

While the frequency ranges varied considerably from subject to subject (supplementary material, [figure S1](#)), the ranking of their responses into classes 1–6 showed little variability. Indeed, the order was strictly preserved in eleven out of the fifteen LCD subjects, and preserved with a single misplacement in the remaining four.

1	2	3	4	5	6
minimal (A1) 2.57 (A2) 2.73 (D1) 2.54 (D2) 2.82 (D3) 2.79 (D4) 2.58 ----- (E4) 2.87	slant (A3) 3.55 (A4) 3.75 ----- curvature (B1) 3.33	extraction (C1) 5.55 (C2) 4.93 ----- curvature + camouflage (B4) 5.69	depth separation (E1) 6.68 ----- curvature + camouflage +vertical degeneracy (B3) 6.66	slant + depth separation (E3) 8.01 ----- shape complexities (B2) 8.42	camouflage + extraction (RDS) (C4) 10.10 (C3) 12.38
3 Hz	4 Hz	6 Hz	7 Hz	9 Hz	
m 2.70 Hz sd 0.45 Hz	m 3.55 Hz sd 0.93 Hz	m 5.39 Hz sd 1.10 Hz	m 6.67 Hz sd 1.35 Hz	m 8.22 Hz sd 1.97 Hz	m 11.24 Hz sd 3.35 Hz

Figure 6. Shifts in threshold frequencies. 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 stimuli identification numbers in brackets are those of figures 1 – 5. The only stimulus that does not find its place naturally in this classification is the slanted cross E2. Its associated threshold frequency (7 Hz) is surprisingly high. Average threshold frequencies and standard deviations are given for each class.

3.4 Miscellaneous observations

A few subjects made fine, correct responses at a certain frequency, and coarser responses at a slightly lower frequency. This was true for stereogram B2’s double curvature, coarsely seen as a dome, or for the cylinders B3 and B4, coarsely seen as convex or concave shapes without elongation axes. Interestingly, the slanted bars A2 and A3 could be seen at low frequency as frontoparallel bars. There were also cases of inverted relief for some stimuli at low frequency and also cases of alternation between normal and inverted depth, as though the left and right images were exchanged at each half cycle.

A classical theme in stereo vision is depth perception in unfused images (eg Ogle 1953; Ziegler and Hess 1997; recent review in Wilcox and Allison 2009). Here, we have a related but different phenomenology. For most subjects there is a stage at which depth is perceived in a fused image, but where the image oscillates laterally. This motion can be interpreted in at least two ways: (i) depth is assigned alternately to the left and the right image, and the succession of still representations produces an apparent motion effect, and (ii) there is a single three-dimensional representation, but it receives alternate leftward and rightward leaning corrections in response to the alternating monocular inputs.

4 Discussion

4.1 Introductory comments

Our initial purpose, in the work presented here, was to explore the potential of the alternating frequency technique in clarifying the nature of the computational problems which the brain has to solve during stereoscopic processing. As a tool, alternating presentations clearly succeeded in producing significant differences in alternation frequency thresholds for various classes of stereoscopic stimuli (see section 4.2 below).

Most of the earlier studies on stereopsis with alternative presentation dealt with stereomotion effects—in particular, the Pulfrich illusion—or the relationship between stereomotion and static stereopsis (eg Morgan and Fahle 2000; Read and Cumming 2005). By their nature, these studies probed phenomena that occur within a few milliseconds. In our studies, when a stimulus is interpreted in depth at 2.5 Hz, each monocular phase lasts 200 ms, so we are in quite a different time range.

We emphasize that why different stimuli require different alternation frequencies cannot be deduced from our results, and does not seem to be easily accounted for by current concepts. We believe that our results become more intuitive when a stereoscopic memory store is incorporated in models of stereoscopic processing (section 4.3). Finally, we argue what seems to be an inescapable conclusion from our discussion—that stereopsis involves several types of qualitatively different computational tasks.

4.2 A tour of stereoscopic difficulties

In the hierarchy of difficulties which emerges from our work, the easiest stimuli are those in which a small number of elements must be positioned in depth, and where there is no calculation of slant, curvature, or shape, no monocular regions to deal with, nor any overlapping regions to dissociate. The only apparent exception to this rule is stereogram E4 with small slanted needles. We propose, in line with previous work (eg Ninio 1985), that the brain has two ways to appreciate the slant of a small segment. One pathway, indirect but fast, would use the different positions in space of the segments' endpoints. A second pathway to slant could use orientation disparities (Herbolme and Ninio 1993), which is more direct *but slower*. We conjecture that the endpoint pathway dominates when the segments are short, as in the case of stereogram E4. This is corroborated by our informal discussions with subjects, indicating that many of them focus on the central part of the stereogram, assign depth to the four internal endpoints, then build their interpretation outwards. Contradistinctively, with longer segments, orientation disparity may dominate, thus slowing down interpretation as seen for instance with stereograms A3, A4, and E3. Note that, whichever pathway serves to compute a surface's slant, large surfaces take a long time to settle in depth with their finalized slant (van Ee and Erkelens 1996, 1999).

Our measurements add little to the debate on the relative speeds of slant versus curvature calculations (see Devisme et al 2008; Rogers and Cagenello 1989). Our easiest stereogram with curvature in this study (B1) is interpreted just as fast as the easiest stimuli with slant (A3 and A4).

Depth discontinuities (defined here as step changes in depth) add difficulty (4.9–5.6 Hz required for stereograms C1 and C2, against 2.6–2.7 Hz for A1 and A2). However, stereograms such as B1 and B2 that were designed to represent continuous surfaces may present gaps in their textures that, according to one reviewer, should be regarded as monocular regions. There have been many studies on how the monocular regions are perceived (recent review in Harris and Wilcox 2009). Here, we did not investigate the status of these regions in the C1–C4 stereograms. The monocular regions may facilitate or slow down stereoscopic interpretations depending on their texture (Gillam and Borsting 1988; Grove and Ono 1999; Grove et al 2002). Whatever extra processing time may be needed to deal with surface discontinuities, it seems to be less than the extra processing time required for the *separation in three dimensions* of two needles forming an apparent cross.

The fact that the textured cylinder with a vertical axis (B3) did not take significantly more time to interpret than the textured cylinder with a horizontal axis (B4) deserves discussion. In the stimulus with a vertical axis, the disparities are constant along any vertical line: there are no shear disparities, and this is known to be detrimental to stereoscopic interpretation (Gillam et al 1988). The 1 Hz difference we report between stereograms B3 and B4 is therefore surprising. However, we note that two subjects interpreted stereogram B4 in depth on the synotophore, but could not interpret B3, and one of the authors (JN) recently developed a complete stereo blindness towards stimulus B3. This could be an age-related pathology (B Gillam, personal communication).

Beyond these points of contact with current issues in stereoscopic perception, we believe that the alternation frequency methodology has the potential to provide a fresh overview

on stereoscopic processing. Our set of twenty stereograms generates a nicely spaced scale of threshold frequencies, from 2.5 Hz to 12.4 Hz. The technique may not be suitable with more complex stereograms, because such stereograms would require alternation frequencies above the 20 Hz level, and would soon enter a range in which rapid alternations have the same effect, due to visual persistence, as entirely static displays. In possession of a scale such as that in [figure 6](#), we are in a better position to explore further issues in stereo vision, using very simple stereograms, thus with better signal to noise ratios than with highly complex RDS. For instance, the technique could be used with stereograms that involve subjective surfaces, illusory disparities, or isoluminant textures. If studies on new stimuli incorporate a selection of our stimuli, one will be able to rank all the results on a single scale. This might bring an element of systematic order in the field—perhaps the foundation for a modest analogue to Mendeleev’s table in chemistry.

4.3 Stereoscopic memory

When a static stereogram is interpreted in three dimensions, “once the figure has been seen, wide conjugate eye movements may be made without ‘losing’ the global percept” (Ramachandran 1976, page 383). The same is true of autostereograms: “once stereopsis is achieved, the observer is free to inspect the entire field of the autostereogram without losing the depth percept” (Tyler 1983, pages 242–243). This stability of the three-dimensional interpretation implies some form of stereoscopic memory.

Under the alternating presentation conditions, the brain would receive an essentially complete information package from the left eye during a ‘left eye phase’. This information would be sustained during, say 100 ms after the end of the left eye phase. The information would progressively deteriorate, as every memory trace does, while the brain receives the sensory input from the right eye during the right eye phase.

During the right eye phase the brain would compare the high-quality information received from the right eye with the sustained information from the left eye. Drawing from work on visual memory, this sustained information may exist at several qualitatively different levels of accuracy, explaining a good deal of the phenomenology. For a very short period, and provided that there is no distracting stimulus, the information could live at a high-quality level, as in iconic memory (Sperling 1960). After a while, the information would be maintained in abridged form, in a short-term visual memory (STVM) store (Phillips 1974). A new stimulus would push the content of STVM into a still lower quality store [a “long term memory” store according to Phillips and Christie (1976)—a “visual working memory store” according to more recent work].

Under the single exposure to each eye condition, the disparity threshold for stereopsis increases with the length of the void interocular interval (eg Ogle 1963). Under the alternative presentation conditions, the disparity thresholds also increase with the void interval duration (eg Ludwig et al 2007; Ross and Hogben 1975; Wist and Gogel 1966). Both observations are consistent with the notion of a progressive decay in quality of the information in the sustained format.

Recent studies on visual memory in scene perception provide further ideas for the interpretation of our results. In scene perception, the eyes move and grab local information in sensory mode—information that is incorporated into a coherent global representation of the scene, built from the assembly of memory traces from previous captures of visual information (eg review in Hollingworth 2008). There is now some insistence on the idea that the global ‘coherent’ representation is much less volatile than the data from which it was constructed (see eg Rensink 2000). Furthermore, a current representation may or may not be updated, depending on a number of factors [see the reviews on ‘change blindness’, eg Simons and Rensink (2005)].

In the alternate presentation tests, part of the information can be easily grabbed, then maintained in nonsensory mode. For instance, the wide rectangle and the two wide arcs of stereogram A2 can be encoded with *approximate* position information. The information about one image may be used to focus the matching tasks with the incoming sensory representation of the other image. On a first cycle, matching would be roughly achieved, but not with enough precision to determine the disparity signs. However, the other image may now be encoded in sensory mode, with improved positional information. If a slanted segment is represented, an approximate matching may assign a disparity sign at one end of the segment, but not be precise enough to assign a disparity sign at the other end of the segment, so the segment will be perceived as frontoparallel, in some cases protruding and in others recessing. This is a very common ‘pathological’ perception, which disappears when the alternation frequency is raised (see section 3.4).

Other features in the alternative presentation phenomenology may have to do not with processing time, but with the logics of representation ‘updating’. Thus, the intermediate frequency stage in which the stereogram is interpreted in depth but swings as a tumbler seems to imply that there is a stable three-dimensional representation, in which the three-dimensional calculations are not updated, but that the brain nevertheless signals the alternating character of the visual input.

We might have in our experiments various regimes of stereoscopic processing, and we have initiated work to segregate the regimes with greater precision. In his initial studies, Ogle (1963) presented left and right images in alternation, and inserted between the two presentation intervals either a void interval without stimulus or a short binocular interval of simultaneous presentation to the left and right eye of their corresponding images. The binocular interval had minimal influence on the results, and we confirmed this feature using presentations on a computer screen, with six subjects and twenty stimuli (data not shown). However, we also found that, when the binocular interval was increased beyond 20 ms, a striking phenomenon occurred: extending the binocular intervals by 20 ms could allow each monocular presentation of the left or the right image to be extended by 40 ms or even longer durations (preliminary results in Rychkova et al 2010). It is thus clear that stereopsis is not always a matter of online processing. It probably makes use of several levels of representations. Various types of information (eg positional versus orientational information, absolute versus relative disparity information) may decay at different rates, thus requiring different updating frequencies to produce a stable three-dimensional percept.

4.4 Clinical implications

We have used alternating presentations of stereoscopic stimuli at various frequencies as a tool to sort out classes of stereograms according to their difficulties. The tool seems to have a much higher resolving power than we anticipated. After this first exploration we hope to use it to gain insight into the processing requirements for other classes of stereograms. We also hope that this work will induce clinicians to consider that stereoscopic competence does not reduce to a single scale of stereoscopic acuity. Stereopsis recruits several circuits dedicated to the solution of different types of stereoscopic problems, perhaps involving different brain areas. The progress made by patients during orthoptic reeducation should be followed on a sample of stereograms that require qualitatively different kinds of stereoscopic interpretation tasks.

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Svetlana Rychkova, daughter of a psychophysicist close to Musati, graduated as an MD specialized in pediatrics (1995) and ophthalmology (1997) at the Medical University of Irkutsk. She worked as an ophthalmologist in several clinical institutions in Irkutsk (1997–2009) then in Moscow. One of her main interests is the visual reeducation of patients after strabismus correction by surgery. Having discovered in some strabismic patients a capacity to fuse two images with a single eye, she developed an interest for fundamental aspects of stereo vision, and attended several ECVF congresses. She is now a part-time scientific collaborator at the Moscow City Psychological and Pedagogical University and works there on children's perceptual abilities.



Jacques Ninio graduated as an engineer from Ecole Polytechnique, Paris, in 1963 then started research in molecular biology, where he is known for work on the accuracy of molecular processes and on mutation strategies in evolution. Finding inspiration in books by Gregory and Julesz, he initiated, as a hobby, work on stereo vision and geometrical illusions in 1975, while leading a team on DNA replication kinetics at Institut Jacques Monod in Paris. In 1992 he joined a team of physicists at Ecole Normale Supérieure, Paris, where he initiated work on visual memory, and is still active as an emeritus director of research. Author of several popular science books, he performed experimental work, theoretical work, or both in a dozen areas. His website at <http://www.lps.ens.fr/ninio> is an extensive as well as critical scientific biography.