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**Chapter published in the book :**  
***Three-Dimensional Television, Video, and Display Technologies***  
**Editors: Bahram Javidi & Fumio Okano**  
**Pages 359 to 396**

**ISBN 3-540-43549-2 Springer-Verlag Berlin Heidelberg New York**

# **The influence of optical distortions and transverse chromatic aberrations on motion parallax and stereopsis in natural and artificial environments**

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## **ABSTRACT**

This chapter examines the potential effects of optical distortions and transverse chromatic aberration on the perception of depth. In particular, I will emphasize the role of motion parallax and stereoscopic vision. Motion parallax implies that the perception of depth can be extracted from a temporal sequence of images that contain different perspectives while stereopsis is the binocular depth perception derived from the disparate views of the two eyes for the same visual scene. It will be argued that motion parallax alone will generate a strong sense of depth, even in the absence of stereoscopic cues. Studies directly comparing motion parallax and stereoscopy will be presented showing that, under certain conditions, these cues can be equally efficient and that there can be an additive effect when both cues are present. A theoretical discussion on how the effect of optical distortions and chromatic aberrations can influence motion parallax and stereopsis from a viewer's perspective will follow. Particular emphasis will be placed on the consequences of optical distortions produced by progressive addition lenses used to correct for presbyopia on motion parallax. We will also discuss how natural and induced transverse chromatic aberrations interact with perceptual phenomena to generate depth illusions. Finally, research avenues will be proposed to answer some of the theoretical and practical issues related to motion parallax in both natural and artificial environments.

**Keywords:** Motion parallax, Stereopsis, Depth perception, Optical distortions, Transverse chromatic aberrations, Ophthalmic corrections, Progressive addition lens, Illusions.

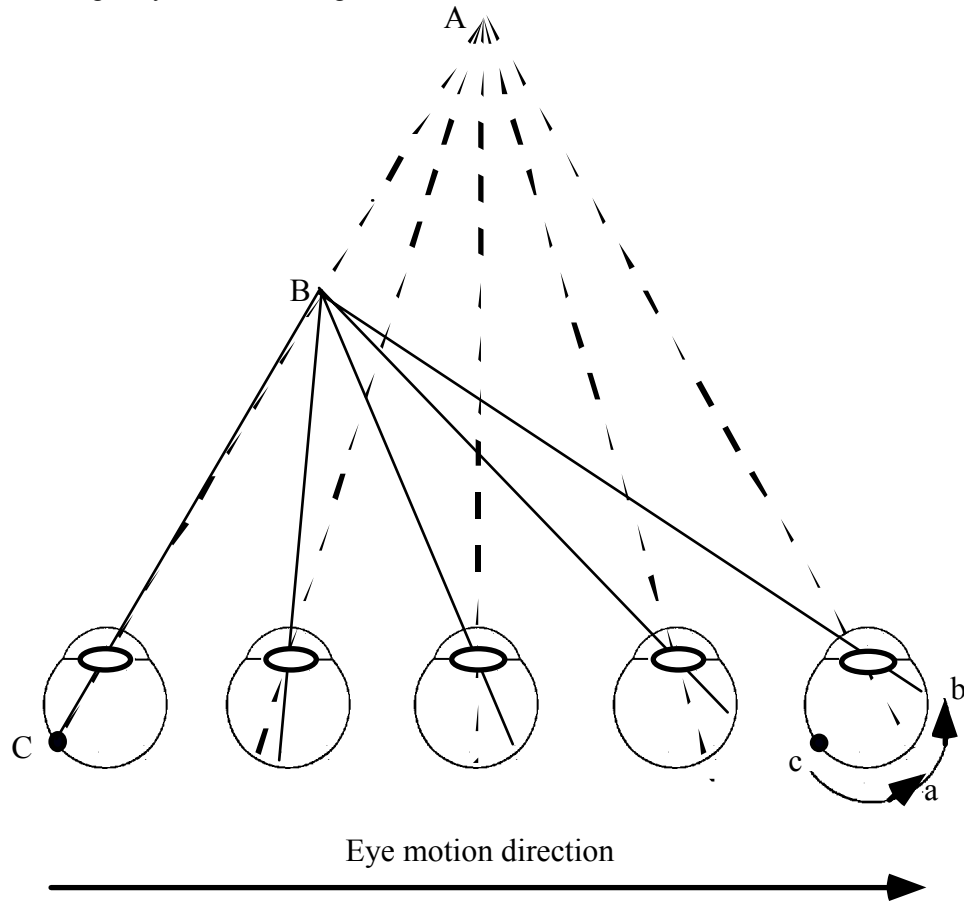
## **1. INTRODUCTION**

The main purpose of this paper is to illustrate the importance of motion parallax and stereoscopy on judgments of relative depth and discuss factors that may impact on these judgments. I will first discuss some basic properties of motion parallax, its interaction with stereopsis, and follow with an analysis on how these cues can be disturbed or distorted in different viewing conditions. I will raise some practical and theoretical issues that have received little attention in the scientific literature but are of critical importance in our daily functions and when viewing artificial displays.

## **2. WHAT IS MOTION PARALLAX?**

When an observer is in motion the visual scene surrounding the person is represented as a drifting image on the retinas of the observer's eyes. The drift speed on

the retina depends on the relative distance of a given object in the image. If the object is close to the observer, the drift speed of this object on the retina will be faster than when the object is further away from the observer. It is well known that this relative motion of the visual image on the retinas, known as motion parallax, is used by the visual system to generate a sensation of depth [1,2]. An illustration of how the distance of objects in a visual scene can generate different drift speeds on the retina of the corresponding points of the light rays is shown in Figure 1.



*Figure 1.* Illustration of motion parallax generated by two points in depth. Point A is distant from the eye while point B is closer and on the same visual axis. As the eye moves from left to right, the projected points a and b on the retina are dissociated because of their respective geometry. The consequence is a longer travel distance on the retina of the projected ray B-b than ray A-a resulting in faster drift speeds for B-b.

This is one of the many cues used by the brain to estimate depth in a visual scene that does not require information from both eyes. For instance, superposition or occlusion (one object overlapping the other), texture gradients (density of elements in the image change as a function of distance), perspective (shape of elements change with distance), shadows and shading, luminance (brighter objects appear closer), among others are all examples of depth cues used by the human brain to estimate distance and depth that do not require binocular visual input. However, it is clear that among all the cues mentioned

above, motion parallax is often considered as being a very efficient cue to generate a sensation of relative depth [1,2].

Figure 1 demonstrates how two points that are aligned relative to the eye in a visual scene, but are distant from one another in depth, will generate a different amount of displacement on the retina when movement is involved. Whether the scene itself is in movement and the eye stationary, or whether the eye position is changing and the scene is static (for example when looking out the window when traveling in a train) the relative displacements are the same on the retina. In this particular example the eye is in motion while the scene remains fixed. The figure illustrates two points in depth within the scene. Point B is close to the eye while point A is more distant. Both points A and B project an image on position C of the retina. As the eye moves (from left to right in this example) points A and B, given the geometrical constraints, travel at different relative distances on the retina and the end result can be seen at the projections a and b where there is a substantial difference in their final positions. The different distances correspond to different perceived velocities as both rays A-C and B-C traveled different distances within the same time span.

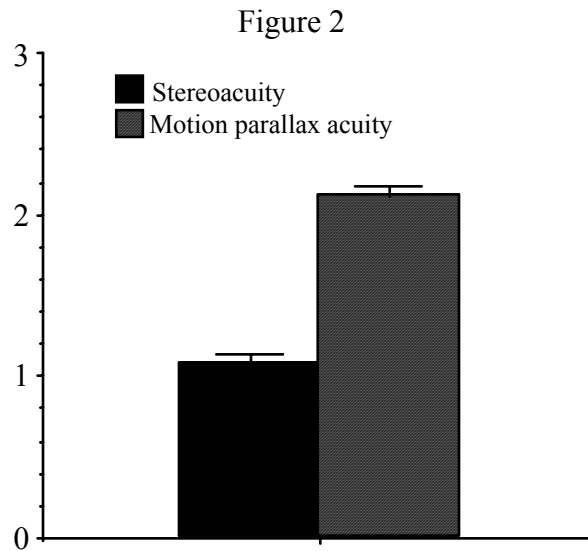
### **3. HOW EFFICIENT IS MOTION PARALLAX?**

As for most perceptual phenomena, the relative efficiency of motion parallax for producing estimates of relative depth depends on spatio-temporal factors and in what adaptation state the visual system is (luminance levels). However, one can illustrate the efficiency of motion parallax for generating a sensation of relative depth by directly comparing it with binocular disparity, which is the ultimate cue for generating small depth estimates. A simple experiment conducted in our laboratory demonstrates this point [3].

#### *3.1 Motion parallax vs. binocular disparity (stereoscopy)*

Let us suppose that we must judge the relative distance of an object that we are fixating in the central part of our visual field (foveal fixation). In this context, it is possible to assess how efficiently an observer judges the amount of separation in depth between two rods. This is a classic depth judgment based on the Howard method [4] where the smallest amount of separation that is necessary to see the difference between two rods in depth under binocular viewing conditions (stereoacuity thresholds) is generally determined. The same judgment task may be used when motion parallax is the only depth cue available.

Such thresholds were obtained with 38 young healthy observers who were enrolled in an optometry course. All had binocular vision as assessed by the randot test and 6/6 visual acuities. The apparatus and procedure are described in detail in Faubert [3]. Thresholds were determined for the binocular (stereoacuity) condition and for a motion parallax condition (monocular). In the motion parallax condition, the chin rest was mobile and was displaced at a frequency of 1 Hz for a distance of 6.7 cm. In other words, the head moved all the way to one side and back to the original side within one second. The viewing in this case was monocular.



*Figure 2.* Mean Log depth acuity thresholds in seconds of arc as a function of the testing conditions for the same subjects. The dark column represents the stereoacuity thresholds while the shaded column represents the motion parallax acuity thresholds. The error bars show the standard error of the mean for each condition.

The results are summarized in Figure 2 where we can directly compare the stereoacuity thresholds with parallax acuity thresholds. The mean log thresholds show that stereo thresholds are better than the monocular parallax thresholds under these conditions. This confirms that binocular disparity is superior to monocular motion parallax for judging relative depth in the central visual field.

Can we conclude from this that the motion parallax cue is inefficient at generating relative depth judgments? Not necessarily. First, we must consider that the task that we evaluated is the optimal condition for binocular disparity because it involves the central visual field. It is clear that binocular fusion is limited to a certain area of the visual field beyond which binocular fusion is rendered inefficient. This binocular fusion area is called Panum's area and has been well described in the literature [5]. Therefore, there are areas where we may be able to judge the relative depth of objects by motion parallax when binocular fusion is impossible. This would most certainly be true under natural viewing or conditions with large viewing displays. In fact, the notion that stereopsis can only be efficient in a restricted portion of the visual field has been used to develop compression algorithms for transferring stereoscopic information contained in standard video signals [6].

Another reason why we must be careful about the interpretation of the present results for estimating the relative efficiency of motion parallax in depth judgments, is the fact that our subject population consisted of healthy binocular viewers. They may not require the use of motion parallax to make judgments about relative depth in the central visual field under these viewing conditions. It is possible, therefore, that when parallax is the only source of information, it may also be a quite efficient cue for making such judgments.

### 3.2 Motion parallax in monocular individuals vs. stereoscopy in binocular individuals

To test this hypothesis, we assessed the motion parallax thresholds of three observers who had lost the use of one of their eyes due to accidents [3]. The three observers had lost the use of their eyes at least 2 years prior but no more than 5 years before participating in this study. All had 6/6 visual acuity in their functional eye. The results are presented in Figure 3 and show that although there is a difference between the motion parallax acuity thresholds of the monocular observers and the mean stereoacuity thresholds of our binocular observers, the difference is reduced by about half as compared to the control subjects' own motion parallax thresholds. Furthermore, the three observers' values fell well within the 95% confidence interval (mean + 2SD) established from the normative data. In other words, there were a number of normal observers who actually had equivalent or worse stereoacuities than the motion parallax acuity thresholds obtained for our three monocular observers. This demonstrates that when binocular disparity is not available motion parallax can be used to obtain relative depth judgments that can, at the very least, be considered within the normal range as far as stereoacuity is concerned.

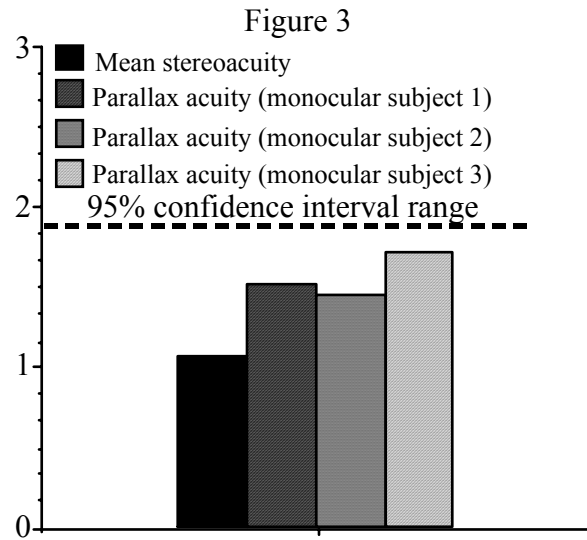


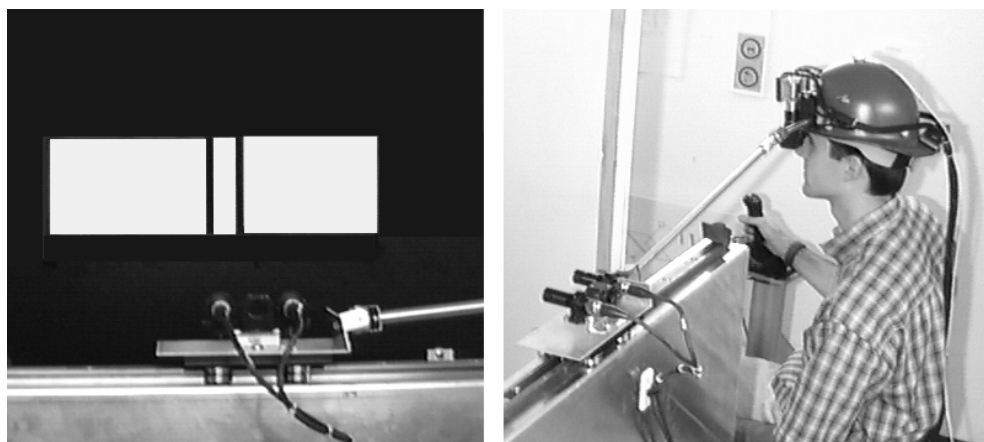
Figure 3. Log depth acuity thresholds in seconds of arc as a function of the testing condition. The dark column represents the mean stereoacuity thresholds for the normal group while the shaded columns represent the motion parallax acuity thresholds for the three monocular observers. The dashed line corresponds to the upper limit of the 95% confidence range for the normal observers.

## 4. INTERACTIONS BETWEEN MOTION PARALLAX AND STEREOSCOPY

The next question is whether both stereoscopic and motion parallax information can be used to improve our ability to make depth judgments. To illustrate this point we can refer to previous experiments performed in our laboratory that were designed to address practical questions of the visual requirements involved in telemanipulation

environments [3,7]. In the electric power industry there are frequent occasions where wires have to be mounted at high levels from the ground and where high currents are involved. To circumvent this problem, electric power companies use robots that are manned by trained personnel. Normally the operator is contained within a cabin that is raised in proximity to the wires and then manipulates the robotic arms. An alternative approach is to operate the robotic arms at a distance via a virtual environment. The questions that were asked in this particular study were: What are the necessary and sufficient depth cues to perform these specific tasks, which involve positioning instruments in holes and assembling cables? Is stereopsis sufficient or should we also consider using motion parallax? The outcome of such questions may have a dramatic impact on the technology used and the production costs.

To answer this question we used a simple depth judgment task similar to the task used in the previous experiment. The experimental setup along with the view from the cameras' perspective are presented in Figure 4.

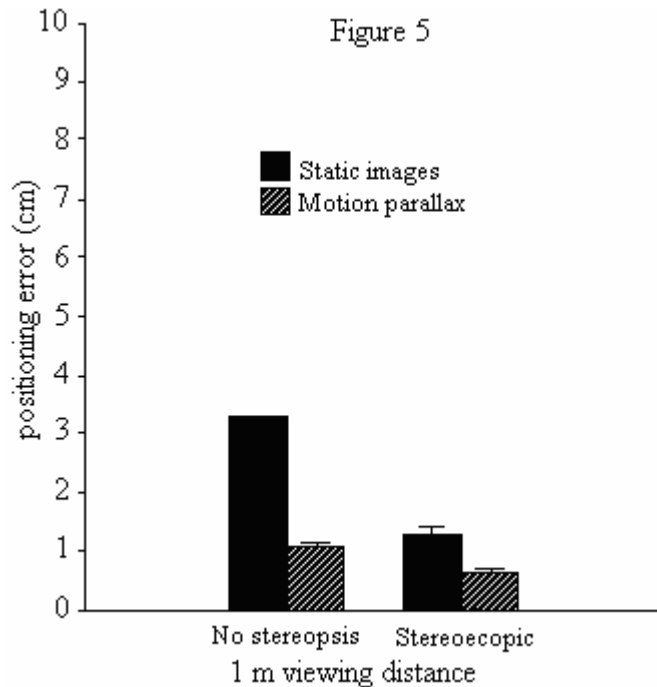


*Figure 4.* Right image shows the subject with virtual reality helmet and the cameras used for viewing the image. The cameras were yoked to the head movements by being placed on a sliding platform. A steel rod attached the sliding platform and helmet. The left image shows the view from the cameras' perspective. See text for details.

Two viewing distances were used. In Experiment 1 the cameras were positioned at 1 m viewing distance and in Experiment 2 the cameras were positioned at 2.6 m. The distances were based on the requirements of the operators' tasks in real-life situations when mounting cables for the electric power company. In one task the operators have to place and pick up instruments in holes when they are positioned at a distance of 1 m and in the other task, they assemble the cables at a 2.6 m viewing distance. As illustrated in Figure 4, the experimental condition consisted of cameras that were facing the target. The camera movements were made possible by placing them on a sliding platform and the platform was yoked to the observers helmet via a steel rod. In this way the lateral displacements of the observer's head produced a perfect correspondence of the camera movements in front of the visual stimulus.

The visual information was transmitted to the viewer by a virtual reality helmet equipped with two monochromatic CCD video displays separated by 64 cm from each other. These displays were each linked with the corresponding left and right cameras permitting a stereoscopic image. We were able to switch from a stereoscopic to a monocular view by allowing the information of a single camera to supply both visual displays. The focal distance of the screens was set at 7.5 mm and the visual field generated by the CCDs subtended 46 degrees of visual angle in width and 35 degrees in height with 100% overlap. The screens consisted of a 500 line horizontal resolution.

The subjects were required to align a mobile rod positioned to the right to match the position of the left rod with the use of a joy stick (see Figure 4). The four conditions tested consisted of; 1) same image to both eyes with no motion parallax, 2) stereoscopic views with no motion parallax, 3) same image to both eyes with motion parallax, 4) stereoscopic views with motion parallax.

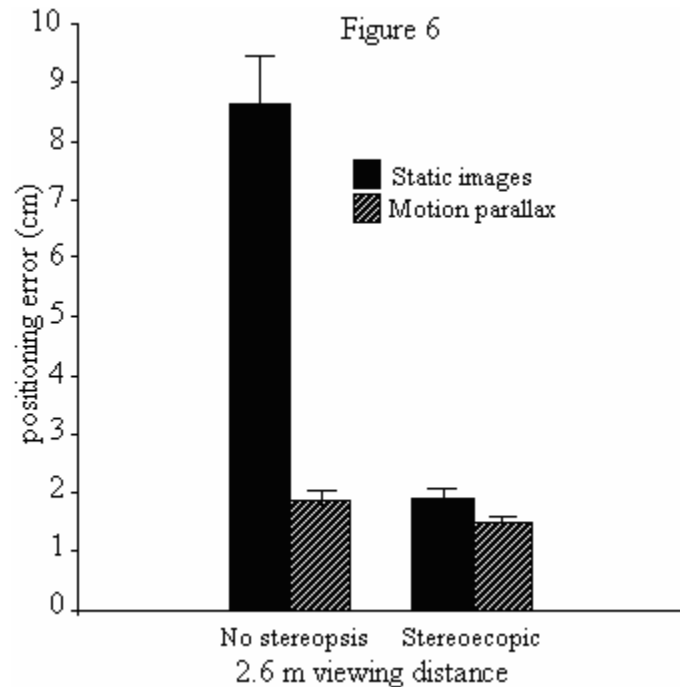


*Figure 5.* Relative positioning error in cm as a function of experimental conditions for the 1 m viewing condition. The dark columns consist of the data obtained when the images contained no motion while the shaded columns correspond to the conditions containing motion parallax. The two left columns show the data for the monocular viewing conditions while the right columns represent the data for the stereoscopic conditions. The error bars show the standard error of the mean for each condition.

The results for both experiments (1 m and 2.6 m viewing distances) are shown in Figures 5 and 6 respectively. The results are quite interesting as they reveal several aspects of stereoscopic and motion parallax cue interactions. Considering the 1 m viewing distance, we can observe that in both the conditions where only stereoscopic or motion parallax cues are presented, there is a dramatic improvement in performance. This



is evidenced by the statistically significant reduction in the magnitude of positioning error of the test rod relative to the reference rod. Furthermore, these cues in isolation appear equally efficient for judging relative depth in this type of task. The results for the interaction condition when both stereoscopic and motion parallax cues are available demonstrate that there is an additive effect resulting in a statistically significant improvement in the depth judgment task as compared to when the cues were presented in isolation.



*Figure 6.* Relative positioning error in cm as a function of experimental conditions for the 2.6 m viewing condition. The dark columns consist of the data obtained when the images contained no motion while the shaded columns correspond to the conditions containing motion parallax. The two left columns show the data for the monocular viewing conditions while the right columns represent the data for the stereoscopic conditions. The error bars show the standard error of the mean for each condition.

The results of the second experiment (2.6 m viewing distance) show a similar trend with the exception that the improvement produced by presenting both cues was about half the magnitude of the improvement obtained with the 1 m viewing condition and did not reach statistical significance. Generally the observers were not as efficient in performing this task as when the 1 m condition was used.

What is striking in these results, and in apparent contrast with the first study, is that motion parallax is equally efficient as the stereoscopic cue for making depth judgments. However, this can be explained by the fact that, in this particular study, both eyes receive visual input with motion parallax. In the first study, only one eye was used in the motion parallax condition. Binocular summation was therefore available in the second study and not in the first. It is well known that visual performance will improve

under dichoptic viewing conditions as opposed to when only one eye is used [8], although the reverse effect can happen if there is asymmetrical input between the eyes [9]. In a sense, the present study is a better estimate of the relative efficiency of motion parallax for generating depth judgments because we can directly compare stereoscopy and motion parallax when both eyes receive visual information.

Another interesting result is that there is an improvement in judging relative depth when both the stereoscopic and motion parallax cues are presented to the observer as opposed to when they are presented in isolation. This implies that these two depth cues share common mechanisms.

Finally, we observed that the facilitation, obtained when both depth cues are present, will vary depending on where the object is positioned in depth relative to the observer. We saw that the relative improvement obtained when both cues were present was much smaller in the 2.6 m viewing condition than in the 1 m viewing condition. We can explain this difference by referring back to Figure 1 and analyzing the simple geometrical effects of viewing distance on motion parallax. As we saw in Figure 1, the closer an object is to the eyes in depth, the more velocity will be generated by the same lateral displacement of the eyes. Therefore, in the 1 m condition there is a larger relative displacement of the visual image on the retina than in the 2.6 m condition resulting in greater motion parallax. Other studies have clearly shown that motion parallax is most efficient at close viewing distances [10].

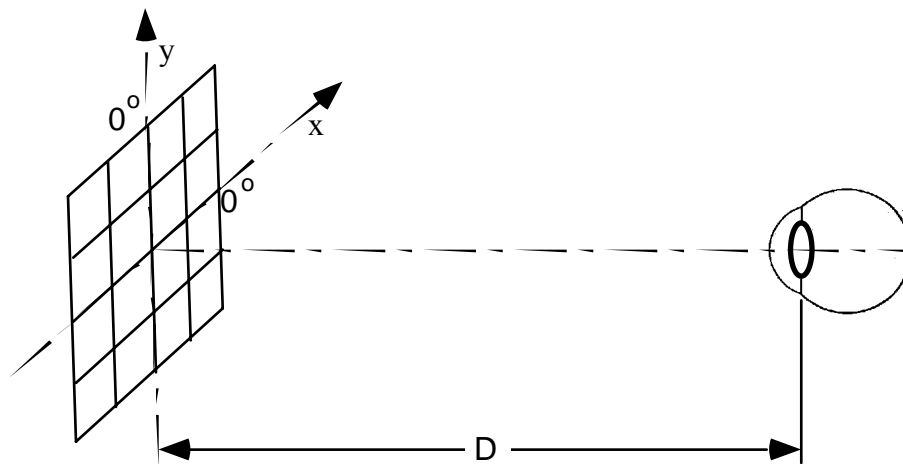
## **5. OPTICAL DISTORTIONS AND MOTION PARALLAX**

What we have established with the studies above is that motion parallax, under certain circumstances, can be as efficient a depth cue as stereoscopic vision for measuring relative depth and this even in foveal vision where stereoscopic function is optimal. As was mentioned above, there is a large zone of the visual field where stereoscopic vision is not available because it is beyond the fusional capacity of the visual system (Panum's area). It is logical that the visual system uses motion parallax under these circumstances to estimate depth. If we believe this assumption then we must consider factors that may affect the perception of motion parallax in the peripheral visual field. One such case is when we use optics in visual displays or simply when observers wear optical corrections (ophthalmic lenses). An optical distortion effect affecting motion parallax would be particularly important in cases of progressive lenses used to correct for presbyopia.

To illustrate this point we can start with simple examples of optical distortions produced by positive (hyperopic correction) or negative (myopic correction) lenses. The model chosen to make this point is based on the Le Grand-Fry approach [11,12]. These optical models have the advantage of establishing possible distortions produced by ophthalmic lenses from a wearer's perspective [13].

Figure 7 demonstrates a simple viewing perspective when a viewer is placed at a given distance from a target. There are no distortions present in the target because no lens is placed in front of the eye. If on the other hand we place a positive lens and we maintain foveal fixation (as shown in Figure 8) then the geometrical outcome of the image changes. What is shown in the image is that point B in the object image is in fact displaced in the periphery by a certain amount depending on the power of the lens (magnification). This displacement is obtained by tracing back from the incidence angle of the ray from point B

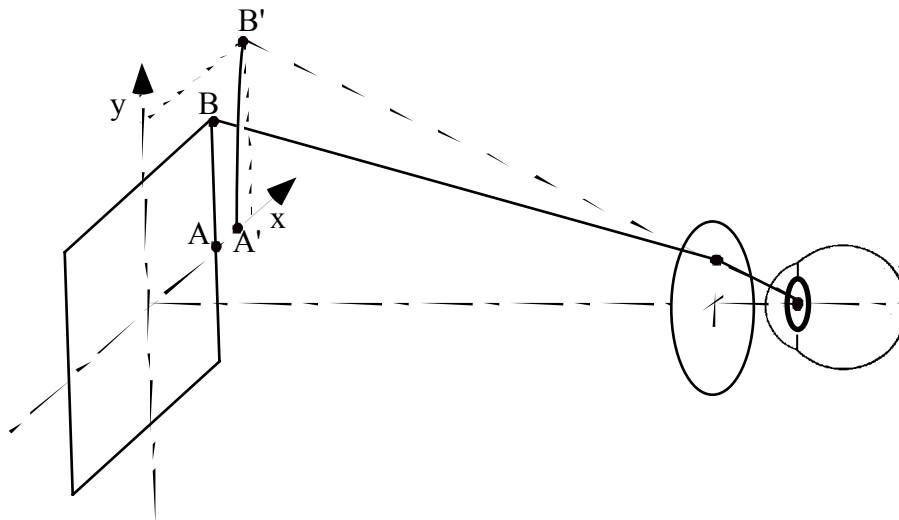
on the image, which has changed angle relative to the eye once it has been refracted by the spherical lens. Point B from the viewer's perspective can be projected back and is now displaced to point B'. The distortion produced by such lenses can be demonstrated by tracing the line AB as viewed by the observer through the lens generating the curve B'A'. If there was no distortion produced by the lens then the edge B'A' would consist of a straight line. This is shown by the straight dotted line perpendicular to axis X projecting to point B'. However, because of the optical properties of the lens the actual projection of the ray is shown by the trace B'A'. The original line BA seen through the lens is actually seen as the curve B'A'.



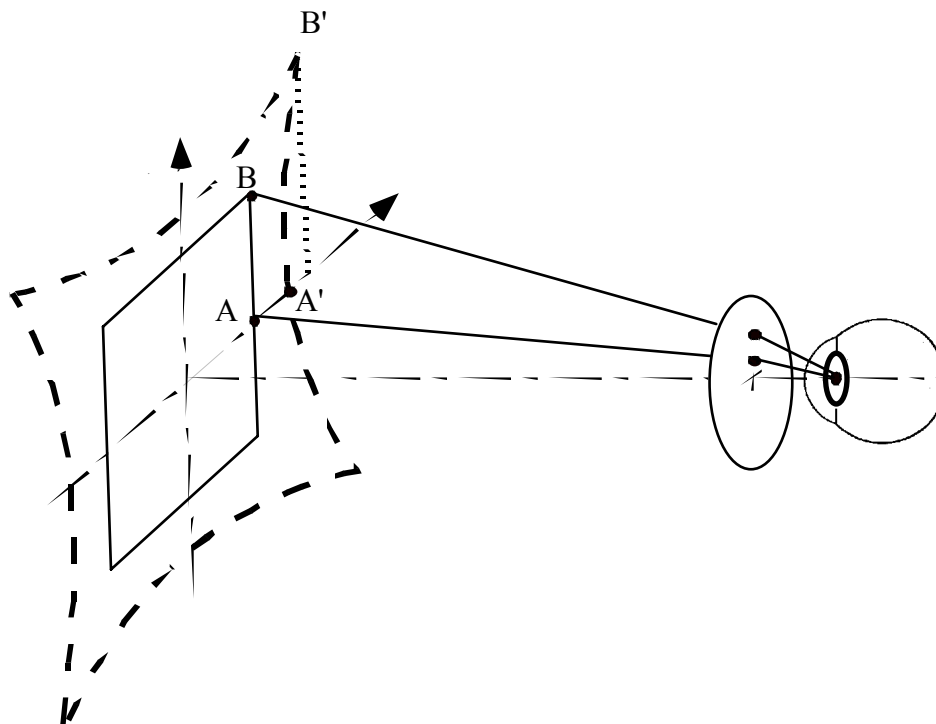
*Figure 7.* Standard viewing condition and image grid used to generate the optical model projections of distorted images as a function of lens type and correction.

Figure 9 represents the new projection of the entire image relative to the viewer's perspective. What can be seen from this is that the corners have been displaced outward and the image has a pincushion distortion at the edges. We can simulate the distortion produced by a plus or minus lens by producing a frontal view of the object grid based on this model. Such projections are shown in Figures 10 and 11 for plus and minus lenses respectively. The lens specifications are presented in the figures. The amount of distortion will of course depend on the power and the type of the lens. Figure 11 demonstrates that a myopic correction will in fact compress the image and produce barrel distortions at the edges from a viewer's perspective.

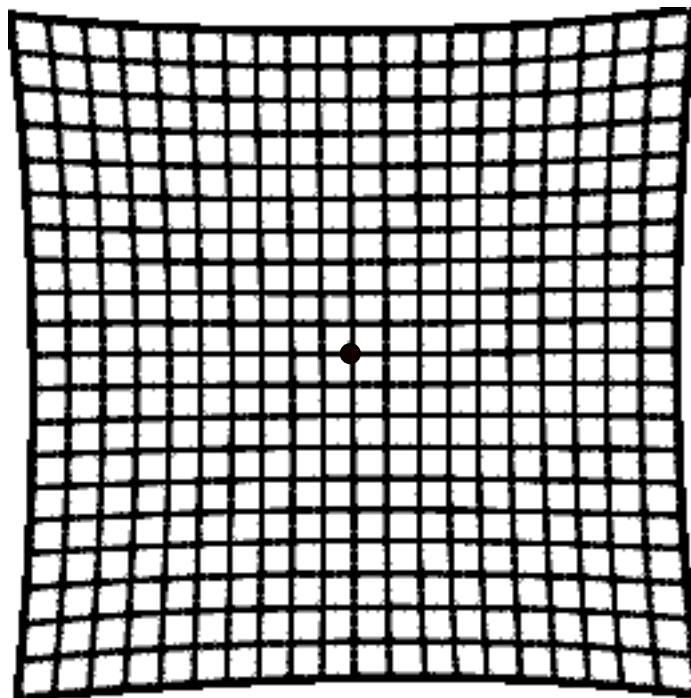
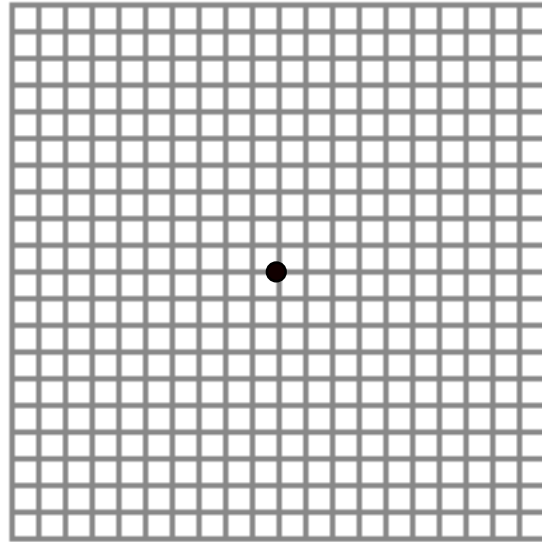
What becomes immediately obvious from such geometrical projections of ophthalmic lens distortions, is that the motion parallax obtained under these conditions will differ from what would normally be obtained without an ophthalmic lens correction. This situation is even more critical if progressive lenses to correct for presbyopia are used. Presbyopia results from changes in the optical properties of the human eye, in particular changes related to the crystalline lens, due to the normal aging process. Almost every human in their 40s will undergo these changes and require some form of positive addition lens correction to see objects up close. The exceptions are the myopic observers who can compensate by simply removing their myopic correction given that they already have a natural positive correction from the optics of their own eyes.



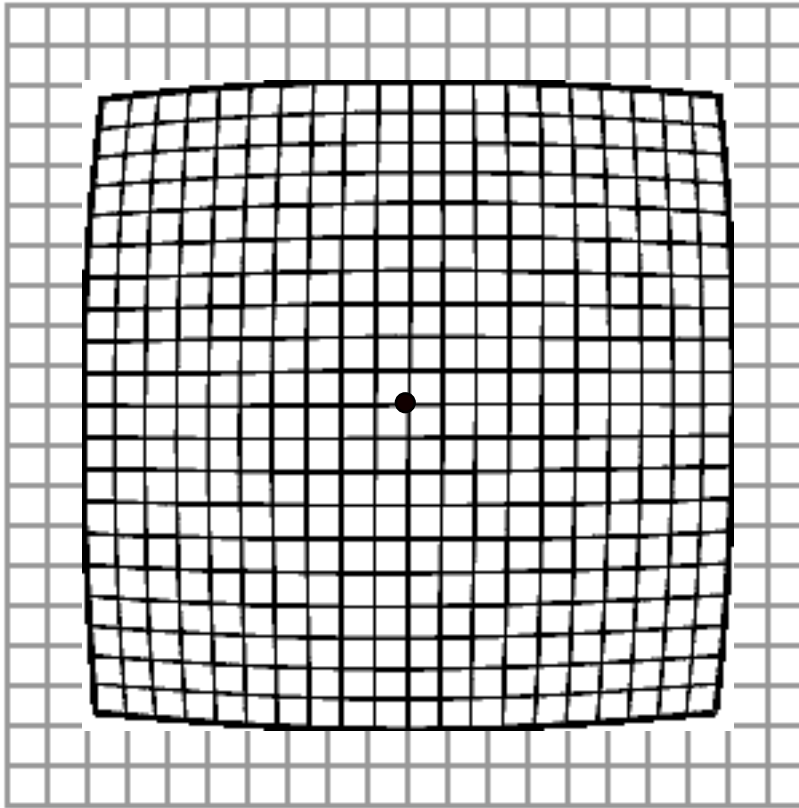
*Figure 8.* Example of the distortion produced by a positive spherical lens from a viewer's perspective. Edge B-A is now projected as the curve B'-A'. It is assumed that fixation is perfectly lined up with the reference optical axis of the lens which in turn is perfectly aligned with the center of the image grid.



*Figure 9.* Example of the model projection of all four edges when seen through a positive spherical lens. See text for details.

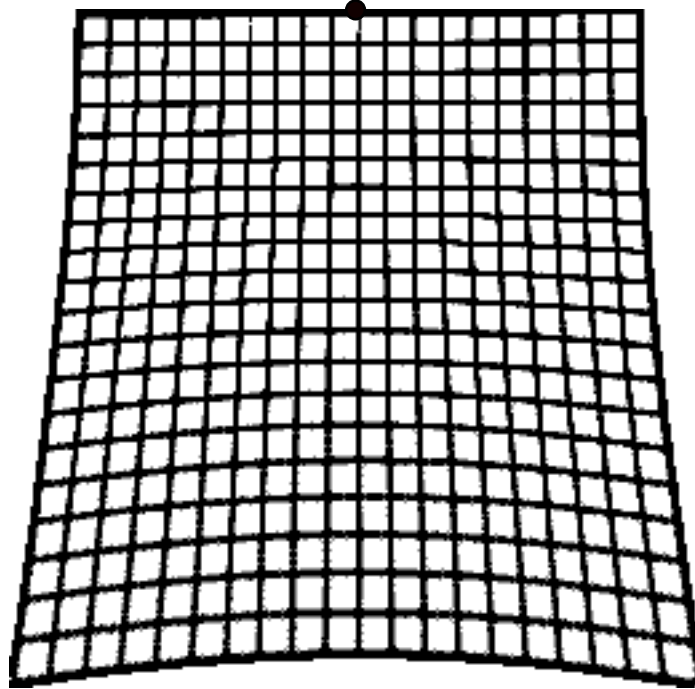


*Figure 10.* The top image shows a front view image of the image grid without lens distortion (light gray). The bottom image reproduces the non-distorted grid superimposed by a front view projection of the distorted image from a positive spherical lens. The black dot in the center of the image shows the fixation point.



*Figure 11.* The non-distorted grid presented in Figure 10 (top image) superimposed by a model projection of a minus spherical lens.

An example of an object distortion obtained from a progressive addition lens is given in Figure 12. It is obvious from such an illustration is that the bulk of the distortion is in the bottom half of the image relative to the fixation point (identifiable by a dot in the top-center part of the image). The potential complications arising from the use of a progressive lens comes from the interaction of two factors that vary simultaneously. As the image moves away from the central axis of the lens, there is both a magnification effect resulting from the increased power gradient of the progressive lens and, as a consequence, there is also an increase in distortion of the perceived image. If the head is in motion while the eyes remained fixated on the same point, one can perceive strong changes in the spatio-temporal components of the image. In other words, the motion parallax component that is perceived under natural circumstances is dramatically changed by the refractive optics. Observers report a sensation of sway when moving their heads and fixating a single point, or when the eyes move behind the lens while the head is maintained in one position [14]. This is the single most important problem to consider in the process of ophthalmic lens design for progressive addition lenses [15].

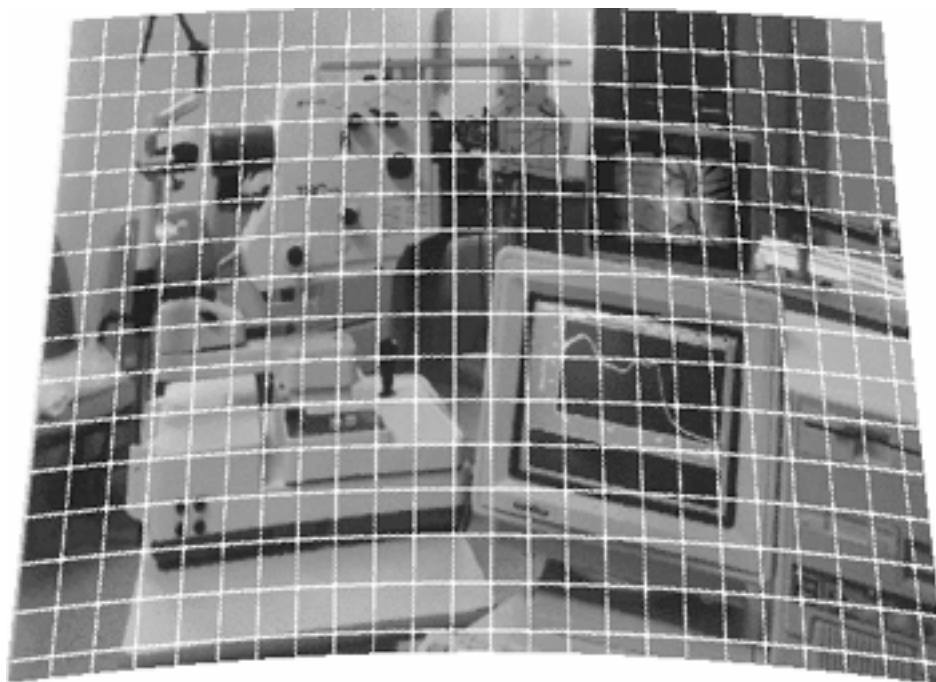


*Figure 12.* Standard grid superimposed with a model projection calculated for a typical progression addition lens. The black dot at the top of the image grid shows the fixation point and the reference axis of the lens. Notice that the distortion from a viewer's perspective is in the lower visual field area and is non-uniform as a function of eccentricity.

To illustrate the effect of progressive lens distortions on a natural image, we have applied the optical distortion model above on a photograph. The image in Figure 13 shows a view from our laboratory. Figure 14 is the result of a possible distortion of this image when viewed from a progressive addition lens if the image is placed in the bottom half of the standard grid. Because there are as many outcomes as there are different corrections, we will not discuss the specific lens characteristics or viewing conditions. What we show is a coarse approximation of the distortions that would be perceived under real conditions. However, it is obvious from the simulations that the world appears distorted and that the images appear projected forward in the lower visual field. The effect would be even more striking with an image in motion or with the observer in motion. We can also illustrate what happens when a viewer looks at oblique angles through the lens or when an observer maintains fixation while moving the head. Figure 15a shows a simulation of the effect of maintaining fixation on an image while moving the head sideways when progressive lenses are used. An asymmetrical distortion of the image results. The effect would be opposite if the head was turned in the other direction from the fixation point (Figure 15b). The reader can imagine the swaying effect when moving the head back and forth in these conditions.

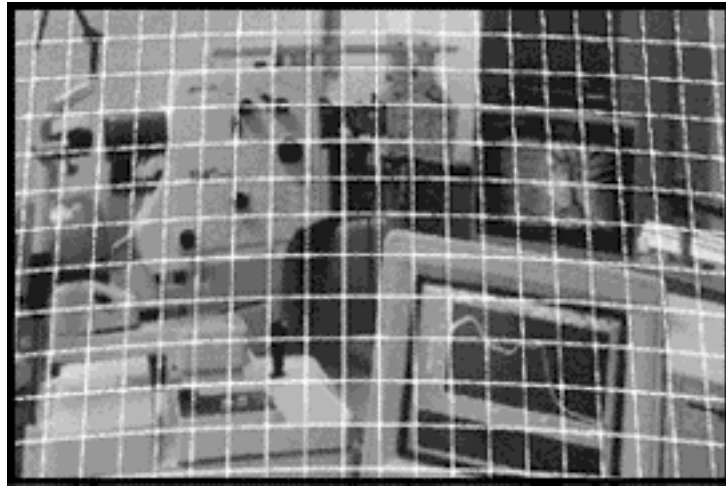


*Figure 13.* Image and grid used for the simulations of the optical distortion model.

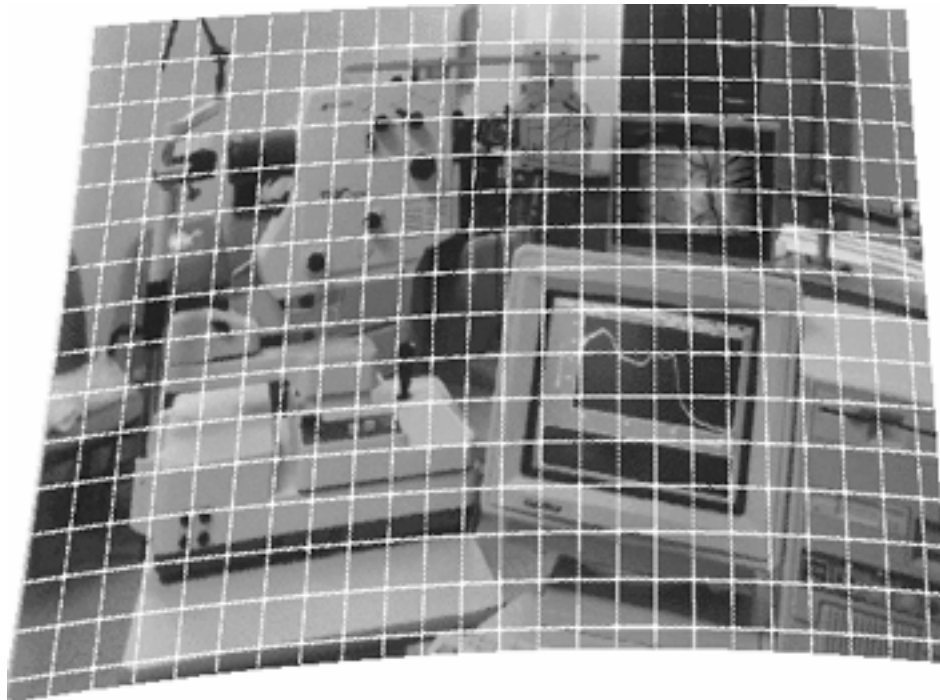


*Figure 14a.* Simulation of the optical distortions produced by a progressive addition lens. The entire grid image distorted by the lens.

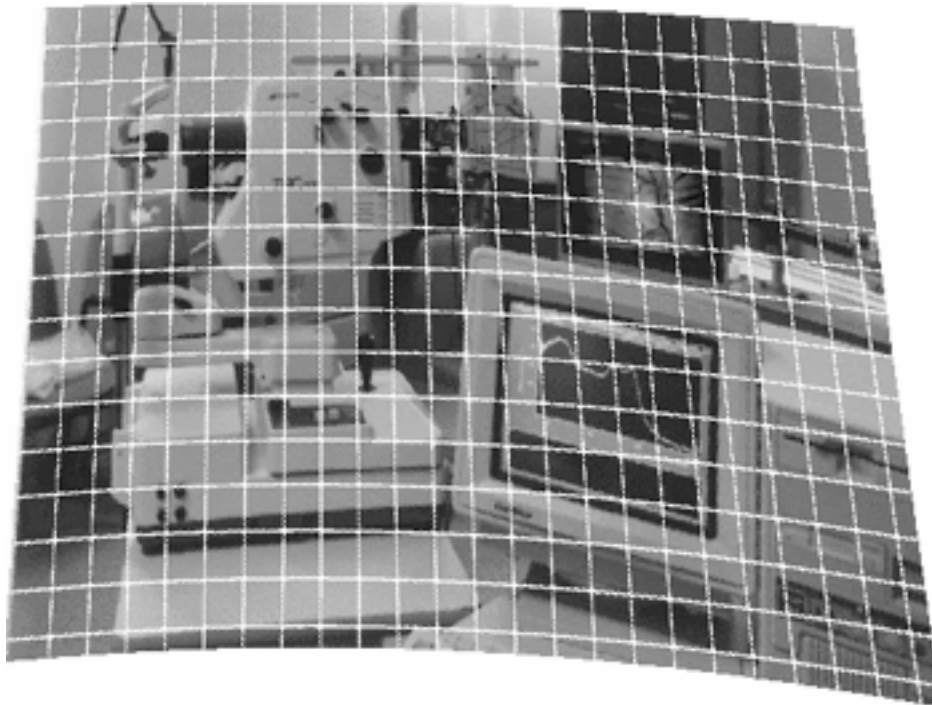




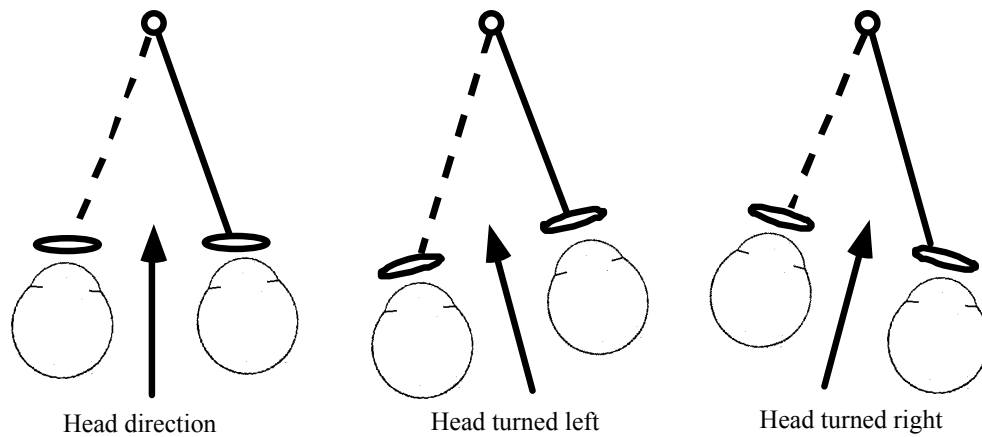
*Figure 14b.* Simulation of the optical distortions produced by a progressive addition lens. The resulting portion of the image in the same visual field area of the original image (Figure 13).



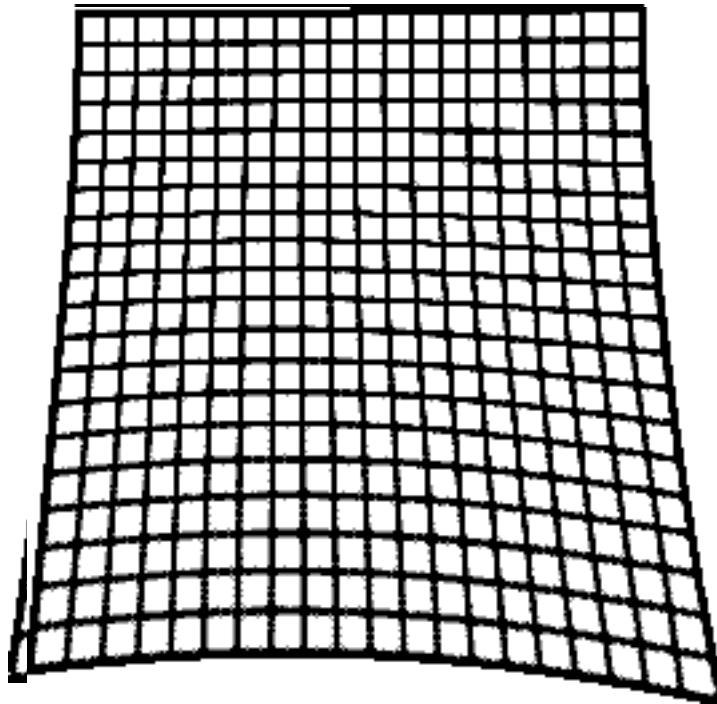
*Figure 15a.* Simulation results of the distortion model when the observer maintains fixation on the same point of the image but moves the head away from the image (See Figure 16a). Simulation results when head is moved rightward.



*Figure 15b.* Simulation results of the distortion model when the observer maintains fixation on the same point of the image but moves the head away from the image (See Figure 16a). Simulation results when head is moved leftward from the fixation target.



*Figure 16.a* Example of how maintaining fixation while moving the head will generate difference incidence angles relative to the lens for each eyes.



*Figure 16b.* Model results showing phase differences for a given position of binocular oblique viewing. These phase differences will vary with the angle of the head relative to the fixation point, resulting in differences in perceived velocities between the two eyes.

## **6. BINOCULAR INTERACTIONS WITH PROGRESSIVE LENSES**

We saw from Studies 1 and 2 above that binocular input to motion parallax is used and is important for the visual system. There is also recent evidence that velocity differences between the eyes can generate a perception of depth [16]. This creates an additional problem for the design of progressive lenses. In fact, Essilor International has recently identified this as the single most important cause of discomfort from progressive lenses. To minimize the interocular difference in motion parallax generated by progressive addition lenses, they now calculate a velocity difference gradient to improve their lens design [15]. To illustrate this point, let us consider what the two eyes are viewing through progressive lenses while fixation is maintained. Figure 16a shows that when the head is moved in one direction, the incidence angles of the image rays are different relative to each eye. This situation will produce differences in the geometry of the projected image to each eye. An example of the superimposed images of the two eyes that are out of phase is shown in Figure 16b. The problem here is that the phase difference is not constant as can be seen from Figure 16a. The results can be dramatic differences in perceived velocity between corresponding points of the visual image. This question has not been studied and must be addressed to understand the observer's perceptual experience of motion parallax under such viewing conditions.

## 7. NATURAL AND LENS INDUCED TRANSVERSE CHROMATIC ABERRATIONS, STEREOPSIS, AND MOTION PARALLAX

### 7.1 What is transverse chromatic aberration?

It is well known that the optics of the eye produce chromatic aberrations [17-19]. Chromatic aberration results from the fact that light refracts differently depending on its wavelength. There are two major components of *ocular* chromatic aberration at the fovea. Longitudinal chromatic aberration (LCA) corresponds to the difference of focus with wavelength while transverse chromatic aberration (TCA) corresponds to a difference of position of the retinal images with wavelength. Figure 17 illustrates the two major components of *ocular* chromatic aberration at the fovea. LCA corresponds to the difference of focus with wavelength between, in this example, the red image (R) and the blue image (B). The red image has been arbitrarily positioned at the fovea. In the top figure, *natural* TCA is shown as the angle between the principle rays of the two retinal images. For clarity the drawing is not to scale, and it has been assumed that the whole refractive system of the eye is situated at the cornea, and that the entrance and exit pupils are superimposed.

### Ocular LCA & TCA

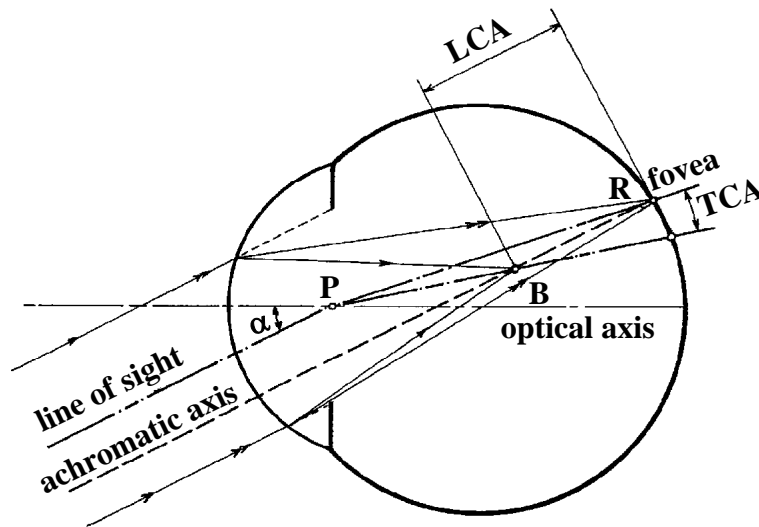


Figure 17: The two components of chromatic aberration at the fovea. Longitudinal chromatic aberration (LCA) corresponds to the difference of focus with wavelength between the red image (R) and the blue image (B). The red image has been arbitrarily positioned at the fovea. Natural transverse chromatic aberration (TCA) corresponds to the difference of position of the retinal images with wavelength. In the figure, natural TCA is shown as the angle between the principle rays of the two retinal images. For the sake of clarity the drawing is not to scale, and it has been assumed that the whole refractive system of the eye is situated at the cornea, and that the entrance and exit pupils are superimposed (adapted from ref. [22]).

Figures 18a to 18d are schematic diagrams representing examples of possible interactions between *natural* and *induced* TCA at the fovea by a prismatic lens. For the sake of clarity, a reduced eye is used and the distances and angles are exaggerated in the graph.

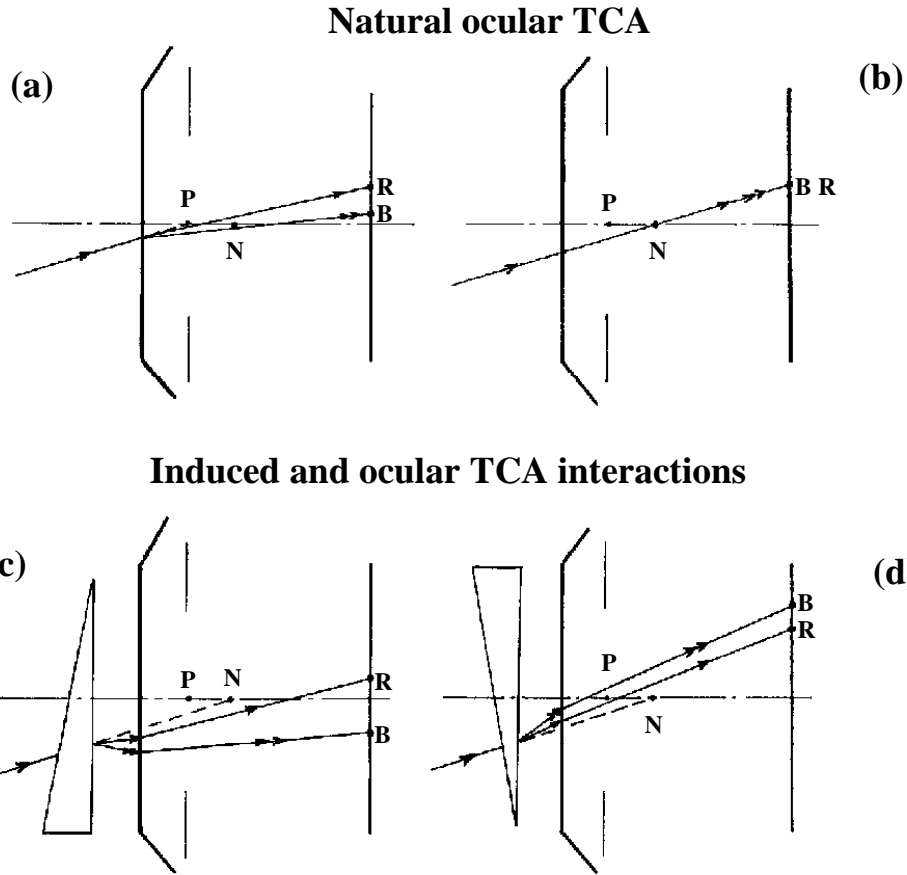


Figure 18: Ocular TCA at the center of the entrance pupil (a). No ocular TCA when the incident ray is superimposed with the achromatic axis (nodal axis) (b). TCA induced by a prism (c). This induced TCA is additive with the ocular TCA. TCA induced by an inverted prism (d). The effects of induced and ocular TCA are opposed (adapted from ref. [53]).

Figure 18a illustrates a condition where there is a naturally occurring TCA as opposed to when the incident ray is co-incident on the achromatic axis (see Figure 18b), which results in the absence of TCA. Figure 18c gives an example of induced TCA from a prismatic lens. Notice that in this case the direction of the natural TCA and the induced TCA are in the same direction and are therefore additive. If the prism is inverted as shown in Figure 18d, the effect of induced and natural TCA are opposed to one another and, as a consequence, the total TCA is diminished. Although ocular TCA and induced TCA are distinguished below, it must be understood that the consequences of both types of TCAs on visual performance should be exactly the same because both produce selective colour phase shifts at the retinal level [20].

## 7.2 Consequences of TCA on visual performance.

TCA can decrease achromatic spatial contrast sensitivity [21-25] dramatically if the spatial frequency component of the stimulus is greater than 1 cpd. It has been shown

that correcting TCA with achromatizing lenses can produce more problems than it solves if the lens is not perfectly aligned with the achromatic axis [20].

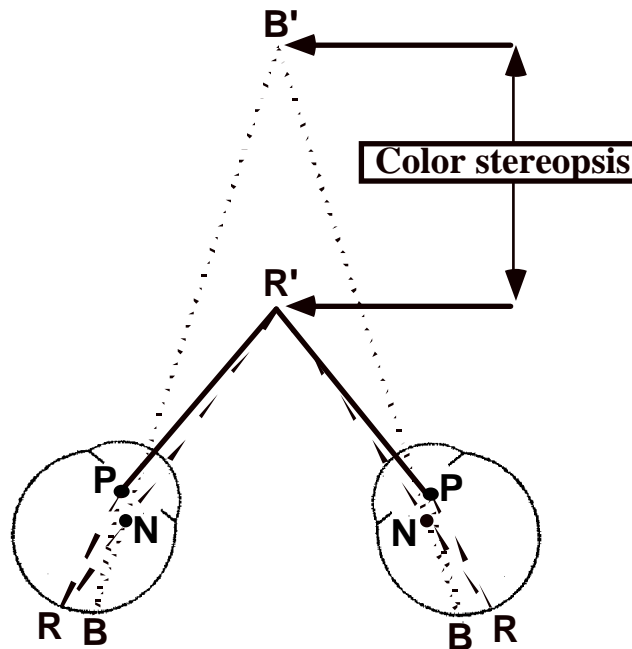
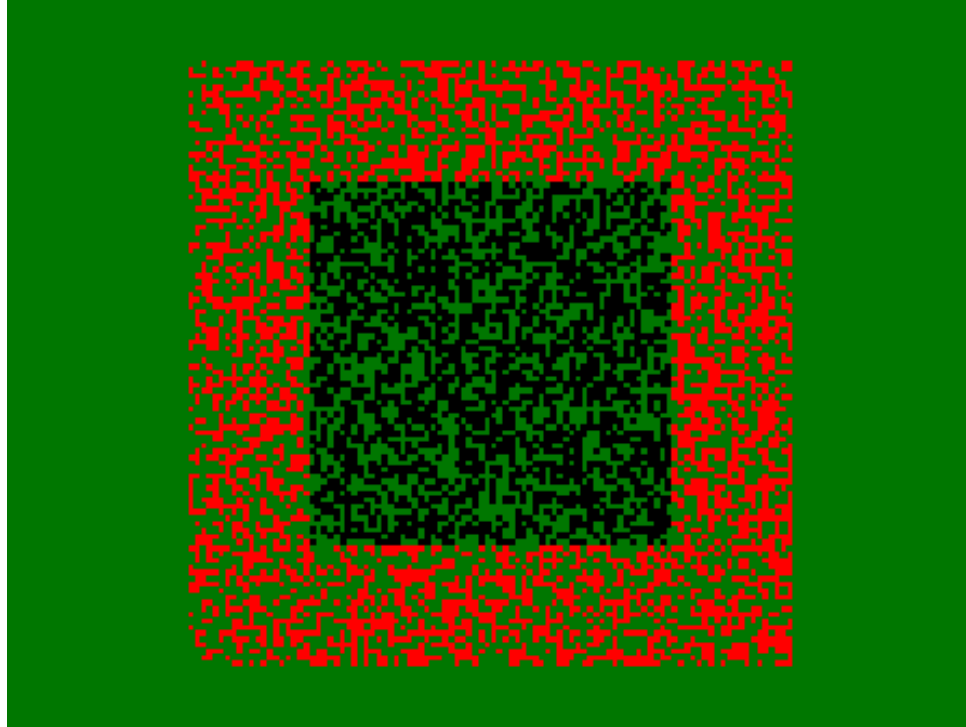


Figure 19. Illustration of how chromatic parallax (TCA) can induce color stereopsis. The image is focused at point  $R'$ . The rays of the red and blue portions of the image are displaced at different angles on the retina producing retinal disparity between the eyes (adapted from ref. [32]).

### 7.3 TCA and stereopsis.

The illusion of depth obtained from viewing two-dimensional colored targets has been reported for many years and has generally been attributed to some form of chromatic aberration [26]. The most compelling example of seeing depth with colored stimuli is evident in conditions of chromostereopsis. Chromostereopsis is when two colors (generally red and blue or red and green) presented in the same depth plane are binocularly perceived as residing in separate depth planes [18,27-31]. The usual stimulus for the study of chromostereopsis consists of a target with red and blue regions where the red portion is either perceived in front of the blue, called positive chromostereopsis, or behind the blue, representing negative chromostereopsis [28]. Over the years several models have been proposed to explain this effect which include longitudinal and transverse chromatic aberrations [26]. However, recent work attributes most of the effects to transverse chromatic aberrations with possible interactions resulting from the Styles-Crawford effect and pupil decentralization [17, 18, 31-33]. The work from other laboratories have focused primarily on optical factors to explain chromostereopsis while I have demonstrated that depth relations in chromostereopsis involve more than optical effects alone by presenting novel color depth illusions [32,33]. Such effects can explain why we sometimes perceive depth from colored stimuli and sometimes not.

Figure 19 demonstrates in a simplified manner how the TCA from the eyes can generate stereopsis and Figure 20 shows an example of where the effects described by Faubert [32] were first observed.



*Figure 20.* Stimulus example where some of these effects were first observed on a computer screen. Some effectiveness of the stimulus is diminished by presenting it on paper due to the loss of saturation and luminance control. See refs. [17,32,33] for other examples.

#### **7.4 Why are such illustrations important to understand when we actually see or do not see color depth effects?**

Color information is present all around us. We know from previous work that the optics of the eye will refract the different colors on different corresponding points of the retina (disparity) due to TCA. There are many circumstances where two given colors (lets say red and green) are seen on different depth planes while the same colors will be seen as having no depth information in a different context. What generates these different percepts given that the optics should produce exactly the same disparity between the colors on the retina? The studies reported by Faubert [17,32,33] address this very issue. Based on observations and measures, the following factors are particularly important in color depth effects.

##### **7.4.1 Same color on different planes and different colors on the same plane**

The first noticeable difference between the usual conception of chromostereopsis and the present phenomenon becomes obvious when carefully observing the pattern in Figure 1. For clarifying purposes, I will refer the small inner square of the stimulus as the center square, the larger background square as the surround, and the remaining as the background. In a given stimulus, one can observe the same color in a different depth plane and different colors in the same depth plane. In Figure 1, observers generally see

the entire inner square composed of both black and green dots as being on the same depth plane and in turn are on a different depth plane than the red and green surround. The surrounding red and green dots are generally perceived as being on the same depth plane. All the green contained in the image, whether it is from the inner square, the surround and the background is exactly the same green (i.e. identical in chromaticity and luminance). The red and green regions perceived on the same depth plane represent areas where disparity from chromatic aberrations must be present, yet, cannot be used by the visual system. At the same time, the same green is perceived on two separate depth planes, which must be the result of other factors than disparity induced by chromatic aberrations.

#### **7.4.2 A notion of reference plane?**

In stimuli such as Figure 20, the removal and replacing of the black dots with the surrounding color eliminates the perception of depth [32]. Yet, the colors responsible for chromatic aberrations are still present. The black is a reference without which the disparity caused by chromatic aberration cannot be used with natural pupils. However, replacing the black dots with bright white dots produces similar depth perception as when using black dots but the images are generally less distinct because of the polychromatic components of white. Therefore, in these stimuli, the black and white portions (luminance information) must be used as a reference depth plane by the brain. Later manipulations demonstrated that the color of the reference plane mattered little as long as it was distinctly brighter or darker than the red and green. The dots normally perceived as being on a reference plane will be referred to as "reference dots". When the reference dots were removed from the stimuli, none of the six observers reported seeing illusory contours, therefore, illusory contours do not appear to be responsible for this effect.

#### **7.4.3 Spatial configuration effects: dot density and dot size play a role.**

The effect was still visible when the dot density was diminished from 50% to 15%, although, some integration time was required by the observers on initial trials. Most observers could not see the depth when first presented, but after staring at the stimulus for many seconds (in some cases several minutes) the depth effect came back implying some form of mental construction.

There appears to be an optimal dot size to maximize depth. At 1.22 meters, the optimal size of the random dots was two to three pixels (about 3 minutes) for all observers. When the dots were smaller (1 pixel) they became difficult to resolve and the effect was not visible. Increasing the size of the dots quickly decreased the impression of depth. Thus, this phenomenon appears to favor high spatial frequency components (fine details).

Another interesting observation was made in relation to spatial configuration when reference dots (black dots in this case) were placed individually in different places of the surround of Figure 20. In this case the random dots did not merge with the surround but either appeared in front or behind the surround congruent with the perceived depth of the center portion of the stimulus also containing reference dots. The reference dots and the red/green dots do not have to be adjacent to produce the depth effect.

#### **7.4.4 Effect still present with a stereoscope and at infinity viewing distances.**

In an attempt to segregate convergence with the depth effect, identical pairs of slides were made of the display and presented dichoptically with a standard stereoscopic viewer. The horizontal placement of the slides was adjusted for each observer so that the



slides were parallel to each eyes and the image was fused. Under these conditions, all observers saw depth in the way described originally when observing the screen. In addition, the two observers who initially did not perceive depth when observing the computer screen, reported clearly seeing depth in the stereoscope condition. Observers were also asked to view the image when closing one eye and all reported not seeing depth monocularly.

Another way to segregate convergence is to increase viewing distance. A slide of the stimulus was projected on a wall in a large room and shown to five of the observers. The green background was 1.03 meters by 0.8 meters. The surround was 0.66 meters and the center 0.38 meters. All observers reported seeing binocular depth. The observers were asked to move backwards until the depth was no longer visible. All observers except one moved to the very end of the room where the depth was still visible at 12.8 meters. The last observer stopped seeing the depth about 0.5 meters before reaching the end of the room. He reported that the dots of the stimulus were no longer visible thus he couldn't see the depth. The observers, without exception, reported that the perceived depth increased while increasing the distance. The observers were also asked to move forward to determine whether the depth was still visible at all distances. Depth was visible until the four meter mark, where shorter distances produced no depth.

#### **7.4.5 Effect of artificial pupils (size and displacement).**

Images were viewed through 3mm and 1mm artificial pupils by three observers for the computer screen, stereoscope, and wall conditions. The artificial pupils were placed on trial frames positioned very close to the eyes. The horizontal positions were varied from side to side to change the transverse chromatic aberration. Adjusting the horizontal position of the 3 mm pupil changed the perceived depth determining that transverse chromatic aberration has an effect on this perceived depth illusion.

Two of the three observers reported seeing the depth with a 1 mm pupil for all three conditions (screen, stereoscope, and wall). One observer could not see the depth when the stimulus was projected on the wall because the luminance was too low for him to detect the stimulus properly but he saw the depth in the stereoscope and on the screen through 1 mm pupils. Moving the artificial pupils did have an effect on the perceived depth implying that TCA affects perception under this condition.

#### **7.4.6 The influence of TCA**

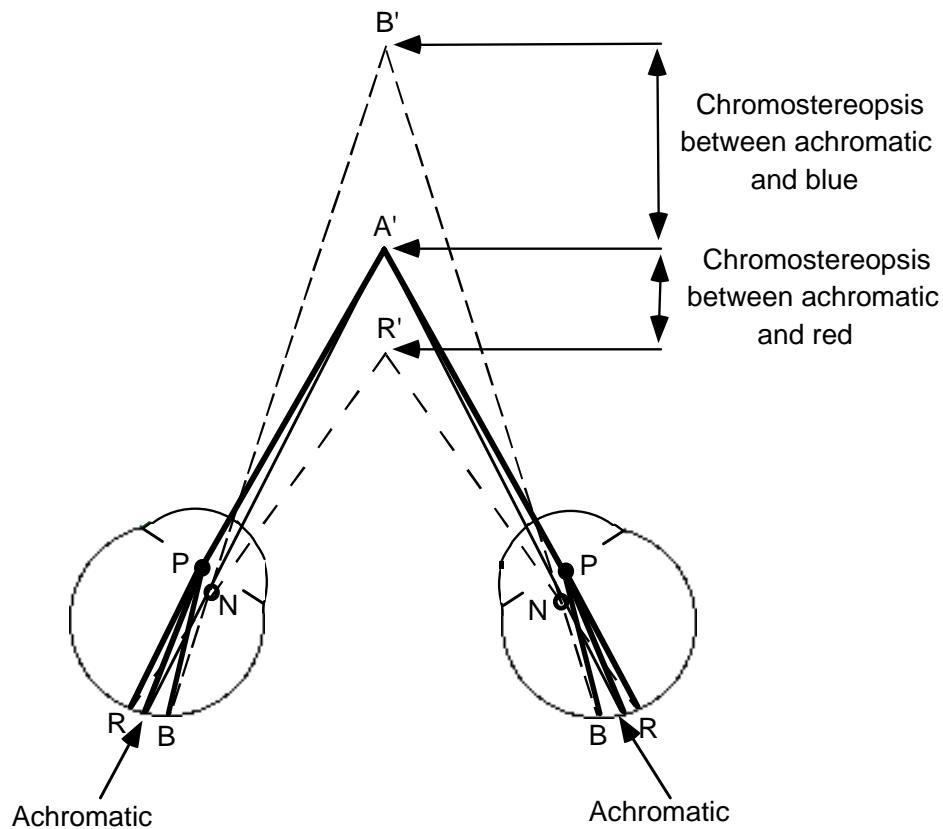
To determine the influence of TCA on these illusions, the effect of displacement of artificial pupils relative to the achromatic axis on the perceived depth was determined. If, as expected from the pilot studies, the perceived depth in this stimulus context is based on TCA then we should observe a relationship between the amounts of displacement of two artificial pupils from the achromatic axis (the achromatic axis represents the optical axis that generates no differences in chromatic parallax between colors). However, if, for the same chromatic conditions, no depth is perceived when the reference dots are absent, we can conclude that the TCA is present but cannot be used by the visual system under this context.

The results clearly supported the notion that the extent of the perceived depth for these stimuli, when reference dots are present, is based on the amount of TCA. However, the fact that under the same pupil and chromatic conditions, but without reference dots, all observers reported that *no depth was perceived* even if the TCA was still induced, clearly

demonstrates that factors other than the TCA alone are essential to explain the perceived depth.

## 8. SEEING DEPTH WITH BLACK AND WHITE AND ONLY ONE OTHER COLOR

Further studies [33] demonstrated that it is not necessary to have two colors of the opposite ends of the spectrum (red and green or red and blue) to perceive color depth effects.



*Figure 21* Model of the lateral displacement of coloured images on the respective retinae and the resulting luminance profile for a positive chromostereopsis condition. Tracing the light rays through the eyes and the relative positions of the red and blue lights on the retinae and the achromatic information. R represents the red light position on the retina and B the blue light position. P represents the pupil entry and N the nodal point. R' and B' represent the perceived depth of the red and blue portions of the image.

Using images such as those proposed by Faubert [32] to facilitate and optimize the detection of chromostereopsis, it was hypothesized that depth should be visible in conditions where only achromatic information and one other color are present in an image. This was done by making assumptions about where the relative position of chromatic and achromatic components in an image should be located on the retinas and,

therefore, where this information should be located in relative depth planes produced by chromostereopsis. Another important assumption presently made is the way the visual system constructs the different depth surfaces. This assumption is based on two properties demonstrated by the visual system when perceiving color depth effects, which have been previously discussed by the author [32]. It was proposed that achromatic (luminance) texture information was often used by the visual system as a reference plane upon which the depth perception is constructed. Furthermore, when the achromatic information was removed from the image, and the other colors were left in, the color induced depth went from very visible to difficult (if not impossible) to perceive. Secondly, that the image information that was embedded in texture information was often perceptually dragged into the same depth plane (capture) even if the optical model predicts that they have different disparity information.

Based on the proposition that gray and black contiguous segments and the gray and blue (or red) contiguous segments in an image should be used as unique surfaces by the visual system, regardless of whether the pupil or other optical sources produce a misalignment relative to the achromatic axis, three predictions were made relative to the depth perceived in images with achromatic light and one other color. 1) Depth should be perceivable with blue/achromatic and red/achromatic images and not require a red and blue portion simultaneously in the image. 2) The depth in the blue/achromatic images should be perceived in the opposite direction than in the red/achromatic images with identical TCA levels and identical pupillary positions relative to the achromatic axis. 3) The perceived depth should be greater for the blue/achromatic images than for the red/achromatic images.

The optical predictions are based on the model presented in Figure 21 and the outcome on the retina of the right eye is illustrated in Figure 22.

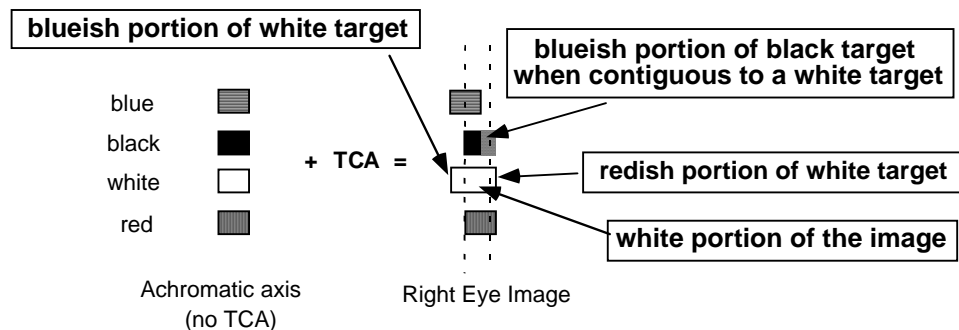
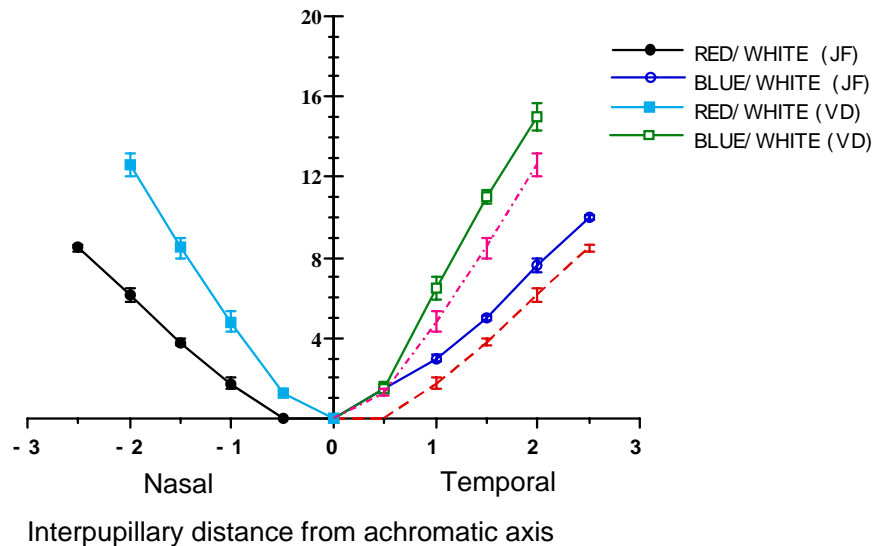


Figure 22. The resulting luminance profiles on the retina for the right eye based on the model presented in Figure 21.

As demonstrated in Figure 22, the action of TCA on a white light target is generally to spread this target. The optical model predicts that the contiguous gray and black portions of the stimulus are positioned between unique blue and red light rays. As argued above, it was hypothesized, that both the gray and black portions together would be used as a unique reference frame to construct the image.

On the other hand, the blue and red elements of the image are shifted in opposite directions relative to the achromatic elements and, consequently, should create opposite

disparities for the same TCA conditions if the achromatic portion is used as the reference plane. Moreover, because the blue light rays in the presence of TCA are situated further from the reference plane than red light rays, magnitude of the perceived relative depth should be greater for a blue/achromatic than for a red/achromatic stimulus.



*Figure 23.* Results of TCA manipulation on the perceived depth for two observers. Notice that to obtain depth in the same direction for the two image conditions, we used nasal displacements relative to the achromatic axis for the red/achromatic condition and temporal displacements for the blue/achromatic position. The red/achromatic results are reproduced by dotted lines on the positive side of the graph for comparative reasons.

The results for the two observers are shown in Figure 23. The horizontal axis represents the amount of displacement from the foveal achromatic axes where negative values are nasal displacements and positive values are temporal displacements. The vertical axis represents the forward perceived depth in mm between the inner square and the surround square as measured by the position of the reference rod. The results clearly support the three predictions made earlier. First, that chromostereopsis can be perceived with achromatic light and a single other color. Second, that the perceived depth is in opposite directions when using blue/achromatic versus red/achromatic for the same TCA levels. Thirdly, that the perceived depth is greater for the blue/achromatic stimuli.

Figure 23 clearly demonstrates that, as the pupillary distance from the foveal achromatic axis is increased, the perceived depth also increases demonstrating the role of TCA in this effect. It was also observed that the inner square of the image was perceived as moving forward with nasal displacements in the case of the red/achromatic images, and was also perceived as projected forward when temporal displacements for the blue/achromatic images were used. When nasal displacements and blue/achromatic images or temporal displacements with red/achromatic images were used the opposite depth effect was produced. That is, the inner square was perceived as being behind the colored surround square on the screen. Figure 23 demonstrates clearly that the perceived

depth for the blue/achromatic condition is generally greater than the red/achromatic condition.

The blue/gray and red/gray images (see ref. [33]) have been shown to many observers under natural viewing conditions and many of these reported seeing depth. Furthermore, when depth was perceived in both images, the observers reported that the relative depth in the images was in opposite directions for the blue/achromatic images and the red/achromatic images and many reported that the perceived depth was greater for the blue/achromatic than the red/achromatic images. Another important point is that the black and gray contiguous elements are always perceived as being on the same depth plane supporting the notion that the brain constructs these elements into only one surface even if the optical model predicts two different disparity values.

The colors generated in the present study were broadband, thus containing other chromatic information, and the achromatic information was composed of the same blue and red elements in addition with a green element. The results obtained under these conditions suggest that the visual system uses the matching dominant wavelengths in broadband color images to establish stereoscopic correspondence.

It is important to realize that, what was proposed in the Faubert [32,33] studies was that optical and perceptual factors are closely intertwined in these phenomena. Neither the optical factors nor the perceptual factors can be taken in isolation to completely explain the color depth effects described. In these studies, a number of concepts have been raised such as the notion of reference plane, perceptual integration time, capture, texture element characteristics etc. These notions attest to the fact that perceiving depth in color images is a multifaceted problem, which must be viewed in a global context in order to fully appreciate these phenomena.

An interesting extension of the optical model predictions is that the gray and black contiguous segments have different disparity information as demonstrated in Figure 1. The fact that this kind of achromatic texture information is never seen as having depth information leads us to two speculations. The first possible explanation is that, because the disparity difference between the gray and black elements is very small, the visual system cannot resolve the difference, or even if the visual system is theoretically capable of detecting the difference, it nevertheless will perceive only one surface a phenomenon known as *pyknostereopsis* [34]. Although this explanation is quite plausible it is not totally satisfactory because, as demonstrated previously, red and green contiguous elements are generally perceived on the same depth plane in natural viewing conditions even if they are quite efficient in producing stereopsis in other parts of the same image. The answer to these questions can possibly lie on how the visual system constructs the different surfaces. One possibility is that the brain generally attempts to construct solid surfaces to make sense of an image with depth information. The visual system may bias against perceiving transparent static images because such images are not frequent in a natural environment. However, under extreme TCA conditions when the disparity between colors is very large, such as when prisms are used, transparent surfaces can be perceived in color images. Perhaps there is a constant struggle between the visual system's natural tendency to construct solid surfaces in depth and the amount of disparity information available in an image.

In the studies by the present author relative to color depth effects, the question of how we perceive such effects in natural environments is always an underlying concern. An extension of this concern involves the following questions: What, if any, is the use of this type of effect in nature? Can animals perceive color depth effects? If so, do predators use this perception to identify preys or do the preys themselves have color characteristics that can help their disguise? It is clear that many animals have some of the basic requirements in order to perceive such effects, that is, they have chromatic dispersion [35] and binocular vision [36]. What is not clear however, is how much TCA is present in different animal types. In any case, it strikes me as quite plausible that animals can perceive color depth effects and that this can in some way be incorporated into the different behavioral schemes which have evolved over the years. An example of a very strong effect that I have observed involves several types of butterflies that have very distinct circle marks on the bottom and sides of the wings, which may appear as two eyes, and can be used as some form of camouflage. What is striking is that these spots can actually appear as being forward or receding in depth giving a remarkable effect of protruding or receding eyes. The color depth effect is clearly involved because the perceived depth from these markings can be reversed or eliminated by displacing artificial pupils nasally or temporally in front of the eyes. I have observed this with the *Precis* type of butterflies (*Precis Rhadama*, *Precis Orythia*, and *Precis Clelia*) and with the *Megisthanes Japetus* butterfly. Here is a possible example where natural selection may have developed these color and texture schemes because it was particularly efficient at producing the illusion of protruding or receding eyes of a much larger organism than the actual butterfly and, as a consequence, keep potential predators at bay.

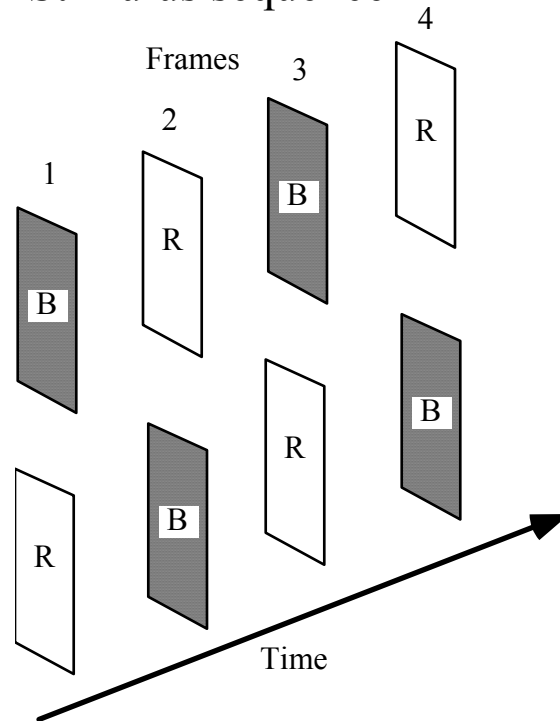
In conclusion, more research is needed in both optical and perceptual aspects to understand the phenomenon in its entirety and to elucidate the whole range of visual experiences produced in color depth effects under natural viewing conditions. Future research will also focus on the role of color and texture patterns, which have evolved in the environment, and what may be the role of such arrangements in the behavioural schemes of the different organisms involved.

## **9. TCA AND MOTION PARALLAX**

If we imagine the scenario presented in Figure 16a, we can deduce that TCA will differ between the colors as we view the lens through different angles. The result will be a difference in perceived velocity between the eyes, which, as we stated earlier, can generate a sense of depth for portions of the image of different colors.

The motion parallax generated by the color of objects in an image can be easily demonstrated. What we have done in the laboratory is use apparent motion to illustrate such effects. Figure 24a shows a simple experimental protocol where the color characteristics of the objects are changed frame by frame (chromatic flicker). The two objects are rectangles vertically aligned with one another. The perceptual experience obtained when no TCA is present is that of up and down apparent motion. However, when enough TCA is present, the perception is lateral motion (see Figure 24b). This effect can be easily reproduced in the laboratory if one looks at the flickering targets through the periphery of the lens or when the stimuli are fixated eccentrically.

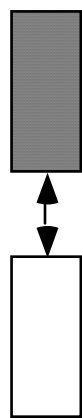
## Stimulus sequence



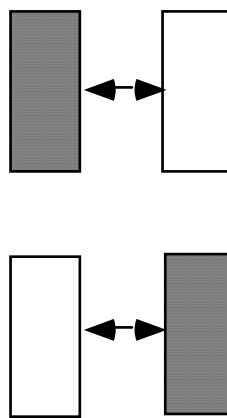
*Figure 24a.* A simple way of illustrating the chromatic parallax effects. Red and blue rectangles are vertically aligned and the colors are alternated with subsequent frames.

## Perceptions

No TCA



With TCA



*Figure 24b.* The perceptual experience when viewing stimuli in Figure 24a differ as a consequence of the amount of TCA. When no TCA is present, the rectangles are perceived as moving up and

down. When TCA is present, the percept is that of lateral movement. This can be observed with eccentric viewing or by looking at angles through ophthalmic lenses.

## 10. EFFECT OF TCA ON COLOR DEFINED MOTION

The role of the chromatic pathway in motion processing has been the subject of some debate [37-51]. Evidence for chromatic motion sensitivity using the motion nulling paradigm has been reported by a number of researchers [37,38,41,52]. For this reason, we decided to directly assess the effect of TCA on chromatic motion thresholds [53].

The operational descriptions of the stimuli are presented in ref. [53] in detail. Essentially, the task consists in opposing an isoluminant (equivalent luminance input for the visual system) red-green (R/G) grating drifting in one direction with an isochromatic (just luminance information) grating drifting in the opposite direction. This generates a perceptual tug-a-war where the winner (isoluminant vs. isochromatic) will dictate the direction of the motion perceived. When the two sinusoidal drifting gratings are perceptually equivalent, the percept is that of a counterphase flicker (no clear direction of motion). This null point is assessed and used to measure the relative strength of the color system to motion perception. The dependent measure is the luminance contrast of the isochromatic grating that is necessary to null the chromatic motion sensation (% equivalent contrast). We manipulated the spatial frequency content of the stimulus (cycles per degree of visual angle or cpd) and the amount of TCA (prismatic diopters or  $\Delta$ ).

The R/G motion thresholds are shown in Figures 25a to 25c for prism base out and 25d for prism base in. The data are plotted as the luminance contrast necessary to null isoluminant gratings (equivalent contrast) on the y-axis and the spatial frequency component of the target on the x-axis. The control data for subject JF showed greater chromatic motion sensitivity than the other two subjects but his values are similar to values previously reported for normal observers [41].

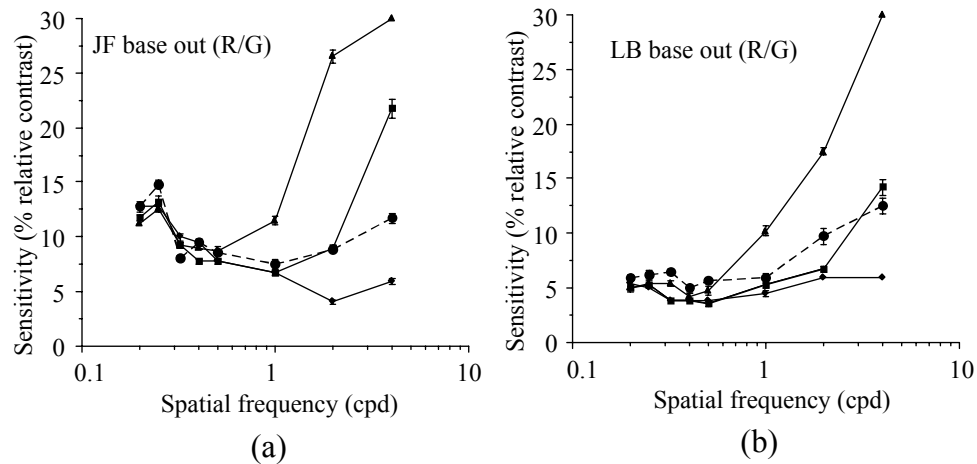
All three subjects show increases in equivalent contrast for R/G motion when the gratings are 1cpd or higher. Subject PS had very low sensitivity, as a result of his deuteranomalous color defect, and then showed dramatic increases in sensitivity with the addition of TCA levels. The data were consistent with our predictions based on the optical effects of TCA in that increasing levels of TCA should produce increases in chromatic motion-nulling equivalent contrasts as a result of luminance inhomogeneities produced by phase shifts. Furthermore, the data also show that for a given TCA value the effect is greater with increasing spatial frequency. All the data for a given TCA increase dramatically with increasing spatial frequency above 1 cpd. The only two exceptions are the values for JF and LB (base in condition) for the highest spatial frequency in the 0.40 $\Delta$  prism condition. However, this is an artificial ceiling effect as the maximum equivalent contrast available in the computer program was 30% for the parameters that we used. An interesting result is the fact that, for two of the observers (JF and LB) the 0.11 $\Delta$  condition produced lower sensitivities at high spatial frequencies than the control condition. It is possible that this effect is due to the naturally occurring TCA of the eye being offset by induced TCA in the opposite direction, thereby producing lower sensitivity values. To test this hypothesis, we retested subject LB who, based on the results, appeared to have the highest level of natural TCA (as evidenced by the highest increase in equivalent contrast values between conditions 1 cpd and 4 cpd) with the base of the prism facing in the opposite direction. According to the hypothesis mentioned above, the sensitivity



should now be increased in the  $0.11\Delta$  and  $0.22\Delta$  conditions relative to the control condition. Results are shown in Figure 25d and the data are just as predicted where the  $0.11\Delta$  and  $0.22\Delta$  conditions now produced chromatic motion sensitivities which were greater than the control condition, demonstrating some form of additivity between the naturally occurring TCA and the induced TCA. This supports the notion that naturally occurring TCA may produce decreases in chromatic motion thresholds when using the motion nulling paradigm.

## 10.2 Higher spatial frequency effects:

The reason that higher spatial frequencies are particularly affected by TCA is illustrated in Figure 26 where we simulated the effect of TCA on sine waves composed of different spatial frequencies. Figures 26a and Figures 26b simulate the presumed isoluminant conditions, with the remnant luminance profiles (dotted lines), for the 1 cpd and 0.25 cpd spatial frequency condition respectively. Notice that under perfect isoluminant conditions (when no TCA is present) the remnant luminance should theoretically remain at zero over space and time. For simulation purposes and for sake of simplicity the isoluminant gratings are presented as having the same physical luminance values. In reality these values would differ between individuals but the relative luminance artifact produced by a given level of TCA would be of the same magnitude as that presented in the model for each observer.



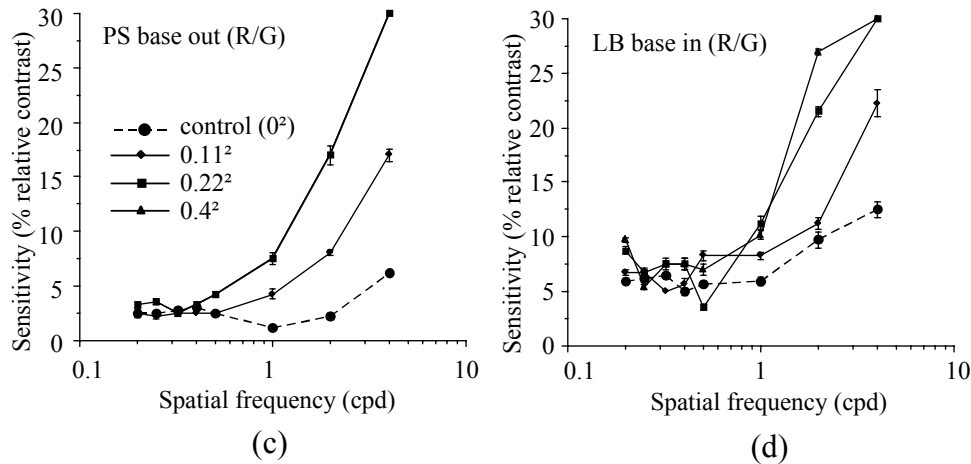
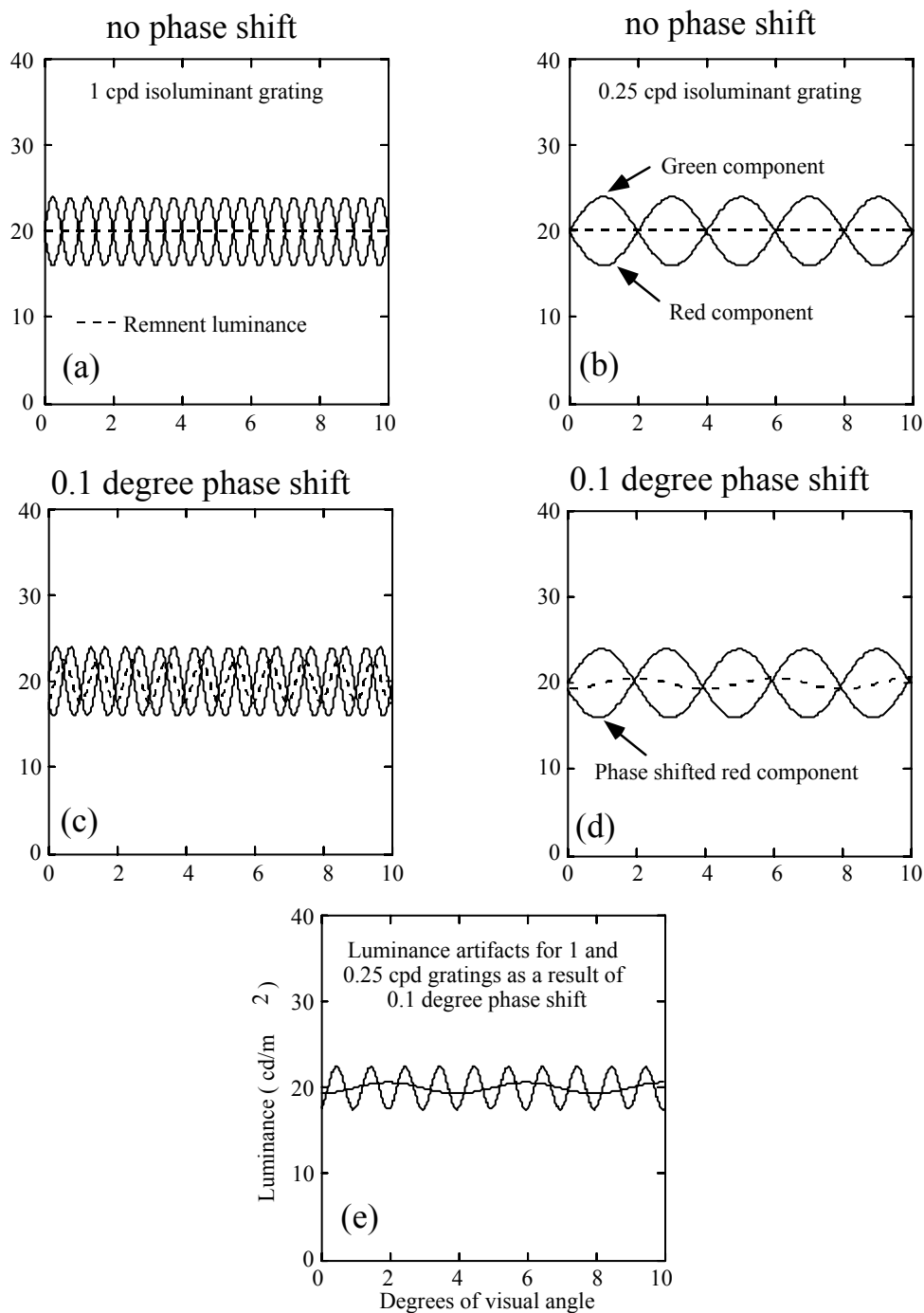


Figure 25. Relative sensitivity in percent contrast for isoluminance R/G gratings as a function of spatial frequency and amount of TCA (a) for subject JF, (b) for subject LB and (c) for subject PS for prism base out conditions and (d) LB for prism base in.

Figure 26c demonstrates that for high spatial frequencies, the relative shift of 0.1 degrees (which is roughly equivalent to the phase shift produced by the  $0.22\Delta$  condition) of the R sine wave as compared to the G sine wave in an isoluminant R/G grating, produces a large luminance contrast artifact as evidenced by the luminance profile generated from the sum of the two sine waves. Conversely, Figure 26d shows why the same TCA value could produce relatively small effects on lower spatial frequency isoluminant gratings. In this case the luminance contrast necessary to oppose the chromatic grating would be very small if the motion signal came only from the luminance artefact. In the case of high spatial frequencies however, the luminance contrast of an isochromatic grating would require a relatively high luminance contrast just to null the motion sensation generated from the luminance contrast artefacts produced by TCA. Figure 26e directly compares the luminance contrast artefacts which would be produced by a 0.1 degree phase shift in the two spatial frequency conditions simulated. It is clear from this illustration that the result on sensitivity values when using motion nulling to measure chromatic motion sensitivity would differ dramatically for the same phase shift conditions but with stimuli of different spatial frequencies.

Results show that a careful control of induced and naturally occurring TCA is necessary when measuring chromatic motion sensitivity at isoluminance for spatial frequencies above 0.5 cpd for R/G stimuli. We can further conclude that chromatic motion sensitivity throughout the visual field can be measured with motion nulling providing that the spatial frequency components of the stimuli are low enough and are scaled with eccentricity [37,38]. Finally, the chromatic motion-nulling paradigm may provide a very sensitive functional measure of natural and induced TCA. Measuring TCA is a difficult problem particularly in the visual periphery. Perhaps one can exploit the use of motion sensitivity in the peripheral vision to determine the amount of TCA that is present with increasing eccentricity.



*Figure 26.* Simulation of colour and luminance profiles for sinewave gratings under experimental isoluminant conditions. (a) The colour gratings (solid lines) and the remnant luminance (dotted line) for a 1 cpd stimulus when no TCA is present. Notice that the remnant luminance is flat. (b) The colour gratings and the remnant luminance for a 0.25 cpd stimulus when no TCA is present. (c) The colour gratings and the remnant luminance for a 1 cpd stimulus when a 0.1 degree TCA-

induced phase shift is present. Notice that the remnant luminance function has a sinusoidal waveform. (d) The colour gratings and remnant luminance for a 0.25 cpd stimulus and a 0.1 degree TCA-induced phase shift is present. (e) A direct comparison of the remnant luminance artefacts produced as a result of the 0.1 degree phase shift for both simulated spatial frequency conditions. Notice that the luminance contrast artefact for the 1 cpd condition is much larger.

## 11. GENERAL DISCUSSION

In summary, we have described in general terms what is meant by motion parallax and we have contrasted its performance with stereopsis by illustrating studies performed in our laboratory. We have also raised issues on how optical conditions may influence our perception of depth with motion parallax and, finally, we have discussed circumstances of conflicting situations that may arise between the motion parallax information perceived from the two eyes.

The attempt was to present some issues which have received little attention in the motion parallax literature and that have practical and theoretical applications. From the issues raised above, we can conclude that several future research orientations are imperative for us to better understand how motion parallax cues to depth can be affected in our day-to-day situations.

- 1) First more research is required relative to the role of motion parallax throughout the visual field, in particular areas where stereoscopic cues become inefficient. Several studies by Regan's group have assessed the processing of stereomotion throughout the visual field [54]. They found that stereomotion visual fields are in fact quite restricted to the central portion of the visual field (20 degrees or less). We still need to know how well motion parallax can be used to perceive depth at different locations of the visual field, as there are many known asymmetries for different perceptual tasks [37,38,55-58].
- 2) We also need to better understand how optical corrections such as progressive addition lenses, and other optical corrections, influence our motion parallax judgments. As demonstrated above, the majority of us will require ophthalmic lens corrections as we go beyond 40 years of age. All of us will be faced with distortions and aberrations that will directly influence how we perceive motion parallax in our daily operations.
- 3) Finally, we need to further study the binocular integration of motion parallax, particularly in the circumstances where the motion parallax between the eyes may give rise to conflicting cues as illustrated above.

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