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Motion parallax, stereoscopy, and the perception of depth: Practical and theoretical issues

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ABSTRACT

This paper deals with practical and theoretical issues related to motion parallax. Motion parallax implies that the perception of depth can be extracted from a temporal sequence of images that contain different perspectives. The present paper will focus on the relative effectiveness of motion parallax as compared to stereoscopic depth perception. It will be argued that motion parallax alone will generate a strong sense of depth, even in the absence of stereoscopic cues. Two 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 the effect of optical distortions and how such distortions can influence motion parallax from a viewer's perspective will follow. Particular emphasis will be placed on the optical distortions produced by progressive addition lenses used to correct for presbyopia. Finally, research avenues will be proposed to answer some of the theoretical and practical issues related to motion parallax in our daily activities.

Keywords: Motion parallax, Stereopsis, Depth perception, Optical distortions, Ophthalmic corrections, Progressive addition lens

1. INTRODUCTION

The purpose of this paper is to illustrate the importance of motion parallax on judgments of relative depth in our daily activities and discuss factors that may impact on this judgment. I will first discuss some basic properties of motion parallax and follow with an analysis on how this cue can be disturbed or distorted in natural viewing conditions. This is not a classic review of the literature as there have been good recent reviews on the subject[1]. Rather, I will try to raise some practical and theoretical issues that have received very little attention in the scientific literature but are of critical importance in our daily functions.

1.1 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

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the visual image on the retinas, known as motion parallax, is used by the visual system to generate a sensation of depth[2,3]. 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.

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.[2,3]

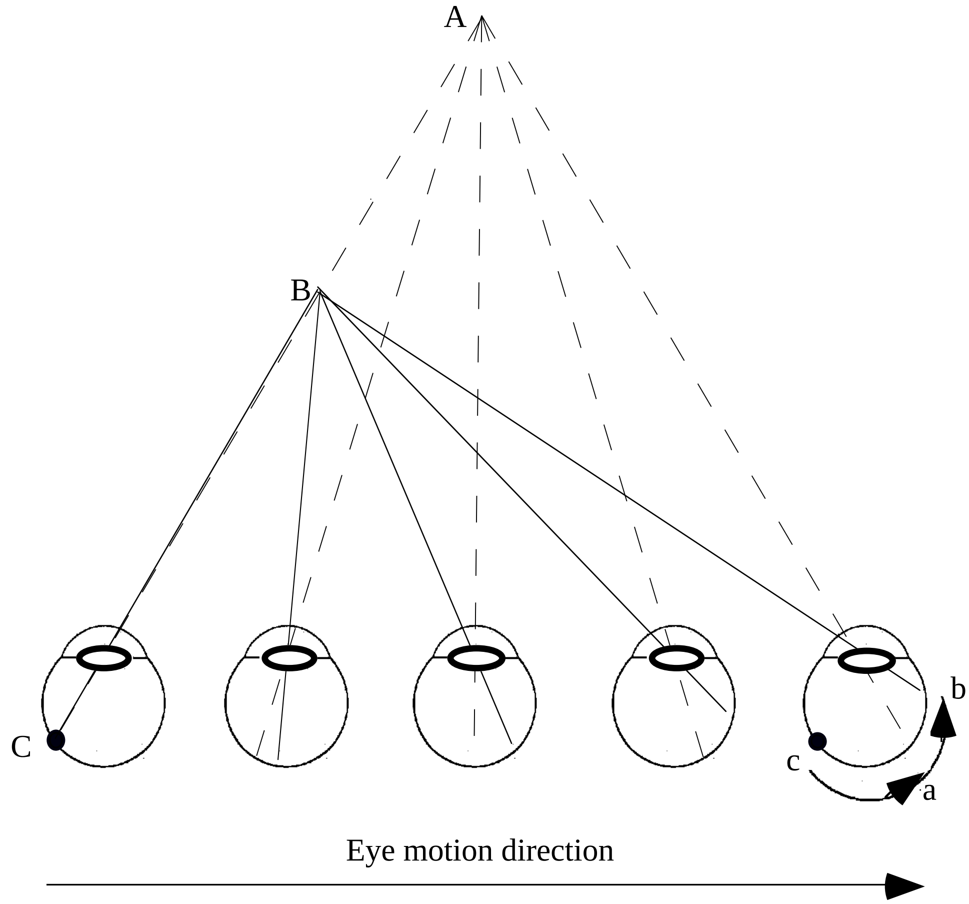

Figure 1. Illustration of motion parallax generated by two points in depth. Point A is distant from the eye while point B is closer and on the same visual axis. As the eye moves from left to right, the projected points a and b on the retina are dissociated because of their respective geometry. The consequence 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.

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.

2. 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 for the purpose of this paper) demonstrates this point.

2.1 Study 1:

2.1.1 Experiment 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.

Methods

Subjects:

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.

Apparatus:

The apparatus was an automated version of the original two rod stereoacuity test by Howard.[4] Two black stainless steel rods (diameter 4.5 min arc at 63 cm) were attached to a small hub which was mounted at the top end of a servo-motor shaft. The axis of rotation of the shaft was vertical and both rods were parallel to this axis and to each other.

The rods were diametrically opposite with respect to the axis. When they were in the subject's frontoparallel plane, the gap between them was 17 min arc when viewed from the test distance of 63 cm. Test disparities were produced by rotating the shaft so that one rod was nearer to the subject. The motor shaft was rotated to give the desired disparity with either the left or the right rod nearer to the subject. Shaft position was monitored by an optical encoder attached to the bottom end of the shaft. Under computer control, the shaft could be rotated to any angular position in increments of 10.8 min arc. By this means, disparities could be presented in increments of about 0.35 sec arc. At startup, the zero disparity position was established by means of an electro-optical limit switch.

The central part of the rods was seen through a rectangular window (1.8° wide by 1.0° high) in a flat metal screen (21° by 21°) which was painted matte white (luminance 45 cd/m^2). The surface of the screen was 15.5 mm in front of the shaft's axis. A black electro-mechanical shutter was mounted at the window on the rod side of the screen. The background screen, against which the rods were seen in silhouette, was 81 mm behind the shaft's axis and had a luminance of 37 cd/m^2.

After the shutter opened, the subject indicated the nearer rod by means of two switches; one for left rod nearer and the other for right nearer. A valid response was made between 0.23 seconds after the shutter opened and 2 seconds after shutter closed. 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

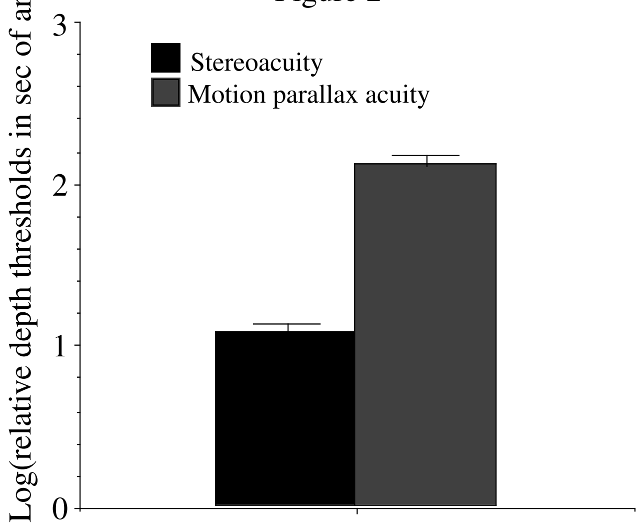

Figure 2. Results of Experiment 1 in Study 1. Mean Log depth acuity thresholds in seconds of arc as a function of the testing conditions for the same subjects. The dark column represents the stereoacuity thresholds while the shaded column represents the motion parallax acuity thresholds. The error bars show the standard error of the mean for each condition.

Results:

The results are summarized in Figure 2 where we can directly compare the steroacuity 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.

Discussion:

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. If 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.

2.1.2. Experiment 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. 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.

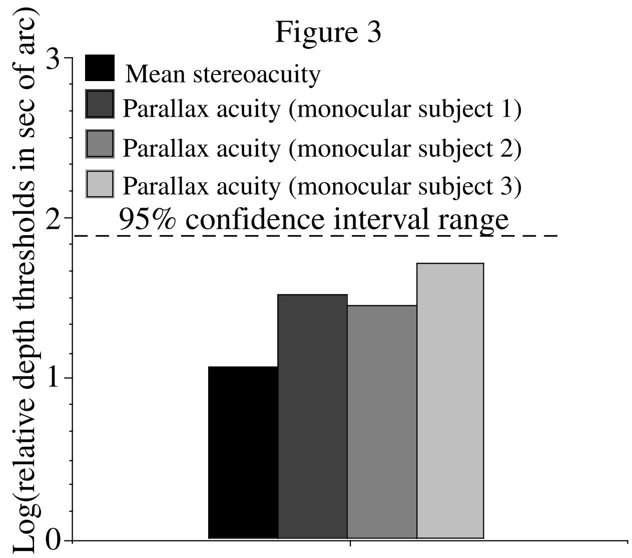

Figure 3. Results of Experiment 2 in Study 1. Log depth acuity thresholds in seconds of arc as a function of the testing condition. The dark column represents the mean stereoacuity thresholds for the normal group while the shaded columns represent the motion parallax acuity thresholds for the three monocular observers. The dashed line corresponds to the upper limit of the 95% confidence range for the normal observers.

3. INTERACTIONS BETWEEN MOTION PARALLAX AND STEREOSCOPY

3.1 Study 2: Experiment1 & 2

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[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.

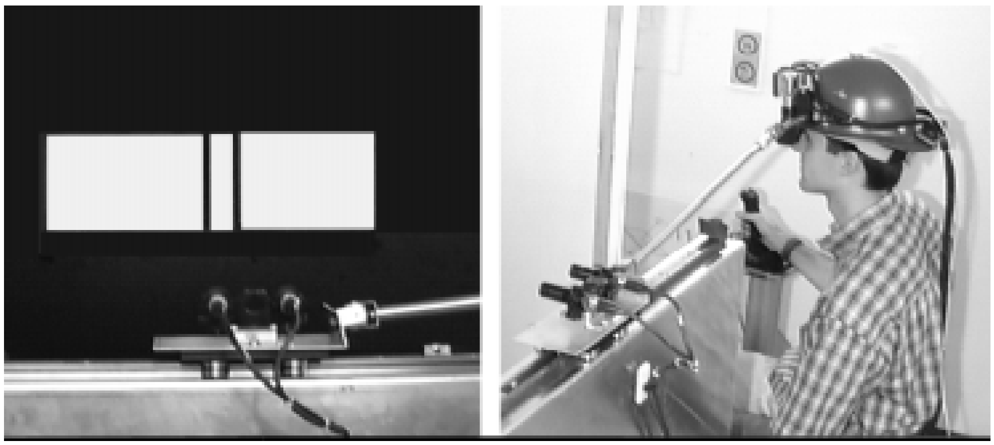

Figure 4. Experimental setup used for Study 2. Right image shows the subject with virtual reality helmet and the cameras used for viewing the image. The cameras were yoked to the head movements by being placed on a sliding platform. A steel rod attached the sliding platform and helmet. The left image shows the view from the cameras' perspective. See text for details.

Method:

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.

Subjects:

Five subjects (one female and four males) with an age range between 22 and 36 years participated in the first study and five subjects (two females and three males) participated in the second study. All subjects had normal or corrected-to-normal visual acuities of 6/6 and had a 20 second of arc streoacuity as measured by the Randot test.

Visual display:

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.

Procedure:

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 two vertical rods were 2.5 cm wide, 71 cm in height and were positioned 20.3 cm apart. On each trial the right rod was randomly positioned at different distances in front or behind the reference rod. The amplitude of the lateral displacements was 20 cm delimited by an auditory cue. Only translation movements were possible. There was no convergence of the cameras. The subjects ran a practice sequence prior to testing. Six trials were carried out for each of four conditions. The four conditions 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.

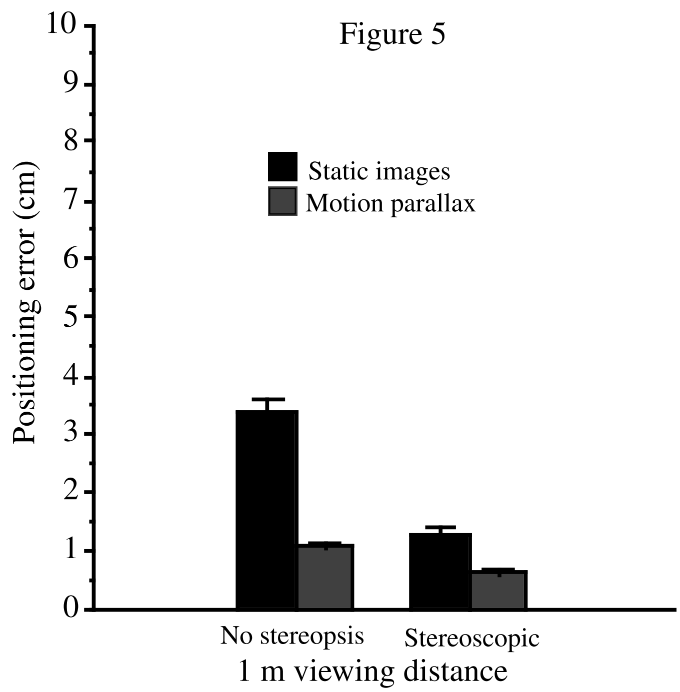

Figure 5. Results of Experiment 1 of Study 2. Relative positioning error in cm as a function of experimental conditions for the 1 m viewing condition. The dark columns consist of the data obtained when the images contained no motion while the shaded columns correspond to the conditions containing motion 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.

Results:

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.

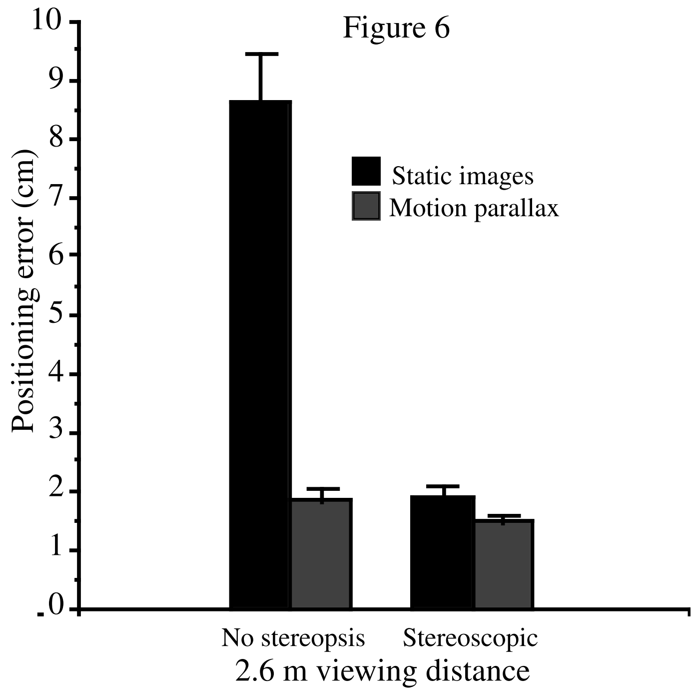

Figure 6. Results of Experiment 2 of Study 2. Relative positioning error in cm as a function of experimental conditions for the 2.6 m viewing condition. The dark columns consist of the data obtained when the images contained no motion while the shaded columns correspond to the conditions containing motion 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.

Discussion:

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 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]

3. 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'.

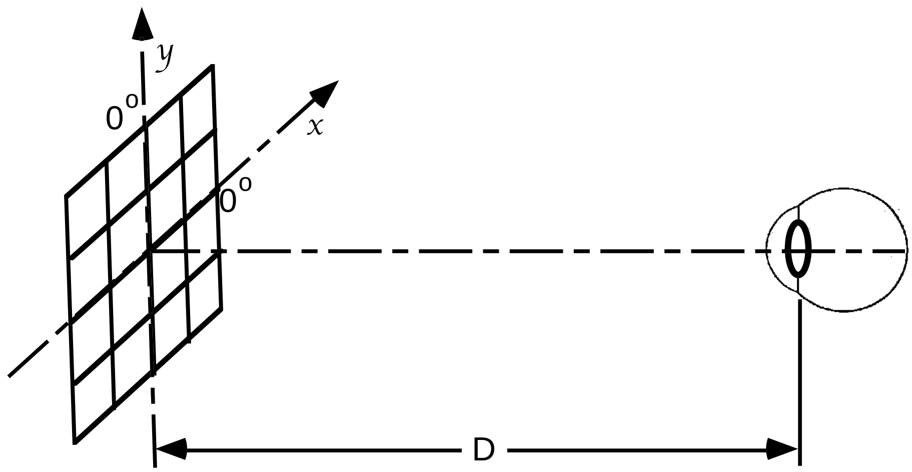

Figure 7. Standard viewing condition and image grid used to generate the optical model projections of distorted images as a function of lens type and correction.

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.

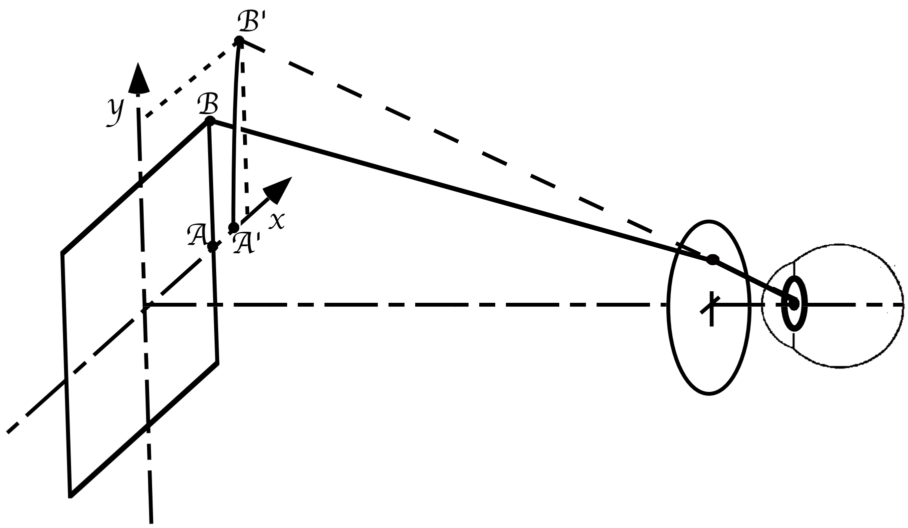

Figure 8. Example of the distortion produced by a positive spherical lens from a viewer's perspective. Edge B-A is now projected as the curve B'-A'. It is assumed that fixation is perfectly lined up with the reference optical axis of the lens which in turn is perfectly aligned with the center of the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

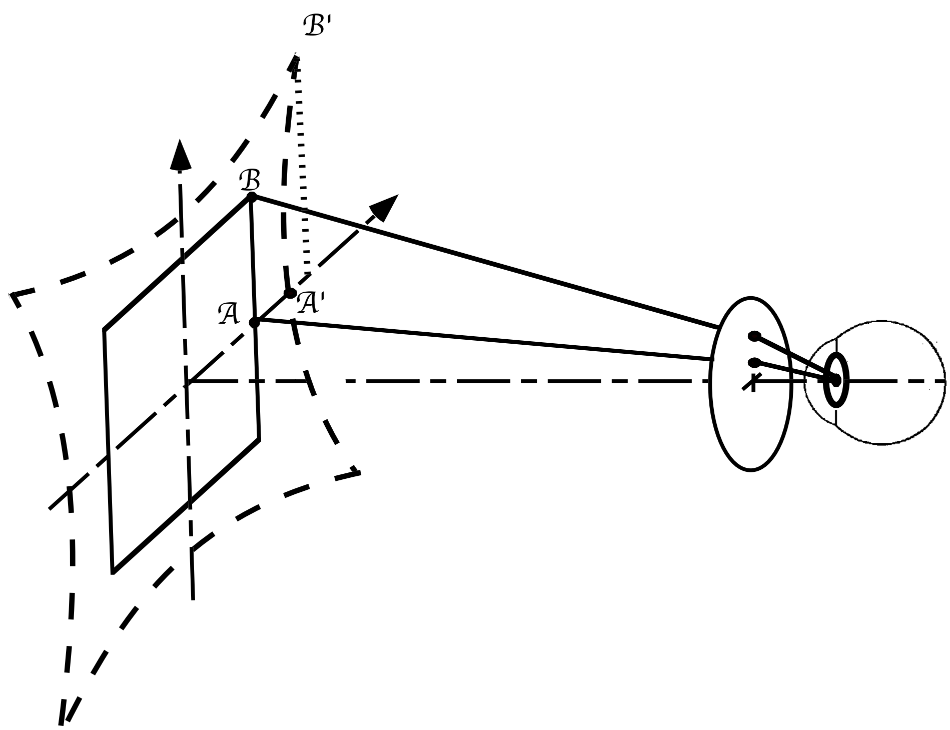

Figure 9. Example of the model projection of all four edges when seen through a positive spherical lens. See text for details.

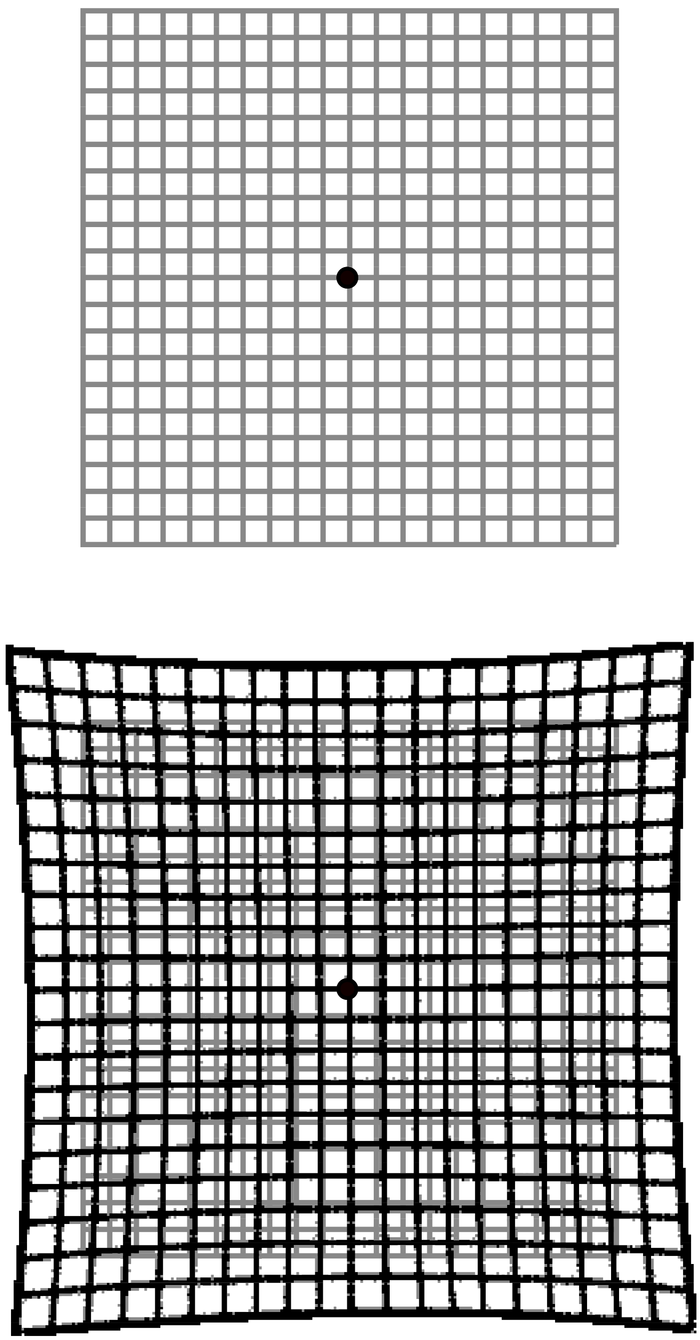

Figure 10. The top image shows a front view image of the image grid without lens distortion (light gray). The bottom image reproduces the non-distorted grid superimposed by a front view projection of the distorted image from a positive spherical lens. The black dot in the center of the image shows the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

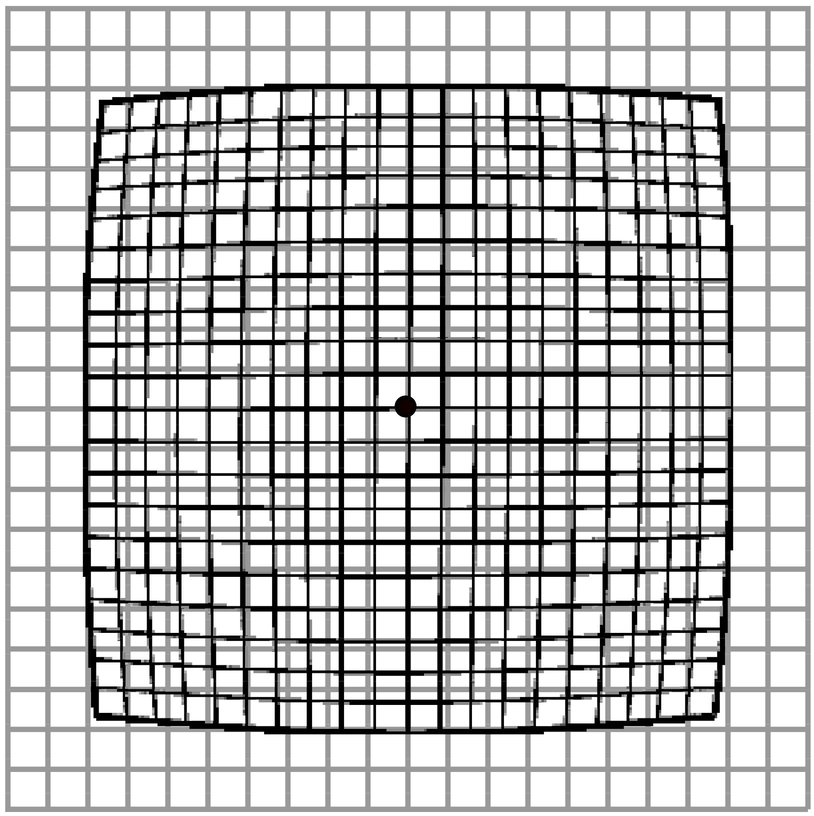

Figure 11. The non-distorted grid presented in Figure 10 (top image) superimposed by a model projection of a minus spherical lens.

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].

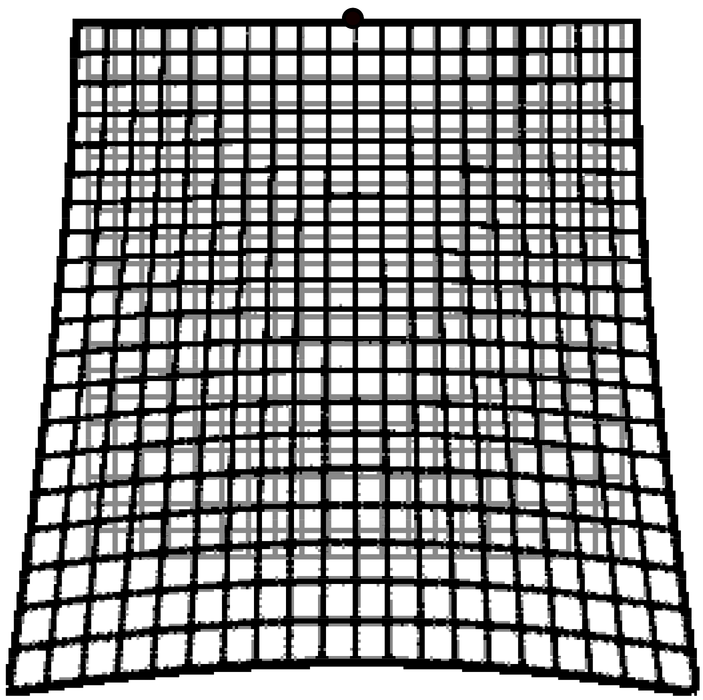

Figure 12. Standard grid superimposed with a model projection calculated for a typical progression addition lens. The black dot at the top of the image grid shows the fixation point and the reference axis of the lens. Notice that the distortion from a viewer's perspective is in the lower visual field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

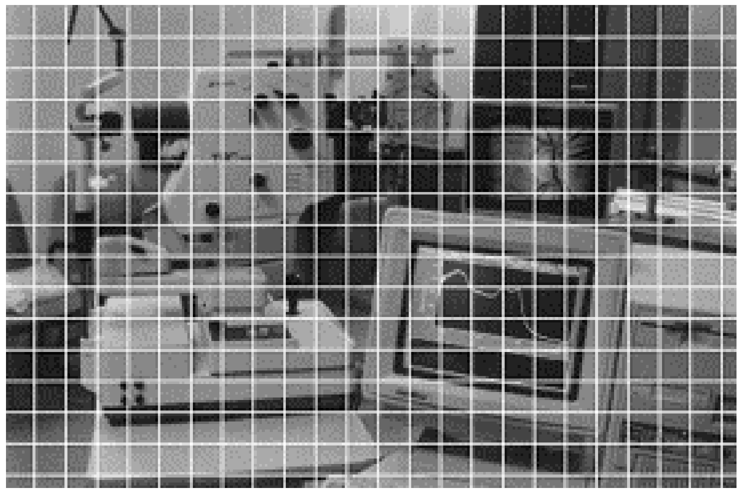

Figure 13. Image and grid used for the simulations of the optical distortion model.

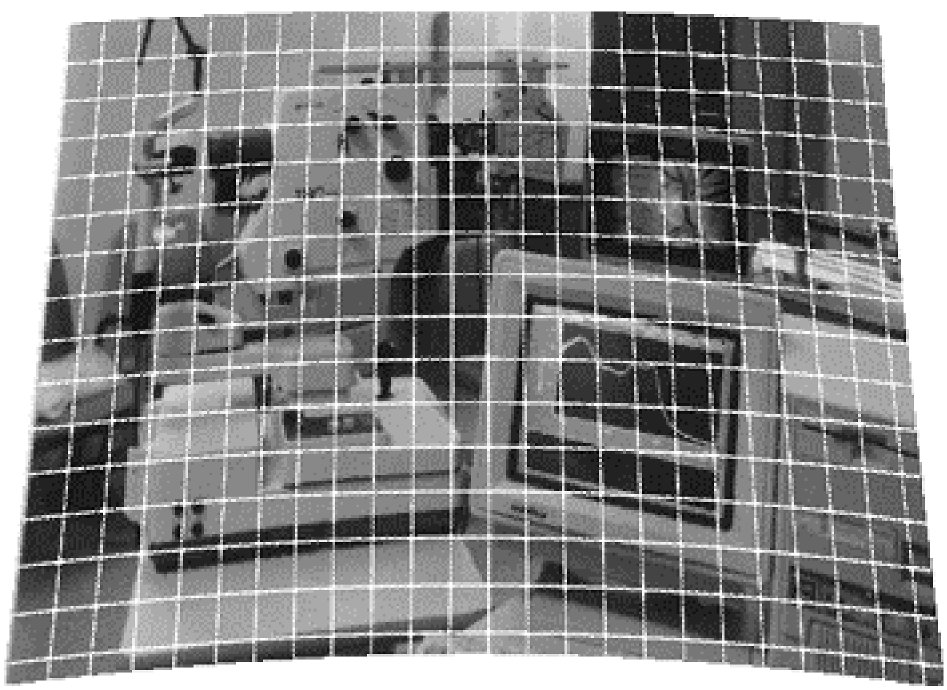

Figure 14a. Simulation of the optical distortions produced by a progressive addition lens. The entire grid image distorted by the lens.

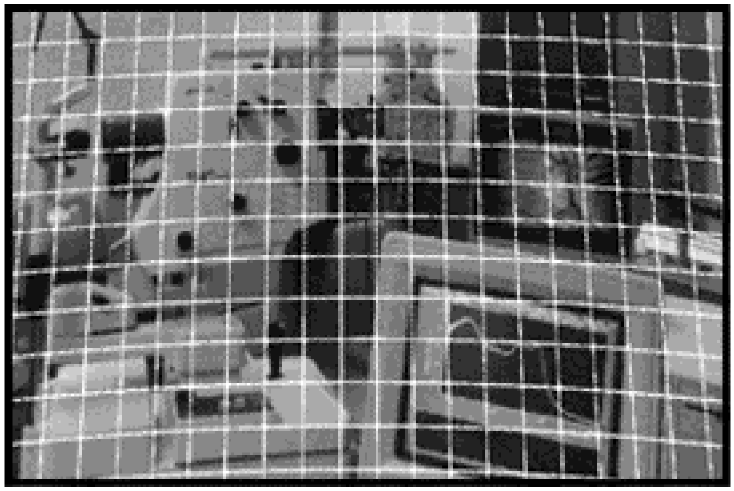

Figure 14b. Simulation of the optical distortions produced by a progressive addition lens. The resulting portion of the image in the same visual field area of the original image.

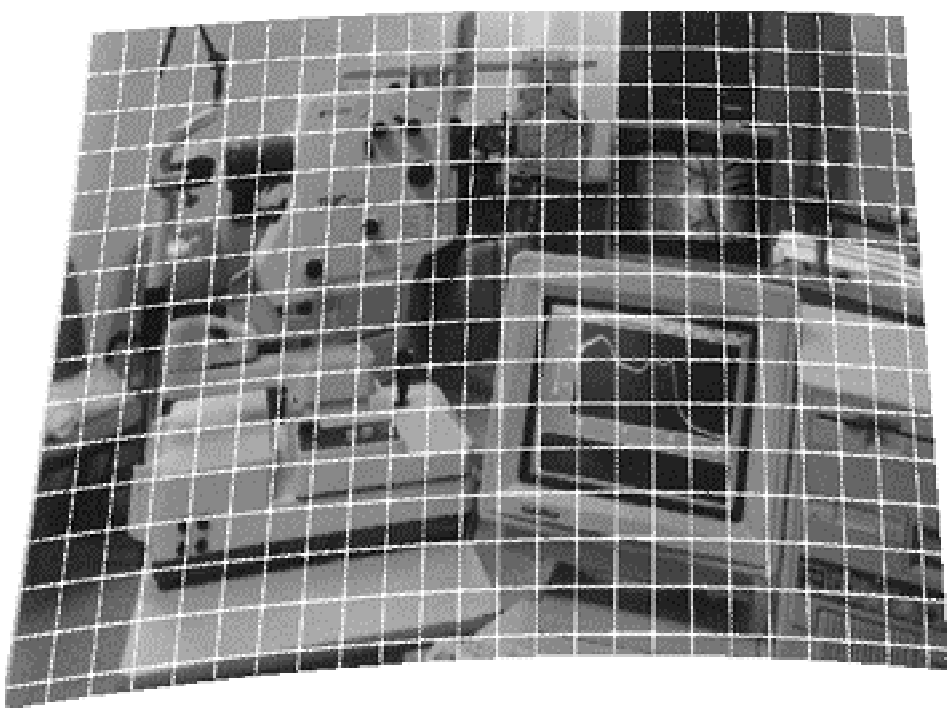

Figure 15a. Simulation results of the distortion model when the observer maintains fixation on the same point of the image but moves the head away from the image (See Figure 16a). Simulation results when head is moved rightward.

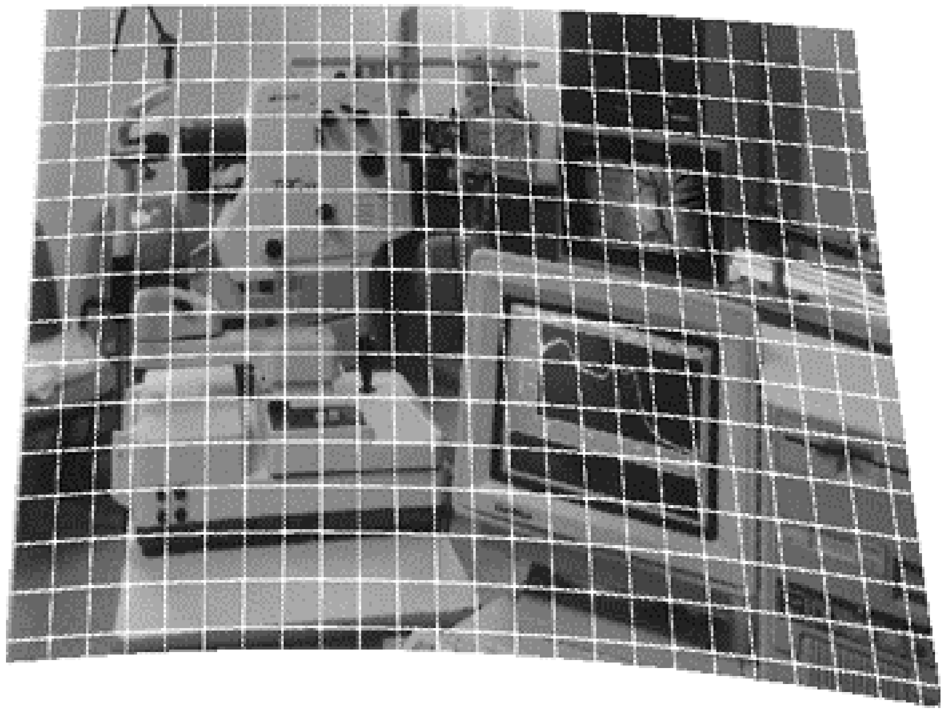

Figure 15b. Simulation results of the distortion model when the observer maintains fixation on the same point of the image but moves the head away from the image (See Figure 16a). Simulation results when head is moved leftward from the fixation target.

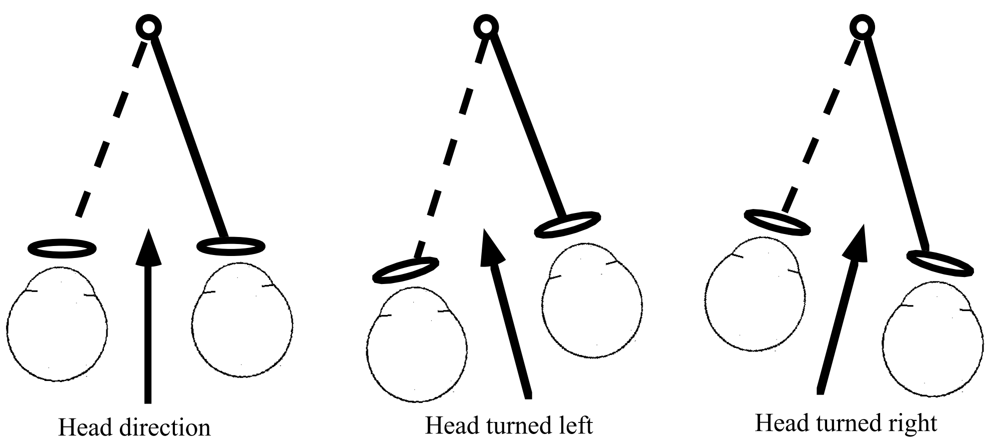

Figure 16.a Example of how maintaining fixation while moving the head will generate difference incidence angles relative to the lens for each eyes.

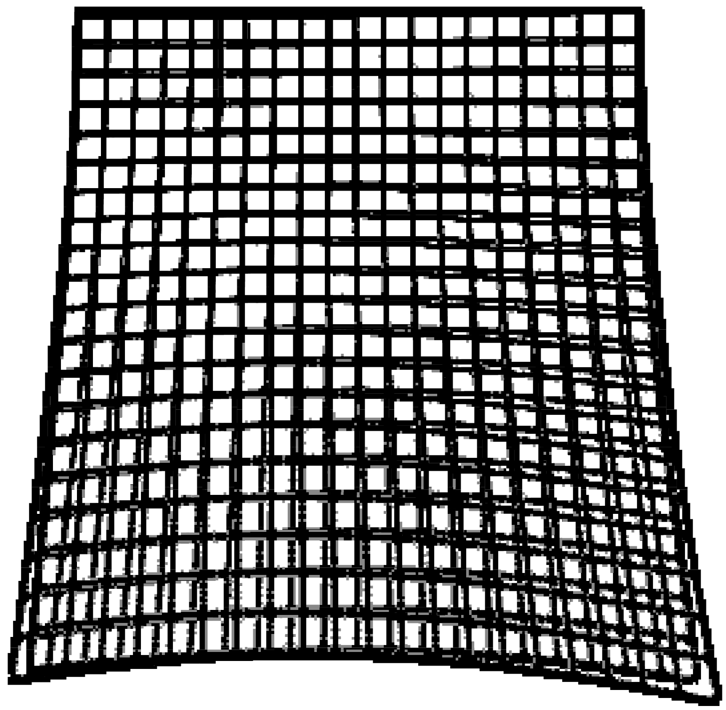

Figure 16b. Model results showing phase differences for a given position of binocular oblique viewing. These phase differences will vary with the angle of the head relative to the fixation point, resulting in differences in perceived velocities between the two eyes.

4. 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.

5. OTHER SOURCES OF DISCREPANCIES IN MOTION PARALLAX

Yet another factor may generate discrepancies between the motion parallax perceived by the two eyes that originates from the refractive properties of different wavelengths. Two sources of chromatic aberration are present in the human eye; longitudinal (LCA) and transverse chromatic aberrations (TCA).[17-19] The first relates to the fact that different colors are not focused at the same point in depth and the second corresponds to situations where two colors are displaced laterally relative to each other. Because the viewing angle of each eye is different, the lateral displacements of the colored rays will also differ between the eyes. Figure 17 demonstrates how these differences can occur between the eyes and it is known that the disparity created in such context can generate color depth effects or chromostereopsis.[20,21] Recent studies have shown that induced TCA will produce changes in perceived motion in motion nulling experiments.[17] TCA can be produced by a natural decentration of the pupil relative to the achromatic axis or by prismatic effects from ophthalmic lenses (when light rays enter at different angles). The second case is particularly evident as we stare sideways through a refractive lens. 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.

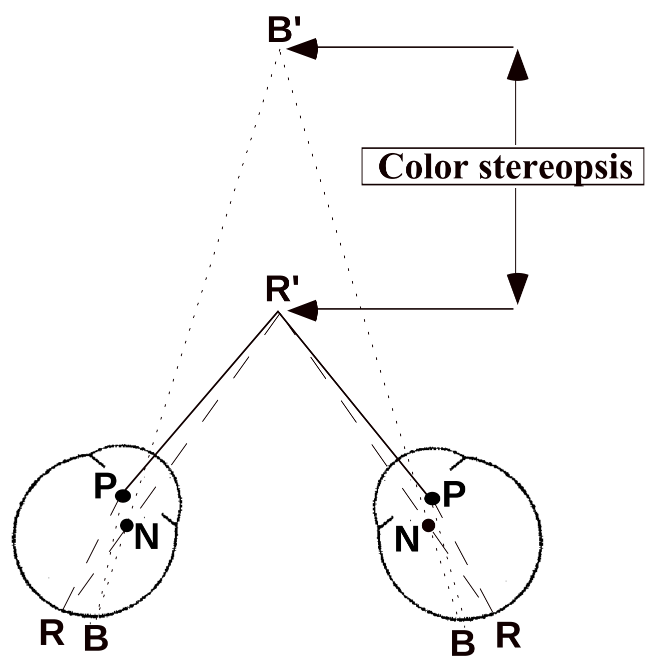

Figure 17. Illustration of how chromatic parallax (TCA) can induce color stereopsis. The image is focused at point R'. The rays of the red and blue portions of the image are displaced at different angles on the retina producing retinal disparity between the eyes.

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 18a 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 oneanother. 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 18b). 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.

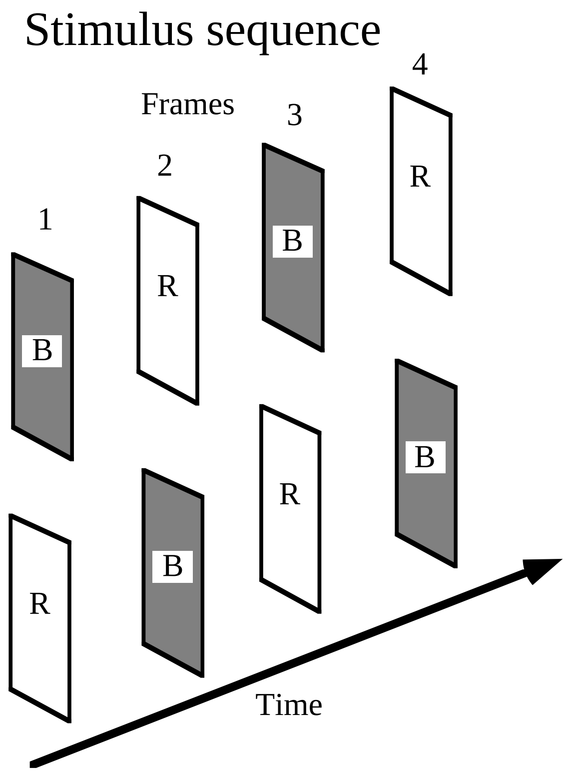

Figure 18.a A simple way of illustrating the chromatic parallax effects. Red and blue rectangles are vertically aligned and the colors are alternated with subsequent frames.

6. 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.

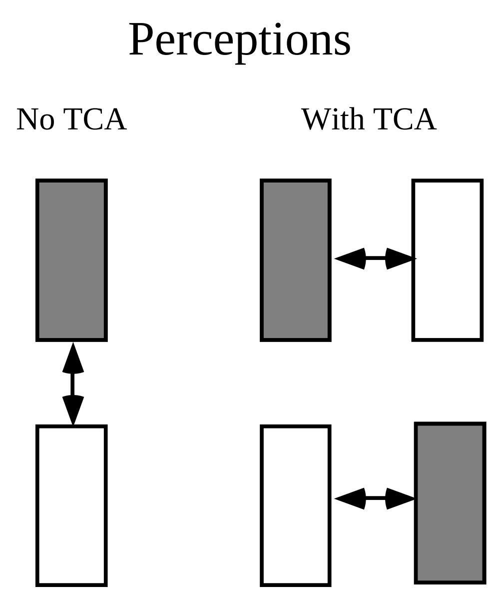

Figure 18b. The perceptual experience when viewing stimuli in Figure 18a differ as a consequence of the amount of TCA. When no TCA is present, the rectangles are perceived as moving up and down. When TCA is present, the percept is that of lateral movement. This can be observed with eccentric viewing or by looking at angles through ophthalmic lenses.

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.[1] They have 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.[22-27]

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 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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