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BINOCULAR VISION SKILLS IN HUMAN OBSERVERS

By

Heather Ajzenman

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ABSTRACT

Binocular vision, the ability to see and merge the information from the two eyes, is the foundation for viewing our three-dimensional world (Hubel, 1995). However, up to 21% of the population may have binocular vision anomalies that impede basic skills such as reading and driving (Hokoda, 1985). Since a person can have 20/20 eyesight even with poor binocular vision, many people are unaware that problems they may have with daily tasks result from their vision. I used eight optometric tests such as the Stereo Fly, random dot stereograms, polarized vectograms, and the Brock string to probe various binocular vision skills in the general Mount Holyoke population. The test results indicate that people vary in the way they weight contextual and retinal disparity cues in interpretation of depth. Three out of 30 non-symptomatic participants showed subnormal stereoacuity which was linked to poor performance on the other optometric tests.

The second portion of my research focused on the variation of binocular skills among individuals with stereovision weaknesses, consisting of participants with diagnosed visual problems, such as strabismus, and participants with complaints of visual deficits, such as double vision. The binocular anomalies group was tested under the same conditions. The results from these participants were compared to the range of visual skills in the non-symptomatic group.

INTRODUCTION

People view the world in depth through monocular and binocular cues. Monocular depth cues can be seen with only one eye whereas binocular depth cues depend on the use of two eyes. Depth perception varies person to person in part because of the way people combine monocular and binocular cues. This ability to combine the cues is dependent on one's ability to use the two eyes. Up to 21% percent of the population may have subnormal stereoacuity skills (Hokoda, 1985), and this can impact daily skills such as reading and driving. This study looks at this range of skills in human observers and hypothesizes that there will be a significant variability in binocular vision skills.

Monocular Cues to Depth Perception

Monocular depth cues depend upon assumptions made about the three dimensional world obtained from a two dimensional image. Six important cues to monocular perception are occlusion, size and position, aerial perspective (haze), linear perspective, motion, and the effects of light and shadowing. Occlusion (Fig. 1) is a cue to depth based on the relative position of objects. If a particular object's view is obstructed by a second object, the observer can infer that the second object is in front of the first. Occlusion is considered a non-metrical depth cue as the relative size cannot be determined but only the relative ordering and differences between the objects.

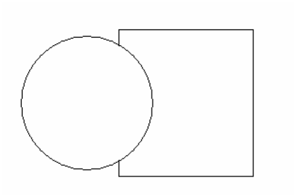


Fig. 1: Drawing of object occlusion.
The square's view is obstructed by the circle, so it is assumed that the circle is in front of the square.

Size and position cues are based on two related monocular cues, relative size and relative height. Relative size and height of objects are compared without knowing the exact size of each individual object. This monocular cue is based on the organization of objects in space when applied to a two dimensional plane, such as a piece of paper, and is expressed through a texture gradient. The texture gradient is based on objects of the same size forming smaller retinal images when further away, so a change of size of an object across the page gives a percept of depth. Since smaller objects are thought to be further away, the placement of large objects at the bottom of the page and smaller object as the top of the page creates a perception of a ground that moves back into the distance (Fig. 2).

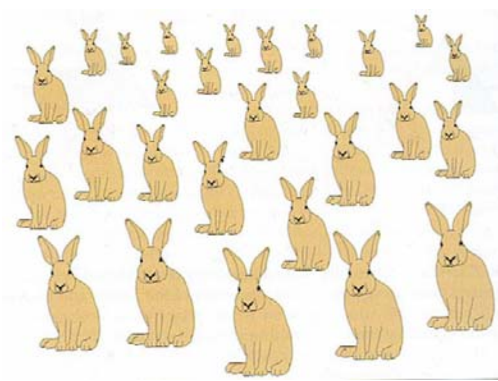


Fig. 2: Relative Size and Position Cues (Wolfe et al. 2006)
A texture gradient is illustrated by the arrangement of larger rabbits at the bottom of the page and the smaller rabbits at the top of the page. This creates a percept of distance and depth as the rabbits appear to be moving back into the distance.

Relative size and height cues together provide only relative metrical information as they do not convey the precise distance between objects. In contrast, an object that is of familiar size such as the size of a hand provides an absolute metrical depth cue. The exact distance and size is known based on the visual angle of the image on the retina.

Aerial perspective (haze) provides another depth cue. Since light is scattered by the atmosphere, an object that is further away looks fainter and less distinct. Objects in the distance appear to have a blue haze (Fig. 3).

Fig. 3: Aerial Perspective (Courtesy of Joaquium Alves Gaspar, 2007).
The mountains in the distance appear blue and fainter due to the increased scattering of light.

Due to linear perspective, parallel lines appear to converge with distance. The only lines that do not appear to converge are lines that lie in the plane that is parallel to the plane of the two dimensional image. The converging lines all approach and meet at a vanishing point (Fig. 4). Linear perspective is a relative metrical cue as it combines with the other monocular cues such as size and position (Wolfe et al. 2006).

Fig. 4: Linear Perspective (Furman University, 2008)
The parallel lines of the railroad track appear to converge at the vanishing point in the distance

Relative motion or motion parallax is also an important monocular cue to determining depth. Close objects appear to move in the opposite direction of the observer's movement while further objects appear to move with the observer. Relative motion can be created from small head movement; movements as small as the distance between the eyes can provide a depth signal (Livingstone, 2002). The information perceived by one eye in two different positions at two separate times is similar to the information of two eyes in different positions at the same time (Wolfe et al. 2006).

Light and shadowing provide a monocular depth cue because different surfaces when illuminated reflect different degrees of light (Fig. 5). Due to the center/surround organization of individual cells in the visual system, there is a high sensitivity to abrupt versus gradual changes in luminance. The visual system is able to discriminate these changes locally and determine if a point is either brighter or darker than a spot in the immediate surround (Livingstone, 2002).

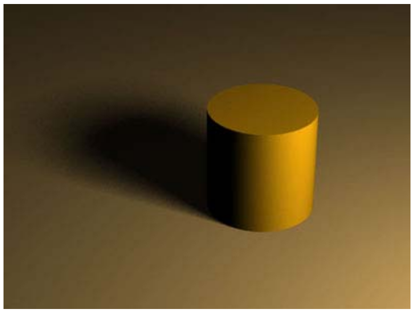


Fig. 5: Light and Shadowing (Dot C Software, 2006)
The cylinder is perceived in depth from the varying degrees of surface illumination along with the shadow cast by the object.

Stereopsis

Stereopsis provides a depth cue that depends upon two eyes. The two eyes see from a slightly different perspective because they are separated by approximately 60 to 65 mm, known as the interocular distance. The binocular visual pathways in the brain integrate the two images of the objects viewed by two eyes into a single percept. In order to make a relative judgment about the depth and distance of an object, first its visual direction must be considered. This requires that the two eyes are aimed at the object. Thus, the two eyes share a common visual direction and the image of the object is cast on corresponding points on the two retinas.

In order to judge the relative distance of an object in space, the two eyes work together by either turning inwards or outwards so that the image of the object falls on the fovea of each retina. The eyes converge and turn inwards when looking at an object up close and diverge, turning outward when looking at an object in the distance (Fig. 6).

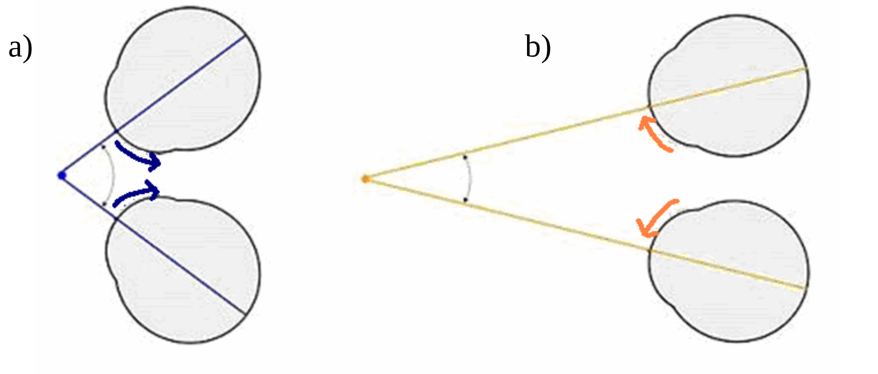


Fig. 6: Convergence and Divergence (SAP Design Guild Team, 2008).

a) During convergence, the eyes turn inwards to fixate on a close object
b) During divergence, the eyes turn outwards to fixate on a far object

Typically during vergence movements, the two images of an object fall on corresponding retinal points that are on the fovea or at the same side and distance away from the fovea on each retina. Thus, corresponding retinal points have zero binocular disparity (Steinman et al., 2000). The objects which cast their images on corresponding retinal points are located on the horopter. Objects on the horopter will be perceived as single. Objects that are considerably farther away or closer than the horopter, cast images onto non-corresponding retinal points and these images will be seen as double (Fig. 7 - Wolfe et al., 2006). This is referred to as diplopia as the image is perceived as coming from different visual directions (Steinman et al., 2000). Typically, we are not aware of these double images.

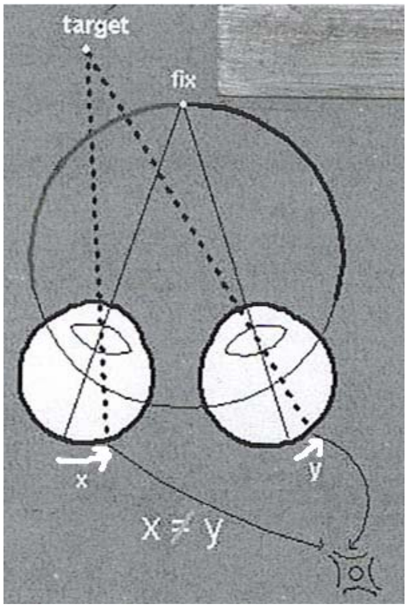


Fig. 7: Perception of Depth (Schiller, 2008)
The object labeled fix is located on corresponding retinal points and is perceived as a single object as it lies on the horopter. The object labeled target lies behind the horopter and therefore lies on two different points of the retina (non-corresponding retinal points). Depending on the degree of retinal disparity, the target will either be viewed in double or perceived as further away in space.

There is a region of space in front and behind the horopter where a single percept can be obtained when objects fall on slightly different non-corresponding retinal points. This area is called Panum’s fusional area (Wolfe et al., 2006). These slightly different retinal points lead to the perception of depth through stereopsis. Stereopsis allows for an object to appear near or far in comparison to the fixation point or horopter due to the images of identical objects being horizontally displaced in the nasal and temporal direction on the two retinas. Stereopsis is based on horizontal disparity on the retinal image position that is not greater than 2 degrees (0.6 mm on the retina – Hubel, 1995). As seen in Fig. 7, the target is beyond the fixation point (horopter) and the image is cast onto different regions of the two retinas. Therefore, the relationship between the visual system and depth can be determined. The greater the binocular disparity, the greater the distance in depth the object is from the horopter.

Stereoscopic depth is perceived based upon horizontal binocular disparity and this disparity can either be crossed or uncrossed in relation to the fixation point. In crossed disparity, the lines of sight from the target to the retina cross in front of the horopter (fixation point) making the percept appear to be closer than the fixation point. Uncrossed disparity makes the percept appear to be further away from the horopter as the line of sight crosses behind the fixation point, as seen in Fig. 7 (Wolfe et al., 2006).

When images cannot be fused properly, troubles with binocularity occur. Double vision arises from diplopia when one object is seen as two images. Binocular confusion results when an image is cast on the retina and a dissimilar image is formed on the corresponding point in the other eye. This leads to different objects being superimposed in the same location. By eliminating a diplopic or confused image through suppression, an input can be "ignored" from one eye.

The Physiological Basis of Stereopsis

Information from the two eyes is first combined through binocular neurons in the visual cortex. Binocular neurons have two receptive fields, one for each eye. The receptive fields for the binocular striate cortex neurons are similar for the two eyes, sharing similar spatial orientation, frequency, speed, and direction of the visual stimuli. Some binocular neurons respond to stimuli that fall on corresponding retinal points (a neural basis for the horopter) while others have the highest rate of firing when stimuli have slightly different retinal image positions. These neurons detect retinal disparity and may be used for stereopsis (Wolfe et al., 2006).

Optometric Tests

To see stereoscopically, one must be able to make vergence movements so that the visual target of interest casts an image on corresponding points of each retina. This process is called bifixation. The greater the range of vergence movements one can make, the greater the fusion range. In this study, I used standard optometric tests to probe stereoacuity, bifixation, and fusion range. The optometric tests used were the Stereo Fly test, Random Dot Stereograms, Real/Unreal Distinction in Diplopic Images, the Brock String test, and Polarized Vectograms.

The Stereo Fly Test

The Stereo Fly tests stereoacuity based on the idea of non-corresponding retinal points. There are a series of four circles arranged on the points of a diamond and while wearing polarized glasses one of the circles appears to come out of the page. The circle that is perceived as coming out of the page is made up of two identical but spatially separate images which are fused in the brain. Since the retinal images fall on close but non-corresponding retinal points, observers will perceive this circle to be at a different depth than the other circles. As one moves along the series, one needs better and better stereoacuity to see the popped out circle. Thus, with this test, I can measure the stereoacuity of different participants.

Fig. 8: Stereo Fly Test
As a participant goes down the series the spatial distance between the two identical circles decrease. As seen with series 1, the bottom circle is blurry because of the overlapping circles. It is harder to distinguish the difference further down the series as the distance between the circles decrease.

Red/Green Anaglyphs of Random Dot Stereograms

The underlying mechanism of stereopsis has been studied extensively by Bela Julesz using random dot stereograms (Hubel, 1995). Two identical arrangements of randomly placed dots are placed on a page except one arrangement is made of red dots on a white background and the other is of green dots on a white background. In the center of the stereogram, a square-shaped cluster of green and white dots are displaced a small amount to the left compared to the corresponding red and white dots. These images are superimposed. When a participant wears the red/green lenses, with the red lens over the right eye and the green lens over the left eye, the image of the square will appear to stand in front of the page whereas reversing the lenses will make the image of the square appear to lie behind the page (Fig. 9).

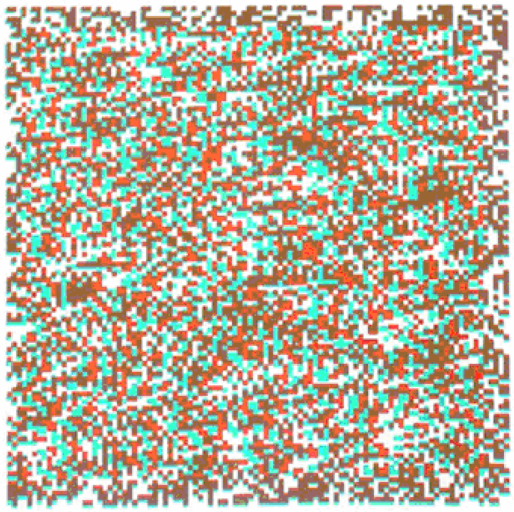


Fig. 9: Random Dot stereogram at 100% dot correlation (Julesz, 1971).

In these anaglyphs, a red dot seen by one eye is correlated with a green dot seen by the other eye. To make stereograms harder to see, Julesz (1971) decreased the number of correlated dots. Individuals with stereopsis deficits are able to notice the change in depth of the center (smaller) square or at least a difference in the center square from the surround in the highly correlated stereograms but their ability to decipher the center from the surround becomes more difficult with the decrease in the random dot stereograms' dot correlation.

To understand this concept better, consider a Julesz black and white random dot stereogram that can be fused using a stereoscope or by convergence and divergence movements of the eyes. If a center square is constructed with a 50 X 50 cell arrangement in a surround of a 100 X 100 cell arrangement, the surround would have a 2 cell nasal disparity, as all the dots would shift over two cells and the center would have a nasal disparity of 4, as all dots would shift over 4 cells. The decrease of binocular disparity is based on the decreased amount of correlated cells. So at 90% dot correlation, 10% of the dots in the center pattern that were shifted are black/white complements and are not fusible. There is an increase of 10% of complemented black/white cells with each 10% decrease in binocular correlation (Fig. 10)

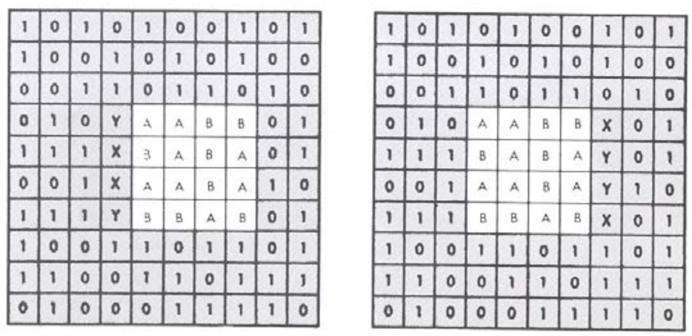


Fig. 10: Construction of a random dot stereogram (Julesz, 1971).
One random dot pattern is created to be viewed by one eye, as seen with the random dot stereogram on the left. The other eye's image is created by copying this left random dot image and displacing the center region horizontally, as seen with the figure on the right. This creates a gap which is than filled with random dots, as represented by the X and Y units. When fusing the two images, this shifted square appears either above or below the plane of the other dots.

When an average observer looks at the diminishing binocular correlations, stereopsis decreases with increasing noise. At first the corners of the square disappear, but a rounded shape in the center still appears to have depth. As the correlation decreases further, dots appear at other depths than the plane of the center square and surround. It then becomes impossible at some point with the decreasing dot correlation to distinguish between the center and surround as the perception of depth is no longer seen. A normal observer should be able to distinguish depth to around 60% dot correlation while an observer with some binocular anomalies could probably perceive some differences in the random dot stereograms with 80% dot correlation (Julesz, 1971).

Real/Unreal Distinction in Diplopic Images

When the horizontal displacement of an image on the two retinas is greater than two degrees and the vertical displacement is greater than a few minutes of arc, the images can no longer be fused in the brain and are viewed as double (Hubel, 1995). Physiological diplopia results from this double vision, as the images formed on the retina are seen as coming from different visual directions. Thus, if you look towards the distance, near images may appear as double (Steinman et al., 2000). In this test, the participants look in the distance but are aware of their finger held a few inches in front of their face. While fixating afar, the finger appears as two images. However, if the participants attempt to touch the two images of the finger, they will discover that only one image can be touched and is thus considered “real”. With this test, I can determine eye dominance in the participants based on which finger image was perceived as “real.”

Brock String

If an observer bifixates a distant object at the midline, a near object will cast an image on the temporal retinas on non-corresponding points, resulting in crossed diplopia. This can be observed with the Brock string. If a participant wears the red/green glasses with the red lens over the right eye and the green lens is over the left eye and fixates on a distant bead on the string, the participant will see two string images in front of the bead, the string image on the right appears green and the string image on the left appears red. The image of the bead is cast within the Panum's fusional area while the images of the string fall on non-corresponding retinal points, outside Panum's fusional area and are therefore seen as double. When fixating on a near object, as when fixating on a close bead in the Brock string but looking at the diplopic image of the strings behind the bead, the distant object is seen as double as the images fall on the nasal portion of each retina. These two strings are seen due to uncrossed diplopia. The left eye will see the left image, a green string and the right eye will see the right image, a red string (Fig. 11).

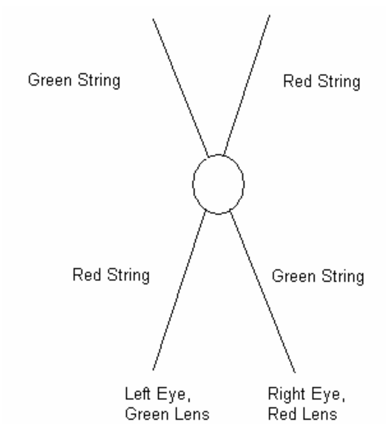


Fig. 11: Typical color orientation of the strings in the Brock String.
In front of the bead, the left string image is red and the right string image is green. Behind the bead, the left string image is green and the right string image is red.

When the bead reaches a certain distance, suppression occurs and the diplopic image is eliminated by "turning off" or ignoring the input, unconsciously from one eye (Steinman et al., 2000). Thus, with the Brock String, I can tell how well an individual bifixates the bead and whether or not they suppress one eye's image.

Polarized Vectograms

The size constancy principle plays a role in depth perception. Objects that are further away cast smaller images on the retina, yet we do not judge them as further away. Size constancy refers to the ability to make a correct judgment about the size of an object regardless of the size of the image projected on the retina (Fig. 12). The perception of size depends on the retinal image size and the perceived distance (Gazzaniga and Heatherton, 2003).

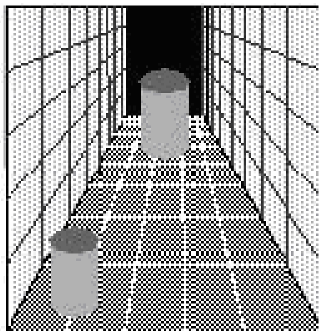


Fig. 12: Cylinder illusion as an example of Size Constancy (Vision Rx, 2008).
This cylinder illusion is a demonstration of size constancy principle The two cylinders in the figure are actually the same size, yet, the target that is closer appears smaller whereas the target that is farther appears larger.

In the polarized vectograms, this phenomenon results in a change of perception of the fused quoit during convergence and divergence. During convergence, crossed disparity cues are used because the right quoit is displaced to the left and the left quoit is displaced to the right. A crossing point results from the nasal and temporal visual directions of the two retinas to the two quoits on the slide. The single fused quoit image is perceived at the crossing point and appears to move closer or in towards the participant. As the eyes turn inwards during convergence, the quoit appears smaller as the distance of the visual axes in the crossing point decreases (Fig. 13). During divergence, uncrossed disparity cues are used because the right quoit is placed to the right and the left quoit is placed. As quoit slides are moved, the eyes must move outwards to fixate properly on the single fused quoit. The line of sight ends up behind the target and the increased distance between these visual axes results in the quoit appearing larger.

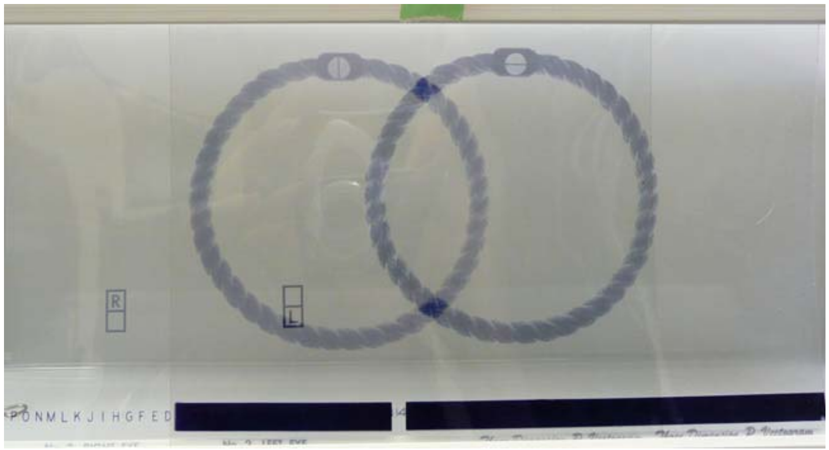


Fig. 13: Image of quoits in polarized vectograms.
This particular figure demonstrates how the right slide is displaced to the left and the left slide is displaced to the right and in order to perceive a single fused quoit, crossed disparity cues must be used.

During convergence, the quoit is perceived as being smaller as it comes closer or in and during divergence, larger as it is goes further away or out (SILO). During vergence there is an expectation (unconsciously) that there will be a change in the retinal image size. Size constancy is maintained as the observer corrects for this expectation. Normally, during convergence as the object comes closer the retinal image size increases. To maintain size constancy the image is made to appear smaller. During divergence, as the object moves further way the retinal image size decreases; so to maintain size constancy the image is made to appear larger. However the quoit is only perceived as moving closer to or further away. In reality the quoit has not moved and its retinal image size has not changed. The distance of an object and size are linked together and the polarized vectograms dissociates these two depth perception cues. Still the brain perceives the quoit as closer or farther even though there is no change in retinal size. The size constancy principle causes the observer to perceive the object as smaller or larger, respectively (Scheiman and Wick, 2002).

Importance of Binocular Vision

Binocular vision which includes stereovision is important for accurate perception of depth and perceiving the action and movement of an object in its surrounding space. A study by Mazyn et al. (2007) looked at the role of stereovision in ball catching. Previous studies have suggested that a lack of stereopsis does not affect such abilities since monocular cues to depth can be used. However, ball catching is based on the perception of the spatial and temporal qualities of a ball in space. In his study, participants with poor stereopsis and catching skills showed no significant improvements after intensive training whereas participants with good stereopsis but poor catching skills showed a 400% improvement after intensive training. This study suggests that the temporal and spatial information of the ball is based primarily on stereoscopic cues.

Stereopsis might also be important in one's reading skills and abilities. A study by Grishman et al. (2007) suggests that there is an association between visual skills and reading abilities, such as comprehension and fluency. These researchers looked at poor readers in high schools of similar socioeconomic levels to see if weak readers had either sufficient or weak visual skills. 80% of the poor readers were found to have binocular anomalies in the areas of stereoacuity, bifixation, or fusion and 40% had more had more than one deficit.

This study will look at the range of binocular skills within individuals with no known binocular disorder and those with binocular anomalies. The purpose of this study is to ask whether binocular skills exist on a continuum and whether each individual varies one from the next. I hypothesize that there will be significant variability within and among these two groups in skills such as fusion and/or vergence ranges, bifixation, and stereoacuity.

MATERIALS AND METHODS

A total of 35 participants from the Mount Holyoke College population from the ages of 19 to 60 were tested on their binocular vision skills. Thirty non-symptomatic participants with no apparent binocular vision problems and five participants with binocular vision anomalies were tested on eight optometric tests: Snellen Vision Chart, Near Vision Chart, Stereo Fly Test, Sighting Eye Test, Real/Unreal Distinction in Diplopic Images, Brock String Test, Polarized Vectograms, and Random Dot Stereograms. The non-symptomatic binocular group (Group A) had no known form of binocular deficiency or other visual difficulties other than refractive error (visual acuity) which all will be reduced with glasses or contact lenses. Each participant had to fill out an informed consent before starting the tests.

Additionally, the 5 participants in the binocular anomalies group (Group B) were asked a series of questions before testing: Have you had any surgeries to correct eye alignment? Have you had any form of visual therapy and if so please explain? Do you wear any specific type of corrective lenses? Describe how you see things? Do you have a clinical diagnosis?

Snellen Vision Chart

A Snellen Vision Chart was used to test the visual acuity of participants from a 20 feet distance to assure that the participants all have normal or corrected to normal 20/40 vision or better. The chart was hung at eye level and the participant stood 20 feet back on a marked piece of tape. The participants read both the 20/30 and 20/20 lines. If the participants had contacts or glasses they wore them during the testing in order to provide a baseline of their corrected acuity for the other optometric tests.

Near Vision Chart

A Near Vision chart was used to test visual acuity at a near distance. The participants sat at a distance of 40 cm (16 inches) from the chart and were asked to read the 20/20 line. If the participants had contacts or glasses, they wore them during the testing in order to provide a baseline of their corrected acuity for the other optometric tests.

Stereo Fly Test

To determine the participants' level of stereoacuity, they looked at the Stereo Fly book from 16 inches away, which contained polarized images of circles and animals. Polarized glasses were worn during the testing. They observed nine displays, each of which had four circles arranged in a diamond shape. The participants were asked which circle of the four seemed to come closer to them, the top, bottom, left, or right. When wearing the polarized glasses, each eye saw the circles from a slightly different perspective and the two circles images were fused in the brain. The Stereo Fly book tests how far apart the circle images must be on the two retinas to perceive depth. In addition to the circles, participant viewed three additional displays; each arranged in a row with five different animals and asked which animals seemed to come closer to them.

Sighting Eye Test

To determine which eye was dominant for sighting, a white piece of paper with the capital letter E was placed approximately at eye level. The participants stood 100 cm (approximately 3.3 feet) away from the letter. They made a triangular window between their two hands by bringing their thumbs in a parallel direction to the ground with all other fingers at a 45 degree angle. They overlapped their hands to decrease the size of the opening. They were then asked to extend their arms into a straight position so their elbows locked. They centered the letter between their triangular hand window with both eyes open. Under these conditions, only one eye can view the letter at any one time. The participants then closed their left eye, opened it, and closed their right eye, and then opened it. Eye dominance was determined by which eye was opened when the object was still seen in the opening. The participants' handedness was recorded to see if any correlations existed between hand and sighting eye dominance.

Real/Unreal Distinction in Diplopic Images

The participants gazed in the distance and brought an index finger within a few inches of their face. If the gaze remained in the distance, two images of the finger were seen. This is a normal response and it is known as physiological diplopia. The participants were asked to reach for and grab each image of the finger. This test demonstrated that only one image of the finger is touchable.

Brock String

To observe bifixation, participants viewed a Brock string which contained an orange bead that could slide along a string. The Brock string was attached to a magnetic cabinet at eye level for the participants, who stood 200 cm (approximately 6.6 ft) away from the cabinet. They wore red/green glasses with the red lens over the right eye and the green lens over the left eye. The string was placed onto the tip of their nose and the participants viewed the bead when it is placed on the tip of the string. They were asked to describe what they saw, how many string images were in front of and behind the bead, the color of the string images, along with any additional observations.

A normal binocular viewer readily sees one bead but two images of the string coming into and out of the bead. The bead was pushed back at 10 cm increments until the participants observed a change in the number of strings or color of the strings. This test examines the ability of participants to bifixate and fuse at different distances. If, for example, they see only one string in front or behind the bead, they are suppressing one eye's input. Under normal conditions, a participant should see two strings before the bead, with the green string on the right and the red string on the left. Two strings should also be observed behind the bead, with the green string on the left and the red string on the right. If the string images appeared to cross in front or behind the bead, the participant had aimed her eyes in front of or behind the bead, respectively.

Polarized Vectograms

To determine the participants' fusion range they were asked to look at two polarized vectograms of superimposed images of quoits (knotted rope circles) placed on a stand at a distance of 16 inches from their eyes. Participants closed their left eye and then right eye to determine if they saw the R and L letters, respectively to establish if they were fixating properly. When both eyes were open, both the R and L were seen along with a cross above the quoit; this is called a suppression check.

While wearing the polarized glasses, each eye viewed a separate quoit but the images of the two quoits were fused in the brain and perceived as one. To determine the participants' range of fusion for convergence, the participants slowly slid the right quoit to the left and the left quoit to the right until they no longer saw one fused image of the quoit. Instead, they perceived either two separate quoits or two overlapping quoits. The number range was noted and then the participant determined if the quoit became smaller or bigger and closer or further to them before the images separated into two.

This procedure was repeated by having the participant slide the quoits in the opposite direction to determine the participants' fusion range for divergence. With the single superimposed image of the quoits, the participants slowly moved the left quoit to the left and the right quoit to the right until they saw two quoit images. The range was determined through a letter notation and the participant determined if the fused quoit became smaller or bigger and closer or further to them before it split into two quoits. A pointer was used to help the participant understand the change in depth and the distance. Throughout this optometric test, the participants were asked if they perceived both the R and L and the cross shape above the quoit to make sure that they were using both eyes.

Random Dot Stereograms (Red/Green Anaglyphs)

To determine the participants' level of random dot stereoacuity, they viewed red/green anaglyphs of increasing difficulty. The participants were given red/green glasses and placed the red lens over the right eye and the green lens over the left eye. The participants were asked what they saw in the random dot stereograms. There were seven red/green anaglyphs presented, ranging from 100% to 40% dot correlation, based on a 10% decrease in correlation between the anaglyphs. The placement of red/green glasses was switched by putting the red lens over the left eye and the green lens over the right eye to produce a depth sensation with opposite polarity.

RESULTS

Group A: No Known Binocular Disorders

A total of 30 participants were tested in the no known binocular disorder group (Group A) using eight standard optometric tests. These tests included the Snellen vision and Near vision test for visual acuity, sighting eye test and the real/unreal distinction in diplopic images for eye dominance, the Stereo fly test for stereoacuity, the Brock string for bifixation and eye dominance, and polarized vectograms and random dot stereograms for vergence and fusion skills. Participants' ages varied from 19 to 60 years old and no differences in binocular vision skills were observed across these age groups. All participants in Group A had a visual acuity of 20/40 or better, some with the aid of corrective lenses.

Stereo Fly Test

Twenty-seven out of 30 participants (90.0%) in group A showed normal stereoacuity between 40 to 80 arc seconds. Three out of 30 participants (10.0%) showed subnormal stereoacuity, with stereoacuity ranging from 100 to 140 arc seconds.

Eye Dominance

Twenty-one out of 30 (70.0%) participants showed a strong preference for their right sighting eye and right hand whereas 5 out of 30 participants (16.7%)

displayed left eye sighting dominance but were right handed. Two out of 30 participants (6.7%) were left handed and both sighted with the left eye. The remaining 2 participants were ambidextrous. One sighted with the left eye and the other with the right eye (Fig. 14).

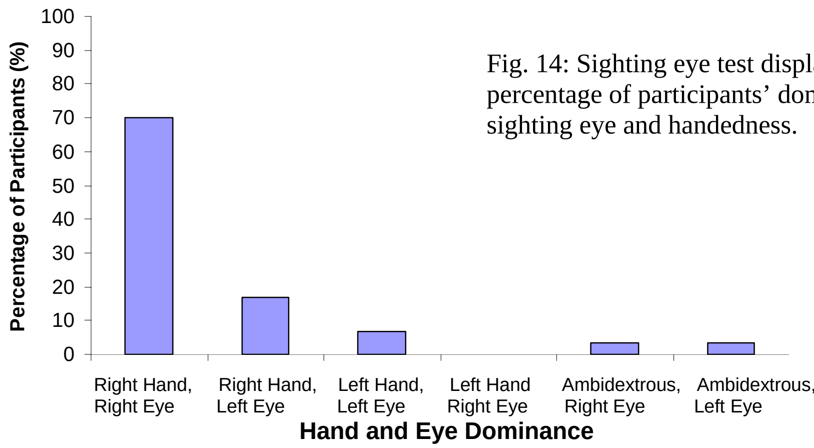


Fig. 14: Sighting eye test displaying the percentage of participants' dominant sighting eye and handedness.

In the real/unreal distinction with diplopic images 18 out of 30 (60.0%) participants were right eye dominant and 12 out of 30 (40.0%) participants were left eye dominant.

In the Brock string test, when the red/green glasses were worn with the red lens over the right eye and the green lens over the left eye, the string images that were red were viewed by the right eye and the string images that were green were viewed by the left eye. When one of the string images was suppressed to form one of the Y-formations, eye dominance was then determined based on the color of the remaining single string image.

Twenty-three out of 30 participants (76.7%) viewed the image of the red string in the Y- or inverted Y-formation, suggesting that in this test they were right eye dominant and suppressed the left eye string image. Two out of 30 participants (6.7%) viewed the image of the green string in the Y- or inverted Y-formation, suggesting that these participants were left eye dominant and suppressed the right eye string image. Three out of 30 participants (10.0%) alternated between viewing a red string image and a green string image, possibly suggesting a balance between the two eyes. The remaining 2 participants (6.7%) viewed no distinct color to the string images and perceived them as either white or yellow. These 2 participants still suppressed one image to view a single string image (Fig.15).

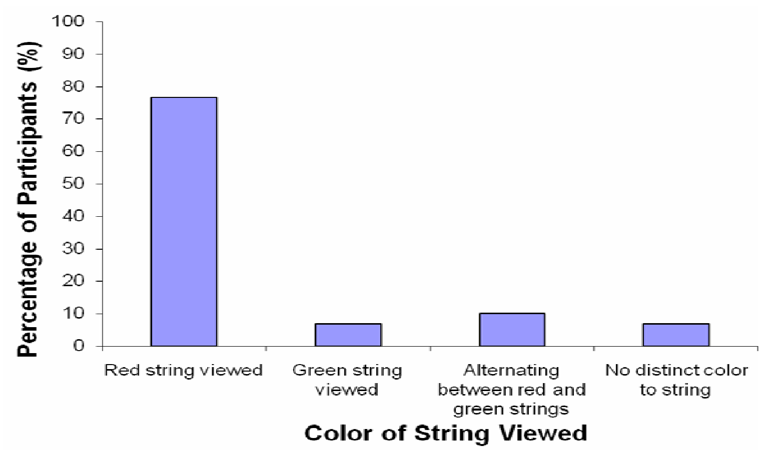


Fig. 15: Color of the String Image perceived in front or behind the bead in the Y- or inverted Y-formation

A three way comparison was made between the percentage of participants that were right eye or left eye dominant in all three eye dominance tests including the sighting eye, real/unreal distinction in diplopic images, and the viewed string image in the Y or inverted Y-formation in the Brock string test. The three eye dominance tests were classified into three separate categories: sighting and real/unreal distinction of diplopic images, sighting and Brock string image in Y-formation, and real/unreal distinction in diplopic images and Brock string image in Y-formation (Table 1, 2, and 3).

Table 1: Dominant Eye in Sighting Eye Test and Real/Unreal Distinction with Diplopic Images

Sighting Eye		Real/Unreal Distinction with Diplopic Images: Right Eye	Left Eye	Unable to determine
	Right Eye	46.7%	23.3%	3.3%
	Left Eye	10.0%	16.7%	-

Table 2: Dominant Eye in Sighting Eye Test and Brock String Image in Y-formation

Sighting Eye		Brock String Image in Y-formation: Right Eye	Left Eye	Alternating Right and Left Eye
	Right Eye	63.3%	6.7%	3.3%
	Left Eye	16.7%	-	10.0%

Table 3: Dominant Eye in Brock String Image in Y-formation and Real/Unreal Distinction with Diplopic Images

Brock String Image in Y-formation		Real/Unreal Distinction with Diplopic Images: Right Eye	Left Eye	Unable to determine
	Right Eye	50.0%	26.7%	3.3%
	Left Eye	3.3%	3.3%	-
	Alternating Right and Left Eye	3.3%	10%	-

Brock String

An X-formation was classified as a participant viewing two string images in front of the bead and two string images behind the bead while the participant fixated on the bead. The 30 participants in Group A viewed the X-formation when the fixated bead was located from 10 cm to 251 cm away, with the mean distance of the bead at 128.6 $\pm$ 44.2 cm. After a certain distance, one of the string images either in front or behind the bead was suppressed resulting in a Y-formation or inverted Y-formation. These participants viewed an inverted Y- or Y-formation when fixating a bead at a distance of 93 cm to 255 cm, with the mean distance of the bead at 162.9 $\pm$ 37.0 cm.

There was a significant difference between the distance of the bead at the X- and Y-formation (T-test, p(58)<<0.001) with the bead distance being greater in the Y-formation than the X-formation. Fig. 16 shows the X-formation as when it was last seen and the Y-formation when it was first seen. The distance between the X- and Y-formation resulted in the intermittent zone where participants would switch between seeing two strings' images and one string image either in front of or behind the bead. The mean intermittent suppression zone distance was 34.1 $\pm$ 30.6 cm (Fig. 17).

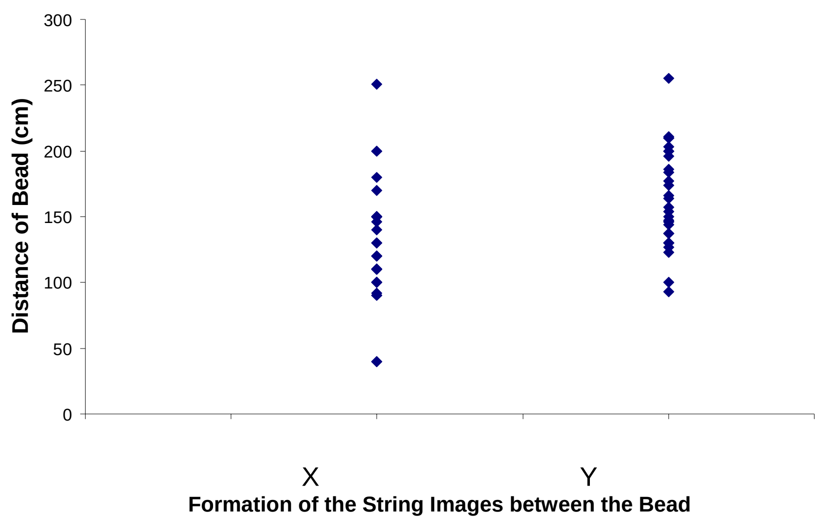


Fig. 16: Perception of X- and Y- formation in the Brock String Test
The range of distances of the bead in the X-formation describes when this formation was last seen for individual participants whereas the range of distance of the bead in the Y-formation describes when this formation was first seen for the individual participants.

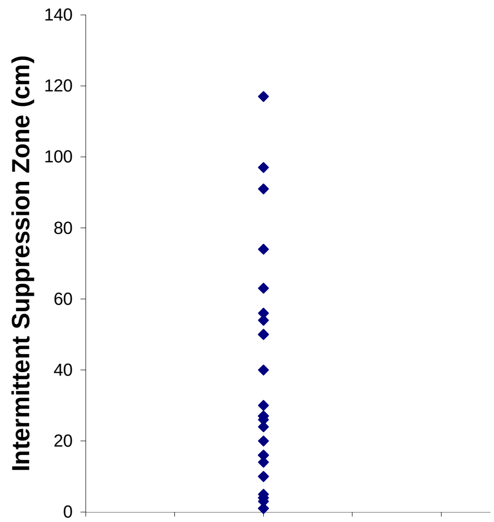


Fig. 17: Intermittent Suppression Zone between the X- and Y- Formation in the Brock String Test
The intermittent zone is described at the specific distance range when each participant would switch between seeing two string images or one string image either in front or behind the bead.

In the Brock string test, once the bead was moved to an undetermined distance, most participants would suppress one string image. Twenty-seven out of 30 participants (90.0%) perceived the inverted-Y formation, by viewing two string images in front of the bead and one string image behind the bead. These participants suppressed one eye's image behind but not in front of the bead. Two out of 30 participants (6.7%) perceived the Y-formation, by viewing one string image in front of the bead and two string images behind the bead. These individuals suppressed one eye's image in front of but not behind the bead. One participant (3.3%) was not able to determine which string image was suppressed in the Brock string test (Fig. 18).

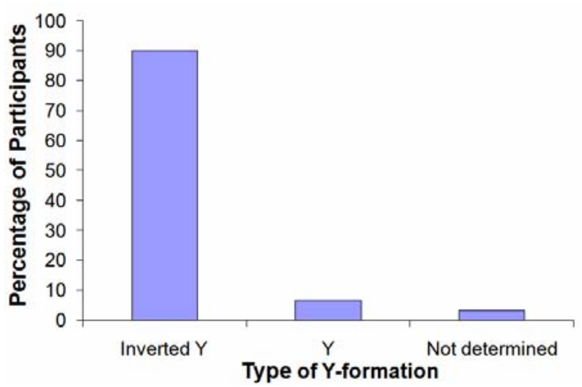


Fig. 18: Type of Y- formation observed after one string was suppressed in the Brock String Test

Polarized Vectograms

When viewing the quoits in the polarized vectograms test, the participants' eyes had to either turn inward (converge) or outwards (diverge) to fuse the two images of the quoits into one and then view the perceived float. This range of convergence and divergence was measured in prism diopters. One prism diopter is the angle formed by a horizontal shift of 1 centimeter at a distance of 1 meter (Fig. 19).

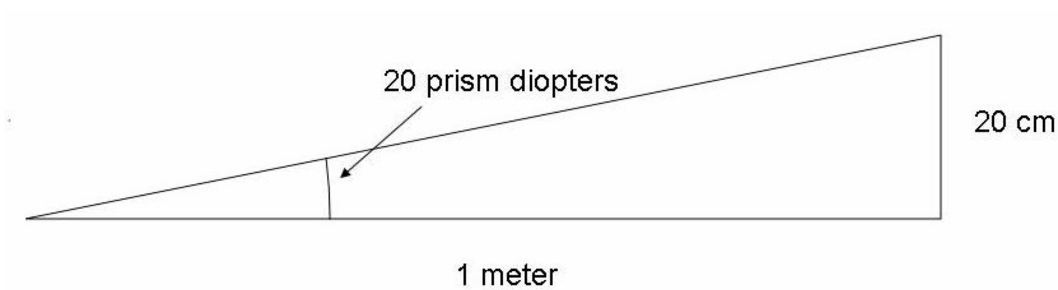


Fig. 19: Prism Diopter

If we assume that the horizontal line is 1 meter long, then the vertical line would be 20 cm high forming an angle of 20 prism diopters.

The 30 participants in Group A had a convergence range from 4 to 33 plus prism diopters, with a mean of 24.2 $\pm$ 14.4 prism diopters. These participants had a divergence range from 4 to 16 plus prism diopters, with a mean of 11.6 $\pm$ 4.2

prism diopters. There was a significant difference between the fusion range obtained during convergence and divergence (T-test, p(58)<<0.001), with the convergence fusion range being larger than the divergence fusion range (Fig. 20).

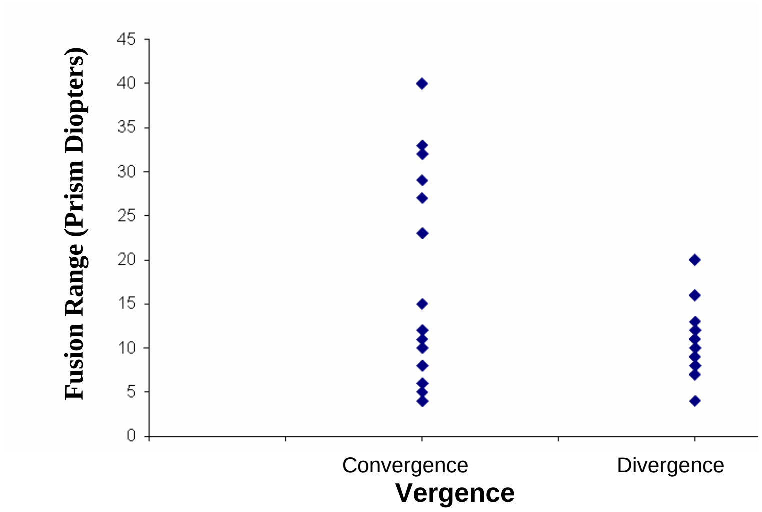


Fig. 20: Fusion Range for Convergence and Divergence

The data were normalized for convergence and divergence ranges to determine if there was any correlation between the fusional ranges. A value of one was chosen for a convergence range of 33 prism diopters and a divergence range of 16 prism diopters. There was no significant correlation between the normalized values of convergence and divergence fusion range in the polarized vectograms (Pitman's test for normal correlation (1939), p>0.05). Examination of Fig. 21 also suggests no correlation between an individual's ability to converge and diverge.

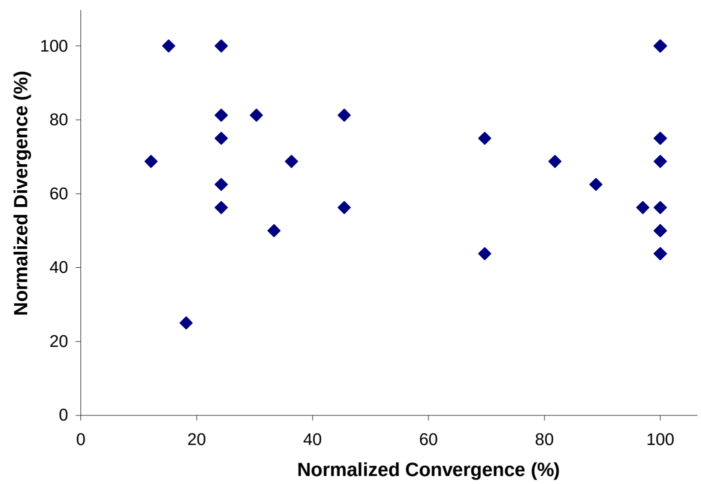


Fig. 21: Normalized Scatterplot of Convergence and Divergence
This shows no trend or correlation between the convergence and the divergence fusion ranges.

During convergence, 20 out of 30 participants (66.7%) viewed the expected (SILO) size and float of the quoit, as smaller and closer to the participants. Four out of 30 participants (13.3%) perceived the quoit as smaller and further. An additional 4 out of 30 participants (13.3%) perceived the quoit as larger and closer. One participant (3.3%) perceived the quoit as larger and further and another participant (3.3%) perceived no float or change in size of the quoit (Fig. 22).

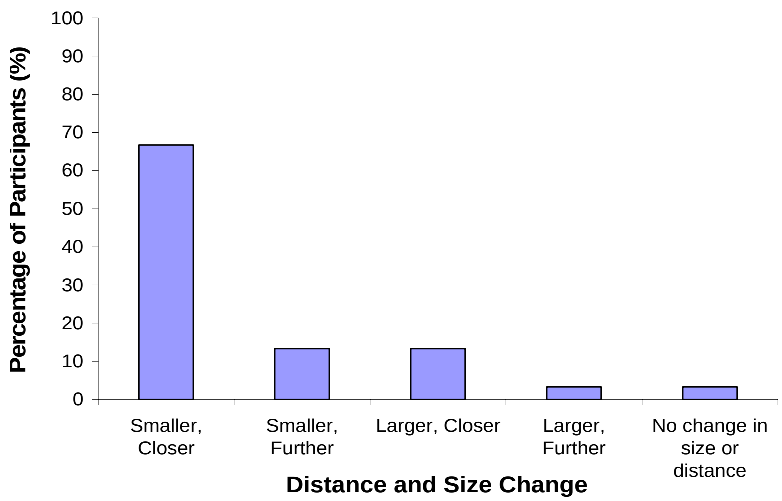


Fig. 22: Perceived Size and Float of Quoit during Convergence

During divergence, 13 out of 30 (43.3%) participants viewed the expected (SILO) size and float of the quoit, as larger and further from the participant. One participant (3.3%) perceived the quoit as smaller and closer while 2 out of 30 participants (6.7%) viewed the quoit as smaller and further. Six out of 30 participants (20.0%) perceived no float and change in size in the quoit. Two participant out of 30 (6.7%) perceived no change in size but perceived the float as further away (Fig. 23).

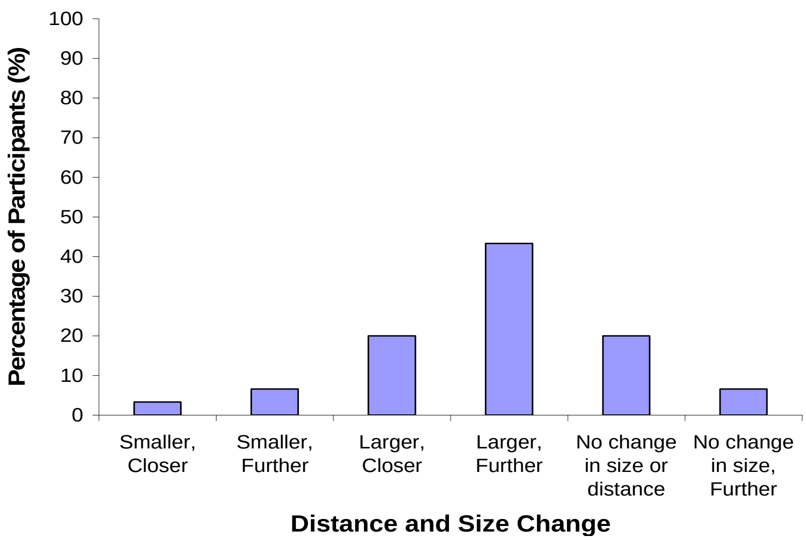


Fig. 23: Perceived Size and Distance of Quoit during Divergence

Thus, the interpretation of float in the polarized vectograms deviated from the SILO effect in 17 out of 30 participants (56.7%).

Random Dot Stereograms

When viewing the random dot stereograms all 30 participants described perceiving three square layers above the plane of the page, when the red lens was on the right eye and the green lens on the left eye, or below the plane of the page, with the green lens on the right eye and the red lens on the left eye. With the red lens over the left eye and the green lens over the right eye, 1 out of 30 participants (3.3%) was able to perceive the smallest square (top square) until 80% dot correlation. Fifteen out of 30 (50.0%) no longer viewed the smallest square after 70% dot correlation and 14 out of 30 (46.7%) no longer saw the smallest square after 60% dot correlation

When the red lens was placed over the left eye and the green lens over the right eye in the random dot stereograms, there was a slight shift in the percentage of participants that were able to perceive the smallest square at certain percent dot correlations. Three out of 30 (10.0%) participants were able to view the smallest square going below the plane of the page up to the random dot stereogram with 80% dot correlation. Twenty-two out of 30 (73.3%) participants viewed this square through the random dot stereogram with 70% dot correlation. The remaining 5 participants (16.7%) did not lose the image of the smallest square until after the random dot stereogram with 60% dot correlation (Fig. 24).

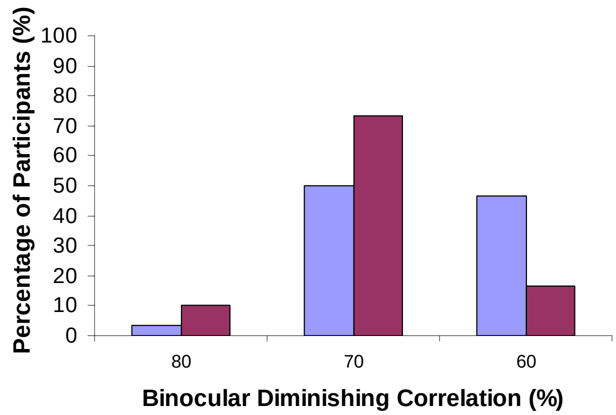


Fig. 24: Diminishing Binocular Correlation Percentage at Which the Smallest Square was Last Viewed
The light blue bar represents when the red lens was over the right eye and the green lens over the left eye; the squares were seen as coming out of the page. The dark purple bar represents when the red lens was over the left eye and the green lens over the right eye; the squares were seen as going into the page.

At 40% dot correlation, participants varied in their descriptions of their perceptions. Their descriptions were categorized in four ways. The four categories were: lose shape or form, lose dimension, decrease in shape or form and dimension, or lose shape or form and dimension. These classifications were based on the viewing condition in which the squares rose in front of the plane of the page or the condition in which the squares went behind the plane of the page. In the first category, participants would lose shape or form to the squares but still see depth, as suggested by dots rising above or below the page or a spherical bulge at a different plane. Participants in the second category would lose depth but still perceive some shape or form, either by seeing a distinct outline of edges or corners or seeing a difference in the color between the squares. In the third category, participants would see a decrease in both shape or form and depth but would still have a hint of some form or structure, whereas in the fourth category participants would completely lose the perception of shape or form and depth and describe seeing just one large square.

When viewing the random dot stereogram with 40% dot correlation and the red lens over the right eye and the green lens over the left eye, 5 out of 30 participants (16.7%) perceived a loss of shape or form. Six out of 30 participants (20.0%) no longer view any form of dimension, 17 out of 30 (56.7%) viewed a decrease in shape or form and dimension, and an additional 2 out of 30 participants (6.7%) perceived no shape or form and dimension.

When viewing the random dot stereogram with 40% dot correlation and the red lens over the left eye and the green lens over the right eye, 3 out of 30 (10.0%) perceived a loss of shape or form. Eleven out 30 participants (36.7%) no longer viewed any form of dimension, 12 out of 30 (40.0%) viewed a decrease in shape or form and dimension, and 4 out of 30 participants (13.3%) perceived no shape or form and dimension (Fig. 25).

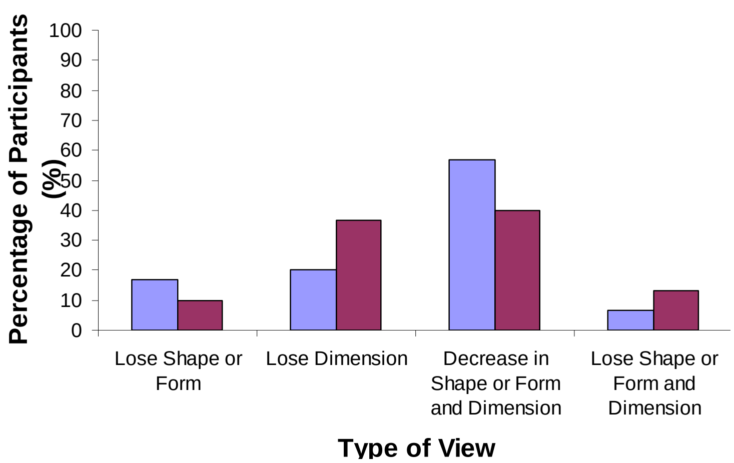


Fig. 25: View Lost in Diminishing Binocular Correlation
The light blue bar represents when the red lens was over the right eye and the green lens over the left eye; the squares were seen as coming out of the page. The dark purple bar represents when the

red lens was over the left eye and the green lens over the right eye; the squares were seen as going into the page.

While viewing the random dot stereograms, some participants were either observed or reported moving their heads side to side and/or up and down. They stated that it was easier to perceive the three layers of squares if they moved their head.

Three Binocularity Subdivisions Within Group A

Due to differences in binocular skill levels, participants were classified into three separate subgroups: Strongly Binocular, Less Strongly Binocular, and Weakly Binocular.

Strongly Binocular

Twenty one out of 30 participants (70%) tested were classified as strongly binocular. These participants correctly viewed three out of the four standard optometric tests: the Stereo Fly test, Brock string, polarized vectograms, and random dot stereograms. Participants that had unexpected results in one test usually did not report SILO when viewing the polarized vectograms, but still interpreted a change in size and distance of the float during convergence and divergence.

For the Stereo Fly test, the expected stereoacuity was 40 arc seconds but participants at or below 80 arc seconds were considered to have within normal stereoacuity. For the Brock string, normal bifixation was classified based on viewing the diplopic images of the colored strings. Correct vergence in the polarized vectograms was based upon the ability to view a fused quoit as the participant perceived a change of size and distance of the quoit during convergence and divergence. Lastly, the random dot stereograms were correctly perceived when three layers of squares were seen rising above or going behind the plane of the page.

The participants' eye dominance was also taken in consideration in the sighting eye test, real/unreal distinction in diplopic images, and the suppressed image in the Brock string test. The participants in the strongly binocular group had either a strong preference for one eye or switched between two eyes during the eye dominance portions of this study. Twelve out of 21 of these participants (57.1 %) had a strong preference for their right eye in the sighting eye test, real/unreal distinction in diplopic images, and the suppressed string image in Brock string test. The other 9 out of 21 participants (42.9%) showed a less distinct preference, using either their left or right eye for sighting. Additionally, 20 out of 21 participants (95.2%) had a stereoacuity of 40 arc seconds and one participant (4.8%) had a stereoacuity of 80 arc seconds.

In the Brock string test, 20 out of 21 participants viewed the color orientation in the correct order; they saw two string images in front of the bead, the right string image was green and the left string image was red, and two strings images behind the bead, the right image was red and the left image was green. The participants noted that both the string images converged and crossed at the bead, resulting in the X-formation (Fig. 26).

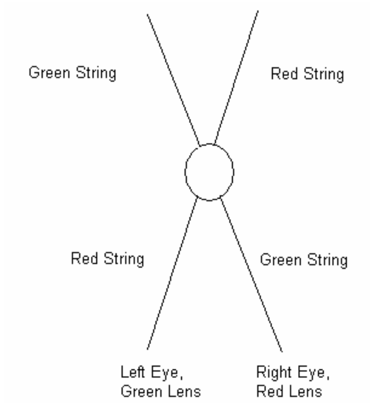


Fig. 26: Typical color orientation of Brock string test that results in an X-formation

At distances beyond 93 cm to 255 cm, these participants also suppressed the image of one of the strings behind the bead, resulting in an inverted Y-formation (two strings seen in front of the bead and one string seen behind the bead). One out of the 21 participants (4.8%) suppressed one of the strings in front of the bead, resulting in a Y-formation (one string seen in front of the bead and one string seen behind the bead). This particular participant described the color orientation differently in the X-formation; there were two strings in front of the bead, the right string was red and the left string was green and there were two strings behind the bead, the right string was green and the left string was red. This participant seemed to confuse her left and right throughout the test so that it is possible that she viewed the color orientation correctly.

The distance until which the X-formation was sustained varied among the participants in Group A. The X-formation was seen from 10 cm to 200 cm. As a result, the intermittent suppression zone distance was quite variable, ranging from 1 cm to 117 cm.

All 21 participants had normal or close to normal vergence ranges; 20 to 25 prism diopters for convergence and 10 to 15 prism diopters for divergence (Scheiman and Wick, 2002). Within the strongly binocular group, 5 out of 21 participants (23.8%) were within normal vergence range, 1 out of 21 participants (4.8%) had small or within normal convergence and large divergence ranges, 4 out of 21 participants (19.0%) had large convergence and small or within normal divergence ranges, and 10 out of 21 (47.6 %) participants had large vergence ranges. Only one of these participants exhibited below normal vergence ranges (6 prism diopters for convergence and 4 prism diopters for divergence) but performed within or above the normal standards on the other optometric tests.

The perceived changes in size and depth varied among participants with strong binocularity. Twelve out of 21 (57.1%) participants perceived the fused quoit during convergence as smaller and closer to them and during divergence as larger and further away to them. This view was known as SILO, seeing the quoit as smaller when inwards (closer to the participant) and larger when outward (further away). SILO was an expected result as it was an indication of the use of disparity cues to judge depth and size. Four out of 21 participants (19.0%) viewed the fused quoit during divergence as smaller and further away and during convergence as larger and closer to them. This view is known as SOLI, seeing the quoit as smaller when outwards (further away) and larger when in (closer to the participant). Four other participants (19.0 %) viewed the fused quoit during convergence as smaller and closer but had some difficulties with determining either change in size or change in size and distance of the quoit, even though their vergence was within or above the normal ranges. Two of these participants could not determine a change of size during divergence while the other two participants could not determine a change of size and distance. One participant out of the 21 participants (4.8%) viewed the size change correctly with convergence but perceived the distance incorrectly and additionally did not perceive any change in size or distance during divergence

When the quoit is localized in space along the z-axis with a pointer, only 13 out of the 21 participants in the strongly binocular groups were tested. When the localization of the quoit (float) in space with the pointer was compared to the perceived change in size and distance of the quoits, 7 out of these 13 participants (53.8%) perceived both the size and localization of the quoit in space according to SILO. Two out of 13 participants (15.4%), who correctly viewed the SILO effect, did not accurately localize the quoit in space; one participant viewed the quoit as in front of the base during convergence and divergence while the other viewed no change in distance. Two out of the 13 participants (15.4 %) perceived the SOLI effect but the localization of the quoit in space was different between the two participants. One participant correctly localized the quoit as closer during convergence and further during divergence while the other participant was not able to localize the quoit in space (pointed to the quoit stand). The remaining 2 out of 13 participants (15.4%) only perceived the quoit as closer during convergence but correctly localized both changes in distance of the quoit during convergence and divergence.

With the red/green anaglyphs of the random dot stereogram, all 21 participants were able to perceive three layers of square rising above or going into the page. These participants were able to see all three layers until the random dot stereograms with 70% to 60% dot correlation. At this point the smallest square (highest on the page with red lens on right and lowest into page with red lens on left), was no longer defined by shape or form and dimension. As the binocular correlation of the random dot stereograms continued to decrease, the perception of what was viewed was different among participants. For the random dot stereogram with the lowest dot correlation of 40%, the participants fell into all four categories based on their descriptions: loss shape or form, loss dimension, decrease in shape or form and dimension, or loss of shape or form and dimension.

Less Strongly Binocular

Three out of 30 participants (10%) were categorized as less strongly binocular. These participants inaccurately viewed two of the optometric tests or incorrectly viewed one test and struggled with one or more of the additional tests. Their eye dominance was also taken in consideration in the sighting eye test, real/unreal distinction in diplopic images, and the suppressed string image in the Brock string test. Most of the difficulties in this group arose from troubles with bifixation, as exhibited in the Brock string test.

One out of 3 participants (33.3%) in the less strongly binocular group had a strong preference for their right eye in the three tests that probed these skills: the sighting eye, real/unreal distinction in diplopic images, and the suppression of a string image in the Brock string. The other two participants (66.7%) showed no distinct preference for either eye and switched between both eyes in the above tests. One participant (33.3%) had a stereoacuity of 140 arc seconds while the other two (66.7%) were at 40 arc seconds but struggled identifying differences between the circles at stereoacuities of less than 100 arc seconds.

With the Brock string, all 3 participants reported the correct X-formation color orientation. Participants in the less strongly binocular groups saw the X-formation from 90 cm to 146 cm and the Y- or inverted Y-formation from 100 cm to 147 cm. The intermittent suppression zone that resulted was quite variable, ranging from 1 cm to 27 cm.

Of the 3 participants, 1 participant (33.3%) perceived the Y-formation while the other 2 participants (66.7%) perceived the inverted Y-formation. The 2 participants that saw the inverted Y-formation had difficulties maintaining an image of only one bead; these 2 participants described seeing two beads and had to refocus in order to see one bead or two very close overlapping beads. The two beads were of different colors. Thus, these participants were struggling with fusing the two bead images into one. One participant in particular did not view the X-formation as typically expected; instead at some distances, she perceived two string images in front of the bead and the string images converged into a single string before it went into the bead. At other distances, this participant saw the X-formation in front of the bead. She saw the two string images cross slightly in front of the bead. These results imply that she was fixating in front of the bead rather than on the bead.

The vergence ranges among these 3 participants varied. Two out of the 3 participants (66.7%) perceived the expected size and float with convergence and divergence. On the z-axis, these 2 participants correctly localized the quoit in space, as closer during convergence and further during divergence with the use of a pointer. One of these 2 participants struggled with perceiving the size change to the quoits but was able to determine size when using the pointer to localize the quoit in space. One out of the 3 participants (33.3%) perceived the expected SILO change in distance on the z-axis during convergence and divergence but was incorrect with the perceived size change. This participant also had difficulty with fusion. She sometimes saw two quoits instead of fusing the two quoits into one. When localizing the quoit in space on the z-axis, the participant had difficulty and identified the quoit as closer or in front of the stand during divergence.

With the red/green anaglyphs of random dot stereograms, all 3 participants in the less strongly binocular group were able to perceive the three layers of squares rising above or going below the plane of the page. These participants viewed the three layers of boxes until the random dot stereograms with 70% to 60% dot correlation. As the binocular correlation of the random dot stereograms continued to decrease to 40%, the report of these 3 participants fell into three out of the four categories: loss of shape or form of the square, a decrease in both shape or form and depth, or a complete loss of shape or form and depth.

Weakly Binocular

Six out of 30 participants (20.0%) were categorized as weakly binocular. These participants incorrectly viewed two or more of the optometric tests while struggling with the other tests. Their eye dominance was also taken into consideration in the sighting eye test, real/unreal distinction in diplopic images, and the suppressed string image in the Brock string test.

These participants had a diverse range of eye preference during the eye dominance portions of this study. Two out of 6 participants (33.3 %) had a strong preference for their right eye in all three eye dominance tests: the sighting eye test, real/unreal distinction in diplopic images, and the Brock string test. Four out of 6 participants (66.7%) switched between their two eyes in these tests. Five out of 6 (83.3%) participants' sighting eye dominance matched their hand dominance whereas 1 participant displayed cross dominance (sighting eye was the opposite of the dominant hand). These participants displayed some difficulty with the real/unreal distinction in diplopic images and it was noted that they often took longer to determine which finger image was the "real" image. One participant (16.7%) had difficulty with seeing two diplopic finger images and saw only one image. It is possible that this participant suppressed the image from one eye.

With the Stereo Fly test, the stereoacuity varied within the weakly binocular group. Four out of the 6 participants (66.7%) showed typical stereoacuity between 40 to 50 arc seconds but showed some difficulties after 200 arc seconds. Two out of the 4 participants (33.3%) had a stereoacuity of 100 and 140 arc seconds.

With the Brock string test, all of the participants in the weakly binocular group viewed the color orientation of the string images in the correct order. Three out of the 6 participants (50.0%) reported a correct X-formation but still showed some difficulty in seeing one bead. This indicates a problem with bifixation on the one bead. One participant saw an unstable image; first she lost a green string in front to view a Y-formation, but then regained the string and lost the green string behind to view an inverted Y-formation. Another participant perceived the two strings in front and behind the bead and reported that the string images were white and yellow rather than green and red. The additional 3 participants (50.0%) either viewed the string images as crossing behind the bead at certain distances or perceived the string images going through the bead at atypical angles. These reports indicate problems with aiming both eyes at the bead. Two out of these 3 participants saw the red string crossing over the green string behind the bead during the X-formation. One of these participants also reported that she did not see a particular color string suppressed in the inverted Y-formation but rather saw a single uniform yellowish white string behind the bead. For one of the 3 participants, the red string intersected the bead at a perfect straight line (from the participant's nose to the wall, a 180 degree line on z-axis) and the green string intersected the bead on the far left edge going from the right side in front of the bead to the left side behind the bead. This result indicates that the left eye was not aimed at the bead. This participant also reported that when a string was suppressed behind the bead to view the inverted Y-formation, the outgoing string was a yellowish white color.

All of the participants in the weakly binocular group were able to bifixate and view the X-formation beyond 100 cm. The X-formation ranged from 110 cm to 180 cm and the Y- or inverted Y-formation ranged from 196 cm. The resulting intermittent zone was variable with a range of 16 cm to 55 cm.

All 6 participants were within normal vergence range for both convergence and divergence, but were typically on the lower end of the continuum. None of the participants correctly perceived the SILO effect and their perception of float varied. Two out of the 6 participants (33.3%) perceived the float correctly during convergence, describing the quoit as smaller and closer. The other 4 participants (66.7%) described the float as larger and closer, larger and further, or as no perceived change in size or distance. All 6 participants incorrectly identified float during divergence, describing the quoit as closer and smaller, closer and larger, or no perceived change in size and distance. Two out of the 6 participants (33.3%) correctly localized the quoit with the pointer (on the z-axis) even though they perceived the float incorrectly. For the remaining 4 participants (66.7%), the perception of float matched their localization of the quoit in space by either placing the pointer in the same area in space where the float was perceived or placing the pointer on the target if no change in size or distance was observed in the quoit.

With the red/green anaglyphs of the random dot stereograms, all 6 participants perceived the three boxes rising above or going into the page. These participants were able to see the smallest square until the random dot stereograms with 80% to 70% dot correlation, excluding one participant who perceived the smallest square until the 60% binocular correlation with the red lens over the right eye and the green lens over the left eye. At the lowest diminishing binocular correlation of 40%, all six participants described the squares within one of the four categories.

Group B: Binocular Anomalies Group

All participants in the binocular anomalies group had visual acuity of 20/40 or better while the degree of binocular vision skills ranged between participants. It was observed that on the 20/20 line in the Snellen vision test, all five participants struggled with deciphering the letters in the middle area. This struggle was representative of a crowding effect, as the letters are hard to read as they are flanked by surrounding letters.

Participant A

Participant A is 22 years old and has no formal diagnosis but complained of double vision. According to the Stereo Fly test, the participant had a stereoacuity of 140 arc seconds. This participant displayed cross dominance by displaying left eye sighting dominance and right handedness. Eye dominance was difficult to determine in the other two portions of this study as the participant was not able to see diplopic images of the finger and had difficulty with the Brock string test.

With the Brock string, this participant reported that the red string image intersected the bead in a straight line, from the participant's nose to the wall, a 180 degree line on the z-axis. The green string was set off to the right and intersected the right edge of the bead, but the participant had a hard time maintaining this image. These data indicate that the participant fixated the bead with her right eye while her left eye was turned inward. The image from the left eye was partially suppressed (Fig. 27).

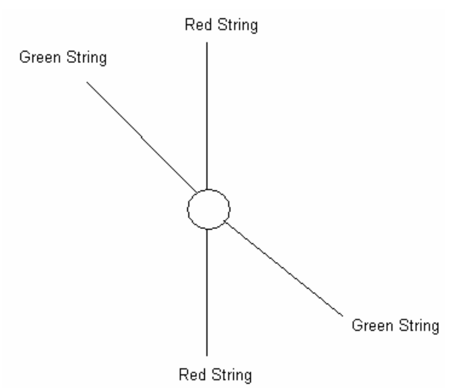


Fig. 27: Participant A's description of the Brock String

The participant also struggled with maintaining an image of one bead and would often see two beads or two overlapping beads. Again, this indicates that the two eyes were not pointing to the same place in space.

The participant's vergence and perception skills in the polarized vectograms and random dot stereograms were within normal range. With the polarized vectograms, this participant's vergence range was 8 prism diopters for convergence and 11 prism diopters for divergence. Thus, her convergence but not divergence range was below normal. Changes in size and distance of the quoits were correctly identified and the SILO effect was quickly recognized as SILO. On the z-axis, the participant correctly localized the quoit in space with the use of a pointer as closer during convergence and further during divergence. The participant was able to perceive all three layers in the red/green anaglyphs of the random dot stereograms. The participant lost the smallest square in the random dot stereograms between 80 to 70% and by 60% was not able to distinguish any difference in shape or form and depth, viewing only one two dimensional square.

Participant B

Participant B is 55 years old and was recently diagnosed with posterior lenticonus in her left eye. The participant's inner lens is 20/20 but the outer portion is not corrected resulting in two different refractions. The participant believed she had normal binocular vision before the lenticonus developed at age 53. According to the Stereo Fly test, the participant had a stereoacuity of 100 arc seconds. The participant's dominant eye varied throughout different optometric tests. Right eye dominance was exhibited in the sighting eye test and the real/unreal distinction of diplopic images but left eye dominance was displayed during the suppression of a string image in the Brock string test. Participant B is right handed.

In the Brock string test, participant B viewed the color orientation in the correct order and also observed the strings to intersect at the bead. Thus, this participant bifixated correctly until 50 cm. Two beads were seen after this point. It was difficult for the participant to fuse the two beads images into one. Often the participant would view two bead images that were touching and lined up horizontally next to each other. The left bead image was seen as red and the green string would intersect this bead while the right bead image was black and the red string would intersect this bead. These reports indicate that the two eyes were not both aimed at the bead at the same time. When the participant was able to fuse the bead into one image, only the black bead was seen. The participant viewed an inverted Y-formation when one eye's input was suppressed and only saw one green string behind. The intermittent suppression zone was 16 cm.

The participant's vergence skills and perception of the polarized vectograms and random dot stereograms were within the normal range. In the polarized vectograms, the vergence range for convergence was 7 prism diopters and for divergence was 12 prism diopters. Changes in size and distance of the quoits were correctly identified and the SILO effect was quickly recognized. On the z-axis, the participant correctly localized the quoit in space with the use of a pointer as closer during convergence and further during divergence. All three layers in the red/green anaglyphs of the random dot stereograms were seen. The participant lost the smallest square with the random dot stereograms with 70% dot correlation, and by 40% was not able to distinguish any difference in shape or form and depth, viewing only one two dimensional square.

Participant C

Participant C is 57 years old and diagnosed with ambylopia (lazy eye) in both eyes. During childhood, the participant had surgery to correct the condition and wore an eye patch from three years of age to approximately 20 years of age. The participant does not remember having vision therapy.

According to the Stereo Fly test, the participant had a stereoacuity of 200 arc seconds. This participant displayed cross dominance by displaying left eye sighting dominance and right handedness. Eye dominance was difficult to determine in the other two portions of this study. In the real/unreal distinction in diplopic images, the participant was not able to see a diplopic image of her finger. She saw only one finger. In the Brock string test, the participant had a difficult time describing the color of the string images, observing the string images as white although she reported that one string had a slight hue of green.

The participant had difficulty with the Brock string test. The participant viewed the strings as white and green. She perceived two beads that were very close together; the left bead was white and the right bead was black. In front of the beads, the left string image was white and the right string image was green. The strings went directly through the beads and remained the same color afterwards. The strings did not form a cross at the beads but crossed closer to the end of the string, creating an X-formation and reversing the color orientation behind the cross. After the strings crossed, the left string image was green and the right image string was white (Fig. 28). This report indicates that she aimed her eyes not at the bead but beyond it.

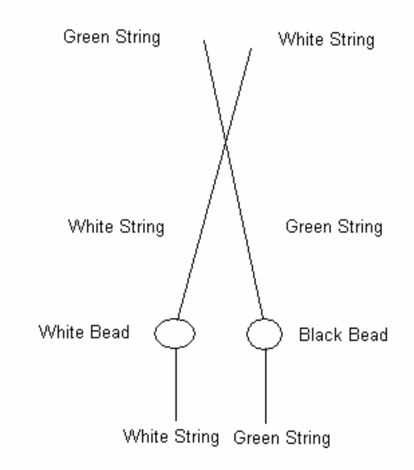


Fig. 28: Participant C's description of the Brock string

As the distance of the bead increased, the participant perceived the two beads moving closing to each other, eventually overlapping and become a single colored white bead after 45 cm. However, by 40 cm string images were no longer crossing behind the bead but at either the two beads images or the single bead. The participant was able to view an inverted Y-formation and only one white string behind. The intermittent suppression zone was 6 cm.

The participant's vergence was within normal range when viewing the polarized vectograms, but she showed some difficulties in deciphering between one fused quoit and two separate quoits. This participant had a difficult time determining at which number or letter increments (measured in prism diopters) that two separate quoits were seen. For convergence and divergence, the vergence range was 13 diopters; however the participant perceived no change in size and float. Not being able to detect the SILO effect, this participant was unable to localize where the quoit image floated in space (in front or behind the stand) and placed the pointer directly on the slide instead.

This participant also had difficulties with fusion in the random dot stereograms. With the random dot stereogram of 100% dot correlation, only two layers were perceived, an outer box-like shape that had a slight percept of depth in the corners and a middle area that was box-like. These shapes either were perceived as going into the page or coming out of the page depending on which color lens was over which eye. By 90% dot correlation in the random dot stereograms, the outer box was flat and on the plane of the page and the middle box like shape became more rounded and closer to the plane of the page; by 80% dot correlation the middle area was still in depth but the shape was indistinguishable. By 70% dot correlation no depth was perceived and only one large flat square was seen.

Participant D

Participant D is 60 years old and has no formal diagnosis but has visual deficits similar to ambylopia. The participant relies mostly on monocular vision and use one eye or the other for sighting. At some points in time the participant is able to use both eyes together. This individual wears glasses to help with binocularity and also acuity and has not had corrective eye alignment surgery or any form of vision therapy.

The participant had a subnormal stereoacuity of 800 arc seconds, according to the Stereo fly test. The participant's dominant eye varied throughout the different optometric tests. During this test, the participant moved the Stereo Fly book while trying to distinguish between the circles. Right eye dominance was exhibited in the sighting eye test and during suppression of a string image in the Brock string test, but left eye dominance was displayed in real/unreal distinction of diplopic images. No cross dominance was shown between the sighting eye test and handedness.

With the Brock string test, this participant viewed the color orientation of the string images in the correct order (0 to 40 cm), but the red string intersected the bead in a straight line, from the participant's nose to the wall, a180 degree line on the z-axis. This indicates that she was fixating and localizing the bead with her right eye. The green string was set off to the left and intersected the left edge of the bead but the participant had a hard time maintaining this image. By 40 cm, the green and red string crossed in front of the bead. The green string image appeared to go through the left side of the bead whereas the red string image had a more direct route through the bead (Fig. 29).

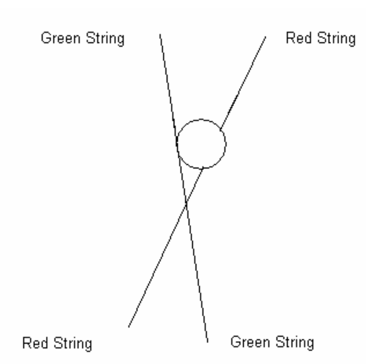


Fig. 29: Participant D's description of the Brock String

The participant was able to view the inverted Y-formation and perceived only one red string behind the bead. The intermittent suppression zone was 30 cm.

This individual's vergence range was below average as measured with the polarized vectograms. The convergence range was 2 prism diopters and the divergence range was 4 prism diopters, and the participant perceived no change in size and float of the quoits. During convergence, the participant viewed only the quoit placed to the left suggesting that she was aware of only the right eye's input. During divergence the left quoit (L) was seen but the participant still had difficulty fusing both quoits. Not being able to detect the SILO effect, this participant was unable to localize where the float was in space (in front or behind the stand) and placed the pointer directly on the slide instead.

The participant also had some difficulties with fusing the random dot stereograms. Only two layers were perceived, the bottom layer was a square on the plane of the page and in the center was a circular but non-symmetrical shape that came above of or below the plane of the page, depending which colored lens was placed over which eye. With the random dot stereograms with 100% to 80% dot correlation, the participant's ability to distinguish the shape and dimension decreased. By 70% dot correlation, no depth was perceived but the participant noticed some difference in the dots but could not describe these differences.

Participant E

Participant E is 52 years old and has strabismus and intermittent exotropia (walled out) in both eyes. The participant underwent two surgeries, one at age five for both eyes and one at age six to bring the right eye back out as it was overcorrected in the first surgery. This participant is unsure if any form of vision therapy was used after surgery. Glasses are worn for acuity and astigmatism. Participant E uses the left eye to sight far and the right eye to sight near and the participant finds it easier to view in the distance. The participant has difficulty with convergence for near targets and also has difficulties with peripheral vision and gauging body placement in space. This has lead to issues with mobility.

According to the Stereo fly test, this participant had a subnormal stereoacuity of 140 arc seconds. The participant's dominant eye varied throughout different optometric tests. This participant displayed cross dominance by displaying left eye sighting dominance and right handedness. In the real/unreal distinction of diplopic images, the participant displayed left eye dominance whereas in the Brock string test, right eye dominance was exhibited.

This participant struggled with perceiving the correct colors and orientation of the strings and bead in the Brock string. This participant initially saw two separate beads from 0 to 30 cm. This indicates that she was having trouble aiming her two eyes at the bead and fusing the two eyes' images into one. Participant E initially perceived the Brock string like Participant C, so that in front of the two beads, the left string was yellow and the right string was green. The strings then went directly through the beads and remained the same color afterwards. The strings did not form a cross at the beads and instead converged into one single yellow string image beyond the bead (Fig. 30). This report indicates that she was fixating behind the bead.

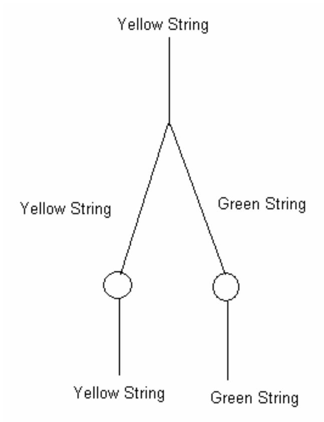


Fig. 30: Participant E's description of the X-formation in the Brock String

From 0 to 30 cm the participant noticed that she used each eye individually and was able to describe this monocular perception from both the left and right eye. One noticeable difference between both views was the different string images' colors. When viewing with the left eye, the left string image was a red/orange color whereas when viewing through the right eye, the left string image was a yellow color. Also when the left eye was viewing the right (green) string it was in focus and the red string was not, whereas when the right eye was viewing the left (yellow) string it was in focus and the green string was not. This indicates that the foveas of the two eyes were not aimed at the same place. From 40 to 150 cm, this participant was able to use both eyes to see the bead at a further distance. The beads continued to come closer to one another and converged into one single bead image. The string image that appeared yellow and red from both monocular views now became a bright colored red in the binocular view. As the bead distance increased, the intersection point of the red string image and green string image behind the bead decreased and eventually the intersection point was at the bead. At this point (120 cm) the red string went directly through the bead (from the participant's nose to the wall, 180 degree line) and the green string went through on the right side. At 135 cm, the green string was only visible in front of the bead, touching it on the right side. This indicates that she aimed her right eye at the bead while the left eye was turned inwards. No green string image was seen behind the bead at 135 cm (Fig. 31). The intermittent zone was 15 cm.

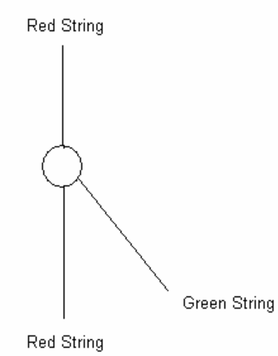


Fig. 31: Participant E's description of the Y-formation in the Brock String

The participant's vergence skills and perception of the polarized vectograms and random dot stereograms were within normal range. With the polarized vectograms, the participant's vergence was 13 prism diopters for convergence and 11 prism diopters for divergence. Thus, her convergence but not divergence range was below normal. Changes in size and perceived float of the quoit were correctly identified and the SILO effect was quickly recognized. Some confusion arose when trying to localize the quoit in space with the pointer. The participant was able to perceive all three layers in the red/green anaglyphs of the random dot stereograms. The participant lost the smallest square by 70% dot correlation and was still able to distinguish some shape in the random dot stereograms with 40% dot correlation but did not perceive any depth.

DISCUSSION

The results of the optometric tests: Stereo fly test, sighting eye test, real/unreal distinction in diplopic images, Brock string test, polarized vectograms, and random dot stereograms suggest that there is a large range of binocular skills among individuals. These variations in skill led to the classification of Group A's participants into three groups: strongly binocular, less strongly binocular and weakly binocular groups.

<u>Binocular Skills Among Group A: No Known Binocular Disorders</u>

Stereo Fly Test

In the Stereo fly test, 3 out of 30 participants (10.0%) showed subnormal stereoacuity, that is stereoacuity below 80 to 40 arc seconds. For these participants, a disparity of 40 to 80 arc seconds in the position of the image on the two retinas was not great enough to perceive the depth difference. A subnormal stereoacuity in the Stereo Fly test was found to be predictive of difficulties with the other binocular skills tests.

Eye Dominance

Participants differed in the relationship of their sighting eye to their handedness. The highest percentage of participants, 70.0% fell into the right hand, right eye group. This result was expected as handedness and eye dominance may be reflective of the dominant side of one's body. However, 16.7% of participants were right handed but left eye dominant in the sighting eye test. The left handed participants, 6.7% were all left eye dominant. A variation in eye dominance was found among the 2 participants that were ambidextrous.

In the real/unreal distinction of diplopic images test, most right handed individuals considered the right eye image as real. This was expected as this was the higher percentage of eye dominance seen in the sighting eye test. Interestingly though, 76.7% of participants were right eye dominant in the sighting eye test whereas only 60.0% of participants were right eye dominant in the real/unreal distinction of diplopic images.

In the Brock string test all participants suppressed one string image when viewing at some distance. 76.7% viewed the red string image. This right eye dominance equaled the percentage of participants that were also right sighting eye dominant. A smaller percentage of participants, 10.0% were left eye dominant. Additionally, 6.7% of participants alternated between the two string images. This alternation of colored string suppression was noticed in all three binocular subdivisions within Group A.

To observe the differences of the participants' right and left eye dominance, a three way comparison was made between all three eye dominance tests: sighting eye, real/unreal distinction in diplopic images, and the viewed string image in the Y-or inverted Y-formation. Among all three tests, the highest percentage of participants showed a strong preference for their right eye. The left handed individuals also show a strong preference for their left eye in the three tests. However, eye dominance results for one test were found not to be predicative of another eye dominance test results. It is possible that some variability resulted from participants in the less strongly binocular and weakly binocular groups, as some of these participants displayed cross dominance. It is possible that cross-dominance is linked to weak binocularity, as 3 out of 5 participants in the group with binocular anomalies (Group B) exhibited cross-dominance. Various studies have suggested that there is increased crossed dominance in stabismics. Many of these individuals display left eye dominance but a right hand preference (Previc, 1993).

Brock String

When viewing the Brock string, most participants either described seeing an X- or a type of Y-formation. An X-formation occurs when two string images were seen in front of the string and two behind the bead. In the Y-formation either two string images were viewed in front of the bead and one string image behind the bead (inverted Y-formation) or one string image was viewed in front of the string and two string images behind the bead (Y-formation). An X-formation is an indication of good bifixation, the ability to aim the two eyes at the same point in space at the same time. The Y-formation shows suppression of one eye's input.

There was much variability among participants in the distance at which the X- and type of Y-formation was viewed. The perceptions of the X and Y-formation at different distances can be explained as a factor of each individual's bifixation ability and indicates that individuals vary in this ability.

Most participants viewed an area in which they could not determine if an X- or Y-formation was occurring or described seeing one string image as disappearing and reappearing. This area was named the intermittent suppression zone. The length of the intermittent zone was quite variable and did not reflect how far back each participant could see the X-formation.

The majority of the participants in Group A, 90.0% suppressed one of the string images behind the bead. This means they suppressed one eye's input at a certain distance. The remaining 10.0% of participants had a difficult time distinguishing the X- and Y-formation from each other.

The variability within the results can be explained by the context of the Brock string test. The participants had to look at a small target and this is more difficult than bifixation in the real world. Objects are typically larger and contextual cues aid in aiming the two eyes at the same target.

The Brock string test was found to be predictive of difficulties with the other binocular skills tests. If participants had trouble with bifixation, they were less strongly binocular and usually struggled with the other optometric tests.

Polarized Vectograms

The participants' convergence range (24.2 $\pm$ 14.4 prism diopters) in Group A was within the normal convergence range of 20 to 25 prism diopters. Their divergence range (11.6 ± 4.2 prism diopters) was also within the normal range of 10 to 15 prism diopters (Scheiman and Wick, 2002).

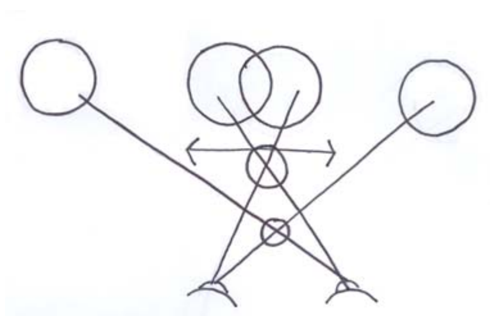
The significant difference between the convergence and divergence ranges of Group A showed that the convergence range was larger than the divergence range. Convergent movements of the eyes are necessary to bifixate objects that are up to 1 meter (100 cm) away. During convergence of the polarized vectograms, the right eye viewed the slide displaced to the left and the left eye viewed the slide displaced to the right. The line of sight by both eyes created a crossing point in space where the single fused quoit was located. However, during divergence there were no eye positioning cues as the right slide was placed on the right side and the left slide on the left side. Thus, the resulting line of sight from each retina did not cross. It is possible that participants performed better on convergence and displayed larger convergence fusion skills as a result of this crossing point cue. There was no significant correlation between each individual's fusion abilities for convergence and divergence (Fig. 21). Thus, one can have good convergence but poor divergence skills or vice versa.

The actual perception of size and float deviated from SILO more than predicted for both convergence and divergence. During convergence, 20 of the 30 participants (66.7%) viewed the quoit within SILO, as smaller and closer to the participant. Interestingly, the highest percentage (13.3%) of participants that deviated from the expected results was for participants that either viewed the quoit as smaller and further or larger and closer. Normally during convergence as an object comes closer the retinal image size increases. However, the brain takes in account the retinal disparity cues that indicate that the object is closer and adjusts for the larger retinal size. It is possible that the participants who viewed the quoit as larger and closer assumed that a closer quoit must be larger. Similarly, the participants who viewed the quoit as smaller and further away assumed that the quoit must be smaller since it was located further away.

During divergence, a larger number of participants deviated from the expected SILO perception as only 13 out of 30 (43.3%) perceived the quoit as larger and further away. The highest percentage of participants (20.0%) that differed from the expected results perceived the quoit as larger and closer. Similar to viewing the quoit during convergence, it is possible that these participants assumed that if the quoit image was perceived as larger than it was closer to them. An additional 20.0% of participants viewed no change in size and float during divergence. It is likely that these participants made poor use of retinal disparity cues to judge size and depth. If these participants' fusion range was small for divergence, the change in the quoit size and float across the z-axis may have been quite small. Since the change was smaller or very minimal, these participants might have assumed that there was no change.

In addition to disparity cues and visual context, convergence is also driven by weak depth cues such as accommodation. After 1 meter, however, only disparity cues and visual context are used for divergent movements of the eyes. Thus, it may be harder to judge float with divergence than convergence.

Moreover, it may be easier to interpret the expected SILO effect during convergence because the crossing point would lead to a precise localization of the quoit in front of the quoit stand. Perceiving float during divergence may also be more difficult because the quoit would be perceived behind the stand. The stand is opaque so the participants had to imagine the quoit behind a solid object (Fig. 32).



Left Eye Right Eye

Fig. 32: Illustration of the crossing point created by the line of sight during convergence. As the right quoit image is displaced more to the left and the left quoit image is displaced more to the right, the eyes must continue to turn inwards to perceive the single fused quoit. The crossing point continues to move closer to the eyes as the eyes turn inwards and aids in the localization of the single fused quoit.

Random Dot Stereograms

The participants in Group A viewed the smallest square in depth in the random dot stereograms containing 80% to 60% dot correlation. Most of the participants perceived the smallest square within the 70% to 60% dot correlation. Even participants in the weak binocularity group still performed within this range. This suggests that this test is not the best standard to determine binocular abilities in individuals. This test does indicate stereoweakness based on the individuals' ability to see the square layers; however, it is not a good standard to determine general strong binocular skills such as bifixation and fusion abilities.

It was observed that some participants would move their heads back and forth or move the book while viewing the random dot stereograms. These participants may have difficulties with distinguishing the different layers of depth and form. By creating a sense of motion, they were than able to rely on their monocular cue of motion parallax.

Three Binocularity Subdivisions within Group A

Participants were divided into three subdivision based on their binocular skills. Twenty out of 30 participants (70.0%) were strongly binocular, 3 out of 30 participants (10.0%) were less strongly binocular, and 6 out of 30 participants (20.0%) were weakly binocular. This percentage of participants with weak binocularity in this study is similar to the percentage found in a study by Hokoda (1985). Within an urban optometry clinic, approximately 21% of patients who were unaware of any underlying conditions were found to have weak binocularity.

Strongly Binocular

No difficulties were observed in the Stereo Fly test with the strongly binocular participants. These participants had stereoacuity within the defined range of 40 to 80 arc seconds. In the Brock string test, all participants perceived the X- and Y-formation and all except one viewed the color orientation of the diplopic string images as expected. The participant that viewed the colors in the reverse order seemed to confuse her right and left throughout the test, so it is possible that she viewed the color orientation as expected but did not report her perception correctly.

It was expected that the strongly binocular group would view the X-formation at a greater distance. An ability to sustain the X-formation is an indication of good bifixation skills. However, the distance to which the X-formation was seen in this group (40 cm to 200 cm) was variable. This shows that even within the strongly binocular group there was a range of binocular abilities.

Even within the strongly binocular group there was variability in the fusion range during convergence and divergence along with variability in the perceived size and float of the quoit. Again, this points out the range of skills even among individual with good binocular skills.

Less Strongly Binocular

The participants in the less strongly binocular group had difficulties with the Stereo Fly test. One participant displayed a subnormal stereoacuity of 140 arc seconds while 2 participants exhibited normal stereoacuity (40 arc seconds) but struggled with identifying differences between the circles at a disparity of 100 arc seconds.

These participants mostly struggled with their bifixation abilities in the Brock string test. The X- and different types of Y-formation were viewed as expected; however, these participants reported viewing two diplopic images of the bead. These observations indicate a problem with bifixation on the bead. Instead, the participants' eyes were aimed in front or behind the bead rather than on the bead.

In the polarized vectograms, this group varied in their abilities to fuse the quoit and perceive the float. One participant struggled with fusing the two quoit images within the normal convergence and divergence range. Also this participant was not able to perceive the float correctly during divergence. It is possible that this participant had a very small vergence range. She could then not fuse the two quoit images and instead viewed each quoit separately. The 2 other participants perceived the expected SILO and accurately localized the quoit in space.

The random dot stereogram test was not indicative of struggles on other optometric tests as all three participants fell within the same range as the strongly binocular group. The participants in the less strongly binocular group were able to perceive the three square layers and viewed the smallest square until the 70% to 60% dot correlation.

Weakly Binocular

In the real/unreal diplopic image test that measured eye dominance, some participants had difficulty perceiving two finger images. It is possible that these individuals are instead suppressing one image. In the Stereo Fly test, the stereoacuity varied among participants. Two of the participants had a stereoacuity of 100 to 140 arc seconds. The other 4 participants had a stereoacuity of 40 to 50 arc seconds but had difficulties perceiving depth and often took guesses at disparities less than 200 arc seconds.

Difficulties with bifixation were observed in the Brock string test. Participants reported seeing two images of the bead indicating that they were not properly bifixating. Participants who had trouble aiming their two eyes at the bead also displayed difficulties with determining the string image colors. Additionally, these participants perceived the string images going though the bead at atypical angles and often the string images would cross behind the bead. One participant showed difficulties with aiming her left eye at the bead. This participant reported seeing the red string go directly through the bead from her nose to the wall while the green string was offset to the right.

The participants in the weakly binocular group also had difficulties with fusion and perception of float in the polarized vectograms. None of the participants accurately perceived the SILO effect. During convergence, these participants may have relied mainly on contextual, not disparity cues, reporting that the float appeared larger because it was seen closer to them. All 6 participants struggled with divergence, having difficulty with aiming their two eyes at the separate quoit images and fusing the image into one.

These participants were able to perceive all three layers of the random dot stereograms, again suggesting that this test may not be the best indicator for measuring binocular skills. The participants lost the smallest square at a slightly higher dot correlation of 80% to 70% compared to the other two subgroups. A good portion of the participants were observed to move their heads during viewing the random dot stereograms. Due to these participants smaller degree of binocular fusion, it is possible that they tried to gain perception through the monocular cue of motion parallax.

Binocular Skills Among Group B: Binocular Anomalies

Each participant in the binocular anomalies group will be discussed individually. However, it was observed that 3 out of 5 participants (60.0%) in the sighting eye test exhibited cross-dominance. These participants were found to be right handed but left sighting eye dominant. One participant in this group may have once been binocular as her disorder developed later in life. This participant did not show any cross-dominance. The percentage of cross-dominance within Group B might be higher if only participants who developed binocular anomalies early in life were considered. Thus, cross-dominance may correlate with poor binocular skills.

A few participants reported seeing letters in the reverse order or letters missing on the charts of the Snellen Vision and Near Vision visual acuity tests. This confusion of letters is referred to as the crowding effect. Crowding is seen when it is easier to read letters on an eye chart if the letters are seen in isolation as opposed to being flanked by other letters (Levi, Song, and Pelli, 2007). Additionally, all five participants had an easier time viewing the quoits during divergence compared to convergence.

Participant A

Participant A is 22 years old and has complaints of double vision. This participant showed some difficulties during the eye dominance tests and displayed cross-dominance during the sighting eye test. She was unable to see the two finger images during the real/unreal distinction of diplopic images. This individual often sees double images and it is possible that these two finger images were not seen because her initial reaction might be to suppress one of the images. Participant A had a stereoacuity of 140 arc seconds.

Participant A showed weak bifixation skills in the Brock string test. She viewed the red string in a straight line from her nose to the wall and the green string offset to the right; showing that this participant fixated with her right eye and had her left eye turned inwards. The participant had a hard time maintaining this atypical X-formation, indicating that she was partially suppressing the image from her left eye. This participant also reported seeing two bead images suggesting that her two eyes were not aimed at the same point in space and she was fixating in front or behind the bead.

Participant A was able to perceive the SILO effect correctly and responded in a very quick manner. Her convergence range was below the normal range but her divergence range was within the typical fusional range. Participant A was also able to perceive the three layers of the random dot stereograms indicating that she is able to interpret binocular disparity cues. It is possible that this participant's binocular deficits were intermittent and she is able to correctly view some images in depth while at other times she is not able to bifixate and sees objects in double.

Participant B

Participant B is 55 years old and was recently diagnosed with posterior lenticonus in her left eye. Her eye dominance varied through the different optometric tests. It is possible that this participant's eye dominance varied among tests because her visual difficulties developed later in life and disrupted her binocular abilities. Her stereoacuity in the Stereo Fly test was 100 arc seconds.

Participant B was able to bifixate at a near distance (up to 50 cm) but at greater distances reported seeing two bead images. At these distance her eyes were not aimed at the bead at the same time. Her ability to bifixate at a near distance can be due to having developed binocularity that was disturbed only later in life. It is also possible that she was not able to bifixate after 50 cm because of the different refractions within her lens which made it more difficult for accommodation of the lens and focusing on the far bead.

Participant B was able to perceive the SILO effect correctly. Her convergence range was below the normal range, but her divergence range was within the typical fusion range. This participant was also able to view the three layers of the random dot stereograms indicating that she was able to use some binocular disparity cues. Again, her ability to perceive depth even when she had some difficulties on other optometric test is indicative of her having developed binocular skills that were disturbed later on in her life by a refractive lens problem.

Participant C

Participant C is 57 years old and is diagnosed with ambylopia in both eyes. She had difficulties with all the optometric tests. This participant displayed crossed dominance in the sighting eye test. Similar to participant A, participant C was unable to see the two finger images during the real/unreal distinction of diplopic images. Additionally, she had difficulties describing the color of the string images, especially the red string image in the Brock string test. In both tests, this participant was suppressing an input from one of her eyes, particularly the right eye in the Brock string test. This suppression could result from her ambylopia as suppression is a method used to reduce her perception of double images. In comparing the results of the Brock string test and sighting eye dominance, it seems that this participant was left eye dominant. Finally, participant C had a stereoacuity of 200 arc seconds.

In the Brock string test, this participant perceived the two string images as parallel; these string images went through two beads and crossed further back in space. This perception was reflective of her difficulty with bifixation. This perception of the string images indicated that she was underconverging, as she did not aimed her eyes at the bead but instead aimed behind it. However, by 40 cm this participant was able to fixate both her eyes on the bead, perceiving a correct X-formation until this distance and later on she suppressed one of the strings behind the bead to view an inverted Y-formation. This ability to fixate properly at a further distance hints at some binocularity ability. With additional practice, it would be interesting to see if this participant could improve her bifixation skills.

Participant C struggled with her ability to distinguish between a single fused quoit and two separate quoits during the polarized vectograms. It was noticed that when she perceived a single fused quoit she was actually only seeing the left quoit image. As seen in the eye dominance test, this participant had a tendency to suppress input to her right eye. By viewing only the left quoit and having difficulties perceiving a fused quoit, it is possible that she was only using her left eye during this test. Since she was only viewing the one quoit, then she was not properly converging and diverging. Additionally, she was unable to perceive a change in size and float indicating that she may have only been using her left eye.

The participant was able to view the random dot stereograms only through the 80% dot correlation and only perceived the middle, smallest square with unclear edges and corners. Often disorders such as ambylopia and strabismus are linked to stereoblindness, the inability to use binocular disparity cues. It is believed that random dot stereograms do not contain any monocular cues to depth, but only binocular cues (Wolfe et al, 2006). However, participant C was able to partially view the random dot stereograms to 80% dot correlation, suggesting that she has some ability to use her eyes in synchrony to perceive depth.

Participant D

Participant D is 60 years old and has visual deficits similar to ambylopia. She also had difficulties with all the optometric tests. Her eye dominance was variable between all three eye dominance tests. She had subnormal stereoacuity of 800 arc seconds meaning that after the first circle arrangement in the Stereo fly test, the disparity images of the two overlapping circles falling on the retina were not great enough for her to see the fused circle in depth.

This participant also had difficulty with bifixation in the Brock string test. Since she perceived the red string image directly from her nose to the wall, she fixated and localized the bead with her right eye. It would be expected that this right eye dominance would be seen in the other two eye dominance test to suggest that this participant suppresses one eye to get a more accurate perception of the world. She was found to be right eye dominant in only two out of the three tests: sighting eye and suppression of a string image in the Brock string test.

This participant had a below average fusion range in the polarized vectograms during convergence and divergence. This participant reported having a difficult time fusing the two quoit images and noticed that she was only aware of the right quoit. This strong tendency for the use of her right eye suggests that this participant is right eye dominant and is often suppressing her left eye input. This is also supported in the inverted Y-formation in the Brock sting test as the participant could no longer see the green (left eye image) behind the bead at 180 cm distance. Additionally, the low fusion range is indicative of the participant’s struggle with seeing the left quoit image and her understanding that she was not seeing a fused single quoit.

Participant D was able to view the random dot stereograms until 80% dot correlation and was only able to perceive the middle, smallest square with its unclear edges and corners. Again, like participant C, since the random dot stereograms are believed to have no monocular cues to depth, participant D shows some degree of binocularity.

Participant E

Participant E is 52 years old and is diagnosed with strabismus and intermittent exotropia. This participant's results in the different optometric tests hinted at intermittent use of monocular and binocular disparity cues. Participant E reported that she used her left eye to sight far and her right eye to sight near; however, there was a great degree of variability in which eye was used to sight far and near in the optometric tests. Additionally, the participant had a stereoacuity of 140 arc seconds in the Stereo Fly test.

This participant had some difficulties with bifixation which lessened as the bead was placed further back on the string. Initially, the participant was not aiming her eyes at the bead, which resulted in a double image of the bead. It was found that she was underconverging, fixating her eyes behind the point of the bead as the string images went directly through the bead and later converged into a single string image. After 30 cm, the participant was able to aim both her eyes closer to the target bead but not directly on the same point as the bead images appeared to overlap. However, she was fixating her eyes within the general area of the bead because she was able to perceive the X-formation. By 120 cm, the red string went directly from her nose to the wall and the green string was at an atypical angle. This indicates that she was aiming her right eye at the bead while her left eye was turned inwards. The participant's ability to merge the bead into one image indicated that is it easier for the participant to view an object in the distance. As the bead was placed further away from the participant, she was able to fixate both eyes in the same general direction. Participant E description of the X-formation after 100 cm indicates that divergent movements of her eyes were easier for her.

Likewise, with the polarized vectograms, participant E's fusion range was within the normal range for divergence and slightly below normal range for convergence. This again indicates that it is easier for this participant to make divergent movements of her eyes to view objects in the distance. The participant was able to use binocular vision skills intermittently throughout the tests, as she accurately perceived the SILO effect for the quoits. Her binocular abilities were also evident by her accurately perceiving the random dot stereograms. She was able to see all three layers and even able to distinguish some differences by 40% dot correlation. Since she intermittently used binocular skills, she may be able to increase her vergence skills with training.

Overall Findings

The results of this study suggest that there is a range of binocular skills among participants. A study by Feldman, et al. (1989) tried to find correlations between tests measuring vergence and other binocular functions. Feldman found that the fusional range of individuals varied based on the size and type of target. Performance also varied with the type of target presented, such as random dot stereograms or polarized vectograms. I also found a large variability among participants' binocular skills, making it hard to generalize from one individual's performance to an entire group. Individuals with and without binocular anomalies perform differently on optometric tests not just because of their binocular abilities but also because of their use of other cues, such as position and context.

The variations of skills within Group B, the groups with binocular anomalies, showed that some participants still had binocular abilities despite struggles on the optometric tests. Some studies, such as one by Hunter et al (2001), suggest that binocular skills cannot be improved in individuals with binocular anomalies. They found that no individuals within this group were able to develop bifixation. However, each individual within Group B showed some indication of seeing the X-formation accurately even if there was some off set of string images or this image formation only lasted a small distance. It is possible that these individuals would be able to improve their abilities through training. Daum (1985) suggest that vergence anomalies can be improved but the effectiveness of visual treatment is not understood because of the lack of scientific studies.

Future studies should look at individuals with similar diagnoses as participants in Group B to see if vergence abilities can be improved through training. An earlier study by Ludlam et al. (1961) used similar optometric tests as a form of vision therapy over a two week session. He found that 76% of these participants developed straight eyes and binocular vision with stereopsis. If participants are able to improve their binocularity and decrease their symptoms, this would hint at plasticity within the brain.

Perception Versus Action

The results of the tests with the polarized vectograms support the hypothesis that separate pathways may exist for perception and action. With the polarized vectograms, some individuals reported that the fused quoit image was located in a different place along the z-axis than the place that they localized the quoit with a pointer. Participants who inaccurately reported the SILO effect were able to localize the quoit correctly with the aid of a pointer. These participants mainly reported viewing a SOLI effect but with the use of a pointer, correctly located the quoit as closer during convergence and further during divergence. The remaining participants who did not accurately interpret the SILO effect subsequently struggled with the localization of the quoit.

The variation in individual abilities to perceive and locate the quoit in space led to further investigation of this interaction. The visual system is believed to be comprised of both a perceptual and visuomotor (action) system. Initially, visual information enters the V1 area in the primary visual cortex but then splits into two streams, the dorsal and ventral stream. Information in the dorsal stream is used for visuomotor control. The ventral stream allows for conscious awareness of a visual percept and for forming visual images and memories. The action and perception systems may to be loosely correlated with the “What” and “Where” systems, receptively. The “What” system or parvocellular pathway is used to discern form, shape, and color of an object while the “Where” system or magnocellular pathway is used to discern movement, depth, and spatial arrangement (Livingstone, 2002).

A previous study by Aglioti et al. (1995), suggested that the action system is more accurate than the perceptual system when judging object location and size. Subjects were exposed to an object that moved a rapidly across a very small distance. The movement of the object was so small and rapid that the subjects were unaware that the object moved. However, these individuals made an accurate saccade for the image of the object and reached for it accurately. Aglioti et al. believed that perception of object location is based on allocentric points of reference, the object location based on the surround, compared to the action system perceiving object location based on egocentric points of reference, the object location based on the viewer’s point as a reference.

Similarly, the existence of separate visual pathways for perception and action may explain a phenomenon with the Ebbinghaus illusion. In the

Ebbinghaus illusion, a central circle of one size surrounded by a group of smaller circles appears larger than the same size circle surrounded a by group of larger circles (Fig. 33) It was found that the participants perceived the center circles as different sizes but accurately judged the size of the center circles with their visuomotor system, precisely adjusting their fingers to grab the middle circle. The different interpretations of these two systems, suggest that the visuomotor system interprets the exact size and location of an object and the perceptual system makes a relative judgment of the object's size and location (Aglioti et al., 1995).

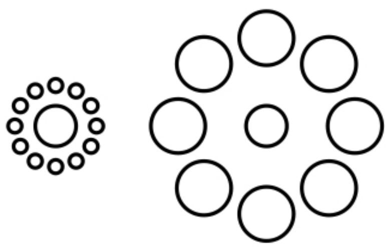


Fig. 33: Perception of Size Illustrated by the Ebbinghaus Illusion (Kitaoka, 2004).
The central circle surrounded by smaller circles appears larger than the central circle surrounded by the larger circles. However, both of these central circles are of the same size.

Some participants had different interpretations of the location of the quoit in the polarized vectograms when reporting what they see versus when localizing with the pointer. This explains why a high percentage of participants inaccurately perceived the location of the quoit yet they were able to accurately represent the location of the quoit with a pointer. This difference of relative and metrical judgment of the perception and action systems incorporated into visual interpretation is another factor in the variation of binocular skills between the participants in this study.

Implications

The results of these studies indicate that binocular vision can span a continuum (Harris, 2002). At one end of the spectrum are individuals whose eyes work together in close to perfect synergy while at the other end of the spectrum are individuals who use predominantly one eye. Harris proposed that the variability in visual skills was based not only on one's binocular skills but also one's ability to direct attention to either a small or wide area along with an ability to "filter" visual information by being more readily aware of relevant stimuli.

Further Thoughts

Can people move along this binocular continuum? If the brain is plastic, people may be able to move along this continuum. Previous studies have suggested that binocular vision can only develop during the critical period early in life (Hubel and Wiesel, 2004). However, research by Ludlam (1961) found that the use of optometric test as a form of vision therapy developed and improved binocularity and stereopsis in individuals with strabismus. These individuals were able to sustain binocular vision approximately 95% of the time. His findings suggest that the development of binocularity may not be dependent on this critical period, as improvements were seen from ages 4 to 44 years. A follow up study by Ludlam and Kleinman (1965) found that 89% of these participants maintained their binocularity. This suggests that with repeated visual training, individuals with binocular anomalies can substantially improve their binocular vision abilities. Therefore, the brain and its visual pathways may not be as rigid as once thought. These individuals can move along the binocular continuum suggested by Harris (2002), to approach binocular synergy.

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APPENDIX A

Glossary

Arc seconds

A minute- an angular measurement that equals 1/60 of a degree
A second- an angular measurement that equals 1/3600 of a degree

Focus- the adjustment of the lens of the eye to make an image clear

Fixation point- the point at which the two eyes converge

Bifixation- aiming both eyes at the same target

Fusion Range- ability to make convergence and divergence movement of the eye in order to bifixate a target and fuse two images of the eyes

APPENDIX B

GROUP A: Division of Participants into Strongly Binocular, Less Strongly Binocular, and Weakly Binocular

Participant 1 (Strongly Binocular)
Age 21, female

- Cross Dominance with Sighting Eye (left eye, right hand), Left Eye Dominant in both Sighting Eye and Real/Unreal Finger, right eye in Brock String
- 40 arc seconds
- Inverted Y, one red string behind, 100 cm for X-formation, 150 cm for Y-formation, 50 cm intermittent zone
- Small convergence range, incorrect SOLI
- RDS: red R/green L- 70%, lose depth, red L/green R- 70%, lose depth

Participant 2 (Strongly Binocular)
Age 21, female

- Strong preference for right eye, Right eye dominant with Sighting Eye (right hand), Real/Unreal finger, and Brock string (red string)
- 40 arc seconds
- Inverted Y, red string behind, 200 cm for X-formation, 210 cm for Y-formation, 10 cm intermittent zone
- Large vergence range, correct SILO
- RDS: red R/green L- 70%, lose shape or form, red L/green R- 70%, decrease in shape or form and depth

Participant 3 (Strongly Binocular)
Age 21, female

- Strong preference for right eye, Right eye dominant with Sighting Eye (right hand), Real/Unreal finger, and Brock string (red string)
- 40 arc seconds
- Inverted Y, red string behind, 92 cm for X-formation, 93 cm for Y-formation, 1 cm intermittent zone
- Normal vergence range, correct SILO
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 70%, lose depth

Participant 4 (Strongly Binocular)
Age 20, female

- Strong preference for right eye, Right eye dominant with Sighting Eye (right hand), Real/Unreal finger, and Brock string (red string)
- 40 arc seconds
- Inverted Y, red string behind, 130 cm for X-formation, 144 cm for Y-formation, 14 cm intermittent zone
- Large convergence, normal divergence range, correct SILO
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 70%, decrease in shape or form and depth

Participant 5 (Strongly Binocular)
Age 21, female

- Strong preference for right eye, Right eye dominant with Sighting Eye (right hand), Real/Unreal finger, and Brock string (red string)
- 40 arc seconds
- Inverted Y, red string behind, 90 cm for X-formation, 130 cm for Y-formation, 30 cm intermittent zone (hinting at less dominance with sighting eye, changing between green and red string but more favoring of right eye)
- Normal vergence range, correct SILO
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 80%, decrease in shape or form and depth

Participant 6 (Strongly Binocular)
Age 20, female

- Strong preference for right eye, Right eye dominant with Sighting Eye (right hand), Real/Unreal finger, and Brock string (red string)
- 40 arc seconds
- Inverted Y, red string behind, 100cm for X-formation, 127 cm for Y-formation, 27 cm intermittent zone
- Large convergence range, smaller end of normal divergence range, SOLI (difficulty with determining size and distance change)
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 70%, lose depth

Participant 7 (Strongly Binocular)
Age 21, female

- Right eye dominant with Sighting Eye (right hand) and Brock String (red string in), Left eye dominant with Real/Unreal finger
- 40 arc seconds
- Y-formation, red string in front, 100 cm for X-formation, 130 cm for Y-formation, 30 cm intermittent, saw opposite (before bead, red on right, green on left, and after bead, green on right and red on left)
- Large vergence range, correct SILO
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R-70%, lose depth

Participant 8 (Strongly Binocular)
Age 19, female

- Strong preference for right eye, Right eye dominant with Sighting Eye (right hand), Real/Unreal finger, and Brock string (red string)
- 40 arc seconds
- Inverted Y, red string behind, 200 cm for X-formation, 210 cm for Y-formation, 10 cm intermittent zone (constant switch between one and two strings behind)
- Large convergence range, saw correct size but incorrect distance (further away), small divergence and no change in size or distance
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 70%, lose depth

Participant 9 (Less Strongly Binocular)
Age 22, female

- Right eye dominant with Sighting Eye (right hand), Left eye dominant with Real/Unreal finger, and switching between right and left eye in Brock String
- 140 arc seconds
- Inverted Y, switching between red and green string behind, 90 cm for X-formation, 100 cm for Y-formation, 10 cm intermittent zone, difficult time seeing one bead, often saw two bead and needed to refocus to see one bead, which was mostly two very close overlapping beads
- Small convergence range and large convergence range, correct SILO, participant struggled with determining size changed and relied on the pointer to determine size change, going back to the action system.
- RDS: red R/green L- 70%, lose shape or form and depth, red L/green R- 70%, lose shape or form

Participant 10 (Strongly Binocular)
Age 22, female

- Left eye dominant with Sighting Eye (left hand) and Real/unreal finger, Right Eye dominant with Brock string
- 40 arc seconds
- Inverted Y, red string behind, 120 cm for X-formation, 123 cm for Y-formation, 3 cm intermittent zone
- Large vergence range, correct SILO, perception and action systems were the same
- RDS: red R/green L- 60%, lose shape or form and depth, red L/green R- 60%, lose shape or form

Participant 11 (Strongly Binocular)
Age 19, female

- Right eye dominant with Sighting Eye (right hand), Left eye dominant with Real/Unreal finger and Brock String
- 40 arc seconds
- Inverted Y, green string behind, 251 cm for X-formation and 255 cm for Y-formation, 4 cm intermittent zone (changing between one and two strings, a clear difference and not just one string flashing in and out)
- Within "normal" vergence range, correct SILO, perception system matched action system with float, float seen from a far distance from stand (21 and 22 cm, in front and behind, respectively)
- RDS: red R/ green L- 70%, lose shape or form, red L/ green R- 70%, lose shape or form and depth

Participant 12 (Strongly Binocular)
Age 21, female

- Right eye dominant with Sighting Eye (right hand), Left eye dominant with Real/Unreal finger, and switching between left and right eye in Brock string
- 40 arc seconds
- Inverted Y, switching between red and green string behind, 150 cm for X-formation, 174 cm for Y-formation, 24 cm intermittent
- Large vergence range, correct with convergence (smaller and closer) and correct with distance in divergence (further away) but perceived no size change. With pointer, at convergence action system was the same as perceptual system but had difficulty determining where to put the pointer
- RDS: red R/green L- 60%, lose shape or form, red L/green R- 70%, decrease in shape or form and depth

Participant 13 (Less Strongly Binocular)
Age 19, female

- Right eye dominant in Sighting Eye (right hand) and Brock string (red string in), Left eye dominant with Real/Unreal Finger
- 40 arc seconds (struggled after 100 arc seconds and originally thought there was no difference)
- Y- formation, red string in front, 110 cm for X-formation, 137 cm for Y-formation, 27 cm intermittent
- Within "normal" vergence range (on lower end of convergence), correct with distance of perceived float but incorrect with size (saw LISO), with pointer in both divergence and convergence pointed to in front of base. Participant struggled with this test, especially with convergence range and seeing the distance between one and two quoits (NOT LOCALIZING PROPERLY…according to Brock String this is where she loses the string)
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R- 70%, lose shape or form

Participant 14 (Weakly Binocular)
Age 23, female

- Cross Dominance with Sighting Eye as Left eye dominant (but right handed), Left eye dominant in Real/Unreal finger, Right eye dominant in Brock string
- 40 arc seconds (struggled after 200 arc seconds)
- Inverted Y, red string behind, 110cm for X-formation, 130 cm for Y-formation, 20 cm interval, participant often saw two beads and became fatigued and unsure of what was being seen
- At lower range of “normal” vergence range, perceived the quoit for convergence and divergence as smaller and closer but action system was correct, as for convergence pointer was placed in front of base and for divergence it was placed behind the base
- RDS: red R/green L- 70%, lose depth, red L/green R- 70%, lose depth

Participant 15 (Weakly Binocular)
Age 53, female

- Strong preference for right eye, Right Eye dominant for Sighting eye (right hand), Real/Unreal Image, and Brock string
- 40 arc seconds (struggled with test)
- Inverted Y, white string behind (originally a red string), 16 cm intermittent, participant saw original X-formation (up to 170 cm) but as the bead distance from the participant increased, the red string would go directly though the bead (from nose to wall) and the greens string intersected the bead at angle, displaced to the left, as the green string flashes in and out the red string become less red and more white, 186 cm for Y-formation
- Large vergence range, perceived smaller and closer for convergence and no change in size or distance for divergence. Difficulty determining where point was with visuomotor (action) system, saw two diplopic images of the pointer (was not truly focusing/fixating on the quoit and as a result the pointer was not at the fixation point, mislocalizing the quoit by not either using retinal disparity cues or had conflicting cues, also it is possible it was easier to perceive the quoit’s size and distance change in convergence as it was not blocked by the back of the box)
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R- 70%, decrease in shape or form and depth

Participant 16 (Strongly Binocular)
Age 22, female

- Cross dominance with Sighting eye, left eye (right hand), Right eye dominant with Real/Unreal finger and Brock string
- 40 arc seconds
- Inverted Y, red string behind, 40 cm for X-formation, 157 cm for Y-formation, 117 cm intermittent
- Large vergence range, correct SILO, action system and pointer was the same as perceptual system
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R- 60%, lose depth…see smallest square below average diminishing correlation percentage

Participant 17 (Weakly Binocular)
Age 22, female

- Left eye dominant in sighting eye (ambidextrous), Right eye dominant in Real/Unreal Finger, using both right and left eye in Brock string
- 50 arc seconds
- Inverted Y, yellowish white string behind, 150 cm for X-formation, 200 cm for Y-formation, 50 cm intermittent (yellowish white string behind, merging input from two eyes, no suppression along with a mix of both green and red strings), at points during the testing the participant did not see the strings cross at the bead but instead behind the bead, where the red string crosses over the green string
- Lower on “normal” vergence range, incorrect with size and distance but action system matched this inaccurate perception
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 80%, decrease in shape or form and depth

Participant 18 (Weakly Binocular)
Age 21, female

- Right eye dominant with Sighting Eye (right hand) and Brock string, Left eye dominant with Sighting eye but had difficulty in seeing two images
- 140 arc seconds
- Inverted Y, red string behind, 180 cm X-formation, 196 cm Y-formation, 16 cm intermittent, saw the red and green string as more of yellow and white colored
- Lower end of “normal” vergence, no perception of size and distance change and with pointer showed no change of distance, on target, relying on action system
- RDS: red R/green L- 80%, lose shape or form, red L/green R- 70%, lose shape or form (higher end of diminishing binocular correlation %)

Participant 19 (Strongly Binocular)
Age 22, female

- Cross dominant for Sighting eye, Left eye dominant (right hand), Left eye dominant for Real/Unreal finger, and Right Eye dominant for Brock string
- 40 arc seconds
- Inverted Y, red string behind, 40 cm for X-formation, 137 cm for Y-formation, 97 cm intermittent
- Within “normal” range of vergence, correct SILO, pointer visuomotor action system distance was the same as perceptual system
- RDS: red R/green L- 60%, lose shape or form, red L/green R- 70%, decrease in shape or form and depth

Participant 20 (Strongly Binocular)
Age 21, female

- Strong preference for right eye, Right eye dominant for Sighting eye (right hand), Real/Unreal finger, and Brock string
- 40 arc seconds
- Inverted Y, red string behind, 120 cm for X-formation, 146 cm for Y-formation, 26 cm intermittent (difficulty with fixating on one bead instead of perceiving two beads)
- Large vergence range, correct SILO, action and perceptual system the same
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R- 70%, lose depth (higher end of diminishing binocular correlation %)

Participant 21 (Strongly Binocular)
Age 34, male

- Strong preference for right eye, Right eye dominant for Sighting eye (right hand), Real/Unreal finger, and Brock string
- 40 arc seconds
- Inverted Y, red string behind, 150 cm for X-formation, 154 cm for Y-formation, 4 cm intermittent
- Large convergence, within normal range divergence, correct with size but not distance, SOLI, action system correct over perceptual for convergence. The participant stated that distance was determined based on general world experiences of objects becoming larger as closer and smaller as further away.
- RDS: red R/green L- 60%, decrease in shape or form and distance, red L/green right- 70%, decrease in shape or form and distance (higher end of diminishing binocular correlation %)

Participant 22 (Strongly Binocular)
Age 32, female

- Strong preference for right eye, Right eye dominant for Sighting eye (right hand), Real/Unreal finger, and Brock string
- 40 arc seconds
- Inverted Y, red string behind, 110 cm for X-formation, 164 cm for Y-formation, 54 cm intermittent
- Within normal vergence range, correct SILO, action system and perceptual system the same for convergence, but with divergence correct with quoit being perceived as further away but visuomotor system pointed to it in front of the base, confusion with action system (can be conflicting cues, also it is possible it was easier to perceive the quoit's size and distance change in convergence as it was not blocked by the back of the box)
- RDS: red R/green L- 60%, lose shape or form and depth, red L/green R- 70%, lose shape or form and depth (higher end of diminishing binocular correlation %)

Participant 23 (Strongly Binocular)
Age 22, female

- Cross Dominance with Sighting Eye, Left eye (right hand), Left eye with Real/Unreal Finger, and using both Left and Right eye with Brock string
- 40 arc seconds
- Inverted Y, co-dominance as one string behind is partially red and green, 150 cm for X-formation, 200 cm for Y-formation, 50 cm intermittent zone (switching between red or greens string or a combined color string)
- Large vergence range, correct convergence as closer and smaller but perceived no change in size or distance with divergence (can be due to a smaller diopter measurement) but with the pointer the action system pointed to the quoit as further away, behind the stand
- RDS: red R/green L- 70%, lose and depth, red L/green R- 70%, lose depth

Participant 24 (Less Strongly Binocular)
Age 23, female

- Right eye dominance for Sighting Eye (right hand) and Real/Unreal finger, Left eye dominant for Brock string
- 40 arc seconds
- Inverted Y, green string behind, 146 cm for X-formation, 147 cm for Y-formation, 1 cm intermittent, participant had difficulty with this test where in front of the bead would see two string that would turn into one red string before it went through the bead or the two strings would cross slightly in front of the bead, the participant would also see two beads or when saw one bead it would switch between the two different colored beads (not fixating properly, fixating point in front of the bead)
- Large convergence range, divergence within normal range, correct SILO, perception systems matched pointer placement in the action system
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 70%, lose shape or form and depth

Participant 25 (Weakly Binocular)
Age 19, female

- Right eye dominant with Sighting Eye (right hand) and Brock string, Left eye dominant with Real/Unreal finger
- 100 arc seconds
- Y to Inverted Y as participant almost completely loses the green string in front; it reappears, and then loses the green string behind, red string behind, X-formation 110 cm, Y-formation 166 cm, 56 cm intermittent (confusion)
- Within lower end of normal convergence range, incorrect with size and distance, convergence was perceived as larger and further away and divergence perceived as larger and closer, yet despite being incorrect with the perception of the quoits the action systems was correct with both size and distance
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 80%, lose depth (higher end of diminishing binocular correlation %)

Participant 26 (Weakly Binocular)

Age 20, female

- Strong preference for right eye, Right eye dominant for Sighting eye (right hand), Real/Unreal finger, and Brock string
- 40 arc seconds
- Inverted Y, red string behind, 130 cm for X-formation, 146 cm for Y-formation, 16 cm intermittent zone, before intermittent zone the participant would sometimes see the green string crossing behind the bead
- Large vergence range, with convergence perceived correct with distance but not size where perception of distance matched the pointer placement in the action system, with divergence perceived no change in size or distance which matched the pointer placed on the slide (action system). The participant struggled with this test and with pointer would outline the left quoit instead of a fused percept
- RDS: red R/green L- 70%, lose shape or form, red L/green R- 70%, lose shape or form

Participant 27 (Strongly Binocular)

Age 21, female

- Strong preference for right eye, Right eye dominant for Sighting eye (ambidextrous), Real/Unreal finger, and Brock string
- 40 arc seconds
- Inverted Y, red string behind, 150 cm for X-formation, 177 cm for Y-formation, 27 cm intermittent
- Small vergence range, incorrect SOLI, action system pointed to slide, no correspondence of float with visuomotor system
- RDS: red R/green L- 70%, decrease in shape or form and depth, red L/green R- 70%, decrease shape or form and depth

Participant 28 (Strongly Binocular)

Age 36, male

- Right eye dominant with Sighting Eye (right hand) and Brock string, Left eye dominant with Real/Unreal Finger, participant has a bit of ambidexterity as uses left hand for other activities
- 40 arc seconds
- Inverted Y, red string out, 110 cm for X-formation, 184 cm for Y-formation, 74 cm intermittent, at first participant saw two string that would converge into one string but when told to re-fixate eyes onto bead participant realized that eyes were not looking at the bead but the string in front of the bead, re-aligned eyes and saw correct X-formation
- Large vergence range, correct SILO, action system equaled perceptual systems
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R- 60%, decrease shape or form and depth(both diminishing binocular correlation percentages at lower end of correlation, hint of strong binocularity)

Participant 29 (Strongly Binocular)
Age 49, female
- Strong preference for right eye, Right eye dominant for Sighting eye (right hand), Real/Unreal finger, and Brock string
- 80 arc seconds (less stereoacuity but does not affect results of rest of test results, still within a normal range)
- Inverted Y, red string behind, 140 cm for X-formation, 203 cm for Y-formation, 1 cm intermittent
- Large vergence range, perceived smaller and closer with convergence and perceived further away for divergence but was too far away and blurry to determine size, pointer placed on middle of slide (interesting because perceptual system “sees” float but the visuomotor/action system does not detect the float)
- RDS: red R/green L- 60%, decrease in shape or form and depth, red L/green R- 70%, decrease shape or form and depth (higher end of diminishing binocular correlation %)

Participant 30 (Strongly Binocular)
Age 31, female
- Cross dominant with Sight Eye, left eye dominant (right handed), Right eye dominant in Brock string and Real/Unreal finger…Balanced eyes
- 40 arc seconds
- Inverted Y, red string behind, 120 cm for X-formation, 211 cm for Y-formation, 1 cm intermittent
- Large convergence, correct with smaller and closer and perceptual system equaled placement of pointer (visuomotor system), lower end of divergence range, perceived no change in size or distance but placed pointer behind the base (action system was correct), saw two quoits rather quickly when slide moved outwards and had a harder time maintaining a single fused quoit during divergence
- RDS: red R/green L- 60%, lose shape or form, red L/green R- 60%, lose shape or form (both diminishing binocular correlation percentages at lower end of correlation, hint of strong binocularity)