CLINICAL REPORT

An Assessment of Stereovision Acquired in Adulthood

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SIGNIFICANCE: Increasing evidence indicates that childhood binocular vision disorders that lead to stereodeficiency may be treated in adulthood. Reports of patients who gain stereopsis as adults indicate that this achievement provides for a qualitatively different and dramatically improved sense of space and depth.

PURPOSE: Increasing evidence suggests that stereopsis can be achieved in adult patients despite long-standing binocular disorders. We polled individuals who gained stereopsis as adults to ascertain their initial binocular disorders, the length of time they were stereodeficient, effective treatments, and the nature of their recovered stereovision.

METHODS: A questionnaire was posted online and announced in a brief article in the journal *Vision Development and Rehabilitation*.

RESULTS: Of the 63 responders, 56 (89%) reported strabismus and/or amblyopia, and 55 (87%) indicated that they had been stereodeficient for as long as they could remember. All but seven participants (89%) achieved stereovision through vision training or a combination of surgery and vision training, and many reported vivid visual changes.

CONCLUSIONS: Despite childhood binocular disorders, patients may be able to achieve stereopsis following interventions in adulthood. This achievement provides for a qualitatively different and dramatically improved sense of space and depth.

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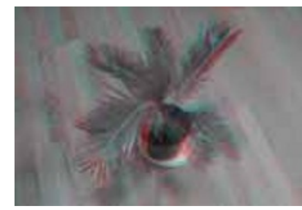

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Poor or absent stereopsis is associated with childhood binocular vision disorders such as strabismus and amblyopia. In the last century, it was assumed that these deficits were permanent if not reversed in early childhood because there existed an early critical period for the development of binocular neurons.[1] However, increasing evidence suggests that some individuals with childhood strabismus and amblyopia, who were once considered stereoblind, may develop or improve stereovision as adults following specific interventions.[2–13]

Often, patients are labeled stereoblind if they cannot pass standard clinical tests for stereopsis. Yet, some strabismic individuals who flunk clinical stereopsis tests are able to see in 3D when they view large disparity, static targets,[14–16] or moving targets located in their peripheral visual fields.[14,17,18] Thus, we will use the term *stereodeficient*, rather than *stereoblind*, to describe the subjects of the present article, even though most of them had no appreciation of depth from stereopsis until they received specific interventions as adults.

Both of us were strabismic since early infancy or childhood and experienced dramatic improvements in stereopsis as adults.[5,6,10] After our stories became public, we were contacted by others with similar experiences, encouraging us to put together a questionnaire (see the Appendix, the Stereovision Survey, available at http://links.lww.com/OPX/A304) to poll individuals who gained stereovision in adulthood. We were interested in their initial binocular disorders, the length of time they had been stereodeficient, the types of effective treatments, and the nature of their recovered stereovision. Our questionnaire was posted online[19] and announced in a brief article in the journal *Vision Development and Rehabilitation*.[20] In addition, we contacted individuals who had written to us about their own achievement of stereopsis as adults. This research adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board of Mount Holyoke College.

We received 72 responses to the questionnaire, but the responses of nine participants were eliminated because these individuals indicated only a few fleeting moments of stereovision that they could not voluntarily recapture. All results described in this article were collected from the remaining 63 responders, 41 of which were female.

Initial Conditions

The 63 responders had the visual conditions commonly associated with stereodeficiency, in roughly the proportions found in the general clinical population (Table 1). Thus, 43 (68%) of the 63 responders reported strabismus, with 32 of these responders indicating esotropia, 10 exotropia, and 1 indicating hypertropia without a horizontal misalignment. Thirty-seven individuals (59%) reported amblyopia. Of these, 24 had strabismus, 12 indicated aligned eyes, and 1 did not report her eye alignment before gaining stereopsis (Table 1). Amblyopia in the aligned group may have resulted from anisometropia or a strabismus too small to be noted cosmetically. In addition, one individual in this group was born with a congenital cataract of one eye, which was surgically removed over the course of two operations at ages 2 and 3 years. One responder did not have strabismus or amblyopia but reported severe convergence insufficiency. Similarly, others who were not strabismic or amblyopic may have suffered from nonstrabismic binocular disorders. Two individuals did not report their pretreatment eye alignment, although both reported aligned eyes after achieving stereovision.

TABLE 1. The number of individuals with a given binocular disorder who achieved stereopsis as a result of nonsurgical and/or surgical treatments

	Binocular Anomaly								
Treatment	ET	ET w/ A	XT	XT w/ A	Hypertropia	Aligned	Aligned w/ A	Unknown	Unknown w/A
Vision therapy	3	4	2	2		5	9	1	1
Vision therapy + previous surgery	7	6		1					
Self-guided therapy		4		2			2		
Self-guided therapy + previous surgery	1	1		1					
Orthoptics		1							
Orthoptics + previous surgery	1	1					1		
Surgery alone	2		1		1				
3D movie			1			1			
3D movie + previous surgery		1							
Total for each condition	14	18	4	6	1	6	12	1	1

A = amblyopia; Aligned = aligned eyes; ET = esotropia; w/ = with; XT = exotropia.

Duration of Stereo Deficiency

Strikingly, 55 (87%) of 63 responders indicated that they have been stereodeficient for as long as they could remember, whereas 3 (5%) reported that they lost stereovision in childhood, 4 (6%) reported that they lost stereovision as adults, and 1 (2%) did not answer this question.

Childhood Treatment

Of the 58 responders who were stereodeficient since childhood, 29 responders received no childhood interventions, whereas 29 responders reported various combinations of nonsurgical and surgical treatments. Nonsurgical interventions included patching of one eye (n = 9), glasses including bifocals and prisms (n = 9), vision therapy (n = 5), orthoptics (n = 5), home exercises (n = 3), dilation eye drops (n = 2), and colored tints worn over prescription spectacles (n = 1). Two esotropic individuals received one surgery in their first year, whereas 18 responders (16 with esotropia, 1 with exotropia, and 1 who reported aligned eyes) received one to three surgeries before the age of 12 years. Although these treatments did not lead to stereovision in childhood, their contribution to the achievement of stereopsis later in adult life remains an open question.

Treatments that Resulted in Stereovision

Treatments in adulthood that resulted in stereovision included vision therapy with an optometrist (n = 41), self-guided therapy (n = 11), orthoptics with an orthoptist (n = 4), surgery (n = 4), and watching a 3D movie (n = 3) (Fig. 1). Twelve of the 32 responders who were esotropic as children were still esotropic after treatments that led to stereopsis, 19 now reported horizontally aligned eyes, and 1 responder did not answer this question. Of the 10 responders who were exotropic as children, 6 responders reported aligned eyes, 3 remained exotropic, and 1 responder did not answer this question. Those who had aligned eyes as children remained aligned with one exception. This individual had suffered as an adult from a stroke that resulted in esotropia. It was only after she gained stereovision with vision therapy after her stroke that she realized that she had been stereodeficient as a child.

In some cases, the achievement of stereovision may have required both surgical and nonsurgical interventions. Although only 4 responders achieved stereovision from surgery alone, a total of 20 participants had undergone surgeries as children or adults prior to the time of their nonsurgical treatments, and 13 reported that the operations cosmetically straightened their eyes in a stable manner. Eight responders (six with esotropia and two with exotropia) gained stereopsis within a year of receiving surgery as adults (three with vision therapy, two with orthoptics, and three with self-guided therapy). At least two individuals underwent surgery with the specific intention of training themselves to coordinate their eyes for stereopsis following improved surgical alignment. For these reasons, the histogram in Fig. 1 indicates, for each nonsurgical treatment category, the number of individuals who had or had not undergone previous surgeries. Effective treatments, broken down by initial visual condition, are shown in Table 1.

Vision therapy has its roots in orthoptics but involves more out-of-instrument exercises (such as the Brock string, polarized vectograms, and projected 3D images), makes greater use of prisms and lenses during therapy procedures, and incorporates more vestibulo-ocular and visual-motor tasks.[4] For strabismic patients, the therapy teaches disparity and fusional vergence movements; that is, it teaches the patient to point the two eyes simultaneously at the same spatial location while looking near and far. This skill is taught with tools, such as the Brock string, which provide the patient with feedback as to where he/she is aiming each eye. Polarized vectograms and computer exercises build fusion ranges and teach the patient to localize the fused targets in depth. For patients with amblyopia, the "good" eye is often disadvantaged so that the input from the two eyes is better balanced, and the amblyopic eye is recruited to complete a central vision task. This strategy is similar to that used in many perceptual learning protocols for amblyopia.[7,9,11–13]

Treatments labeled "self-guided therapy" involved the use of 3D books, Nintendo 3DS, Vivid Vision (a virtual reality tool), balance exercises, and the Brock string. All nine responders who taught themselves to see in 3D emphasized that they actively worked to refocus and align their eyes. The most striking case involved a man who engineered his own rehabilitation at age 37 years. He wrote,

> "In 2010, I found out about Sue Barry and read her book. There are no COVD-certified optometrists where I live. I imagine it might horrify you but I mostly performed vision therapy on

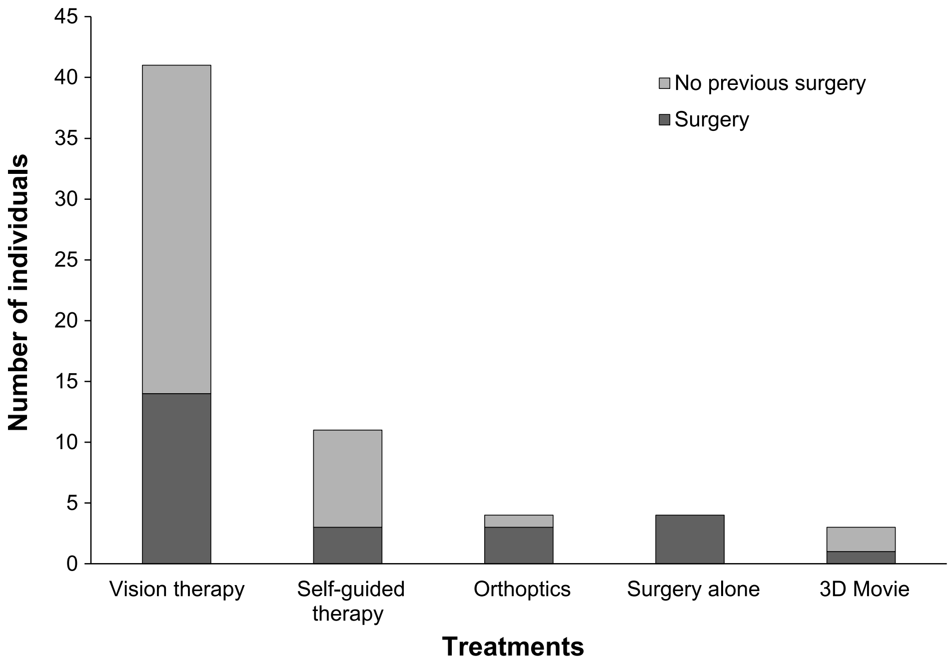

FIGURE 1. The number of individuals who achieved stereovision following different treatments is indicated by the length of the dark or light gray bars. Dark and light gray bars indicate previous surgeries or no surgeries, respectively.

myself using what I learned from Duckman *Visual Development, Diagnosis, and Treatment of the Pediatric Patient* and Griffin [and Grisham] *Binocular Anomalies: Diagnosis and Vision Therapy* both of which I ordered online."

This man then devised his own red/green anaglyphs on the computer and, while viewing the anaglyphs with red/green lenses and prisms, demonstrated to himself that he had the capacity to see in 3D. He then underwent surgery on one eye that reduced his esotropia from 55 to 15 prism diopters. He wrote,

> "I gave myself 4 weeks to allow the muscles to heal, then I resumed my own vision therapy. It wasn't immediate, but within about a week I gained reasonably stable fusion with some stereopsis. Initially, it required a conscious effort but soon became second nature."

Surprisingly, two individuals gained stereopsis after standing on their heads. One explained,

> "I started standing on my head every morning. I didn't have my vision in mind at all, but waking up and toning the muscles all up and down my body. Six months later, my lazy eye turned on, at the age of 69."

Age when Stereovision was Achieved

The age at which the responders achieved stereopsis ranged from 15 to 79 years, with an average of 44.1 (SD, 15.3) years (Fig. 2).

Nature of Stereovision

The achievement of stereopsis had a strong impact on the responders, although many felt that their stereovision was subnormal. Thus, three indicated that they saw with stereopsis only when they concentrated on aligning their eyes. An additional three indicated that they were aware of stereopsis only while viewing objects or scenes with prominent depth such as looming tree limbs or falling leaves or while watching 3D movies. Two additional responders saw with stereopsis only in particular directions of gaze, whereas four reported that their ability to see in 3D varied with levels of fatigue, lighting conditions, or the consistency with which they practiced their vision therapy procedures. Stereopsis was compromised in four others because of damage to one retina or amblyopia, which had been reduced but not eliminated.

Stereoacuity scores were obtained for an additional 12 responders, which measured 40 (n = 5), 60 (n = 1), 70 (n = 2), 150 (n = 1), 200 (n = 2), and 400 to 800 arcseconds (n = 1). A 13th individual indicated that he could see pop-out of the wings on the Stereo Fly. Scores greater than 40 arcseconds indicate subnormal stereoacuity, but it is harder to interpret the five 40-arcsecond scores. While normal stereoacuity may be in the 5- to 20-arcsecond range, the Stereo Fly test only probes down to 40 arcseconds, and this may have been the test used with some or all of the five responders.

For some, stereopsis emerged fleetingly at first, then stabilized and deepened, but three described a sudden onset of stereopsis while driving, walking the dog, or teaching a class. The length of time that the responders had seen with stereopsis varied from a few weeks to 43 years, with a mean of 5.9 years and a median of 3.5 years (first and third quartiles = 1.5 and 6.5 years, respectively). Only one individual complained of diplopia following the onset of stereovision. She had made major gains with stereopsis and decreased her amblyopia with 1 year of weekly vision therapy. Three years after stopping the therapy, her ability to fuse and see in 3D decreased, and she began to experience diplopia.

Only three responders reported negative impacts of stereopsis. One described her first 3D view (of tree limbs jutting out at her)

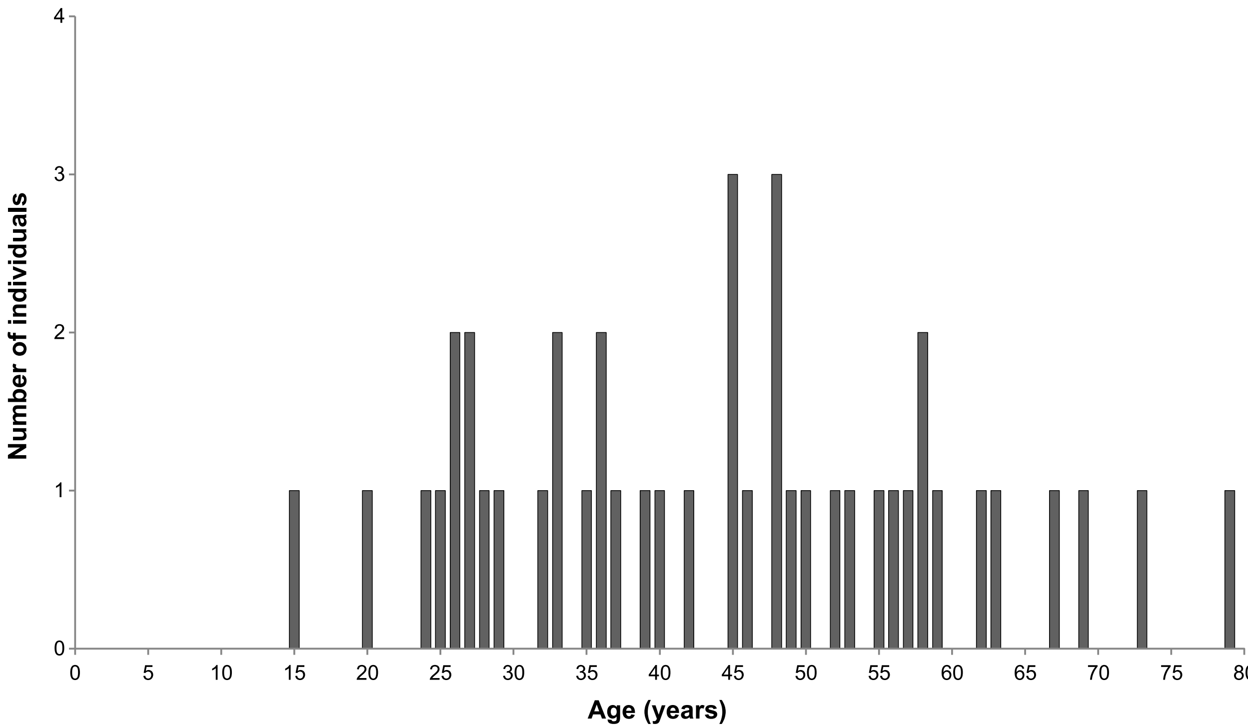

FIGURE 2. Age in years at which responders achieved stereovision. The question regarding age at which the responder achieved stereovision was added to the questionnaire 2 days after it was first posted online so that the first 16 responders did not answer this question. However, for three of these responders, the age at which they gained stereopsis could be determined from their descriptions in the comment sections of the questionnaire. Of the 47 responders who answered the questionnaire after the age question was added, 40 provided a specific age. Thus, while all responders achieved stereopsis as adults, the exact age was obtained for 43 of the 63 responders.

to be frightening, a second found stereopsis to be disconcerting, and a third reported that the visual changes resulted in irregular sleep patterns.

In contrast, 22 responders expressed delight, even astonishment, at their first 3D experiences. Although their first views were of ordinary objects such as tree branches or pot handles popping out toward them, they described these experiences with glowing words and phrases such as "a miraculous/mystical experience," "amazing," "joyous," "awesome," "beautiful and overwhelming," "I was shocked," "it felt like I was taking a hallucinogenic drug," "I started seeing the space between things," "everything is much crisper now," and "it [stereopsis] has changed my life in many ways." Responders described more comfort in everyday activities including reading, driving, hitting a tennis ball, negotiating stairs, and even understanding the feelings of others. Indeed, an e-mail from one responder, a man with amblyopia, included the following:

> "I now look at people in a way I never used to; I really watch them. I am catching fleeting expressions; …I understand local space now in a way I never used to; so I can reach out… to pass something accurately to just the right place to be useful to someone else… But I suspect that there is more to it even than the list of obviously stereoscopy-related improvements in observational and manipulative skills… People seem to respond to me with greater warmth and empathy than they used to; it is as if I have somehow become nicer to know, while at the same time I am thinking they are nicer than I thought."

The most consistent and striking result from the questionnaire involved the length of time that our responders were stereodeficient. Eighty-seven percent of responders indicated that they had been stereodeficient for as long as they could remember. These results may appear inconsistent with animal studies that suggest a critical period in early life for the development of binocular neurons.[1] However, the vast majority of animal experiments have involved recordings of neurons in V1 that respond only to the central 5 degrees of the visual field.[21] Eye misalignment will prevent overlap from each eye of the small receptive fields of these central V1 neurons but not necessarily of the larger receptive fields of more peripheral or higher-area neurons. As a result, strabismus may affect binocular neurons in a central/V1 to peripheral/higher-area progression. Experimental data, obtained primarily from central neurons in V1, may have exaggerated the effects of strabismus on the binocular nature of neurons throughout the visual cortex and underestimated the potential for some degree of stereovision in strabismic individuals.

Studies in the mid-1980s demonstrated that 60 to 70% of children with normal vision see with stereopsis at 3 to 4 months of age.[22] When outfitted with prism goggles to compensate for eye misalignment, the same percentage of esotropic infants also demonstrated stereopsis.[22] Thus, binocular neurons and circuitry may be present in the brains of many infants with esotropia, which is the most common binocular disorder in early childhood.[4] Beyond 4 months, however, stereopsis was rapidly lost in the esotropic population.[22] It is during this time that infants begin to reach for objects with their hands.[23] While doing so, an esotropic infant will experience diplopia and visual confusion (seeing two objects that are spatially separated in the same location). In order to obtain a single view of the world to allow for accurate movements, the child will most likely suppress the input from one eye, thus disrupting and masking binocular circuits. These neurons and circuits, although suppressed and immature, may never be lost entirely, making it possible for individuals, stereodeficient since early childhood, to achieve stereopsis as adults.

While stereopsis has been considered most useful for near viewing and for eye-hand coordination tasks, our responders did not mention improvements in demanding near tasks such as sewing. Instead, they reported that "everything I saw had depth to it," including plants, grass, and trees. Liu et al.[24] determined the range of disparities that an observer may encounter while walking in a forest. Disparities spanned a distribution of 4.5 degrees with a mean of 4.07 arcminutes or 244 arcseconds. Similar disparity distributions were found for indoor scenes.[24] Thus, the mean disparity was more than 10 times the threshold for normal stereoacuity as measured in several clinical tests and within the range of stereoacuities that many of our responders may have attained.

When our responders gained stereovision, they most commonly reported that pot handles and tree branches popped out toward them in a novel way. Using the following equation,[25] we can estimate the minimum difference in depth between two objects that an individual with a given stereoacuity can discern for a given fixation distance:

$$\delta \approx \Delta d \cdot I / \left(D^2 + \Delta d \cdot D\right)$$

where δ is the stereoacuity converted from arcseconds to radians, Δd is the physical depth between the two objects in meters, I is the distance between the two eyes (average is 0.064 m), and D is the fixation distance in meters.

If our responders achieved 200 arcseconds of crossed stereoacuity, then they could use their stereopsis to distinguish the difference in depth between an object that was 1.00 m and another that was 0.984 m away. This difference of 0.016 m (0.6 inches) is certainly shorter than the length of pot handles so that the responders reaching for a pot 1 m away should see the handle protruding from the pot in stereo depth. Although monocular depth cues and experience would inform them that the handle is in front of the pot, the sense of the handle projecting through and hovering in a palpable volume of empty space was novel and surprising.

Even individuals with stereoacuities poorer than 800 arcseconds may experience a novel or improved stereo sense. Stereopsis occurs over a large range of disparities from several arcseconds to several degrees. Indeed, this range may be mediated by two different stereopsis systems.[26–30] While these systems have been characterized somewhat differently by different investigators, all classifications distinguish the two systems in part by their disparity sensitivity. Both a "fine" system and "coarse" system operate over a wide range of disparities, but only the coarse system works at the largest disparities (>1 degree) that still provide a percept of depth. The coarse system does not require a precise match between the images provided by the two eyes and can tolerate several degrees of vertical misalignment.[29–32] At the largest disparities, coarse stereopsis may not provide a veridical measure of depth but may still provide the sign of depth, that is, whether a target lies in front or behind the fixation point.[26,27,29,30,32]

Given its tolerance for dissimilar images, coarse stereopsis may be available to many people with amblyopia and strabismus if the eye alignment is off by only several degrees. However, people with strabismus or strabismic amblyopia have poor or nonexistent disparity vergence responses.[33,34] Their habitual way of seeing is to suppress the input from one eye, which impedes disparity vergence and any sense of depth through stereopsis. Thus, treatments that promote better balance between the two eyes, disparity vergence movements, and fusion of stereo targets may reduce interocular suppression, improve eye alignment, and facilitate a transition from a monocular way of seeing to one with coarse stereopsis, causing the viewer to exclaim, "Everything I saw had depth to it." These changes may set in motion a positive feedback loop. Because the coarse stereopsis system initiates disparity vergence movements to targets with large disparities,[35] activation of coarse stereopsis may lead to further improvements in eye alignment and an enhanced ability to exploit and tune the coarse and fine stereopsis systems lying latent in the brain.

A shift to a more binocular way of seeing has additional advantages beyond the use of disparity cues. When one's view is partially blocked by an occluding object, there is a portion of the visual field behind the occluder that is seen by only one eye.[36–39] Thus, only the right eye sees a narrow strip to the right, whereas only the left eye sees a narrow strip to the left of the occluder. If the occluder is narrower than the interocular distance, the combined view from the two eyes allows one to see the region behind the occluding object.[36,39] Acquisition of this skill may help explain the comment of one of our responders who recounted that, after achieving stereopsis and thus after learning to integrate information from the two eyes, she could see around and behind objects.

In order to distinguish and locate where one object ends and the next begins, we must recognize the edges of objects. Every object, whose edges are not blocked from view by an occluding item, presents one or more vertical boundaries. The visual system makes use of the monocular, unpaired region at these vertical boundaries to signal a depth discontinuity and thus enhance our perception of the edge.[36–38] For example, the visual system may note that the right eye sees a region to the right of an object that the left eye does not see, thus signaling a depth discontinuity and highlighting the right edge of the object. When our responders shifted from a monocular to a more binocular way of seeing, and assuming that their eyes were fairly well aligned, they may have been able to exploit information about monocular unpaired regions to detect depth discontinuities and edges. This ability may be particularly important for those with strabismus. Because strabismus causes a doubling of vertical contours, one adaptation may be to reduce sensitivity to vertical lines,[40] thus decreasing the ability to detect edges. Improved eye alignment and the ability to exploit monocular unpaired regions may help explain why everything looks "crisper" after learning to compare information from the two eyes.

This questionnaire-based study suffers from several limitations. Responders were assured anonymity so that, for most cases, we could not confirm whether their reports were consistent with clinical evaluations. There is the danger of a positive bias in these reports, and we did not poll individuals who did not achieve stereopsis following adult treatments. Moreover, our responders do not represent a random sample or even necessarily a representative sample. The makeup of participants may be weighted toward those who achieved stereopsis through vision training because a link to the questionnaire was provided on S.R.B.'s "Stereosue" Facebook page,[19] which discusses neuroplasticity and sensory rehabilitation.

A detailed comparison of effective treatments among the different clinical groups would be premature because of the low numbers within some groups and the importance of additional clinical details. For example, the term *amblyopia* covers more than one disorder, including strabismic amblyopia, anisometropic or refractive amblyopia, and deprivation amblyopia, each with its own set of deficits.[12] Many adults with longstanding strabismus suffer not only from horizontal but also from vertical or cyclotorsional misalignments. Vertical misalignments of one degree or more reduce or eliminate horizontal vergence responses to horizontal disparities[35] and also have severe impacts on stereopsis at small disparities,[30] yet their presence was not queried in the questionnaire.

However, individuals who responded to this questionnaire suffered from the range of conditions that are commonly associated with stereodeficiency. Eighty-seven percent of our responders indicated that they had been stereodeficient for as long as they could remember, suggesting the presence of a childhood condition. Esotropia is the most common form of strabismus reported by our responders and is the most common form of strabismus in early childhood.[4] Moreover, amblyopia, reported in 59% of responders, has its onset usually by age 3 years.[12]

That stereopsis emerged in individuals with a range of binocular disorders parallels results of perceptual learning studies in which participants with strabismus and/or amblyopia achieved stereopsis through training.[7–9,11–13] Perceptual learning stereovision protocols and vision therapy share similar strategies in providing tasks designed to reduce interocular suppression, restore a more equal balance between the two eyes, and promote fusion. The tasks are repetitive, require attention and practice, and provide feedback.

In summary, adults may be able to achieve stereopsis despite childhood binocular disorders. This achievement provides for a qualitatively different and dramatically improved sense of space and depth. Reports from those who achieve stereopsis in adulthood may provide insights into the contribution and importance of binocular vision and stereopsis to visual and space perception in general.

ARTICLE INFORMATION

Supplemental Digital Content: The appendix, the Stereovision Questionnaire used in the study, is available at http://links.lww.com/OPX/A304.

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