https://doi.org/10.2352/ISSN.2470-1173.2018.04.SDA-109

Use of virtual reality to assess and treat weakness in human stereoscopic vision

Benjamin T. Backus, Brian D. Dornbos, Tuan A. Tran, James B. Blaha, Manish Z. Gupta
Vivid Vision, Inc.
San Francisco, California, USA

Abstract

Many people cannot see depth in stereoscopic displays. These individuals are often highly motivated to recover stereoscopic depth perception, but because binocular vision is complex, the loss of stereo has different causes in different people, so treatment cannot be uniform. We have created a virtual reality (VR) system for assessing and treating anomalies in binocular vision. The system is based on a systematic analysis of subsystems upon which stereoscopic vision depends: the ability to converge properly, appropriate regulation of suppression, extraction of disparity, use of disparity for depth perception and for vergence control, and combination of stereoscopic depth with other depth cues. Deficiency in any of these subsystems can cause stereoblindness or limit performance on tasks that require stereoscopic vision. Our system uses VR games to improve the function of specific, targeted subsystems.

Introduction

Some 10% of the population has anomalous stereoscopic depth perception (SDP), including stereo-blindness [1]. Why is SDP so variable across people, and what fraction of people who do not see stereoscopic depth could see depth from binocular disparities if treated? The answers to these questions are not yet known. As a start, we observe that SDP is complex. Proper SDP requires control of vergence eye posture, regulation of interocular suppression, extraction of binocular disparity despite residual binocular misalignment, utilization of disparity to estimate depth and adjust convergence, and combination with monocular depth cues. Development of SDP during childhood is correspondingly complicated, leaving room for large individual differences and presenting an opportunity: identifying and treating one weak link may sometimes be sufficient to recover SDP, or it may at least enable the rest of the system to improve through perceptual learning. This approach is commonly used in clinical settings by vision therapists using methods developed over the last century and more, but its efficacy has not yet been adequately quantified [2]. Here we describe a flexible treatment environment, built on this clinical tradition, that uses virtual reality (VR) to supplement clinical treatment of binocular vision anomalies. This tool is expected to improve treatment outcomes and to make clinical studies easier to conduct and interpret in the future.

Patients are highly motivated

Rehabilitative treatments of all sorts require a high degree of motivation and engagement. In 1906, Worth [3] described the importance of patient engagement regarding visual rehabilitative therapies: "[the patient] will, therefore, only permit the exercises so long as he finds them attractive and interesting." Given that people can function in the world without stereoscopic vision, what motivates a patient to improve his or her binocularity? What benefit does stereoscopic vision give to an individual? Wells [4] wrote, "it is evident that the first indication is to teach the patient the fascination of true binocular fusion." There must be a benefit to the patient to gain stereoscopic vision, and the patient must be engaged and care about the outcome of the rehabilitative process.

More recently, neurobiologist Susan Barry, once stereoblind herself, described her vivid recovery of stereopsis in *Fixing My Gaze* [5]. Barry and Bridgeman [6] surveyed 63 individuals who recovered stereopsis in adulthood. These individuals described stereoscopic vision as "miraculous," amazing," "shocking," and even "life-changing". Ogle elegantly stated, "We need only to look out through a window at the foliage of a number of trees at different distances to appreciate how readily we can discriminate with binocular vision the depth relations among trees, branches, and leaves, whereas with monocular vision the trees appear more or less as a spatially undifferentiated mass of leaves and limbs…the principal and significant sense of depth arises through the phenomenon of stereopsis" [7].

Related work

Early case studies

The earliest reports of rehabilitation of stereoscopic vision emerged in the late 19th and early 20th centuries. Émile Louis Javal, a French ophthalmologist, is credited with one of the earliest contributions to visual rehabilitation. While treating his sister's strabismus, Javal postulated that that squint (strabismus) occurred due to faulty binocular fusion [8] He developed a method of orthoptic treatment exercises using a stereoscope. Javal [9] described techniques of visual rehabilitation for strabismic and amblyopic patients such as correction of refractive error, occlusion, fusion, and stereopsis that are utilized even today.

Worth [3] described a series of cases whereby binocularity is recovered though fusional exercises using the amblyopscope, an instrument he developed in 1895 [10]. Reports by Mayou [11] and Lyon [12] described similar success of rehabilitated visual acuity, fusion, and stereopsis. Berens et al. [13] even reported that "full stereopsis is obtained in 59 [percent] of all cases of alternating strabismus". Clearly, documentation for the ability of the human visual system to recover stereoscopic vision is not new.

Orthoptics and vision therapy

Orthoptics and vision therapy are two largely separate traditions for assessing and treating visual disorders. They share common features as non-surgical methods of visual rehabilitation, but today, orthoptists practice most often under the care of an ophthalmologist, often a strabismologist, while vision therapy is practiced more often (but not exclusively) in optometry settings. Orthoptics comes from the Greek words *orthos*, meaning straight, and *optikos*, meaning eyes or sight. Orthoptics primarily addresses the oculomotor components of binocular vision in both strabismic and non-strabismic disorders. Vision therapy addresses a wider range of visual deficits and includes rehabilitative therapies that help patients develop or improve a wide variety of visual skills including oculomotor dysfunction, eye coordination disorders, accommodative anomalies, strabismus, and amblyopia [14], [15]. Visual rehabilitation techniques utilized in common by orthoptists and vision therapists are numerous and include patching therapy, oculomotor exercises, anti-suppression therapy, accommodation therapy, and vergence therapy, among others.

A notable recent success for vision therapy is in the treatment of convergence insufficiency (CI). In CI, the eyes don't turn inward sufficiently during near work such as reading, which leads to double vision, headache, and/or eye strain. CI can be treated using vision therapy [16].

Perceptual learning

"Perceptual learning" has come to refer to a particular type of training that involves repetition of a task (often thousands of trails) with the goal that improvement of skills extends beyond the specific task to other abilities. Perceptual learning principles may be used in visual rehabilitation activities. Tasks may require a patient to use both eyes together with the intent of improving visual acuity, rebalancing binocular input across the two eyes, or improving stereoscopic vision. Ding and Levi [17] reported on a small cohort of stereodeficient individuals that recovered stereoscopic vision following a perceptual learning task that utilized both monocular and stereoscopic targets. Following training, adult patients showed significant recovery of stereopsis and reported the ability to see in depth and appreciate 3D movies.

Perceptual learning can occur in natural settings. A recent study reported that dressmakers demonstrate better stereoscopic vision compared to non-dressmakers. It is likely that simple task repetition, such as sewing, provides the visual system with a form of perceptual learning [18]. However, patients with stereodeficiency probably respond better to targeted visual rehabilitation tasks that focus directly on stereo training, as compared to other rehabilitative techniques or experiences [19].

Training for nonstereo skills in VR

The possibilities for VR in therapeutic settings has been widely recognized. VR has been used for gait training, motor rehabilitation following stroke, behavioral therapy including treating phobias and post-traumatic stress disorders, and cognitive rehabilitation following post-traumatic brain injury [20]–[23]. VR provides a unique platform for rehabilitation by integrating feedback of multiple sensory systems [24]. Visual, auditory, and proprioceptive senses can be mixed in an individualized, experience-dependent therapy environment, while the use of an interactive, virtual environment can be made enjoyable, so patients are encouraged to perform prescribed therapy [22]. Therapeutic changes in skills or behaviors then occur by one of two methods: repetitive stimulation (as in perceptual learning) or by means of teaching alternative or compensatory strategies [25].

Training of stereo depth perception in VR

Visual rehabilitation using virtual reality has primarily focused on improvement of visual skills, especially visual acuity (ability to see fine details such as small letters) in patients with amblyopia. SDP is often measured as a secondary target in amblyopia studies, however. Preliminary results using the Vivid Vision system from a small trial on amblyopia were favorable [26]

VR offers a unique platform for direct training of stereopsis. Vedamurthy and colleagues used a mixture of monocular and binocular cues that adjusted image presentation to subjects in a VR bug squashing game. Subjects were tasked with squashing a dichoptically presented virtual bug with a plexiglass cylinder on a slanted surface. This method meshed the concept of perceptual learning with visual scaffolding. The game adjusted the level of monocular or binocular cues presented to the subject based on correct or incorrect responses. Following training, the majority of subjects displayed improvement in stereoacuity [27].

In summary, there is good reason to believe that VR therapies that target stereoscopic vision are likely to be effective. VR therapies can implement existing methods from a long clinical history of vision therapy to improve SDP in patients, while making the treatments more interesting and enjoyable. In addition, computer control of the treatment in VR will allow for greater consistency of therapy across patients, which will make it more feasible to study efficacy, and will make it possible for a single clinician to treat many more patients.

Stereoscopic depth perception is complex

From clinical practice, we know that binocular vision, and SPD in particular, are complex. Let us consider the various subsystems that must all be operating correctly for SPD to occur.

First, the eyes must be properly aligned physically. In a computer vision system, two cameras can be set to face forward, with corresponding objects in the two images identified by software. The binocular disparities (change of position from one image to the other) of objects in the scene can then be measured in pixels, no matter whether the disparity is large or small. The human visual system is different. The neural wiring that measures binocular disparity in humans operates over a smaller range of disparities. Especially for small disparities, the visual system requires that the objects being measured for disparity fall on the two retinas close to *corresponding points.* If the object falls on the fovea in one eye, it must fall at or near the fovea in the other eye; it must not fall in peripheral vision. Thus, the human visual system is by design a converging system: the angle of convergence between the two eyes must be correct so as to put the two images of an object onto corresponding locations of the two retinas.

The ability to align the eyes physically is called motor fusion, while the ability to match the images, across small residual differences in retinal position, is called sensory fusion. A person with strabismus has poor motor fusion: they cannot get the eyes physically aligned. In some cases it suffices, for the recovery of SDP in a person with stereodeficiency, to gain physical alignment of the eyes [28]. This alignment can be done through eye muscle surgery, the use of prisms (which move the visual stimuli to where the eyes are pointing rather than moving the eyes), or vision therapy.

In other cases, however, the brain will not support sensory fusion even when the object's image falls on corresponding retinal locations in the two eyes. For example, many people with strabismus also have chronic suppression of one eye, or alternate suppression. During suppression, the brain selects one eye for seeing and input from the other eye into visual cortex may be greatly reduced (e.g. [29]); without cortical without input from both eyes at sites of binocular combination, sensory fusion is impossible.

Yet sensory fusion is neither necessary [30] nor sufficient for SDP, because binocular disparities must be measured and extracted from the images. A classic stage in vision therapy is "flat fusion"

[10]. A person with flat fusion can combine information from the two eyes without suppressing either eye, but a person may have flat fusion ability without SDP. In fact, different neural mechanisms are used to measure the "crossed" disparities of objects that are nearer than the fixation point in the scene, and the "uncrossed" disparities of objects that are farther than the fixation point [31], [32].

Finally, suppose a person can measure binocular disparities and even use them to achieve motor fusion (which is, after all, the adjustment of the eyes' convergence until the fixated object has but a small residual disparity). The ability to measure disparity is, by itself, is no guarantee that the perceptual system will *utilize* disparities correctly for the construction of apparent depth. Utilization is perhaps the least understood of the required stereoscopic abilities. However, it seems likely that the reason why depth perception exercises are clinically useful, in persons with motor fusion and flat sensory fusion, is that such a person must learn not only to better measure disparities, but also to better utilize disparities that they can already measure. In support of this proposition, normally sighted people adapt to systematic optical distortions that change the relationship between disparity and depth [33], and they vary widely in the relative extents on which they rely on specific depth cues when multiple cues are available [34].

The Vivid Vision System

The Vivid Vision System utilizes consumer-grade virtual reality hardware, a VR-capable computer, and custom-designed VR software designed to provide fun, immersive games and gesture controls for visual rehabilitation. The system was in use in 108 clinics world-wide as of January 2018. It is available in two configurations: one for use in the office or clinic under supervision of a clinician, and one for use by patients at home. All internet connections and data storage are done through secure HIPAA-compliant encrypted protocols. The application software is written using the Unity framework, which allows it to run on multiple hardware platforms.

The clinical system consists of:

- a head-mounted display (HMD), typically an Oculus Rift or HTC VIVE
- any of the following hand-held controllers or gesture trackers: Oculus Touch, Xbox, Vive controller, and Leap Motion hand-gesture tracker
- a desktop or laptop computer with high-end graphics, running the Microsoft Windows OS
- a touch-screen monitor for clinicians to adjust settings and view users' progress
- back-end "portal" software running on the company's servers, to support the web-based interface used by doctors to keep track of patients and their sessions as well as billing
- desktop application software (executable code) for playing the games and running tests

The Home version is designed for patients to use daily at greatly reduced cost per session, but still under the supervision of a doctor. The home version differs from the office version in the following ways:

- it uses either a smartphone-based "mobile" headset and compatible hand-held controller, currently the Sony Gear VR, or the Rift/VIVE HMD together with separate computer
- it implements a slightly reduced set of testing and gaming features compared to the clinical version, due to limitations in computer graphics capability of the smartphone

The home version connects to the company's servers over the internet using the patient's home wifi or cell-phone data plan.

As of January 2018, the system uses six games to provide treatment. The goal in providing several different games is two-fold, to keep the player engaged by providing a variety of experiences, and to provide activities requiring different visual skills. Some games contain monocularly visible elements, so that flat fusion is required to perform the task. For example, in the *Breaker* game (figure 1), the patient hits target bricks using a ball and moveable paddle, in a 3D variant of the classic Atari game Breakout. Typically, the ball would be shown only to the eye that the patient normally suppresses, while the paddles are shown to the other ("dominant") eye. To hit the ball with the paddle the patient must fuse the two eyes' images, so both objects are visible simultaneously. Thus, Breaker targets sensory fusion. SDP makes the experience more three-dimensional, but it is not necessary to have SPD to play the game.

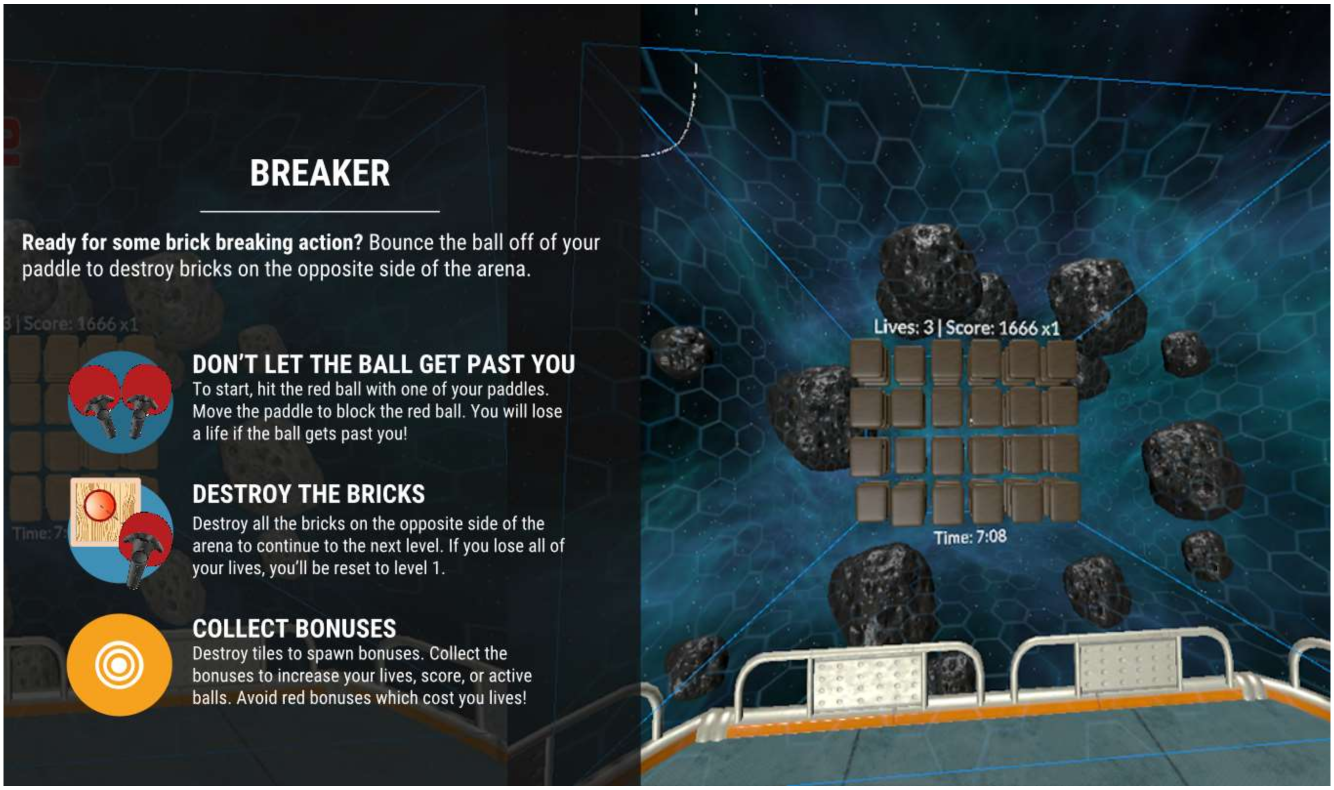
By contrast, in *Bubbles* (figure 2), SDP is necessary to do the task. From 2 to 12 target bubbles are arrayed about a central marker, and the player must "pop" them with her hand, starting with the closest bubble and proceeding to the farthest until all bubbles are popped. The bubble array can be fixed to the head to prevent motion parallax from being a depth cue, and the sizes of the bubbles can be fixed so that all bubbles subtend the same visual angle, which prevents relative size from being a depth cue. Thus, Bubbles targets the utilization of disparity for seeing depth. Other games and activities give practice maintaining motor fusion *per se*, encourage the integration of multiple depth cues, emphasize the use of disparity to control hand movements, require speeded responses, and use binocular luster, attention to peripheral visual field, vergence eye posture control, and acuity practice (up to the HMD spatial resolution of roughly 6 cycles per degree).

The games can also be run using global, patient-specific parameters for *interocular luminance/contrast ratio (ILCR),* to help reduce interocular suppression during game play; *blur*, to selectively reduce contrast energy at high spatial frequencies in the dominant; *prism offset,* which displaces the images in opposite directions, to compensate for binocular misalignment; and *object size,* which can be increased to improve visibility in the amblyopic eye.

Reducing luminance may be as effective as reducing contrast when penalizing the stronger eye to improve interocular balance [17], and Vivid Vision takes a hybrid approach that adjusts both luminance and contrast. The ICLR and prism parameters can be set by the doctor before game play, based on separate tests done in the office by a clinician and/or tests done within the headset itself. The clinician will typically try to adjust these parameters towards their null, balanced values over the course of treatment. In-game tests allow the clinician to monitor eye dominance, phoria, stereoacuity, acuity (using an optical insert that minifies the screen), and vergence (motor fusion) ranges.

Health concerns

A recent opinion piece raised the question of safety [35]. The optics in VR are not perfect, so the user's visual system must work with, and presumably adapt to, this imperfect and unnatural input. In addition, most HMD's have fixed accommodative demand: to see the screen clearly, the user must keep the lenses in their eyes



BREAKER

Ready for some brick breaking action? Bounce the ball off of your paddle to destroy bricks on the opposite side of the arena.

DON'T LET THE BALL GET PAST YOU
To start, hit the red ball with one of your paddles. Move the paddle to block the red ball. You will lose a life if the ball gets past you!

DESTROY THE BRICKS
Destroy all the bricks on the opposite side of the arena to continue to the next level. If you lose all of your lives, you'll be reset to level 1.

COLLECT BONUSES
Destroy tiles to spawn bonuses. Collect the bonuses to increase your lives, score, or active balls. Avoid red bonuses which cost you lives!

Figure 1. User manual page for at-home players, for the *Breaker* game.

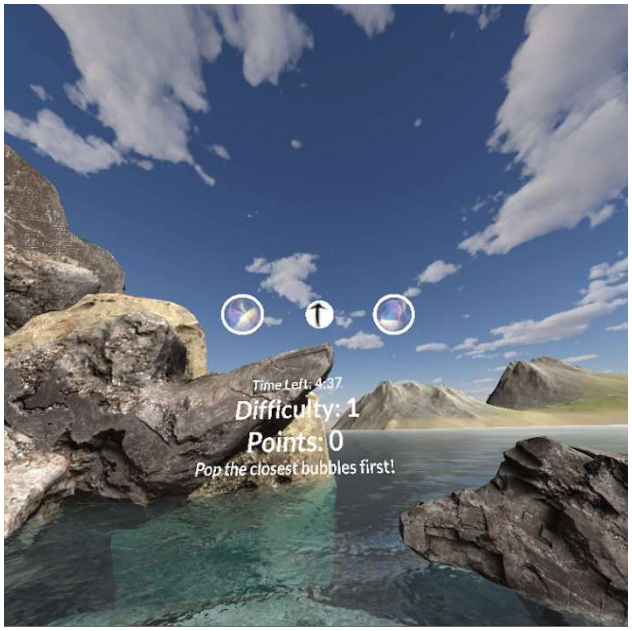


Figure 2. Image seen by player in the *Bubbles* game. In this game the player uses a gamepad or virtual hands to touch the closest bubble. To prevent relative size from being a distance cue, the bubbles are adjusted in 3D size to subtend the same visual angle. It is thus impossible to perform above chance levels using only one eye; SDP is essential to do the task.

focused at some constant distance of approximately 1.5 m. That is unnatural, because in the real world, the lenses within the eyes must accommodate to bring near objects into focus whenever the eyes converge binocularly.

We do not know any reasons for concern when using the Vivid Vision System for vision therapy. The system is used under the care of a vision care professional, who can monitor eye strain and discontinue use if needed. Perhaps more importantly, however, it is a longstanding component of vision therapy to dissociate accommodation and convergence intentionally. In many patients, accommodation and convergence are coupled very strongly to each other but with systematic error. For example, a person with hyperopia (far-sightedness) must accommodate to see objects clearly at infinity. This accommodative response to achieve focus can cause the eyes to turn in (converge), causing double vision. Developing greater flexibility in the relationship between accommodation and convergence is thus an active goal in vision therapy, and this goal is compatible with the fixed accommodative demand of HMDs.

Outlook for use of VR to treat stereo

The use of VR in commercial systems will make it possible to realize a number of new benefits. Patient data can be collected and aggregated over the internet; patients can assess their own binocular vision abilities using apps provided over the internet, that can suggest when a visit to an optometrist may be warranted when amblyopia, strabismus, convergence insufficiency, or lack of SDP are suspected. Eye tracking is being built into a new generation of HMD's and this capability should be useful to assess the speed and accuracy of eye movements for motor fusion.

Conclusion

Deficiency of stereoscopic depth perception is typically a problem of the central nervous system, unlike many other disorders that affect visual ability, that originate in the eye, such as color vision deficiency. The brain suppresses input from one eye, or cannot combine the inputs into a fused image, or cannot utilize image differences (disparities) to control vergence eye movements or to construct apparent depths within visual perceptions. Virtual reality is well suited to provide the brain with special-purpose visual stimuli for tasks and training that target the specific visual skills causing the lack of SDP in the individual. Automated treatment protocols and a large database of treatment outcomes will make it possible to recognize the most effective treatments for specific categories of patient.

The value of SDP in real-world situations is still not well established. People who gain SDP in adulthood have provided first-person accounts of its utility (Barry & Bridgeman, 2017). To be sure, many eye care professionals are convinced of its utility. In any case, the rich world of 3D experiences is likely to become accessible to greater numbers of people through the use of virtual reality-based treatments.

References

[1] W. Richards, “Stereopsis and stereoblindness,” *Exp. Brain Res.*, vol. 10, no. 4, pp. 380–388, 1970.

[2] B. T. Barrett, “A critical evaluation of the evidence supporting the practice of behavioural vision therapy,” *Ophthalmic Physiol Opt*, vol. 29, pp. 4–25, 2009.

[3] C. A. Worth, *Squint : Its Causes, Pathology and Treatment*. P. Blakiston’s Son & Company, 1906.

[4] D. W. Wells, “The Value of Fusion Training and Methods for Its Development,” *Am. J. Ophthalmol.*, vol. 8, no. 1, pp. 46–53, 1925.

[5] S. R. Barry, *Fixing My Gaze: A Scientist’s Journey Into Seeing in Three Dimensions*, 1st ed. New York: Basic Books, 2009.

[6] S. R. Barry and B. Bridgeman, “An Assessment of Stereovision Acquired in Adulthood,” *Optom. Vis. Sci.*, vol. 94, no. 10, pp. 993–999, 2017.

[7] K. N. Ogle, “Some aspects of stereoscopic depth perception,” *J. Opt. Soc. Am.*, vol. 57, no. 9, pp. 1073–1081, Sep. 1967.

[8] S. Mayweg and H. H. Massie, “Amblyopia ex-anopsia (suppression amblyopia); a preliminary report of the more recent methods of treatment of amblyopia, especially when associated with eccentric fixation in cases of strabismus,” *Br. J. Ophthalmol.*, vol. 42, no. 5, pp. 257–269, May 1958.

[9] E. Javal, *Manuel théoretique et practique du strabisme.* Paris, France: Masson, 1896.

[10] C. Worth, “The etiology and treatment of convergent squint,” *The Lancet*, vol. 157, no. 4054, pp. 1323–1327, 1901.

[11] S. Mayou, “The result of orthoptic treatment in divergent strabismus,” *Br. J. Ophthalmol.*, vol. 19, no. 1, pp. 37–46, Jan. 1935.

[12] M. Lyon, “Some Results of Orthoptic Training in Adults,” *Am. J. Ophthalmol.*, vol. 19, no. 8, p. 702–7??, 1936.

[13] C. Berens, B. F. Payne, and D. Kern, “Orthoptic training and surgery in hyperphoria and hypertropia combined with lateral deviations,” *Am. J. Ophthalmol.*, vol. 18, no. 6, pp. 508–524, 1935.

[14] A. H. Cohen *et al.*, “The efficacy of optometric vision therapy. The 1986/87 Future of Visual Development/Performance Task Force,” *J. Am. Optom. Assoc.*, vol. 59, no. 2, pp. 95–105, Feb. 1988.

[15] K. J. Ciuffreda, “The scientific basis for and efficacy of optometric vision therapy in nonstrabismic accommodative and vergence disorders,” *Optom. St Louis Mo*, vol. 73, no. 12, pp. 735–762, Dec. 2002.

[16] M. Scheiman *et al.*, “A randomized clinical trial of treatments for convergence insufficiency in children,” *Arch. Ophthalmol. Chic. Ill 1960*, vol. 123, no. 1, pp. 14–24, Jan. 2005.

[17] J. Ding and D. M. Levi, “Recovery of stereopsis through perceptual learning in human adults with abnormal binocular vision,” *Proc. Natl. Acad. Sci.*, vol. 108, no. 37, pp. E733–E741, 2011.

[18] A. Chopin, D. M. Levi, and D. Bavelier, “Dressmakers show enhanced stereoscopic vision,” *Sci. Rep.*, vol. 7, no. 1, p. 3435, Jun. 2017.

[19] D. M. Levi, D. C. Knill, and D. Bavelier, “Stereopsis and amblyopia: A mini-review,” *Vision Res.*, vol. 114, pp. 17–30, Sep. 2015.

[20] L. Zhang, B. C. Abreu, G. S. Seale, B. Masel, C. H. Christiansen, and K. J. Ottenbacher, “A virtual reality environment for evaluation of a daily living skill in brain injury rehabilitation: reliability and validity,” *Arch. Phys. Med. Rehabil.*, vol. 84, no. 8, pp. 1118–1124, Aug. 2003.

[21] C. L. F. Chan, E. K. Y. Ngai, P. K. H. Leung, and S. Wong, “Effect of the adapted Virtual Reality cognitive training program among Chinese older adults with chronic schizophrenia: a pilot study,” *Int. J. Geriatr. Psychiatry*, vol. 25, no. 6, pp. 643–649, Jun. 2010.

[22] K. Brütsch *et al.*, “Virtual reality for enhancement of robot-assisted gait training in children with central gait disorders,” *J. Rehabil. Med.*, vol. 43, no. 6, pp. 493–499, May 2011.

[23] S. Bouchard *et al.*, “Using Virtual Reality in the Treatment of Gambling Disorder: The Development of a New Tool for Cognitive Behavior Therapy,” *Front. Psychiatry*, vol. 8, p. 27, 2017.

[24] N.-Y. Lee, D.-K. Lee, and H.-S. Song, “Effect of virtual reality dance exercise on the balance, activities of daily living, and depressive disorder status of Parkinson’s disease patients,” *J. Phys. Ther. Sci.*, vol. 27, no. 1, pp. 145–147, Jan. 2015.

[25] A. A. Rizzo, J. G. Buckwalter, and U. Neumann, “Virtual reality and cognitive rehabilitation: A brief review of the future.,” *J. Head Trauma Rehabil.*, 1997.

[26] P. Žiak, A. Holm, J. Halička, P. Mojžiš, and D. P. Piñero, “Amblyopia treatment of adults with dichoptic training using the virtual reality Oculus Rift head mounted display: preliminary results,” *BMC Ophthalmol.*, vol. 17, no. 1, p. 105, Jun. 2017.

[27] I. Vedamurthy *et al.*, “Recovering stereo vision by squashing virtual bugs in a virtual reality environment,” *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, vol. 371, no. 1697, 19 2016.

[28] G. K. von Noorden, “Bowman lecture. Current concepts of infantile esotropia,” *Eye Lond. Engl.*, vol. 2 (Pt 4), pp. 343–357, 1988.

[29] D. P. Spiegel, A. S. Baldwin, and R. F. Hess, “The Relationship Between Fusion, Suppression, and Diplopia in Normal and Amblyopic Vision,” *Invest. Ophthalmol. Vis. Sci.*, vol. 57, no. 13, pp. 5810–5817, Oct. 2016.

[30] J. M. Wolfe, “Stereopsis and binocular rivalry,” *Psychol. Rev.*, vol. 93, no. 3, pp. 269–282, 1986.

[31] W. Richards, “Anomalous stereoscopic depth perception,” *J. Opt. Soc. Am.*, vol. 61, no. 3, pp. 410–414, Mar. 1971.

[32] E. E. Birch, J. Gwiazda, and R. Held, “Stereoacuity development for crossed and uncrossed disparities in human infants,” *Vision Res.*, vol. 22, no. 5, pp. 507–513, 1982.

[33] W. J. Adams, M. S. Banks, and R. van Ee, “Adaptation to three-dimensional distortions in human vision,” *Nat Neurosci*, vol. 4, pp. 1063–4, 2001.

[34] M. S. Landy, L. T. Maloney, E. B. Johnston, and M. Young, “Measurement and modeling of depth cue combination: in defense of weak fusion,” *Vision Res.*, vol. 35, pp. 389–412, 1995.

[35] M. Mon-Williams, “Is virtual reality bad for our health? The risks and opportunities of a technology revolution,” 2017. Accessed on-line Oct. 29, 2017 from https://medium.com/@UniversityofLeeds/is-virtual-reality-bad-for-our-health-the-risks-and-opportunities-of-a-technology-revolution-31520e50820a

Author Biography

Benjamin T. Backus, PhD, received his BA in mathematics from Swarthmore College (1985), taught in Oakland Public Schools, received his PhD in vision science from UC Berkeley (1997), and postdoctoral training in neuroscience from Stanford University (1999). He was Assistant Professor of Psychology at UPenn (2000-2007) and is currently Associate Professor at the SUNY College of Optometry, where he runs an NIH-funded lab. He joined Vivid Vision, Inc. as Chief Science Officer in October 2017.

Brian D. Dornbos, OD, FAAO, received his BS in vision science from Ferris State University (2008) and his doctorate in optometry (OD) from the Michigan College of Optometry at Ferris State University (2012). He completed his post-graduate residency and joined the Department of Veterans Affairs as a Staff Optometrist and Clinical Optometric Educator. He currently serves as Director of Optometry for Vivid Vision, Inc.

Tuan A. Tran, OD, received training in mechanical engineering from Michigan State University, and his doctorate in optometry from Michigan College of Optometry at Ferris State University. He completed his post-graduate residency in pediatrics and binocular vision at Southern College of Optometry. He is co-founder and Chief Optometrist at Vivid Vision, Inc.

James B. Blaha has multidisciplinary training from Lansing Community College, MI. He is the co-founder of several companies, including DogeAPI and the full stack web services company Oxavi Design, and he served as CTO at ZoneCity. He grew up with amblyopia and strabismus. After seeing a TED talk by Susan Barry, he created VR software that he used to gain stereoscopic depth perception himself. He then started Vivid Vision, Inc. where he serves as CEO.

Manish Z. Gupta has training in mathematics from Lansing Community College, MI. He served in the Global Business Services arm of IBM as a Business Analytics and Optimization consultant. He co-founded and wrote software for the cryptocurrency wallet and payment platform DogeAPI with Mr. Blaha, which they sold in 2014. He co-founded and currently serves as CTO for Vivid Vision, Inc.