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Clinical use of the Vivid Vision system to treat disorders of binocular vision

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Abstract

New head-mounted displays and virtual reality software make it possible for the first time to deliver customized, dichoptic visual stimulation at reasonable cost to patients with binocular vision disorders. These disorders include stereo-depth deficiency, amblyopia, convergence insufficiency, and strabismus. Vivid Vision, Inc. has pioneered this new treatment approach and has the leading commercial product, used in more than 100 optometry and ophthalmology clinics worldwide. The Vivid Vision System use games that are fun to play in order to improve adherence. Children typically respond better to binocular vision treatments than do adults, and recent studies in adults suggest that treatments using Vivid Vision are effective; however, large clinical trials with better controls are needed to quantify effectiveness across this heterogeneous patient population.

Contents

Introduction

Orthoptists and vision therapists have used vision exercises to treat disorders of binocular vision for more than 100 years. Treatment practices were well-established by the 1930's, based on theory and case-based medicine (Dobson 1933). By the 1950s, amblyoscopes were in widespread use, allowing for dichoptic stimulation to treat strabismus and squint (Smith 1950). Pleoptics developed as a scientifically well defined, neurologically informed approach to binocular therapy that was widely practiced (Loudon and Simonsz 2005). However, by the 1960's it was clear from controlled studies that eye muscle surgery and patching produced better outcomes for strabismus and amblyopia than did pleoptics (Von Noorden and Lipsius 1964; Miller and Cibis 1960).

Background

Since then, vision therapists have continued to treat binocular vision disorders using "behavioral vision therapy" exercises. Top optometry schools in the country, including Southern College of Optometry, SUNY College of Optometry in New York, and the University of California at Berkeley, have vision therapy (VT) clinics and offer training in VT. Schoolchildren with reading difficulties are often referred to VT for evaluation and possible treatment. The modern practice of VT includes prescribed patching and referrals for surgery. Orthoptics has become an allied profession of ophthalmology, providing tests of visual function before and after surgery, and exercises to improve eye alignment and depth perception. VT is widely believed by professional practitioners to be effective, and it receives enthusiastic support from patients and their parents. Unfortunately, very few controlled clinical trials have tested the effectiveness of VT. Studies based on individual cases and small samples dominate the literature. It is not that VT has been shown not to work, but rather that it has not yet been properly tested.

Convergence insufficiency (CI) is the exception to this rule. After decades of disparagement, behavioral treatment for CI was properly tested and shown to be effective (Scheiman et al. 2005). Until clinical trials for other forms of VT are conducted, however, its effectiveness will remain in doubt. Arguments against the use of VT can legitimately cite an absence of positive clinical study results (Barrett 2009). Recent experimental studies have shown that adults with amblyopia can recover significant binocular function (see Related Studies below) but their findings have not yet been incorporated into clinical best practices.

Vivid Vision

Vivid Vision, Inc. was founded by CEO James Blaha, a programmer who suffered from strabismus and amblyopia. In 2014 Blaha used an Oculus Rift Development Kit to implement treatment ideas from the recent literature on suppression, perceptual learning, and amblyopia. Using stereoscopic displays, with displacements to compensate for his strabismus and reduced luminance for his non-amblyopic eye to reduce suppression, he became able over the course of several weeks to see stereo depth and to read with his amblyopic eye. The team now includes fellow programmer and co-founder Manish Gupta, optometrist and co-founder Tuan Tran, two additional programmers, an additional optometrist, 3 sales and marketing staff, a vision therapist, and science advisor Benjamin Backus.

The Vivid Vision System is most often used under the care of an optometrist or ophthalmologist, usually as a supplement to other VT treatments and exercises. The product “gamifies” VT to make it fun. As clinicians and researchers in the field request new features, they are reviewed and quickly built into the product. Vivid Vision is sold only to doctors, not directly to the public. This strategy has allowed for rapid development so that rigorous testing of a stable version should soon be possible.

General principles of treatment

Any system capable of learning will learn better under some conditions than others. The Vivid Vision system works to improve binocular vision along these six major principles:

1. **Engagement**. The player must attend to the visual stimuli, using both overt attention (where the eyes are pointed) and covert mechanisms. Visual attention increases the signal-to-noise ratio of visual representations within the cortex (Martinez-Trujillo and Treue 2004; Ferrera 2016; Silver, Ress, and Heeger 2007) so that learning mechanisms have more to work with. Traditionally vision therapy has seen attention as essential to learning (Griffin and Grisham 2002; Press 1997) and attention was the common element across recent demonstrations that perceptual learning exercises can improve amblyopia in adults (Tsirlin et al. 2015). Engagement also includes caring about the outcomes of one's behaviors, in other words, "trying to do well," because the feedback signals that are essential for training are more likely to be utilized well when engagement is high.

2. **Easy-to-hard**. Learning systems generally do best when operating at level of difficulty that is challenging but do-able. If the visual system can't do a task at all, it is difficult for learning to proceed (Ahissar and Hochstein 2004; Hochstein and Ahissar 2002).

3. **Balanced input**. Input to cortex is often greatly reduced, either chronically or from active ("clinical") suppression by cortex when both eyes are open. Balancing the interocular contrast and/or luminance of the stimulus restores perceptual contributions from the weaker eye (Ding and Levi 2014; Huang et al. 2011; Mansouri, Thompson, and Hess 2008; Li et al. 2013). Reducing suppression per se has an immediate benefit on acuity and stereo-depth perception (Thompson et al. 2008) and anti-suppression therapy alone can result in long term gains (Hess, Mansouri, and Thompson 2010; Black et al. 2012), but perhaps even more important, balancing the inputs is in principle necessary for learning to occur in mechanisms that combine inputs from the two eyes, including both sensory fusion and the extraction of binocular disparities.

4. **Corresponding retinal images**. If the eyes are not physically aligned, they must either be brought into alignment, or else the stimulus must be displaced in one eye relative to the other, so that similar images fall onto corresponding parts of the two retinas. The normal binocular visual system tolerates some deviations from perfect alignment by means of sensory fusion (Panum's fusional area; for review see (Cameron 1982), and double images can elicit depth percepts and vergence responses (Westheimer and Tanzman 1956; Siderov and Harwerth 1993). However, fusion and good stereoacuity both require that images be in good binocular correspondence (Blakemore 1970).

5. **Use of peripheral vision**. Binocular vision affords larger fields of view. Attention must be allocated to the periphery in order for objects to be detected (Posner 1980), or else the objects must be salient. In a properly functioning visual system, objects that are stereoscopically near attract attention to peripheral locations in the field (Caziot and Backus 2015).

6. **Visuomotor integration**. Binocular vision guides manual behavior (Knill 2010; Melmoth and Grant 2006; Watt and Bradshaw 2003), and VR games that requires reaching and grasping allow the trainee to practice binocular skills in a natural context concurrently control of the visual inputs to optimize visual learning.

The Vivid Vision System

The Vivid Vision System (version 2.5, July 2017) is available in two configurations: one for use in the office or clinic under direct supervision of a clinician, and one for use at home. All internet connections and data storage is done through secure HIPAA-compliant encrypted protocols. The application software is written using the Unity framework, so that it can run on multiple hardware platforms.

Vivid Vision Clinical

Vivid Vision Clinical is a complete virtual reality system designed for in-office use. The 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

Vivid Vision Home

The Home version is designed for patients to use on a daily basis 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:

- 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
- 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.

Games

The application is actively being developed, modified, and expanded. It currently includes six games:

- **Ring Runner** (fly a spaceship through rings and shoot asteroids)
- **Hoopie** (catch a basketball with a hoop attached to the head)
- **Breaker** (hit target bricks using ball and moveable paddle in a 3D variant of the classic Atari game Breakout)
- **Pepper Picker** (manually pick peppers from a bush as they become visible by changing color in the amblyopic eye)
- **Bubbles** (use your hand to pop the closest of several bubbles)
- **Turbo** (identify and touch the correct target, that you must identify as quickly as possible using multiple depth cues including both stereo and motion parallax)

Each game is 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
- **object size**, which can be increased to improve visibility in the amblyopic eye.

Reducing luminance appears to be just as effective as reducing contrast when penalizing the stronger eye to improve interocular balance (Ding and Levi 2014), and Vivid Vision takes a hybrid approach that reduces both. The ICLR and prism parameters are 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.

Each of these games emphasizes a particular set of visual skills. Bubbles isolates stereoscopic depth perception using a stereoacuity task, while the other games integrate multiple skills that the patient works on concurrently. Different skills receive different emphasis within different games. These skills include flat fusion (the task requires seeing two objects at once, each presented only to one eye), stereoscopic depth perception, control of hand position using stereoscopic depth, use of binocular luster, attention to peripheral visual field, vergence eye posture control, and acuity (up to HMD spatial resolution). A separate brochure describes each of the games in greater detail.

Tests

Currently available tests include:

- **Dominance**: quantitative test for interocular balance using visibility within a dichoptic contrast display
- **Four Dot**: a VR version of the Worth Four-dot test for suppression
- **Angles**: a subjective alignment test for the angle of deviation, assuming NRC

Beta support also exists for these tests:

- **Stereogram**: test of stereoacuity using random-dot stereograms
- **Contrast sensitivity** as a function of spatial frequency (only up to 5 cpd)
- **Stereoacuity**, using an optical insert that minifies the screen
- **Acuity**, using an optical insert that minifies the screen

These tests have proven useful to clinicians, and test-retest reliability is generally good. Preliminary comparisons with existing standard clinical tests show good agreement with the tests in Vivid Vision, with the exception of the Worth 4-Dot test, which is perhaps not surprising given that many factors contribute to binocular rivalry.

Using VR to treat binocular visual disorders

Like the amblyoscope, the VR headset allows direct independent control of separate images for the two eyes.

Advantages and current limitations

Like previous computer-based methods such as the HTS Amblyopia iNet program, VR treatments can automatically adjust the level of task difficulty, tracking the patient's ability as it improves, and does not require constant supervision by the clinician. But in addition, the treatments can be made immersive, and much more fun for patients to do. The promise of good adherence, together with recent literature on perceptual learning in adults, is stimulating a great deal of new research and development in the use of VR to treat binocular disorders in both children and adults. The best uses of VR for treatment are undoubtedly still to be discovered, but there is now sufficient cumulative experience with VR systems such as Vivid Vision to see that VR will become a permanent feature of the treatment landscape.

VR still has limitations. Simulator sickness used to be a significant problem, but the newest generation of VR headsets use high frame rates, predictive tracking, and shorter display latencies, which greatly reduces simulator sickness (Buker, Vincenzi, and Deaton 2012). The two principal limitations that remain are the relatively low display resolution of current HMDs relative to central vision in humans, and the lack of a wide-spread standard for accurate built-in eye tracking. In addition, HMD's are currently unable to track changes in accommodation (lens focus), and they use a fixed dioptric power (accommodative demand) corresponding, typically, to between 2m of distance and optical infinity.

Current HMD's use approximately 1000 pixels across a field of view 100 deg wide. At 10 pixels per degree, the maximum spatial frequency that an HMD can display is 5 cpd. Thus, HMD's have only one sixth of the spatial resolution they would need to support foveal acuity for 20/20 vision, and one twelfth what would be needed to support the best human vision at 20/10 acuity. The Finnish company Varjo has developed a method using eye trackers, moving mirrors, and a second display panel for each eye that keeps a high resolution image within central vision, but the cost of this system is too high for wide-spread use in vision therapy. The primary limitation posed by the relatively low resolution of HMD's is the inability to test and treat acuity in patients with 20/100 vision or better. Acuity can be addressed directly in patients with severe amblyopia worse than 20/100, and some gains in acuity are expected simply from treating suppression. Stereoscopic vision can also be addressed, because unlike fine stereopsis at stereoacuity limits, the use of supra-threshold disparity in ordinary environments relies heavily on intermediate spatial frequencies (Schor and Wood 1983). Anti-aliasing techniques cause the centroids of multi-pixel objects to be relatively accurate. Alternatively, Vivid Vision developed a custom optical insert that minifies the screen, that was used to measure acuity and stereoacuity.

Inexpensive built-in eye tracking is likely to be common in HMD's by the end of 2018. At that point it will be possible to explore new automated treatments for convergence insufficiency, and to provide automated testing and treatment of binocular function before and after surgery for strabismus. Orthoptists and vision therapists spend a lot of time looking at their patient's eyes, for both diagnosis and treatment. The problem of knowing where a patient's eyes are pointing is one reason why many studies of perceptual learning in adult amblyopes have been restricted to anisometropic patients with good binocular fixation. However, the images in a VR headset can also be aligned using nonius lines and other psychophysical measures, and a doctor can measure phoria outside of the device to find a comfortable prism offset for the patient. Thus, current devices do allow for measurement and compensation of binocular misalignment, even without eye tracking.

Suppression

Suppression is treated in VR primarily by adjusting luminance and contrast in the two eyes separately, until the patient can see both eyes' images at once in the context of a game requiring that both images be used. Suppression is not always distinguished from interocular balance. Suppression is both a cause and result of amblyopia, and it limits stereoscopic depth perception. It presumably blocks not only the ability to see in stereo, but also the ability to learn how to see in stereo, so it is a primary target for treatment in most patients. Among the binocular anomalies, suppression is perhaps the most easily treated.

It is not widely appreciated that regional suppression of one eye's image by the other's is essential for good binocular vision. The visual mechanisms for suppression are responsible for letting us see with one eye what the other eye cannot see. However, whenever both eyes look at the same object, corresponding images are necessary for fusion and stereopsis to occur.

Strabismus

Strabismus is complicated, as is its treatment using VR. Strabismus varies greatly from one patient to another. Some strabismus, including many intermittent exotropias, can be treated using exercises alone. Field reports include cases in which patients needed less prism over time, to the point of good alignment without surgery, but we have not yet studied these claims systematically. The Vivid Vision system is well suited for use before and after surgery, to improve sensory fusion and reduce the size of the central zone. The system can accommodate patients with manifest strabismus angles, using simulated prism, up to about 20 prism diopters (11 deg).

Some strabismus is not likely to benefit at all from VR treatment. For example, many patients with albinism do not have binocular innervation of primary visual cortex, so they are unlikely to develop the ability to make use of the binocular disparities that are needed to control vergence eye posture and see stereo depth, since binocular disparities are measured by neurons in that brain area.

Intractable diplopia is a concern when treating strabismus, but for reasons that are not well understood, it has not occurred in modern studies (e.g. PEDIG Writing Committee, 2010).

Amblyopia

Amblyopia is most famously characterized by a loss of visual acuity, but visual crowding and loss of stereo depth perception may be more consequential in everyday situations. These three symptoms of amblyopia are treated in VR using activities that penalize suppression and reward binocular combination, and, in patients with worse than 20/100 acuity, activities that require the use of high spatial frequency visual content. Binocular approaches to amblyopia should, in principle, be more effective than patching, because binocular neurons must presumably be re-wired to accept greater input from the amblyopic eye. It is not clear exactly why patching works, but it does--albeit slowly, and with significant objections by the patient.

Stereo-deficiency

Stereo vision is treated in VR using a coarse-to-fine approach. Many patients with strabismus history are stereoblind, while for patients who can see some stereoscopic depth, it is generally stereoacuity (the ability to see depth from very small disparities) that is most affected; many patients retain the ability to see depth from large disparities. Stereoacuity can be limited by fixation disparity, suppression, or the inability to extract disparities from binocular stimuli, all of which are targeted for treatment in VR by the Vivid Vision system.

Convergence insufficiency

CI is treated in VR using exercises to extend vergence ranges. These exercises are conceptually similar to the “vectographs” used in VT: the binocular vergence demand of the stimulus is changed, and the patient must re-fixate to do the task, such as extracting depth from disparity within a fused target or reporting the relative locations of two nonius lines. In real world situations, accommodative demand changes with vergence demand as a target gets nearer or farther away. We do not at present have a way to control the focal distance of the stimulus, which is fixed, typically at about 3m (0.33 D). However, for many patients there is a benefit in learning to decouple vergence and accommodation; it may be a step towards better use of disparity as a cue for controlling vergence eye posture.

Academic studies of efficacy the Vivid Vision system

Two studies tested early versions of Vivid Vision as a treatment for amblyopia in adults. Both were preliminary studies and both reported positive results, but both had limitations. (Žiak et al. 2017) used the system to train 17 adults with anisometropic amblyopia. Training consisted of eight 40-minute sessions: two per week for four weeks, with 20 minutes of Ring Runner and 20 minutes of Breaker per session. Amblyopic-eye visual acuity and stereo vision both improved significantly. Mean acuity in the amblyopic eye improved from logMAR 0.58 ± 0.35 before training to 0.43 ± 0.38 afterward (mean ± SD, $p < 0.01$). Mean stereoacuity improved from 263 ± 135 arcsec before training to 177 ± 152 arcsec afterward ($p < 0.01$) and 6 of the 8 subjects who did not have measurable Randot-circle stereoacuity before training were measureable afterward. A limitation in this study was the absence of a randomly assigned control group. The effect sizes were larger than one would expect from simply taking the tests the second time.

Aderman et al. (Aderman et al. 2015) conducted a small, masked, randomized trial using an early version of Vivid Vision, which measured comfort, suppression, acuity, and stereoacuity as outcomes. The study had three arms: patching of the amblyopic eye, dichoptic viewing (with stereo), and synoptic viewing (both eyes seeing the same image). Participants ran 15 sessions of 30-60 minutes each over 3 weeks. Acuity and stereoacuity were measured using the headset, using a custom optical element that fitted into the HMD and that minified pixels in central vision by approximately 6x. The authors demonstrated minimal discomfort from the treatments and excellent agreement between clinical and within-HMD measures of acuity and stereoacuity. There was a trend toward greater improvement in stereoacuity with greater time spent playing the games, and for dichoptic viewing as compared to the other conditions. The study was limited by the small number of subjects (N=14 total), which made it underpowered, and by the heterogenous mixture of anisometropic, strabismic, and mixed amblyopes who may respond differently to dichoptic therapy.

These studies bolster the claims of clinicians that Vivid Vision is effective for treating stereo-deficiencies. One study found that visual acuity improved but the lack of a control condition limits the strength of the finding.

An NIH-funded research study is underway in the laboratories of Dennis Levi and Daphne Bevalier, at UC Berkeley and Geneva, to measure the benefits of training for stereo depth perception in particular. Vivid Vision's technology will be used to deliver the visual training in these experiments.

Use in children

Binocular disorders are treated during early childhood whenever possible, because the developing visual system has greater plasticity compared to adults and older children. Patching is most effective as a treatment for amblyopia before the age of 7y (Holmes et al. 2011) and is often not attempted after the age of 10y or 12y. Strabismus surgery is done at any age, but the expectation for recovery of stereoscopic depth perception is much lower in older children and adults (Banks, Aslin, and Letson 1975; Birch, Fawcett, and Stager 2000). Convergence insufficiency has costs for learning during school years. For these reasons children are the most attractive target for treatment of binocular vision. Vivid Vision is already in wide use by individual doctors, mostly optometrists, to treat children. Thus, it is reasonable to conclude that at least some fraction of the pediatric population is able to tolerate the treatment. Anecdotal reports suggest that children do benefit, but the primary treatment outcomes have not yet been assessed systematically.

Reasons why an individual child might be a poor candidate for treatment include:

- Small head, with an interpupillary distance less than the minimum supported by the device, resulting in unnatural divergence demand
- Small head, unable to support the weight of the HMD for duration of the treatment
- Sensitivity to simulator sickness may be different than in the adult

- Sensitivity to mismatches between vergence demand and the fixed accommodative demand of the HMD
- Lack of ability or interest to play the VR games
- Anomalous retinal correspondence, in the case of a strabismic patient

A mismatch in IPD can be remediated in software by displacing the images physically. HMDs are becoming lighter over time, but this remains a potential obstacle for a small child. Susceptibility to simulator sickness has not been characterized for children. Asthenopia can be caused at any age by mismatch between vergence and accommodation; in children this should be monitored until normative data can be obtained. And it is of course of critical importance that games be engaging. One attempt at dichoptic training in children reported significant adherence problems for this reason, with only 22% of 176 children achieving 75% adherence or better (Pediatric Eye Disease Investigator Group 2016), with outcomes that were no better than and possibly worse than patching. By contrast, pediatric optometrists often save a Vivid Vision session to be the last activity in a visit, as a reward to incentivize the child's cooperation on other, less enjoyable tasks.

The problem of individual variation when testing effectiveness

The greatest problem to overcome in testing effectiveness, in children or adults, is the problem of individualized treatment. In the clinic, Vivid Vision is part of a larger treatment plan. Two patients with the same acuity in their amblyopic eye will typically differ greatly in etiology as well as their secondary signs and symptoms. In designing a treatment plan, a skilled provider will take into account the patient's refractive history, family history of visual disorders, whether the patient was born prematurely, suppression, vergence range and phorias, accommodative reserves, speed and latency for accommodative and vergence responses, the relationship between the patient's accommodation and vergence eye posture, and so on.

These factors are then used in the context of theories of developmental binocular vision to design the treatment plan. For example, in a patient with amblyopia who has strabismus history but no refractive error, the doctor may treat the amblyopia as developmentally secondary to suppression, and emphasize exercises to promote sensory fusion and motor fusion early on. If the patient has no strabismus history, then acuity, or binocular integration at high spatial frequencies might be addressed first, using penalization by means of dark filters or blur. If the patient has a deep and chronic suppression, patching would be emphasized during early treatment. In a patient with poor accommodation, the doctor might work to ensure focused retinal images across a range of viewing distances. The patient may have diplopia, anomalous correspondence, and/or regional suppression scotomas that need to be addressed.

In short, binocular vision is complicated. It depends mutually on sensory fusion, motor fusion, and accommodation, which means that a patient who has poor skills in one area will not have received the visual inputs necessary to do well in the others. Thus, a doctor must typically work on several fronts simultaneously, making assessments of the patient's' visual skills before and during the treatment. A skillful doctor will take an adaptive, flexible approach, watching as the patient does different exercises to decide which ones are likely to be of benefit, and if the patient does not improve within a few weeks, the doctor will try a different approach.

Conclusion

The ability to combine engaging game play with high level, adaptive visual stimuli provides a powerful platform for testing and treating visual system disorders. In particular, binocular vision disorders lend themselves to treatment with perceptual learning strategies in VR. Vivid Vision leads this rapidly growing industry by several years, as measured by the current state of its products, actual use in clinics, and intellectual property.

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