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Eye Exam in the Virtual World: a Pilot Study

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Abstract:

This study investigated the feasibility of using three-dimensional (3D) technology as a multi-functional visual stimulus to assist the clinical eye exam. Specifically, we examined: (1) whether the receding movement of a 3D fixation target into distance could relax the accommodation of non-cycloplegic hyperopic subjects so that accurate refraction measurements could be achieved; (2) the feasibility of using the left-eye and right-eye images from the 3D monitor as the light source to perform swinging-flashlight pupil tests; and (3) the implementation of 3D technology to interrupt the binocular visual/motor fusion as required for the clinical cover test to identify strabismus.

Using a 3D TV to provide visual stimuli and a photoscreening (PS) device, near-infrared (NIR) eye images were acquired and analyzed for each of the three objectives. The result of accommodation test showed that with visual stimuli, the maximal hyperopic refractions could more accurately suggest the patients' true refractions and the more hyperopic patients responded more to the 3D projected distance. However the very mild hyperopia did not show significant response. The pilot tests also showed distinguishable normal and abnormal pupillary responses with 3D image illumination and also the difference in phoria and tropia in the ocular alignment test using 3D stimuli.

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Running Title: VR for Eye Exam

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Introduction:

In recent years virtual reality (VR), augmented reality (AR), and various types of 3D-imaging technology have blossomed. Stereoscopic technology provides more realistic perception to viewers. In medical practices, it allows more accurate analyses of the morphology, and therefore, helps to improve surgical accuracy, reduce operation times, and enhance patient safety [1, 2]. 3D technology can also be applied in an altered way, for the vision assessment. Stereoscopic viewing requires both eyes to work in coordination as they converge, focus, and track the target. Deficiencies of such coordination reveal difference between two eyes and undiagnosed problems [3]. As indicated in the "3D in the classroom" document from American Optometry Association, "the ability to perceive depth in a 3D presentation is an effective vision health indicator that has much higher sensitivity than the standard eye chart that has been used for the last 150 years" [4].

Children with ocular diseases are often unaware of their impairment until a later stage when treatment is less effective. The importance of regular vision screening is indisputable, but comprehensive examinations for all children would put a significant strain on limited clinical health-care resources. The growing popularity with children in VR and 3D-video games has provided a potentially effective treatment for amblyopia [5-7] and a promising intervention of children's myopic development [8] and may be an approach for assisting and lessen the burden of pediatric vision assessment. Currently, a large number of clinical ocular exams rely on the clinician's observation while visual stimuli are applied with tools that include a penlight, an eye patch or a visual occluder, an optotype, and fixation targets at different distances. While 3D technologies, especially when presented as animation, are attractive to children, they could simultaneously function as a versatile clinical tool that provides independent optical stimuli to each of the viewers' eyes without their awareness. A supplementary infrared camera could record binocular images and track eye response for clinicians' review. Examples of potentially applicable eye exams include at least: 1) tests that evaluate ocular alignment (Hirschberg test), 2) extra-ocular motilities tests (EOM), and coordination (convergence) test, 3) the swinging flashlight pupil test that assesses afferent and efferent neurological pathways, 4) an accommodation test that measures the ability to change focus in response to stimulus distances, 5) the cover test to assess the magnitude of a phoria or a strabismus (tropia), and 6) the Bruckner test for screening strabismus, anisometropia, media opacities, and posterior pole anomalies in infants and children.

This pilot study investigated the feasibility of using 3D technology as a multi-functional visual stimulus. A NIR video camera captured eye images of retinal reflex and thereby observed ocular activities as the patient viewed 3D animations. We examined whether the recession of a 3D cartoon character into far distances could relax accommodation in hyperopic patients. We demonstrated the approach of using 3D monitor to perform the swinging flashlight pupil test. Also examined was the application of 3D technology to interrupt the binocular visual/motor fusion as the cover test requires.

Experiment and Method

The human subjects of this pilot study were 155 volunteers with an age range of 4 to 81 years old who were recruited in their visit at Walmart vision center [9]. We used a binocular infrared photoscreening (PS) device, the Dynamic Ocular Evaluation System (DOES) [9, 10], to monitor the eyes' activities, including the pupil sizes, gaze angles, and refractions while the subject viewed three short 3D videos through a binocular eye piece. DOES also used a customized

(Continued on page 24)

computer code to determine the image quality and the presence of any imperfections from eye lids, eye lashes, eye movements or defocusing based on the pupil's circularity, lack of boundary sharpness, presence of corneal reflection, and significant location-shifting between images.

All subjects received comprehensive eye exams in the same visiting period.

Accommodation Test

The first of the three tests in this study is to check the feasibility of relaxing visual accommodation by 3D stimuli. Although the ocular accommodation driven by 3D displays were discussed in many studies [11-18], the relaxing of accommodation in hyperopic objects has never been studied. Because that measuring hyperopia in children is often masked by accommodation, and hyperopia is a significant risk factor of developing amblyopia, it is important to relax children's accommodation for accurate assessment. In optometric practices, the fogging technique, which places a positive lens in front of an eye while the eye views a distant target, is often used for relaxation purpose. However, the effectiveness of this technique is often insufficient. Since ocular accommodation can be driven by many different types of monocular and binocular visual cues, Horwood and Riddell investigated and compared the effectiveness of several of them and they concluded that the most effective stimuli to relax accommodation was the binocular targets receding into the distance [19]. The test here is to examine whether the 3D target that recedes into the distance could also relax accommodation effectively like the real physical objects used by Horwood and coworkers.

In the clinical testing cohort, we included only hyperopic subjects younger than 35 years of age who had healthy accommodation. Both eyes of the subjects must be hyperopic, their cylinder-refractive error must be less than 1.5 diopters, and the best corrected visual acuity (BCVA) obtained from phorometry or un-corrected distant VA must equal or better than 20/30. Strabismic, amblyopic, and dilated patients were excluded. Only 16 subjects, all between the ages of 5 and 20 years, fulfilled these inclusion requirements.

The 3D animation for this test used a cartoon character dressed in a doctor's white gown. On the 3D screen the character was presented which then attempted to walk slowly from its location to three farther distances. To capture the attention of the patient, at each of the four standing distances, the cartoon figure stood still for 3 seconds with a flashing or spinning object on his hands. The first standing position was at the screen distance of 75-cm, which corresponds to 1.3 diopters. The farthest distance was 6 m calculated by assuming a 60-mm inter-pupillary distance (IPD). The fixation target size at furthest distances, was equivalent to the letter size in 20/400 lines of the eye chart.

To determine the patient's accommodation activity, we used a NIR photoscreening (PS) device, the Dynamic Ocular Evaluation System (DOES) [9, 10]. The DOES refraction precision is 0.45 diopter for spherical equivalent between +4 and -4 diopters. Binocular refraction measurements were obtained during the last second at each of the four fixation distances. This test was performed in normal room-light condition.

Pupil Test

The second test simulates the clinical swinging-flashlight pupil-function test. Since 3D technology can deliver independent left- and right-eye images to produce stereoscopic perception, this feature was used to illuminate each pupil independently with different levels of visible light while the pupil sizes of both the direct-illuminated and the consensual eyes were recorded with infrared camera in 20 frames per second.

The 3D screen first presented a dark screen for three seconds for spontaneous dilation. Then a bright and large cartoon figure of about 1/3 of the screen area, popped up, and the image on the screen illuminated the eyes for half of a second. Three seconds later this cartoon figure reappeared visible for only the right eye. Another three seconds later the pop-up happening was repeated for only the left eye. The illumination timing is illustrated in Figure 1. The screen was dark for the rest of the time. The 3D screen was placed at 50 cm in front of the examinees in this test.

Cover Test

Strabismus is one of the important screening

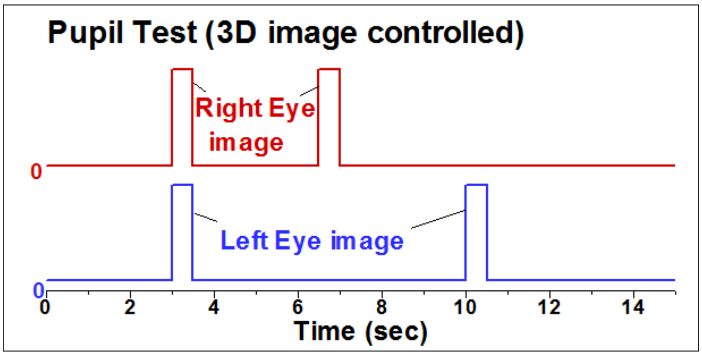

Figure 1. The timing of illumination of pupil test. The red and blue lines indicate the right and left eye images launched respectively from the 3D screen.

targets that link to amblyopia development. The Hirschberg method is a simple and objective test to identify the binocular mis-alignment. It measures the locations of corneal light reflections. Any asymmetry between the two eyes or significant deviation from the pupil centers indicates a potential ocular mis-alignment. Although this method is easy to implement, the diagnostics is not as reliable when compared to the subjective cover-uncover test, which actively disturbs the binocular vision to stimulate and reveal the abnormality [20, 21]. Cover test is usually considered the clinical standard, but it requires a more skilled clinician to perform the test. In this demonstration, we use 3D technology's separated right-eye and left-eye input feature to eliminate the visual fixation target from the background to one eye to achieve the similar effect of using a visual occluder in the clinical cover test. The disappearance of the viewing object in one eye will prompt the viewer to use the other eye to look at the target which is similar to the "cover" portion of the cover -uncover test. The reappearance of the absent fixation target in the 3D image is similar to the "uncover" portion. In the video, we created a fixation target that moves from the left of the screen to the right and then, in reverse motion to return to the left corner of the screen. The 3D screen was divided into three viewing regions: 1) the center region was for binocular viewing where both eyes could see the moving target; 2) on the left-side of screen, only the left eye could visualize the target, and 3) on the right screen, only the right eye could see the target. This design of forward- and return-tracks provided for both eyes a cover-switch and an uncover-switch as illustrated in Figure 2. By continuing monitoring both eyes' gaze angles, using Hirschberg analysis, as they followed the target across the screen, we are able to determine the magnitude of fixation shifts without using a physical occluder. The monitor was positioned at 50-cm in front of the examinees.

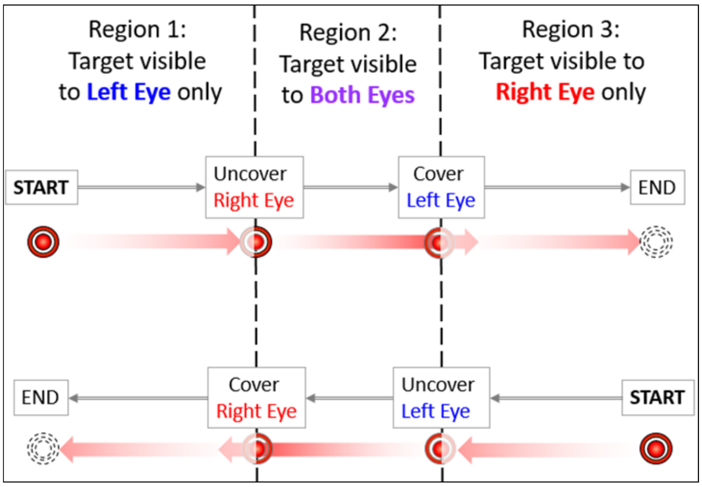

Figure 2. Illustration of the cover test in a 3D screen that was divided into 3 regions: the left where only left eye could see the target, the center where both eyes could view the target, and right portion where only right eye could see the target. When a fixation target moves across two boundaries between regions, the cover or uncover effect was produced as indicated.

Results and Discussion

Accommodation Test Result

Figure 3 shows the result of the accommodation measurement of the 16 hyperopic patients (labeled alphabetically from A to P followed with the age and race). The refraction measurements are presented in spherical equivalent refraction (SE). Normally, the accommodation magnitudes of two eyes are approximately equal and are just sufficient to compensate the one eye with less accommodation demand. Therefore, both the right eye (OD) and left eye (OS) measurement results were plotted (side-by-side) for comparison. The upper chart in Figure 3 includes 8 subjects with higher hyperopic levels (the Y-axis is scaled from -2 to +7 diopters). The lower chart includes less hyperopic subjects (the Y-axis is scaled from -2 to +3 diopter). The 4 gray shaded bars, marked as D1 to D4, indicate the measurements under viewing the 3D target at 4 fixation distances from near (D1=75 cm) to far. The black bar on the right-most was the clinical gold standard measurement of each eye: either the clinical subjective measurement for adults or the cycloplegic retinoscopy for young children performed by the clinician. The screen distance of D1=75 cm corresponds a maximum accommodation stimulus of -1.3 diopter. The farther distance toward infinity might relax accommodation toward a presumed 0 diopter. As shown in the 2 charts, practically all of the subjects showed mild myopia or some degree of accommodation during

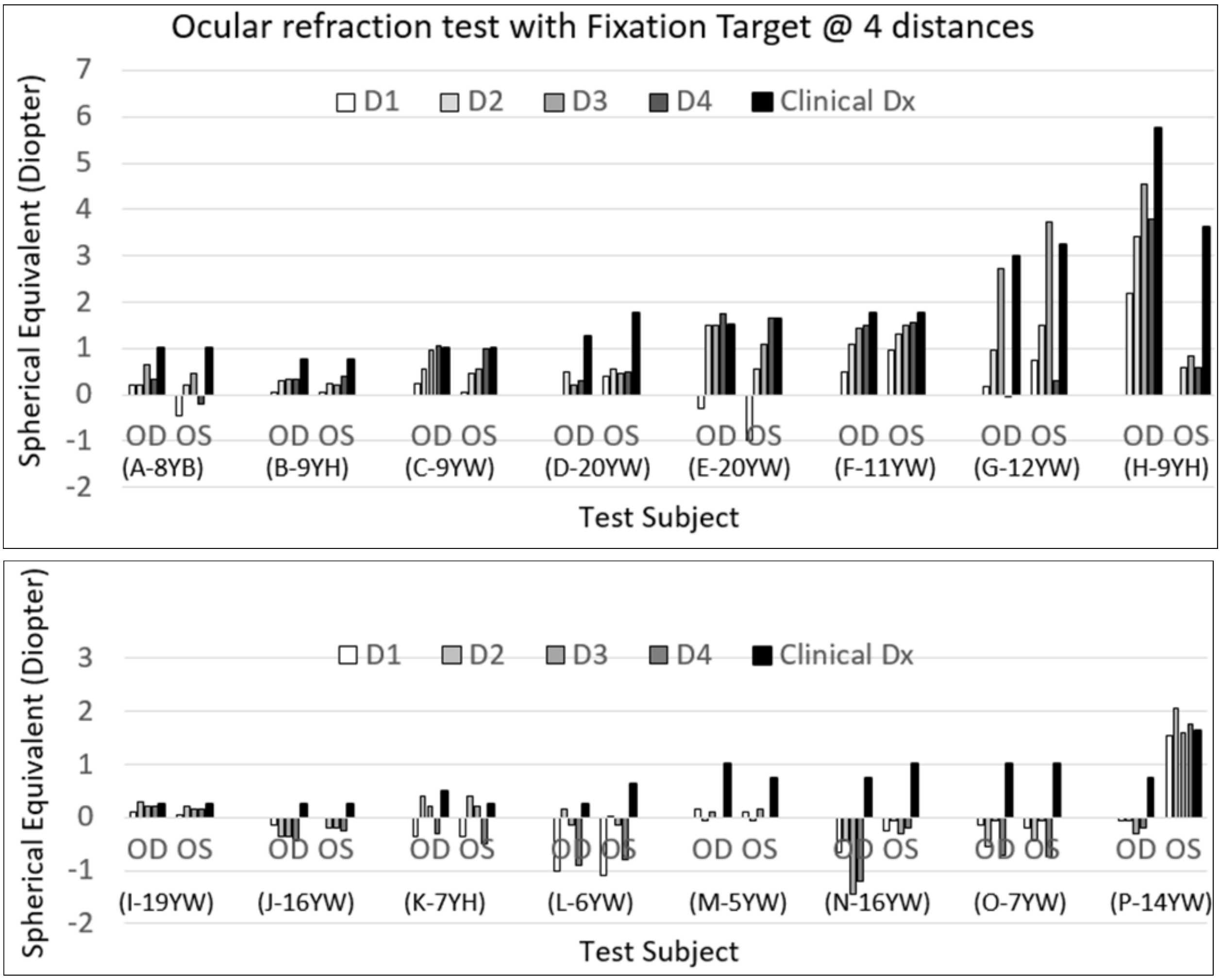

Figure 3. Accommodation test results (bars in 4 gray shades) in comparison to clinical gold standard eye exam result (black bars). D1, D2, D3, and D4 correspond to results obtained under 3D target distances at 75cm to far distance. Total n=16 subjects.

the measurements. As an example, the subject E-20YW was measured as myopic when presented the fixation target at D1. As the fixation target receded to D2, D3, and D4 distances, the magnitude of accommodation gradually decreased and the total refraction approaches the clinical refraction. Some of the measurements showed maximal hyperopic refraction at viewing stimulus D3 rather than stimulus D4. This could be the loss of attentiveness due to reducing size of fixation target or the broken fusion at D4. A few patients had experienced double-images and loss of stereoscopy at occasion in the viewing. Because the perceptional distances, D2- D4, were calculated based on an inter-pupillary distance (IPD) of 6 cm rather than the individual's IPD, for a younger patient with IPD< 6 cm, the projected distance could result in a double-image. This effect was observed in young subjects A-8YB, G-12YW, H-9YH, and K-7YH.

In subjects with very mild hyperopia (<+1 diopter) including J, L, M, N, and O, the 3D figure and its distance did not appear to be affective to their accommodation. They appeared to accommodate with small magnitude constantly.

Pupil Test Result

For healthy eyes, both the muscle and stroma of the iris and the afferent and efferent neurological pathways of either eye are well, if either eye is illuminated, the pupillary response is such that both pupils contract equally. The pupil-test results are shown as the pupillograms in Figures 4 to 6. In the pupillograms, the two purple vertical lines indicate the 0.5-second interval when the cartoon picture was

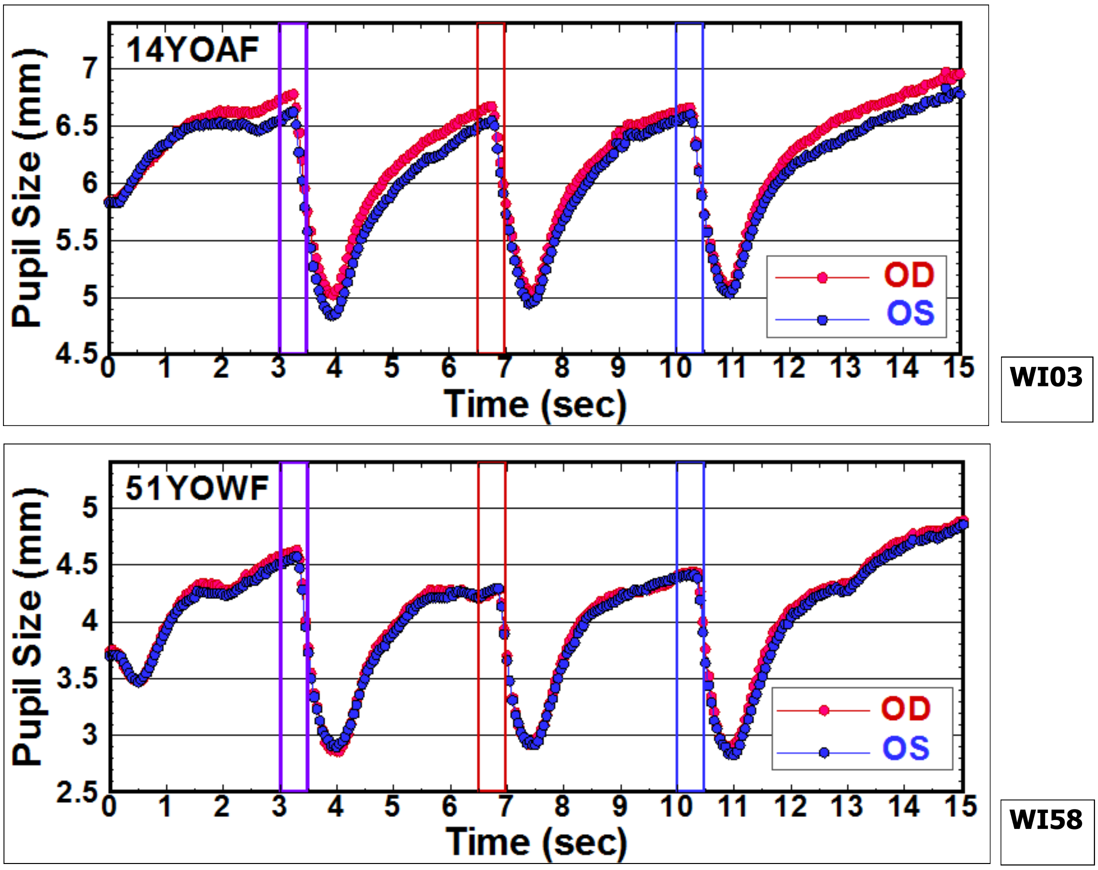

Figure 4. Pupillograms of two normal cases. The purple vertical lines indicate the 0.5 second period when the cartoon picture was shown to both eyes. The red and blue lines indicate the monocular illumination to right and left eye, respectively.

launched (visible) to both eyes. The two red lines and two blue lines specify the right-eye and left-eye monocular illumination periods, respectively. Figure 4 presents two normal cases with clinical description of PERRLΘRAPD, meaning "Pupils are Equal, Round, and Responsive to Light without Relative Afferent Pupillary Defect". The upper pupillogram belongs to a fourteen year- old Asian female. The lower pupillogram belongs to a 51 year-old white female whose pupils were naturally smaller in comparison to the younger patient. For both subjects, both pupils contracted and re-dilated synchronously for the three illuminations as normal pupils should. The latency for normal pupils to respond to light to contract is about 0.2-0.5 second. The contraction and re-dilation speeds are generally in the range of a few mm/sec. The result showed that the screen brightness change using the presence and absence of a large cartoon character on screen is sufficient to induce pupil contraction and re-dilation for examining the pupil health.

Figure 5 is the pupillogram of a case of positive relative afferent pupillary defect (+RAPD) that was caused by a trauma incident. Unfortunately, this eye also suffered from cataract and strabismus (ET). As a result, the automatic analysis computer-code failed to find the left pupil due to the low signal-level in the infrared photograph. Thus, the left eye data were missing in the pupilogram analysis. The pupilogram indicated that as the screen illuminated the right eye, the right pupil contracted from 4.9mm to 3.55mm. When the screen light illuminated only the injured left eye, the optic nerve could transmit light but contraction occurred to a lesser degree from 4.9 mm to 4.1 mm. The brain interprets this as a decrease of light level, and the brain's response is to have both pupils contract less to admit more light in. Despite only one eye being illuminated, this dilation response was observed in both eyes. This was identified when we manually examined the video images. The clinician also validated that this eye responded to light but to a lesser degree.

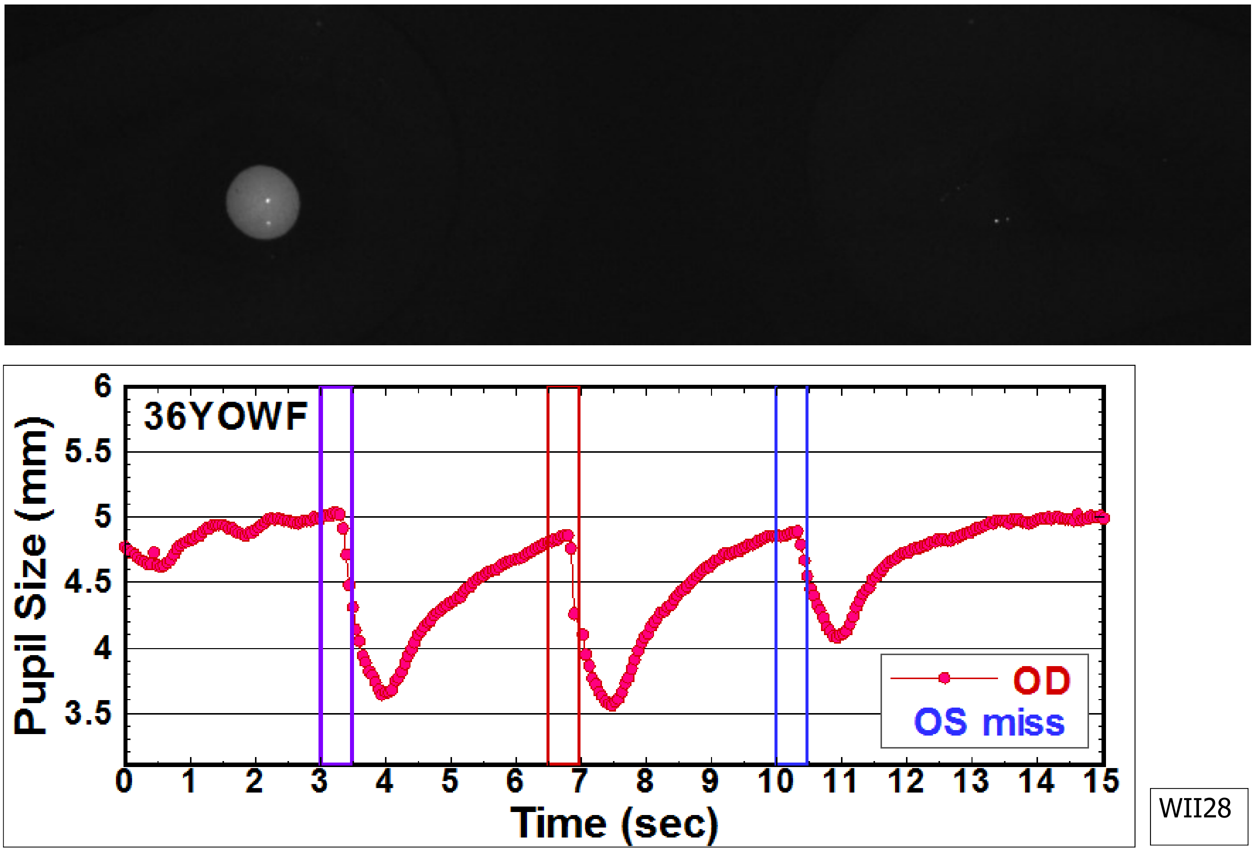

Figure 5. Pupillograms of a patient with +RAPD optical nerve damage

Figure 6 shows a case of anisocoria. The clinical record from the optometrist was P(5→4/4→3)IRL-APD. The infrared images in Figure 6 revealed the dark-adapted (upper image) and the illuminated and contracted (middle image) pupils. Both showed an apparent difference in size between two pupils. The pupilogram showed the magnitudes of photopic and scotopic anisocoria. The missing and scattered data points in pupillogram are caused when the 7-year-old young patient blinked and looked away from the screen.

Cover Test Result

Figures 7 to 9 show the cover-test results of a typical normal, a phoria, and an esotropia cases. The upper part of Figures 7 and 9 are the infrared images of the patients' pupils at the primary gaze where the corneal-reflections are approximately at the center of the pupils for normal cases. The displacement of corneal reflection provides an index of each eye's gazing angle (Hirschberg Method). When an eye rotates toward one side, the reflection moves toward the opposite direction. The X-Y plots in Figures 7 to 9 illustrate the binocular eye movement as the patient looked at the fixation target moving across the three viewing zones on the 3D

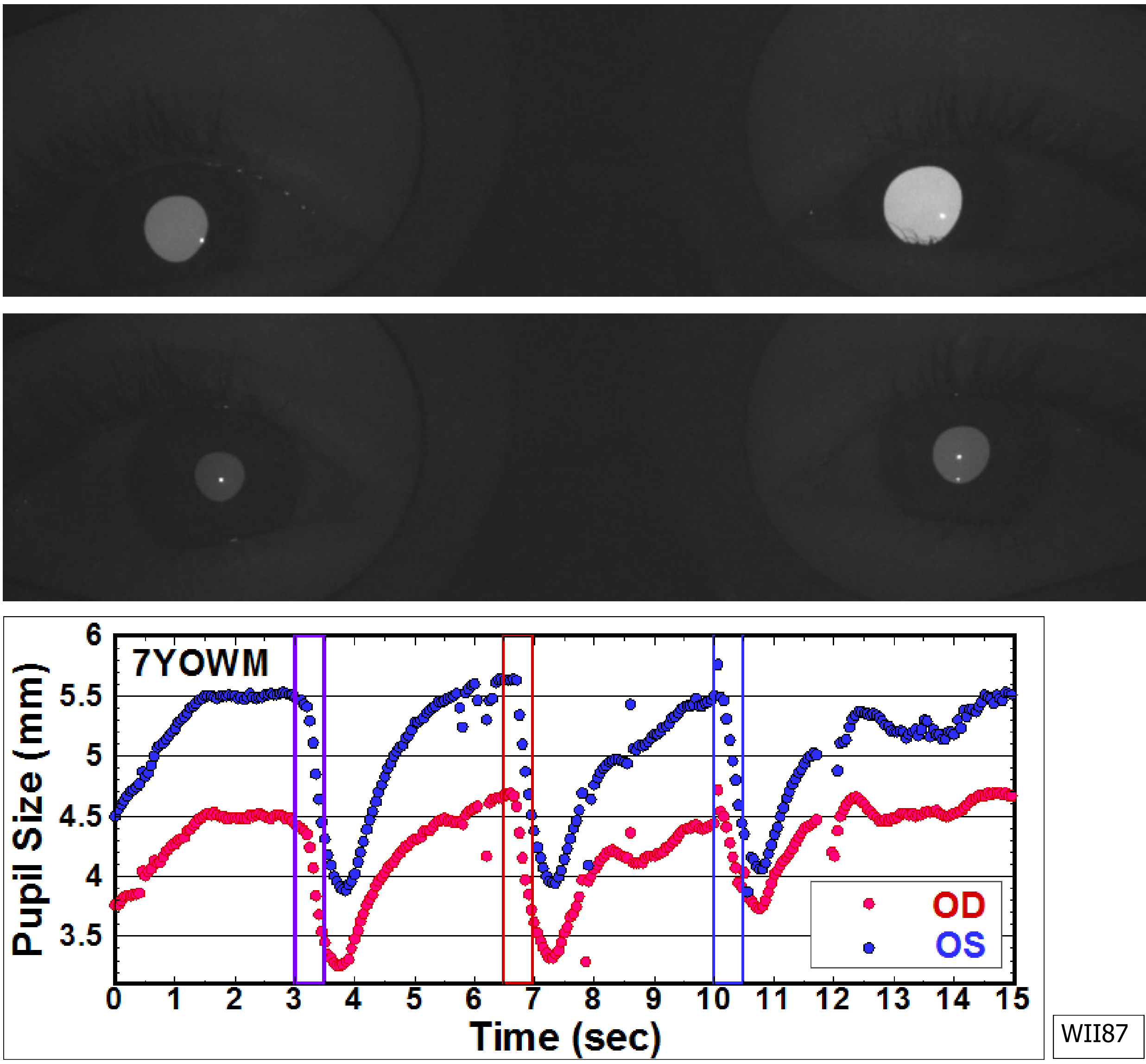

Figure 6. Pupillograms of a 7 years old boy with anisocoria

screen and return. The X-axis is the location of the angular fixation target. The Y-axis specifies the corneal reflection's displacement from the center of pupil. The negative and positive signs correspond to left- and right-gaze or the fixation target location to the viewer respectively. For clarity, the forward and reversed paths are presented separately in upper and lower plots. Arrows indicate moving direction of fixation target.

Figure 7 shows a typical result of the healthy normal eyes. The right- and left-eye data are specified in red and blue symbols, respectively. The slope and offset around the origin (x=0) indicate the individual eye's Hirschberg ratio (HR, ~22.5+/-0.3prism/mm for both eyes) and the fovea kappa angle (~10.5 +/-0.7) respectively.

Cover and uncover effects took place when the target moved across the boundaries between monocular and binocular viewing regions. These are indicated with small arrows in the plots. For the results of a typical normal case, both cover and uncover of either eyes' should not result to any significant re-alignment (deviation) from the track. Both eyes followed the target

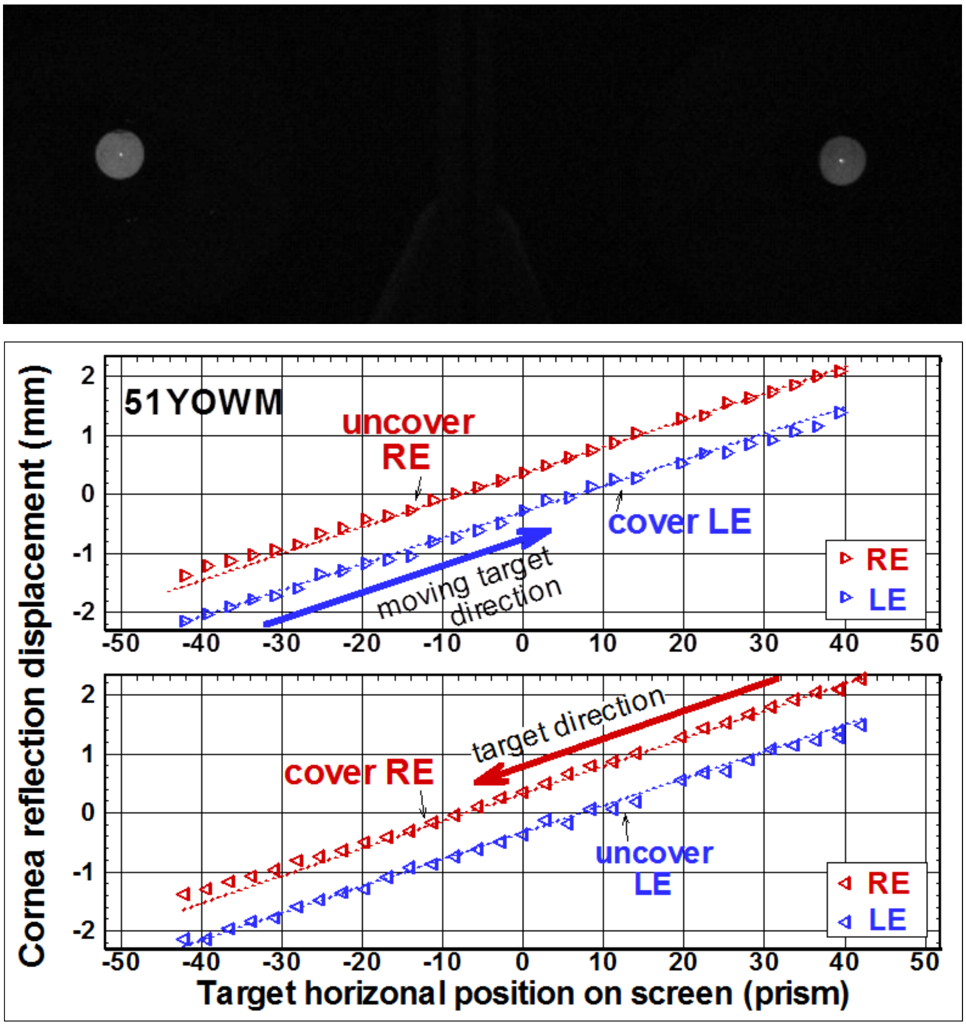

Figure 7 Cover test result of a normal case. Upper part shows the pupils images at the primary gaze. In the lower X-Y plots, RE and LE indicate data of the right eye (in red) and left eye (in blue) data. The fixation target was moving from left-to right on the upper X-Y plot, and from right-to left in the lower plot.

smoothly without being disturbed by the cover and uncover destructions.

Phoria is a deviation that occurs when fusional stimuli are absent. For binocular viewing, both eyes' foveas are aligned to the fixation target. When one eye is suddenly covered, the (relative) alignment is assumed appropriately by the covered eye. However, the eye will gradually relax and drift away from the initial projection. When a covered-eye was uncovered, this eye would quickly re-align (its fovea) to the visual stimulus to form motor fusion and reclaim binocular vision. Therefore, the uncover shifting is more noticeable than the cover drifting. Figure 8 shows a case of phoria. In the upper plot, the fixation target was presented on the left side of screen for only the left eye and started to move toward the boundary of the binocular zone in the center of screen. When passing the boundary, the covered right eye (in red) was uncovered and a quickly rotation of a few prisms of angle toward left (- sign) (to catch up with the target) was observed; meanwhile the left-eye (in blue) remained following without differing from the track. After passing the binocular viewing zone and entering the right-eye-viewing zone at about the12 prism location, the left eye was "covered". The now-covered left eye slowly drifted behind (gradually to the left; i.e. - sign). In the lower X-Y plot when the target started from right and moved to left, the same phenomenon was observed with the left- and right-eye alternated. For either eye, it slowly deviated from assumed trajectory when visual stimulus suddenly disappeared, and it quickly re-aligned when visual stimulus was resumed.

One thing to be addressed is that the clinic cover test is commonly performed for both near-fixation (~40cm) and distant- fixation. Since this particular experiment was performed only at a fixed distance of 50 cm, the demanded vergence for binocular viewing was equivalent to ~6 prisms of angle for eyes with inter-pupillary distance (IPD) of 6 cm. If the cover test was performed with a distant fixation, the degree of phoria is

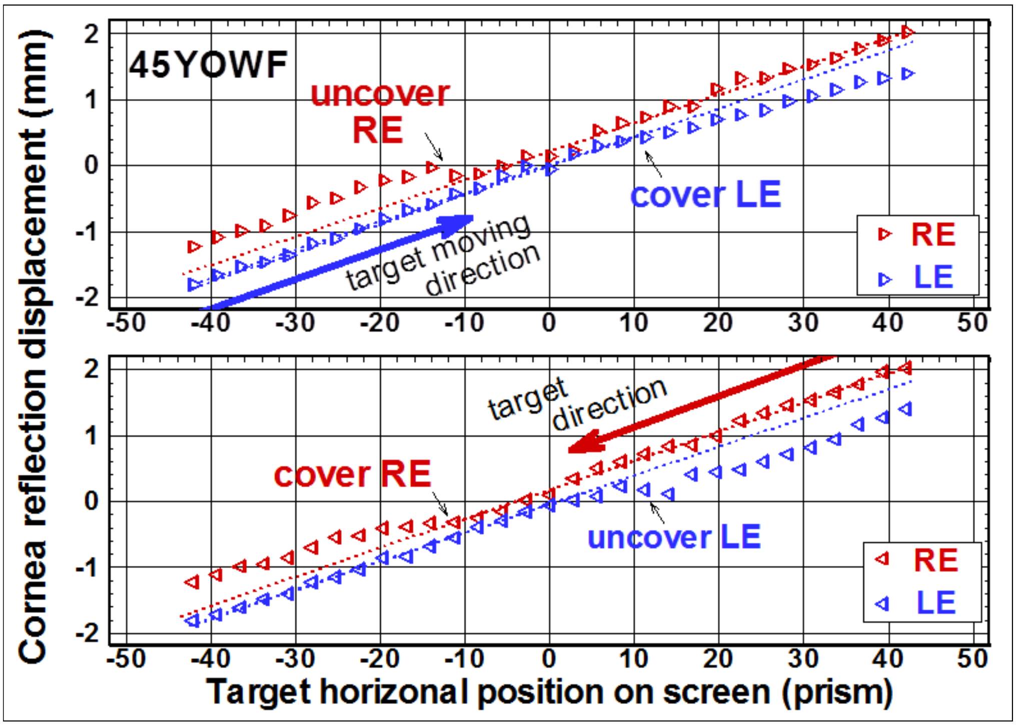

Figure 8 Eye alignment test result of a case of phoria. RE: right eye data; LE: left eye data. The fixation target was moving from left to right on the upper plot, from right to left in the lower plot.

likely reduced. Generally, if patient's binocular vision is not compromised, a small degree of phoria is still considered normal.

For a tropia, the binocular viewing motor fusion is not present. When a viewing target is presented to a tropia, only one eye is aligned to the target whether it is a right-eye, left-eye, or alternating between the two eyes. Figure 9 shows a case of a left esotropia (LET). The binocular image at the primary gaze has shown a large cornea reflection deviation on the left eye. In the X-Y plot, it is notable that the left-eye data (blue) exceed the right-eye data (red), indicating the left eye gaze direction deviated toward right. The primary gaze (cross symbols at x=0) also indicates the significant deviation from zero point (y=0). When the fixation target was presented from the left-side of the screen to the left eye (in blue symbols along the arrow), the right-eye (red) followed with a significant deviation toward the left. When the right eye was uncovered at around target location of -10 prisms, it immediately took charge for the viewing task. Then, as the left eye was covered at a location of approximately +10 prism location, the right eye continues to work, thereby indicating a dominant right eye. Only when this leading (good) eye is covered, would the problematic (left) eye be forced to take charge. The data also show that the eso-deviation (distance between red and blue symbols) was amplified at patient's the left-side viewing and decreased toward her right-side-viewing.

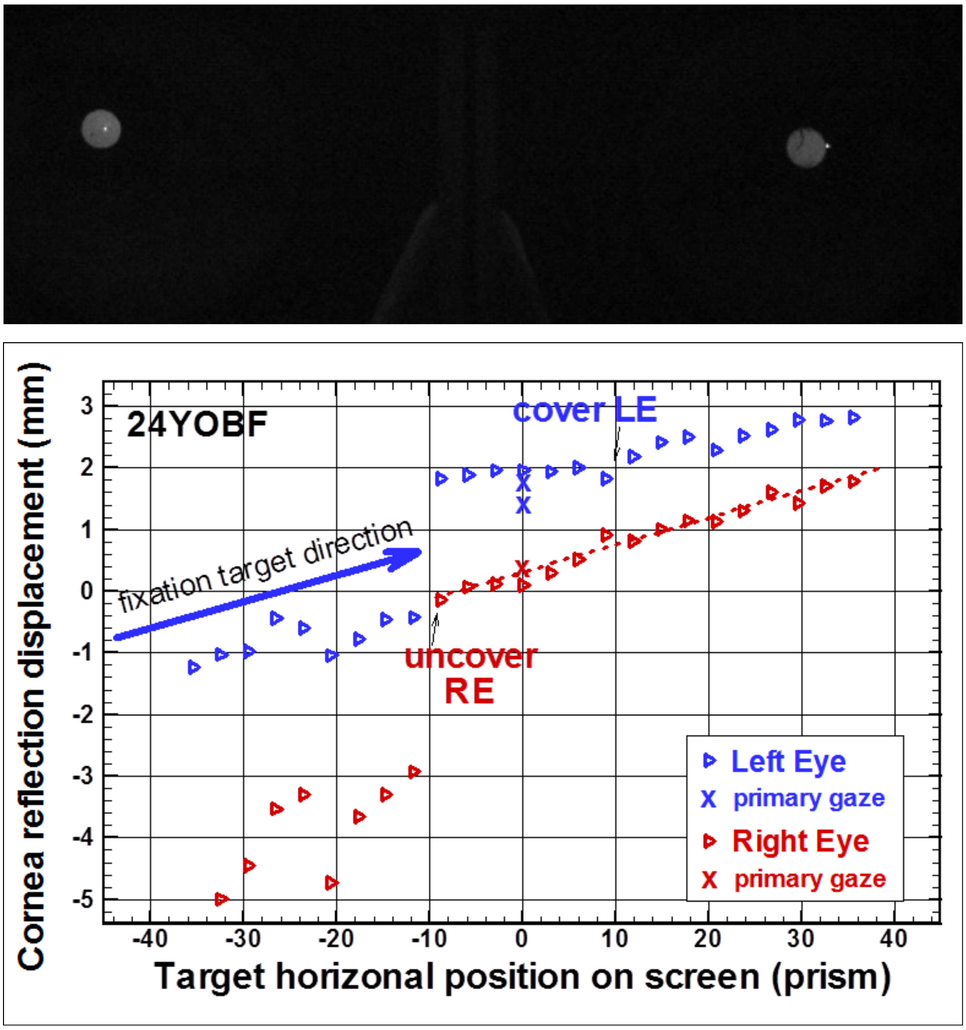

Figure 9. Eye alignment test result of a left eso-tropia (LET) case. Upper image is the infrared image at primary gaze. Lower image is the eye tracking data.

Summary

The ability of 3D technology to deliver independent binocular visual stimuli was investigated as a versatile clinical tool for evaluating binocular vision health. Of the large number of potential applications, three specific tests were conferred in this study.

We first examined the prospect of using the 3D images to relax hyperopia's accommodation so that the accurate refraction status can be assessed objectively without using sedation eye drops. Our result with a small number of subjects shows that stereoscopic images appeared to relax the accommodation in patients with hyperopia greater than 1 diopter. Though the result is promising, the experiment requires a larger number of participants with more extensive hyperopic range to gain more solid data. During a typical cartoon viewing, children are usually much engaged in the story, and their eyes follow the main character intensively. The refraction measurement could be performed multiple times to study the optimal stimulation to assess the maximal hyperopic refraction and reduce the error due to accommodation.

We also investigated the swinging-flashlight pupil-function test by delivering non-synchronous pulses of bright image to the eyes. We showed the pupillogram results of typical normal cases, an anisocoria case, and a case of +RAPD. The typical 3D TV screen was sufficient to provide proper illumination levels for pupil test, and the pupillogram result provided clear indication of the abnormalities. This demonstration showed the use of 3D display to obtain dynamic pupil response to light stimuli, which could also possibly be applied to the assessment of pain, alertness, study of pharmacodynamics, and psychiatry.

Lastly, the cover test was performed with an objective 3D moving-bull-eye-target. We demonstrated a new automatic method of cover-uncover test with the self-calibrated individual's HR and kappa angle. Results of the normal eyes, the phoria, and the tropia were compared.

There are many advantages in the 3D visual stimuli eye assessment. In additional to having a playful and close-to-natural viewing and testing atmosphere, the use of NIR video prevent the difficulty of observing patients directly in typically dimmed clinic room illumination. Digital results from such applications can be easily stored and evaluated by clinicians at convenient times in high resolution and slow motion if desired, which could reduce stress for both patient and clinician. Digital recording helps to improve quantitative assessment and therefore, diagnostic accuracy. Furthermore, digital data make automatic Computer Aided Diagnosis (CAD) possible to develop and allows establishing database and promoting advance in the Big Data era.

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