Eye tracking and game mechanics:

An evaluation of unmodified tablet computers for use in vision screening software for children

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Abstract

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Binocular vision issues are a primary cause of reading and writing difficulties among children, with as many at 25 percent of school-aged children needing vision therapy. Vision issues are a better predictor of academic success and quality of life than race or socioeconomic status. In spite of validated screening exams and vision therapy to address these issues, the vast majority of children are never examined, or if examined do not receive follow up care. Barriers to access include financial limitations, availability of qualified eye care professionals and child engagement in screening and therapy. Current screening and therapy methodologies are not scalable, but computer programs and mobile applications already deployed in medical and behavioral fields offer insight to the impact that new screening and therapy technologies could provide. However, potential negative effects from the prolonged used of tablet screens must also be considered. A study was conducted to evaluate the use of computer vision and machine learning algorithms to estimate user gaze when applied to video input from an unmodified tablet computer. Accurate gaze estimation would enable the development of tablet-based vision screening and therapy applications. Recommendations for future work are made based on the results of this study.

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Introduction

Comprehensive studies illustrate the negative relationship of poor vision to academic performance, literacy and quality of life. The diagnostic and treatment tools available are proven to be accurate and effective. They are not, however, affordable, accessible, or well known to most parents, educators, or even pediatricians. As such, the vast majority of children go unscreened for serious and easily treatable vision issues. When screenings are conducted, children in need of vision therapy are not likely to receive the treatment they need. (Zaba, 2011)

Vision screening and vision therapy have consistently high rates of improvement across a wide swath of studies. The issue is not that sufficient tools are unavailable, but that children do not have access to the tools, and there are not enough eye care professionals to provide comprehensive examinations and therapy to affected children. (Carvelho, Allison, Irving, & Herriot, 2008; Scheiman et al., 2008; Shin, Park, & Maples, 2011)

The goal of this thesis is to evaluate the feasibility of using touch-based games deployed on unmodified tablet computers to address the unmet need for visual screening and therapy in children around the world. The initial study evaluates the ability for computer vision algorithms to use the video input from an unmodified tablet computer to evaluate user gaze.

Chapter I - Rationale

The rationale for this thesis is grounded in practice and research from the fields of optometry, vision theory, game design, computer vision and machine learning. This chapter synthesizes concepts from these areas into a clear vision of purpose for this thesis. This chapter is organized into the following sections:

Vision and Literacy: This section illustrates the importance of vision to literacy and academic success. It details the specific aspects of vision that are most impactful.

Vision screening and therapy: This section outlines the rates, successes and failures of vision screening and therapy.

Barriers to screening and therapy: This section details the barriers to access to vision screening and therapy games.

Vision screening and therapy tools: This section outlines the current tools and software used for vision screening and therapy, including the benefits and drawbacks with each type of tool.

Game-based screening and therapy tools: This section details the benefits of incorporating the theories of gamification into screening and therapy regimens, including positive effects on compliance and long term outcomes.

Mobile applications in screening and therapy use: This section details the success of mobile apps in screening and therapy in a variety of healthcare uses, as well as initial studies with mobile apps in the vision space. It includes limitations of the current offerings.

Use of machine learning in eye tracking: This section details research on the use of machine learning algorithms on tablet computers for eye tracking, including limitations with these studies.

Mobile hardware and software advances: This section details how advances in tablet hardware and software warrant the exploration of development of more powerful and flexible tablet-based vision screening and therapy tools.

Vision and Literacy

While it seems intuitive that vision plays a critical role in reading and writing, vision is paid little mind when a child's literacy skills fall behind. Literacy education typically focuses on practicing letter and sound recognition, rote memorization of common words, or phonemic awareness. Engaging with students who pass distance acuity tests (the only vision test mandated in most schools) and yet still struggle with reading and writing is puzzling and frustrating to teachers and parents alike. Increasing numbers of studies show visual factors are a primary cause of beginning reading failure and current school screenings are inadequate in scope and vigor. (Young, Collier-Gary, & Schwing, 1994)

Visual factors are more significant predictors of academic success as measured by the standardized Iowa Test of Basic Skills (ITBS) than race or socio-economic standing. (Maples, 2003) The most significant visual factors are related to binocular vision, such as tracking and teaming. Tracking refers to the fine eye movements required to follow a line of print. Tracking requires both central vision and peripheral vision to be well developed. Teaming is the term for eyes independently following the same object – like text on a page – which allows the brain to merge the inputs received by each eye into a single, coherent image. Another example of teaming is what happens as objects move nearer or farther from the observer; the eyes point inward as the object gets closer in order to maintain focus, which is why your eyes cross if you look at the tip of your nose. If the input from one eye is consistently weaker, the brain may begin to ignore it, resulting in amblyopia. If untreated, amblyopia can result in the brain entirely ignoring the input from one eye, resulting in single-eye blindness even when the eye is structurally sound.(Hunter, 2013)

One particular type of teaming issue, convergence insufficiency, is directly linked to reading problems. (Simons & Grisham, 1987) Convergence insufficiency is diagnosed as the inability to converge on a point, or to sustain convergence. Symptoms of convergence insufficiency include double vision, blurred vision, headaches when performing near work such as reading, and difficulty concentrating. (Scheiman et al., 2008) Convergence insufficiency is known to affect approximately 7% of the general population. (Daftari, Alvarez, Chua, DeMarco, & Ciuffreda, 2003) Based on the number of children counted in the 2010 United States Census results, convergence insufficiency could affect roughly 5,100,000 children in the United States. (Howden & Meyer, 2011)

Undiagnosed and untreated visual impairments have significant impacts on the social and academic well-being of children. Several research studies compare the rate of visual impairment to juvenile delinquency and academic failure in school children. In one study, 46% of students in the Youth ChalleNGe program for high school dropouts were found to have a previously undetected vision problem. (Bleything, 2008) With proper eye examinations in early childhood, treatment of these vision problems may have drastically changed the academic future of students now failing out of high school.

In a 1999 study, which compared the results of adjudicated adolescents given the New York State Optometric Association (NYSOA) Vision Screening Battery and the Developmental Eye Movement (DEM) Test with that of a control group of New York University graduate students, found significant differences between the test results for the two groups. 74% of juvenile offenders failed at least one vision test, with the surprising conclusion that 25% of the academic difference between the two groups could be explained by failures on tracking and convergence tests alone. (Zaba & Johnson, 1999) While reasons this failure on tracking tests could account for so much of the difference are purely conjecture, the relationship itself is statistically significant and troubling.

Vision Screening and Therapy

Comprehensive eye examinations by eye care professionals are designed to test a full range of visual health measures, such as distance acuity, near acuity, eye health, eye tracking, eye teaming, and many others. While all children should undergo several comprehensive eye examinations during early childhood and school years, the availability and access to examinations make this impractical for many children. Vision screenings are less comprehensive tools intended to identify students that may have vision issues, who should be seen by an eye care professional for a comprehensive eye examination as soon as possible. Should the examination reveal issues with eye tracking or teaming, vision therapy may be prescribed by the eye care professional as a means of treatment.

Vision therapy is a specialized treatment provided by developmental optometrists. Most therapy takes place in the optometrist's office, but occasionally, at-home exercises are added as a supplement. Vision therapy methods differ by practice, but include games and exercises designed to encourage and support proper eye movement and coordination. Examples include focusing on objects as they move near or far from the student's face, quickly discerning numbers in the field of vision, or using red-blue glasses to practice stereo vision on a video screen. While much debate exists in the fields of ophthalmology and optometry considering vision therapy, many studies show it is an effective means of treatment for binocular vision issues. (Shin et al., 2011)

Screening and therapy rates

The World Health Organization's Vision 2020 initiative aims to eliminate preventable blindness by the year 2020.("WHO | What is Vision 2020?," 2014) Despite this initiative, globally speaking, there is no coherent vision screening or therapy program in place. A recently conducted survey of member countries of the International Orthoptic Association revealed 89% of respondent countries have pediatric vision screening programs. However, only 56% are funded by the government and only 28% are obligatory in nature. The types of screening tests used, the setting for testing, and the referral criteria for each test vary widely by country. (Matta & Silbert, 2012) The only consistent finding is that not enough children are being screened in any of the respondent countries.

The lack of proper screening is by no means limited to third-world or undeveloped nations. A three-year study conducted in Canada found that over 10% of preschool children screened had significant vision problems that had been previously undiagnosed. The researchers were surprised by these findings; given Canada is a country with government-subsidized vision care that includes comprehensive eye examinations. (Robinson, Bobier, Martin, & Bryant, 1999) In countries without a single-payer health care system the screening rates are much lower.

Within the United States, comprehensive eye examinations are the exception, rather than the norm. Only 5 out of 50 states have adopted policies that require eye examinations for pre-school and school-aged children. State-wide comprehensive vision exams in Kentucky, as mandated by recent legislation, resulted in prescriptions for corrective lenses for 14% of pre-school aged children screened. (Donahue, 2010) Without the state mandate, it is likely these children would have remained unscreened and suffered the academic consequences of vision issues through no fault of their own. It is clear from the results of these screening programs that current vision screenings are insufficient to properly detect visual impairment in children.

Increased screenings are particularly necessary for underserved and vulnerable populations, such as urban minority youth, rural youth, and Native populations. A recent study conducted in low-income populations in Boston found 37.4% of children screened had significant vision issues, either in visual acuity or stereopsis. (Register, 2010) Native American populations have been shown to have significantly higher rates of visual impairment that the general population of the United States, with a substantial impact on quality of life. (Mansberger et al., 2005; McClure, Choi, Becker, Cioffi, & Mansberger, 2009)

Efficacy of screening and therapy programs

Vision therapy has been employed in lower income schools to effectively increase the academic performance of students. A study done at the Mather School in inner city Boston, MA showed promising results for an in-school vision therapy approach. (Orfield, Basa, & Yun, 2001)

Treatment of amblyopia and convergence insufficiency show great success in ameliorating the symptoms of both conditions. Treatment often results in children not requiring glasses or accommodative technologies that they would otherwise have required as adults. Treatment for amblyopia is far less effective at ages 7 and older; supporting the recommendation that screening by age 5 is preferable as time is allowed for treatment to be effective. (Mathers, Keyes, & Wright, 2010) In addition to the effectiveness of treatment for amblyopia, treatment is also extremely cost-effective. (Donahue & Ruben, 2011)

Comprehensive amblyopia screening in young children (aged 1-2.5) years reduced the incidence of amblyopia at 8 years of age from 2.5% in a control group to 1% in the screening group (P = .0098). (Eibschitz-Tsimhoni, Friedman, Naor, Eibschitz, & Friedman, 2000) Additional studies show screening of preschool aged children (aged 3-4 years) resulted in a 45% reduction of amblyopia at age 7.5 years in the screened population when compared to a control population. (Mathers et al., 2010)

Treatment of convergence insufficiency has success rates higher than that of amblyopia, with 73% of children receiving in-office vision therapy for convergence insufficiency showing an improved outcome after only 12 weeks of treatment. (Scheiman et al., 2008) Given the success of in-office vision therapy and lack of availability of this level of therapy for most children, it follows that finding a way to extend vision therapy outside the office across a wide population and area would be of great benefit.

Literature review of vision screening methods

An electronic search of peer-reviewed journals was conducted using University of Washington library resources. The UW Worldcat catalog, IEEE Explore catalog, and Google Scholar were searched for broad terms intended to provide a large pool of initial articles from which to select relevant candidates. The UW Worldcat results were intentionally limited to peer-reviewed articles. Figure 1 lists the number of articles returned by each search.

Search term	**IEEE Explore**	**UW Worldcat**	**Google Scholar**
Vision screening	875	12278	640000
Preschool vision	8	6879	74300
Amblyopia	29	8297	45900
Convergence Insufficiency	31	740	19500

FIGURE 1 - JOURNAL SEARCH RESULTS BY SEARCH TERM AND SOURCE

For articles pertaining to screening tests, only articles meeting the following requirements were included in the literature review:

1. Specificity and sensitivity for the screening calculated in the study, or sufficient information provided to calculate specificity and sensitivity
2. Use of a gold standard[1] examination to evaluate the effectiveness of the screening tool
3. Age of screening participants of 0 to 10 years.

[1] "Gold standard" refers to an examination that has been validated and is recommended for use by optometric or ophthalmologic associations such as the American Association for Pediatric Ophthalmology or the American Academy of Optometry

4. Preference was given to studies that evaluated the effectiveness of nurse or lay-screeners.

Articles included in the reference sections of those selected for inclusion were also examined.

Additional screening guidelines from the following academic bodies were considered: American Academy of Pediatrics, American Academy of Ophthalmology, American Association for Pediatric Ophthalmology and Strabismus, and the United States Preventative Task Force.

Research studies are available for a wide variety of screening methods. However, the study designs, referral criteria, and analysis methods provide a landscape of results too disparate for direct comparison. Conclusions can be drawn regarding the types of screening and performance of tests in general. Performance of screening tests was dependent on the age of the child being screened. Researchers were unable to determine if this variance should be attributed to the difficulty in screening children or the development of visual systems over time. (Schmucker et al., 2009)

Optotype screening tools

The familiar Snellen chart, used by optometrists and physicians since the American Civil War, is the most famous example of an optotype chart. Patients are positioned at a predetermined distance from the chart and asked to read lines of optotypes (in this case Roman letters) in rows of decreasing size. The smallest row that can be read by the patient determines their distance acuity. However, 53% of children diagnosed with amblyopia had normal visual acuity, suggesting binocular distance visual acuity alone is not a sufficient screen for amblyopia. In this same study, no evidence was found to suggest early screening led to a larger number of incorrect referrals. (Hu, Starling, Baynham, Wager, & Shun-Shin, 2012) A study that evaluated the accuracy of optotype tests results by nurses found the results vary greatly depending on the experience of the test proctor and age of the patient. (Ore, Tamir, Stein, & Cohen-Dar, 2009)

Studies show optotype tests with symbols, rather than letters, can be more effective with children aged 3 to 5 years. The Vision in Preschoolers study found that nurses and lay persons achieved higher sensitivity on average with the Linear Lea Symbols test at 10ft, while lay screeners achieved strikingly higher sensitivity with the Single Lea Symbols test at 5ft. Researchers posit these differences may be explained by the closer distance making children more comfortable during the screenings or the single presentation of optotypes allowing children to focus better on the task at hand. (The Vision in Preschoolers Study Group, 2005)

Stereopsis screening tools

Stereopsis screening tools are designed to measure a patient's ability to perceive in stereo, that is, their 3D vision. Most stereopsis tests make use of specially designed goggles, either red-blue or polarized, to isolate the eyes for evaluation, or test the ability of the eyes to work in concert. While wearing the goggles, patients are presented with images designed to appear 3D for normal eyes and asked to complete tasks involving the images. Their success is measured as the indicator of the ability of the eyes to coordinate vision.

In the Vision in Preschoolers Study, Random dot E tests and Stereo Smile II tests had sensitivities of 42% and 44% respectively, and were significantly lower than the sensitivities of all other tests studied (P = 0.0001), including Non-Cyclopegic Retinoscopy – a universally acknowledged gold standard examination – autorefractors and the Lea Symbols optotypes test. (The Vision in Preschoolers Study Group, 2004)

Random dot E tests have been shown to be less effective than visual acuity tests, to the extent that including Random dot E tests together with visual acuity tests reduces the effectiveness of the visual acuity test. (Schmidt et al., 2006) The low sensitivity of these two stereopsis screening tools makes them poor candidates for emulation in future screening programs.

Photoscreeners

Photoscreening devices capture a photograph of the patient's eyes while an off-axis flash is used. The resulting images show the flash reflected in the eyes and can be used to identify refractive errors, strabismus, and amblyopia. Photoscreening results are variable depending on the grader evaluating these images. In one study, no one grader achieved more than 70% sensitivity and specificity. (Tong et al., 1998)

The first commercially available photoscreener was the MTI photoscreener, developed by Dr. Howard Freedman of Redmond, Washington. The MTI photoscreener is a camera using instant film, much like a Polaroid camera, that contains 2 images taken with an off-axis flash that rotates 90 degrees between photos. The instant film on which the Photoscreener relies is increasingly rare, and a lack of supply may result in the obsolescence of this screening tool. The resulting photos must be analyzed by an expert for refractive error and conditions which lead to amblyopia. The MTI Photoscreener has been found to have 83% sensitivity and 68% specificity, though both may be improved by additional training of photo evaluators. (Berry et al., 2001) A subsequent study found a sensitivity and specificity of 81%. (D. I. Silbert, Arnold, & Matta, 2013)

Digital screening tools

Digital screening tools have evolved to replace or supplement traditional eye examinations in the last three decades. The eyes are observed or recorded during testing to clinically evaluate abnormalities of eye structure, motion and coordination. To understand how these tools work, and whether they can be translated into software-based tools, a survey of research on current tools was conducted. See Table 1 for the details of this search.

Digital photoscreeners have been developed to decouple photoscreening from instant film requirements and decrease the time needed for examination of the captured photos. Photo examination methods differ between the various available photoscreeners. (Committee on Practice and Ambulatory Medicine and Section on Ophthalmology, 2002)

The iScreen photoscreener is a handheld camera unit that uses LEDs to ensure the camera is at the optimal distance to capture accurate images. The images are uploaded directly to iScreen Vision Central Analysis to be examined by trained technicians. The results are stored in an internal database for future reference. iScreen records meet HIPAA requirements.("iScreen Vision," 2010) iScreen has a sensitivity of 87% and a specificity of 76%, on par with the MTI Photoscreener. (D. I. Silbert et al., 2013)

The PlusOptix Vision Screener captures a digital image of the patient's eyes and evaluates the image in situ with an integrated interpretation program. The results are stored in an internal database that can be used to print reports or import results to the physician's Electronic Medical Records system. ("PlusOptix," 2013) Initial studies of the PlusOptix Vision Screener found sensitivity of only 42%, (Dahlmann-Noor et al., 2009), but improvements made to subsequent versions are promising. The PlusOptix S04 Vision Screener has a sensitivity of 95%, but specificity of only 50%, meaning half of referrals will be false positives. (Ugurbas, Alpay, Tutar, Sagdik, & Ugurbas, 2011)

Autorefractors

The Welch Allyn SureSight Vision Screener is a handheld autorefractor. It uses wavefront analysis of each eye to calculate the interocular difference in spherical and cylindrical refractive error. A significant interocular difference indicates the presence of amblyopia. Autorefractors, like photoscreeners, cannot be used to evaluate convergence insufficiency.

The state of Tennessee provides state-wide vision screening for children aged 1 to 5 years old, sponsored by the Tennessee Lions Club. The program is transitioning from use of the MTI

Photoscreener to the Welch Allyn SureSight Vision Screener. Between October 2004 and September 2007, more than 200,000 children were screened, with more than 15,000 screens performed using the Welch Allyn SureSight Vision Screener.

Of the 15,749 children screened with the Welch Allyn Suresight Vision Screener, 1,154 children were referred for additional screening by an optometrist. 553 children received a gold standard examination and 64 were found to have amblyopia. The estimates of refractive error provided by the Welch Allyn Suresight Vision Screener loosely correlated with those found in a formal eye examination, with r^2 values of 0.25 for spherical refractive errors and 0.37 for cylindrical refractive errors. (Silverstein, Lorenz, Emmons, & Donahue, 2009) The false-positive rate for screenings in this study was over 80%, far beyond the 10% false-positive rate considered acceptable by family practice physicians surveyed regarding adoption of preschool age vision screenings in general practice. (Kemper & Clark, 2006)

Additional studies evaluating the Welch Allyn SureSight Vision Screener have echoed these findings, finding the low sensitivity and high false positives in screening results make this tool an insufficient substitute for a comprehensive eye examination. (Vricella, FitzGerald, & Krumholtz, 2002) Though adjustments made by researchers to the software referral criteria increased the sensitivity and decreased false-positives, the end results were not comparable to formal eye examination results. (Rowatt, 2007)

Convergence Insufficiency Screening

The primary scientifically validated method to diagnose convergence insufficiency is use of the Convergence Insufficiency Symptom Survey. (Rouse et al., 2009) The survey consists of a set questions asked of the patient, that pertain to the symptoms of convergence insufficiency, such as “Do your eyes ever hurt when reading or doing close work?” Each question is answered on a 5-step ordinal scale from 'Never' to 'Always'. A score of 16 or greater on the survey results in a diagnosis of convergence insufficiency. (Borsting et al., 2003) While statistically validated, this survey requires a self-awareness that is not typically present in young children, making it more suitable for older children and adults.

Barriers to screening and therapy

Despite the prevalence of binocular vision issues across a broad swath of children, and the existence of validated screening and therapy tools, the vast majority of children are not screened or treated. The barriers to treatment are many, including lack of access to care, financial limitations, educational shortcomings among parents and professionals, and political differences within concerned fields.

Figure 2 lists the most common barriers to vision screening for preschoolers, as determined from a study conducted with family physicians in the United States.

Barrier	**% of respondents**
Children are not cooperative with screening	39
Lack of insurance for follow-up care	25
Screening is too time-consuming	21
Lack of training	19
Lack of eye care providers	17
Lack of specificity	13
Lack of sensitivity	9
Concern about parental reaction to false-positive rate	5

Figure 2 – Barriers to vision screening by family physicians (Kemper & Clark, 2006)

A lack of insurance for follow-up care is the second most prevalent barrier, right after the lack of cooperation from young children during screenings. Infants as young as five months display pursuit and saccade tracking patterns that are approximate to those of adults(Von Hofsten & Rosander, 1997), but keeping them engaged long enough to evaluate binocular vision is a challenge. While this thesis does not directly address the issue of child cooperation, games and apps developed based on the results of this thesis will hopefully engage the interest of young children and increase their compliance with screening and long term therapy.

In addition to the cost of follow-up care, the cost of the equipment to conduct the initial screening can be prohibitive in many communities. The American Academy of Pediatrics lists the highest barrier for the use of photoscreeners and autorefractors is the high initial cost of the hardware, accessories, supplies and time needed to train staff. (Miller & Lessin, 2012)

When the equipment needed and insurance are both available, a child must still be recognized as at risk for binocular vision issues and referred to a professional for care. Stakeholder interviews with educators, optometrists, ophthalmologists, family practice physicians, and children's welfare advocates revealed that none of these professionals had been taught the gravity of binocular vision issues, how to detect them, or what to do if they are detected during their professional educations. Without professional knowledge of binocular vision issues, it is a safe bet parents are not being informed or counseled in how to approach their child's wellbeing in this area.

Support for the development of a tablet-based vision screening and therapy game

Studies show that nurse and lay-screeners can be as effective as optometrist and ophthalmologists when provided with proper tools and training. (Robinson et al., 1999; The Vision in Preschoolers Study Group, 2005) Laypersons can effectively screen for visual defected with the assistance of computer-based screening programs. (Briscoe, 1998) By directing development of screening tools toward use by a variety of proctors, including optometrists, nurses and lay screeners, the population of children that can be reached increases dramatically.

Photoscreening can be done with any camera or video system that can capture images and interpret the same. A computer could be used to capture and interpret results at once, perhaps reducing the variable nature of result interpretation currently seen with human graders. (Committee on Practice and Ambulatory Medicine and Section on Ophthalmology, 2002)

Monocular optotype visual acuity testing is the most reliable test for amblyopia (when defined as an interocular difference of two or more lines on an optotype chart), with single, crowded symbolic optotypes being particularly effective. (Hartmann et al., 2000) Optotypes can be adapted for inclusion in a software-based tool. A study comparing the results of a traditional optotype chart and a computerized version found that the computer-based screening increased the efficiency and sensitivity of screening, suggesting computer-based optotype screening could simultaneously reach more children and provide more accurate results. (Schlenker, Christakis, & Braga-Mele, 2010)

Photoscreeners and autorefractors have the potential to reduce testing times and screen directly for amblyopia. In both cases, the primary source of variability in results, sensitivity and specificity is the experience of the test proctor. (Schmidt et al., 2006) Computerizing the photo capture and results analysis may eliminate this variability.

Game-based screening and therapy tools

Game-based vision and screening and therapy tools have been developed to increase patient compliance and motivation. Thus far the games developed have had varied rates of efficacy as screening tools and improvements of vision issues when used for therapy.

EyeSpy 20/20 is a software program designed to screen for visual acuity and stereopsis in children ages 4 and up. The software combines optotype screening (using the optotypes R, S, Z and K) and stereopsis screening using red-blue dissociative glasses. Students are asked to play a set of games lasting 3-5 minutes, the results of which are stored in a school specific database and used to refer students for examinations by licensed eye care professionals. ("Vision Quest 20/20," 2013) EyeSpy 20/20 can be installed on any Windows laptop or desktop computer, and requires the use of a set of red-blue dissociative glasses and extended mouse with a ten foot cable. Children are seated at a specified distance from the computer monitor during testing.

A 2009 study compared the results obtained from EyeSpy 20/20 with those of professional eye examination by a pediatric ophthalmologist. The study found that screening results from EyeSpy 20/20 when a patch was used to isolate eyes were not significantly different from those of the pediatric ophthalmologist (P=0.508). However, when the red-blue dissociative glasses were used, the EyeSpy 20/20 results we significantly different from those of pediatric ophthalmologist (P=0.035). EyeSpy 20/20 has the potential to be an effective screening tool, but further development is required to reduce the rate of false positives. (Trivedi, Wilson, Peterseim, Cole, & Teed, 2010)

Researchers in Italy have proposed a video-game based therapy to treat amblyopia using the contrast method. The contrast method of amblyopia therapy involves presenting a high-contrast image to the amblyopic eye and a degraded image to the non-amblyopic eye in order to stimulate the amblyopic eye. (Vitali, Facoetti, & Gargantini, 2013) The game is rendered using a desktop computer with a graphics card that supports 3D rendering and glasses that restrict the vision of each eye at high frame rates to isolate the input of each eye simultaneously. This approach eliminates the possible damage to sight in the non-amblyopic eye that is otherwise introduced in therapy based on suppression of the non-amblyopic eye.

Joint therapy for strabismus and amblyopia has been proposed by researchers in Poland, using a desktop computer and a set of red-green anaglyph glasses to achieve stereoscopic effects. (Kosikowski & Czyzewski, 2009) The user is presented with a screen that contains a red cross-hair image and green cross-hair image, which the user attempts to merge into a single image.

A 3D version of Pacman was developed to treat convergence insufficiency. This program makes use of a custom-built mirror stereoscope to direct different input to each eye. (Carvelho et al., 2008) A diagram of the mirror stereoscope used can be seen below in Figure 3.

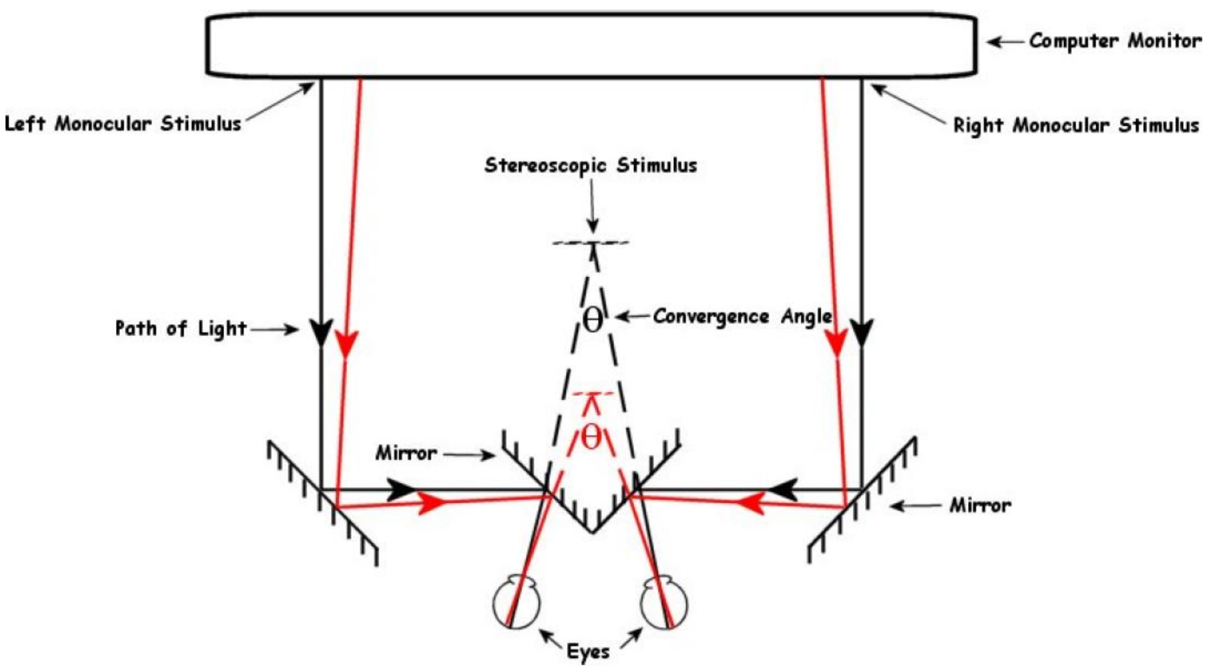


FIGURE 3 - MIRROR STEREOSCOPE (Carvelho et al., 2008)

Game mechanics require both eyes to be used in order to successfully complete in-game tasks, such as the collection of points and power pellets. Surveys of the participants show video games as vision therapy tools were more enjoyable and motivating than traditional vision therapy, inspiring high compliance rates.

Viston-VR™ is a virtual reality game developed to treat amblyopia by presenting the amblyopic eye with a more detailed and dynamic version of the image presented to the normal eye. The player observes 3d stereoscopic images, but the amblyopic eye is forced to do more work than the normal eye, resulting in a significant improvement of vision in the amblyopic eye.(Qiu, Wang, Liu, & Yu, 2007)

Lazy Eye Shooter is a modification developed for Unreal Tournament 2004, a popular first person shooter based on the Unreal Engine. Lazy Eye Shooter modifies the original game play to include separate video feeds for each eye. The video feed for the normal eye is degraded, while the feed to the amblyopic eye is bright and includes additional items necessary for gameplay. In the initial pilot study, all participants experience improved vision. (Bayliss, Vedamurthy, Bavelier, Nahum, & Levi, 2012) The first-person-shooter content of Unreal Tournament makes this particular game inappropriate for use with school aged children, but the concept behind the programming is certainly extensible to other subject areas. As with other programs that rely on additional equipment, the game requires the use of a stereoscope or video glasses to separate the input to each eye.

Researchers coupled a computer simulation of a traditional eye treatment method – involving red light flashes and rotating fields of black and white stripes – with a patient monitoring system in a hospital in China. (Qiu, Wang, Liu, & Li, 2007) The doctors had access to ongoing progress reports of each patient and the ability to alter therapy regimens dynamically to account for patient progress. With the treatment and monitoring in place, patients' vision improved dramatically.

Even though the studies above all describe successful vision therapy games, they also all require special hardware. Required hardware ranges from custom-built mirror stereoscopes to expensive video displays to heavy video glasses. Work has been done developing games that use lighter, more comfortable NVIDIA 3D glasses, but even these cost $140 and the games will not function without them. (Gargantini, Bana, & Fabiani, 2011) Games have not yet been developed that will be truly affordable for underserved populations.

Mobile application developed for vision screening and therapy

Several apps have been developed for the mobile space that are intended for use in vision screening and therapy as well. A mobile app designed to treat amblyopia showed significant improvement after a brief pilot study. (To et al., 2011) Researchers used a lenticular screen placed over the LED display of an Apple iPod Touch to send different images to each eye of the patient playing the game. Using a simple Tetris-like game, with blocks presented to different (or both) eyes, patients demonstrated significant improvement in both acuity in the amblyopic eye and stereoscopic depth perception. Several patients were no longer considered amblyopic after the pilot study was finished. While this study required patients to rest their chins on a fixed chin rest to mitigate the effect of patient movement on the accuracy of the lenticular display, the researchers posit the front facing camera available on mobile devices could be used to calculate the position of the patient's face and eyes, using this information to calibrate the image during gameplay to account for changes in distance and angle inherent in using mobile devices outside a laboratory setting.

The Portable Eye Examination Kit, or PEEK, is a program that runs on a smartphone, with the addition of a special phone case that contains a lens which sits over the phone's rear facing camera. Using this lens, proctors in the field can view inside a patient's eye, evaluating them for signs of glaucoma or preventable blindness. Tests are ongoing in Kenya and Guatemala, with promising initial results. PEEK also includes simple distance acuity testing, in the form of a Tumbling E optotype test. Use of the Tumbling E test means that patients do not need to be literate in order to undergo the screening, as it only requires they point in the same direction as the legs of the capital letter E presented on the screen. The proctor then swipes the screen in the direction the patient points to bring up the next optotype. Several other modules for PEEK are under development now, including an exploration of how to measure binocular vision using a smartphone. (Peekvision.org, 2014)

Use of computer vision in eye tracking

For a study on using eye movements to direct actions on a tablet screen, two neural networks were coupled together in an attempt to convert a user's eye movements into interface actions on a tablet computer. The first neural network used the input from the camera to isolation eye position, and the second – the real-time eye movement interaction protocol (REMI) – used the output of the first neural network to translate the information into an action for the interface. A visible light spectrum camera was used for this study, set on an easel at a fixed distance from the participant. (Holland & Komogortsev, 2012) A usability study conducted on similar neural network software found that in order to achieve results with accuracy comparable to commercially available eye tracking solutions, the neural network training time required would be long enough to induce user fatigue. (Holland, Garza, Kurtova, Cruz, & Komogortsev, 2013)

Another program employed Haar classifiers to isolate the eyes and iris within images before feeding the results into a single neural network to estimate gaze. The final gaze estimates were accurate to within 4°, but with several important caveats.

- Users were not permitted to wear glasses, or to move their heads in any direction.
- Gaze estimation was accurate for one particular quadrant of the screen.
- At least one minute of training time per user was required to get baseline accuracy for gaze detection, and if the light source or user moved in such a way that the reflection in the pupil moved retraining was required.

The authors suggested longer training times, or pre-training with a large dataset of possible eye appearances may mitigate the retraining requirement. Noise contained in the visual input from the web camera was suggested as the potential cause for inaccurate gaze detection when users moved or looked at different quadrants of the screen. (Sewell & Komogortsev, 2010)

The Eye Gaze Tracker device uses two infrared cameras to isolate a user's pupils. (Mimica & Morimoto, 2003) The first is positioned on the central axis of the device, causing a bright reflection in the pupil that is customarily used by gaze tracking software. The second is positioned off axis, resulting in an image with pupil reflection. Computer vision algorithms are used to subtract the dark image from the bright image, and then select the largest possible remainder as the pupil. During calibration, the user is asked to focus on fixed points on a screen, allowing the program to train its results accurately for the given user, based on the light and dark images. The calculations themselves are robust to different users (after calibration) but are still bound by the user holding still during testing, there is no tolerance of user movement.

Kim and Ramakrishna take a novel approach of using the mathematical definition for the center of an ellipse (in this case the iris of the human eye) to determine the center of the pupil. Working in a culture with predominantly dark irises, which are often difficult to distinguish from black pupils, and eyelids that can obscure much of the iris, they adapted computer vision algorithms to use this Longest Line Scanning method. (Ramakrishna, 1999) The authors demonstrated computer vision algorithms could reliably estimate the users' gaze in fixed lighting conditions and with limited head movement, but recommend the testing of software in varied environments and with users that span expected variations in eye characteristics.

Computer vision and machine learning techniques can be used to robustly track pupils outside the normal circular shape due to the angle of the face or camera. A dark-pupil image – which is captured using an infrared camera – goes through several layers of processing. The pupil region is determined using Haar-like classifiers. The pupil region is the segmented through the use of k-means clustering of a histogram of the intensity of the image, into light and dark clusters, choosing the dark cluster as the pupil. The pupil is then morphologically transformed to fill in imperfections introduced by eyelashes or occlusions, before canny edge detection is used to isolate possible pupil edge points. Finally, a set of ellipses are fit to subsections of possible edge points using RANSAC iterations. The resulting pupil fits were accurate in real time. (Swirski, Bulling, & Dodgson, 2012) The software in this study tracked pupil location, but does not estimate gaze based on tracking results.

EyePhone is a gaze-tracking program developed for use on smartphones. The camera input is used to estimate which of nine segments of the screen a user is viewing (top-left, top-center, top-right, middle-left, middle-center, middle-right, bottom-left, bottom-center, or bottom-right). An on screen menu consists of a large button in each of these segments. Looking at a segment causes the button to be highlighted, and a blink of the eyes activates the button. Figure 4 illustrates the EyeMenu interface when a user is looking at the SMS button in the bottom-left segment of the screen.

FIGURE 4- EYEPHONE EYEMENU ON THE NOKIA N900 (MILUZZO, WANG, & CAMPBELL, 2010)

Miluzzo, Wang and Campbell evaluated the EyePhone program in a variety of conditions and found that artificial lighting produced less accurate results than daylight, and that a moving user significantly decreased accuracy as anticipated by the researchers. Accuracy also suffered at increasing distances between the user and phone, with an initial decrease at distances greater than 18-20cm and a severe decrease after approximately 45cm. (Miluzzo et al., 2010)

Challenges for this research

Current eye tracking software relies on infrared cameras and stationary cameras and users, neither of which is practical in the mobile space. Computing power required for real-time gaze estimation has been unavailable on mobile computers in the past, but new advances in hardware may have eliminated this challenge.

Chapter I.5 – Educating Young Eyes Project

History

In the summer of 2013, Helen Spencer and Katie Johnson approached Dr. William Erdly, of the University of Washington Bothell, requesting the University consider undertaking a project to address the unmet vision screening needs of children in the state of Washington. At this same time, Olajumoke Fajinmi and I sought Professor Erdly's advice on final projects for our Masters program that had the potential to positively impact the lives of others in a meaningful way. So began the Educating Young Eyes (EYE) project. Graduate students in the Masters of Science in Computer Science and Software Engineering program researched, designed and implemented the software behind the EYE program, and undergraduate students in the Interactive Media Design program contributed their design and artistic skills to the look and feel of the EYE products. See Appendix G for a list of students that have contributed to the project thus far. EYE is an ongoing project, which will likely encompass several years of development by many graduate and undergraduate students at UWB.

Goals

The immediate goal of EYE is to make vision screening and therapy accessible and appealing to children and parents and provide the means for the adults in a child's life to monitor his or her progress. As the project continues, it is our hope that sufficient data will be gathered to allow researchers and developers to refine the screening and therapy games and to contribute materially to the field of vision screening and vision therapy. The data gathered can also be made available to policy makers shaping the future strategies for children's health care and education as it relates to vision issues.

Program Components

The EYE project is developing four program components: an educational website, a cloud-based data storage solution, and browser-based access portal, and a tablet-based access and game interaction portal.

Education Website

The education website for EYE contains information on the project, vision screening and therapy, and emerging news and research in the field. It is our hope parents and teachers will find this site while searching for answers to their questions regarding vision screening and therapy.

Cloud-based data storage

Data for EYE is stored in a cloud-based data storage solution, ensuring it is consistently available to users in diverse locations. All data will be protected by a permissions structure that limits users' access to those records for which they should have permission. For example, a parent can see records only for her children and a vision therapist can see records only for his patients.

Web application portal

The web application portal features customized experiences for different users groups, such as parent-guardians, eye care professionals, education professionals and authorized researchers. Each group can access the records for which they have permission and communicate with other users where applicable. This portal is the main point for interaction with the data available, and for the download of anonymized data for research purposes.

Mobile access portal and screening games

The mobile access app has been developed initially for Windows 8-8.1 tablets, but will be released in Android and iOS versions at a later date. The mobile app gives authorized users access to personal data and games designed to screen for vision issues or provide vision therapy as prescribed by an eye care professional. The app also allows parent-guardians and eye care professionals to track the progress of children in their care.

The purpose of this thesis is to evaluate the feasibility of these games, determine requirements for developing the games, and investigate the game sprite mechanics that should be utilized to create games that accurately induce eye movements similar to traditional screenings.

Chapter II – Requirements and Development

The chapter details the requirement gathering and development phases of the thesis. It includes observations of real world screening techniques and technologies, as well as consideration of the efficacy of current tools and the barriers to screening. Tablet computer hardware, software and the use of neural networks in eye tracking are discussed. Details of the hardware and software used for development and descriptions of the game mechanic simulation are provided.

Observations

The graduate students working on EYE accompanied our advisor, Dr. William Erdly, to a local elementary school in October 2013 to observe and participate in a binocular vision and cross-lateral developmental screening, following the Red Flags screening guidelines. Red Flags screenings were developed by Katie Johnson, a first grade teacher and one of the primary stakeholders for the EYE program. The results of the screening are intended to let teachers and parents know of students that should be seen by an eye care professional for further evaluation; they are not diagnostic in nature.

The screening comprises 5 measures:

Tracking- a pencil is moved horizontally in front of the student while the observer make note of the students eye movements

Teaming – a pencil is moved along a student midline from far to near, while the observer makes note of the student's eye movements

Balance – the student is asked to balance on one foot with the eyes covered and uncovered, and then to repeat this on the other foot. An observer records the number of seconds (up to 10) that the student is able to balance

Skipping – the student is asked to skip a length of the hallway and back, while the observer makes note of the quality of movement

Crawling – the student is asked to crawl cross-laterally for a short distance, and back to the starting point, while the observer makes note of the quality of movement

In the past screening results have identified alarmingly high numbers of children with possible binocular vision issues, the summary results of the screening we observed are below in Figure 5. The full screening results are in Appendix A.

screening measure	children failed	children screened	% children failed
Vertical tracking	36	80	45%
Horizontal tracking	25	80	31%
Teaming	25	80	31%
Skipping	15	63	24%
Crawling	24	75	32%

FIGURE 5 – SUMMARY OF RED FLAGS SCREENING OBSERVED OCTOBER 2013

After the Red Flags screening observation, the students and Dr. Erdly met with a local Developmental Optometrist and Vision Therapist, Dr. Alan Pearson, in his Bothell clinic. Dr. Pearson demonstrated current techniques and technologies used for vision screening and therapy, and shared his observations on requirements for new software. First hand observations supported the conclusions from my literature review that current technologies are cumbersome, expensive, and often confusing to parents and children. Dr. Pearson shared the opinion that vision screening and therapy tools should be easier to understand, widely accessible and part of a comprehensive program. He also shared his conviction that parents, guardians, and eye care professionals need a medium to coordinate the care of children in a centralized and transparent manner. Dr. Pearson is developing a program to facilitate this communication.

Suitability of tablet computers for evaluating reading

In order to be an effective approximation of eye movement when reading, screens must be shown to be comparable to the written word in terms of reader perception. Eye movements when reading e-books on a tablet or e-reader are similar to eye movements when reading from printed material, in both the mean duration of fixations and percentage of regressions during fixation. (Zambarbieri &

Carniglia, 2012) Analyzing the eye movement of children as they interact with tablet computer displays should approximate the way in which they read the printed word as well.

Holland and Komogortsev used an Apple iPad2 and a neural network to show tablet computers can be successfully used to track eye movement, with several important considerations. Cameras in tablet computers often filter all light except that from the visible spectrum, causing the input to be dependent on the ambient light available. Due to the portable nature and general use case of tablet computers, users are often at unpredictable distances and viewing angles from the tablet camera, making accurate detection of gaze direction more difficult. (Holland & Komogortsev, 2012) The low image quality and processing power of the tablet in this study reduced the overall sampling rate of images, resulting in an accuracy of 4.42 degrees, slightly lower than the 3.68 degree accuracy seen with desktop PC tracking systems.

Cameras in current tablet computers have increasingly higher resolution; the tablet used for development in this study has a 2.0 megapixel camera, over 6 times the 0.3 megapixel resolution of the iPad 2 used by Holland and Komogortsev. (Holland & Komogortsev, 2012) Their study involved determining the location of a user's gaze on the tablet screen (for use as an interface), not for evaluation of gaze to estimate binocular vision accuracy, but similar methods could be adapted to our purpose.

Tablet computer used for development

A middle-of-the-line Windows 8 tablet was purchased from NewEgg.com, a popular website available to the public. The tablet was chosen for its operating system and display size and resolution, to meet the requirements determined from the review of literature. Tablets with higher and lower processing power and memory were also available.

See Figure 6 for technical specifications of the tablet computer used for development and testing.

CPU	Intel® Atom™ Z2760 Processor
Operating System	Windows® 8 (32-bit)
Display	11.6" LED HD, 1366 x 768, 16:9
CPU Clock Speed (Max.)	1.8 GHz
System Memory	2GB DDR2L
Web Camera	2.0 MP HD (Front), 8.0 MP HD w/Flash (Rear)

FIGURE 6 - SAMSUNG ATIV SMART PC 500T (MODEL XE500T1C-A04US) SPECIFICATIONS (SAMSUNG, 2013)

Consideration of potential harm

Given the goal of improving binocular vision in children, it is of paramount importance that we consider the inherent shortcomings of the chosen media, tablet computers. In order to be confident in recommending vision games be used widely, we must be certain to avoid the inadvertent harm that this media can cause.

Computer screens present visual information in a medium vastly different from the printed page, with poor contrast and definition and continuous backlighting of the images. Screens also encourage direct forward viewing, exposing more of the eye than the traditional downward gaze used when viewing printed materials. Sustained near-vision activities, such as writing and editing text, contribute to a lack of vergence, and increased convergence insufficiency and asthenopia. When using a computer screen, these effects are significantly stronger than performing the same tasks using a printed copy of the material. (Rosenfield, 2011) Extended use of computer screens can lead to a condition known as Computer Vision Syndrome or CVS.

CVS symptoms can be divided into three categories: ocular surface related, visual-accommodative, and extra-ocular. Ocular surface symptoms, such as dry and itchy eyes, are related to environmental factors and low blink rate, and do not need to be considered in this program. Visual-accommodative symptoms include blurred vision, double vision, slowed change in eye focus and eye fatigue. Extra-ocular symptoms include posture related complaints such as sore back and neck muscles from prolonged poor posture while seated at a computer. (Blehm, Vishnu, Khattak, Mitra, & Yee, 2005)

The quality of display, type of display, and characteristics of the images displayed directly affect visual-accommodative symptoms of CVS. Higher screen resolutions produce sharper, clearer images, reducing the strain of eyes attempting to bring these images into focus. Low monitor refresh rates (between 50HZ and 75Hz) increase premature and disrupted saccades. With high resolution and refresh rates, LCD screens have been found to have the best performance in search time, fixation time and fixation frequency per line when compared to CRT monitors. (Blehm et al., 2005)

Several explicit recommendations for reducing the risk of CVS can be gleaned from studies on the subject:

- Screen size and font size impact the distance at which mobile devices are typically viewed, with phones being held closest to the eyes, followed by tablets, computers, and televisions. The close proximity and small type face inherent on the smallest screens exacerbate CVS symptoms and should be avoided. (Rosenfield, 2011)
- Mixed-case typography with at least .5 character-space between words and 1 character space between lines are easier to interpret than crowded characters presented in all upper-case lettering.(Constanza, 1994)
- Screens should be 35-40cm away, at a viewing angle of 15 degrees below horizontal from the eyes. Near and distance tasks should be alternated to encourage correct accommodation. (Yan, Hu, Chen, & Lu, 2008)

Computer Vision Syndrome affects 90% of workers in the United States that use computers for more than 3 hours per day. (Blehm et al., 2005) The 2001 U.S. Census Report listed 54 million children as daily computer users. (Torrey, 2003) More recent studies have found American children between the ages of 8 and 18 spend about 7.5 hours per day using electronic media (including televisions and computers). (Rosenfield, 2011) Children are more susceptible to CVS than adults for a variety of factors. Children are more likely to attribute discomfort when using a computer to the computer screen or their own eyes, and do not think to adjust environmental factors such as lighting or postures. Computer workstations are often configured for adults and are not suitable for a child's smaller size. Children are also more likely to continue an enjoyable experience (such as a computer game or television show) for long periods despite discomfort. (Yan et al., 2008)

The most effective way we can work to not contribute to CVS in children is to limit the amount of time spent using the screening or therapy tools each day. (Kaldenberg, 2011) Because we cannot limit other screen usage (such as lessons at school or games at home) we must also be mindful of ways to actively combat the symptoms of CVS.

EyeTab

EyeTab is a C++ program built by Erroll Wood and Andreas Bulling as a proof-of-concept for eye-tracking on an unmodified tablet computer.(Wood & Bulling, 2014) EyeTab combines several open source libraries to provide a prototype for gaze tracking with a Windows-based tablet computer and standard built-in front-facing camera. The purpose of this research is focused on the use of gaze-tracking as a means to navigate the user interface of a phone or tablet, or for integration in gaze-aware applications.

OpenCV

The OpenCV library was developed to provide a common source of computer vision and machine learning algorithms to support the development of computer vision applications across industries.

The open source license allows OpenCV to be used for academic and commercial applications. OpenCV is native C++, but has interfaces for C++, Java, Python and MATLAB for use with Windows, Mac, Linux and Android. (Itseez, 2014)

Eigen

Eigen is a high-level C++ library containing templates for complex matrix mathematics. It allows for direct integrations of machine learning algorithms into programs at the compiler level, rather than relying on external programs, such as MATLAB, for data analysis. Eigen is optimized for speed and ease of use and extensively tested for difference compilers and operating systems. Eigen is licensed under MPL2 open source license, which permits its use in open and closed source applications. (Jacob & Guennebaud, 2014)

How EyeTab estimates gaze

EyeTab uses computer vision and machine learning techniques to estimate gaze in real-time from video input. The first stage uses cascading classifiers to identify an eye pair, and reduces the Region-Of-Interest (ROI) to the area of the image that contains the eye pair. Reducing the ROI decreases the area of the screen that subsequent algorithms will evaluate, increasing the efficiency and speed of the overall program. Gradient vectors are calculated for each point in the ROI to determine the eye centers, which are defined as the point with highest inverted intensity and where the most gradient vectors intersect. The eye centers are used to calculate refined ROIs for each eye.

Each refined ROI undergoes a polar transform, the output of which is used to find the edge of the iris using a vertical derivative that isolates the edge between the iris and the sclera. After these results are transformed back to Euclidian space, a parabola is projected onto the upper eyelid edge and used to discard any outlying points in the eyelashes that may have been detected during the polar transform.

Using the camera's internal parameters and an assumption about the average size of a pupil, the eye ellipse is then back-projected into a 3D sphere, and the point-of-gaze (POG) is calculated as the point at which the vector from the eye center of this sphere intersects the screen. EyeTab then averages the POG for both eyes, and smooths the results using the previous 5 POG measurements to account for outliers. Figure 7 below shows the scomponents of EyeTab as represented by the authors.

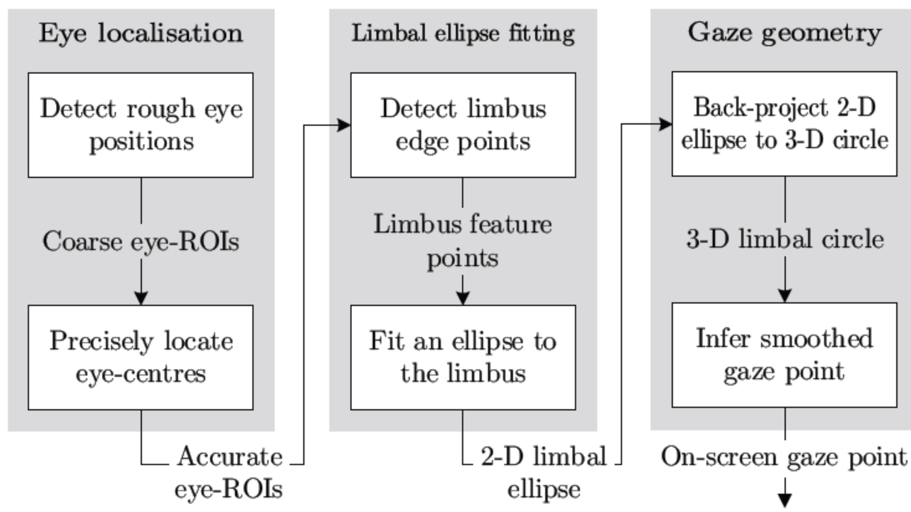


FIGURE 7 - COMPONENTS OF EYETAB SYSTEM (Wood & Bulling, 2014)

Results of initial EyeTab study

Wood and Bulling conducted a prototype evaluation with eight adults in typical office lighting and without restricting head movement. The results of this preliminary evaluation showed an accuracy of 6.88° of visual angle and 12 frames per second processing ability. While the authors admit the accuracy of EyeTab is lower than that of other programs surveyed which use infrared camera technology, EyeTab is far more robust in its tolerance of lighting conditions and user motion. For this reason, EyeTab was chosen over other models as a basis for the work in this thesis. The EyeTab source code was made available by the authors on GitHub. (Wood & Bulling, 2014)

Changes made to EyeTab

EyeTab was developed to detect gaze direction for applications that allow gaze control, that is, applications an end user can control with their eyes instead of touch or speech input. Because of this, it was tested with an average POG of both eyes on static targets. For the purposes of this study, we are interested in the ability to tracking POG in each eye (and average) for a dynamic game sprite mimicking analog screening protocols.

EyeTab was modified to instantiate and update time and Point variables to track POG and eye center for both eyes, and to output data during runtime for use in later analysis. Several variables internal to EyeTab's gazegeometry.cpp file were also updated to reflect the technical specifications of the tablet used in this study, rather than the Helix Thinkpad used in the initial work by the original authors. Details regarding the metrics computed and output during runtime can be found in the Data Analysis portion of this thesis.

Game Sprite Simulation

Screening tests chosen for simulation and how they are operationalized

For the initial development phase, I chose to focus on measures of tracking for several reasons:

1. Tracking is consistently one of or the most significant factor in a bunch of studies which I will elaborate on and cite right here
2. Tracking tests do not require simulating three dimensions, making the development faster and more reliable – not quite the right word, think about it some more
3. Current analog tracking tests are designed to be completed by laypeople, unlike diagnostic screening tests by eye care professionals that often require extra equipment and extensive training

The tracking measures chosen for adaptation were taken from the SCCO 4+ test, NSUCO Oculomotor Test and King-Devick Test. These measures were chosen specifically for the reliability of the tests from which they were adapted and the ease of adaptation for viewing on a tablet screen. The SCCO 4+ was developed by the Southern California College of Optometry, and is both quick and reliable for measurement of fixations, pursuit and saccade tracking. The NSUCO Oculomotor Test was developed by the Northeastern State University College of Optometry. Both tests involve tracking a moving target that is positioned centrally to the patient and moved by an observer. (Scheiman & Rouse, 2006) Performance on the NYSOA King-Devick test is directly related to reading performance in 5 and 6 year olds. (Kulp & Schmidt, 1997) This same study showed the Developmental Eye Movement (DEM) test was too difficult for students in this age group, with 22.7% of children unable to complete this test. For each measure, the pattern is initially completed with a dot with a 32 pixel diameter and then again with a 64 pixel diameter dot, and finally with a 128 pixel diameter dot. These diameters were chosen as typical sizes of sprites in computer games.

The SCCO 4+ protocol for evaluating pursuit tracking involves moving a fixed target in front of the subject's face while the tester observes eye movement. The target is moved in straight vertical, horizontal and diagonal lines in alternating directions. For the game mechanics simulation, this is operationalized as a dark dot on a light background that mimics these same motions on screen. The dot moves along the horizontal, vertical and diagonal medians of a 640 pixel square area in the center of the screen. Each traversal of the screen takes 2 seconds to complete. Examples of games that use this mechanic are those with smooth horizontal or vertical movement of game sprites, such as Tetris, Space Invader and Pacman.

The NSUCO Oculomotor Test protocol for evaluating pursuit tracking involves holding a stick with a small ball in front of the subject's face. The ball is then moved clockwise and subsequently counterclockwise in a circle roughly the size of the subject's face. While the ball is moved, the tester watches the subject's eyes as they follow the motion of the ball. Each circle should take 4 seconds to complete. For the game mechanics simulation, this is operationalized as a dark circle on a light background. The circle completes an elliptical path clockwise twice, and then counterclockwise twice taking 4 seconds for each ellipse. The elliptical path is 640 pixels in diameter in order to occupy the space recommended by NSUCO protocols. Examples of this motion in games include games with an elliptical object path, such as Fruit Ninja, or a circular focus, such as the Ipad game with the panda on the rotating planet that I need to look up.

The King-Devick test involves reading numbers on a page, arranged at varied intervals in a pattern from left-to-right and top-to-bottom that emulates the typical reading direction in English language books. The student reads the numbers as quickly as possible, and is evaluated based on their speed and accuracy. (Kulp & Schmidt, 1997)Accuracy and speed are not assessed in this initial test, but the same distribution of stimuli and movement required to complete the test are replicated. Accuracy and speed may be measure in future games developed based on the results on this study. For the game mechanic simulation, the King-Devick test is represented by a dark circle on a light background. The circle moves from left-to-right in staggered intervals (similar to the length of written words on a page) from top-to-bottom in 4 rows. The rows are contained within a 640 pixel square area centered on the screen.

The NSUCO Oculomotor test for saccade tracking involves two different colored balls held apart in front of the student's face, at eye level on a horizontal plane. The student is asked to look at one ball, and then the other, as the tester observes the student's eye movement. If the student is able to follow directions and look back and forth a total of 5 times, they are considered to have passed the evaluation. In the game mechanics simulation, this is represented by a dot on either end of the horizontal median of a 640 pixel square area centered on the screen. Only one dot appears on the screen in each frame, the dot on which the student should focus.

Chapter III – Methods

This study seeks to evaluate the feasibility of software designed to estimate eye gaze using an unmodified camera on a tablet computer. The study specifically addresses the accuracy of eye gaze evaluation during pursuit and saccade tracking activities in environments with restricted and unrestricted motion.

Experimental design

Participants were assigned to one of four groups, based on the restriction of motion during the study and the order in which game mechanics are presented. Figure 8 outlines the possible groups to which a participant could be assigned.

Group	Motion restriction	Measure Block
Group 1	Restricted	A-B, B-A
Group 2	Unrestricted	B-A, A-B
Group 3	Restricted	B-A, A-B
Group 4	Unrestricted	A-B, B-A

FIGURE 8 - CONDITIONS BY STUDY GROUP

If assigned to restricted motion, participants are seated 40cm from the tablet in use, and the tablet is placed in a stand during gameplay. If assigned to unrestricted motion, the participant is permitted to hold the tablet at a natural distance and angle without feedback from the investigator, as they would do outside the study environment.

In order to counterbalance possible presentation bias in the order of game mechanics, I employed a randomized block design. Game mechanics are divided into blocks based on the visual motion they are intended to evaluate. The order in which each block is presented was varied based on the group to which each participant is randomly assigned. Block A comprises game mechanics intended to evaluate pursuit tracking, while block B comprises game mechanics intended to evaluate saccade tracking.

Participants were assigned to groups by drawing from a box containing slips of paper on which the group numbers are written. The slips of paper contained numbers evenly distributed across the groups. To ensure an even distribution of participants to the various conditions, slips of paper were not replaced after being drawn.

During the study, software and hardware performance metrics – such as frames-per-second and memory utilization – were recorded. This information will be anonymous and presented in aggregate form. It was gathered to understand the software and hardware requirements to run the program on future tablets.

Participants

The target participants for this study consist of students in the Interactive Media Design and Computer and Software Systems departments at the University of Washington Bothell. The following factors were considered when selecting this participant group:

- Diversity of population including age, gender and ethnicity
- Interactive Media and Design and Computer Science and Software Engineering students interact with computers and tablets frequently as a requirement of their area of study. This mitigates the possible effect of unfamiliarity with tablet computers as a confounding factor.
- Availability for research participation and positive experience for future academics

Students involved with the development of the algorithm and game mechanics simulation were excluded from this study.

As this study is intended to evaluate the feasibility of the tools, rather than their efficacy, we did not require our participants to be representative of the intended audience. The exception to this rule is pupil size. Because the final application will be expected to interpret video input of users' eye movement, it was important that the feasibility study be conducted with participants whose pupil size is reasonably representative of children ages 5-7. While studies show children's pupil size increases with age, the increase from age 4-7 to adulthood is less than 1.5 millimeters (J. Silbert, Matta, Tian, Singman, & Silbert, 2013). The same study found no significant difference in pupil size between genders, negating a need to have a gender-representative sample for this study.

A minimum of 20 participants per main effect criteria (in this case, restricted motion) were recruited. Ideally, the number of participants would be divided equally among participant groups. The target for participation was therefore a minimum of 40 students.

Participants were recruited using an email sent to students in the Interactive Media Design and Computing and Software Systems departments at the University of Washington Bothell. A copy of the recruiting email can be found in Appendix B. A limited number of participants responded to the recruitment email, so the participant pool was expanded to include members of the Technical Support department at a Seattle software company. This participant pool contains the same demographic diversity and technical experience as the initial student population. None of the participants report to the principal investigator, and no incentives or disincentives were offered for participation.

Measures

Study participation consisted of completing 2 measures, outlined below in Figure 9. The total time needed to complete all measures was 6 minutes.

Measure	Time required to complete
Demographic Survey	2 minutes
Image viewing and video recording	4 minutes

FIGURE 9 – SUMMARY OF MEASURES INCLUDING TIME REQUIRED TO COMPLETE

Demographic questionnaire

The demographic questionnaire consists of a list of general demographic questions which request information on factors such as a participant's age, gender, experience with tablet computers, and any previous diagnosis of vision related issues. The answers to this questionnaire may be used in exploratory analysis of the data gathered, to determine if age, gender, experience, or known vision issues have any effects on the accuracy of the gaze tracking algorithm. The demographic questionnaire is available in Appendix C.

Tracking exercise and recording

A simulation was developed to mimic techniques used by proctors in analog vision screening and therapy. Participants viewed this simulation on a tablet computer, having been instructed to follow the objects with their eyes during the simulation. The following figure details the translation of these mechanisms into their simulated representations.

Block	Visual measure	Source	Operationalized form
A	Pursuit tracking	SCCO 4+ test	Smooth horizontal, diagonal and vertical motion
A	Pursuit tracking	NSUCO Oculomotor Test	Circular motion, both directions
B	Saccade tracking	King-Devick Test	Left-to-right staggered horizontal movement in multiple lines
B	Saccade tracking	NSUCO Oculomotor Test	Staggered appearance of dots on the left and right margin of a horizontal line

FIGURE 10 – OPERATIONALIZED SCREENING TECHNIQUES USED IN GAME MECHANIC SIMULATION

The tablet's front facing camera was used to capture video input for analysis as the simulation was played on the tablet screen.

Procedures

The room set up for the study consisted of a table with two chairs (one for the participant and one for the investigator). See Figure 11 below for a diagram of the study room.

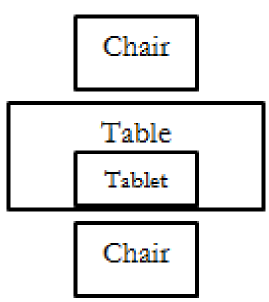


FIGURE 11- LAYOUT OF STUDY ROOM

Upon arrival at the study room, each participant was greeted by the investigator and presented with a copy of the Informed Consent form. The participant was given time to read the form and ask clarifying questions before choosing whether to participate. A copy of the Informed Consent form is available in Appendix D.

If the participant elected to sign the Informed Consent form, he or she was given a copy of the signed form and assigned a "Participant ID" by drawing from a box containing slips of paper on which potential "Participant ID"s were written, to be used to identify all materials and information obtained during the study. The "Participant ID" was recorded on the Demographic Questionnaire before continuing.

The participant was then provided the Demographic Questionnaire and given 2 minutes to complete it.

Following completion of the Demographic Questionnaire, the participant was presented with the tablet computer on which they observed the simulation. Participants assigned to the unrestricted motion condition were asked to hold the tablet as they would normally when playing mobile games. Participants assigned to the restricted motion condition were seated 40cm from the tablet, which was placed on a stand. The distance of 40cm was chosen in accordance with recommendations to reduce the chance of occurrence of Computer Vision Syndrome. The tablet was not held or moved during participation.

During observation, the investigator stood behind and to the side of the participant to avoid distracting the participant. When the animation finished, the participant was thanked for their time and informed their participation was complete.

Data Collection and Preparation for Analysis

Code for use in study

A simple C#/XAML program was written to capture video input while participants viewed one of two simulations, depending on group assignment. The program consists of 3 pages, an entry page containing a space for the Participant ID and two buttons, labeled "A" and "B". After the participant enters their Participant ID and presses the button as instructed by the investigator, either page A or page B is navigated to. Page A and Page B contain a CaptureElement to record video input and a MediaElement to play the simulation – each MediaElement is bound to the correct simulation file for its page.

When Page A or Page B is navigated to, the following events are triggered:

1. Device cameras are enumerated, and if more than one is present the second camera is chosen. By camera enumerations standards, this ensures the front-facing camera is chosen.
2. The camera is initialized, and on initial program execution requests permission from the user to record input. (In the study this was done once by the investigator prior to participant interaction to avoid interruption during participant use)
3. The MediaElement MediaOpened event triggers a call to begin outputting 720p resolution MP4-encoded video to an output file named for the ParticipantID, using the convention "output_<ParticipantID>.mp4"
4. The MediaElement MediaEnded event triggers a call to cease outputting to the video file.

The full code for this program is available in Appendix E.

EyeTab data modifications

Code was added to EyeTab to gather and output metrics to a comma delimited .csv file format during execution. The following figure details the metrics output by the EyeTab program.

Metric	What is it?	Purpose
SYSTEMTIME now	Time with millisecond precision	Sync eye gaze tracking and simulation
String FPS_string	Frames per second processed	Evaluate processing ability of eyetab
Point2i eye_0	x,y coords of eye0 gaze	Track gaze point for eye_0
Point2i eye_1	x,y coords of eye1 gaze	Track gaze point for eye_1
Point2i eyes	x,y coords of average POG	Track average gaze point for both eyes
Point eye0c	x,y coords of center of eye0	Track eye center estimated for eye0
Point eye1c	x,y coords of center of eye1	Track eye center estimated for eye1

FIGURE 12 – METRICS GATHERED AND OUTPUT BY MODIFIED EYETAB PROGRAM

The time and average POG are used to compare the EyeTab estimates to the known x- and y-coordinates of the dot in the simulation in order to determine the accuracy of EyeTab. The individual POG for each eye will be used to evaluate the difference in POG between both eyes for the same frame, which has the potential to show one eye is contributing more to the average POG and skewing the resulting gaze estimation. This may be an additional insight, and may be proof that EyeTab is actually more accurate than previously thought, because the inaccuracy is caused by users with binocular vision issues skewing the estimating ability.

The estimated eye center for each eye is output in order to track the in frame location which the algorithm determines is the center of each eye. The presence of non-zero data in these columns indicates eyes were detected, and comparing the differences in x and y coordinates can help determine if the eyes detected are on the same plane in the frame. Larger differences in the x coordinate, for example, may show that one eye was detected along with one eyebrow – which would be at a lower x coordinate.

Additional programs used

Windows Performance Monitor (perfmon) was used to capture metrics regarding processor and memory utilization by the EyeTab process during execution.

Data preparation

Demographic survey responses were manually transferred to an Excel file. The Likert scale question responses were recorded as their corresponding integer on a scale from 1-5 for ease of analysis.

The csv file generated by the EyeTab algorithm contains a line for each frame in the input video file. For each line in the csv file, the Euclidian distance from the known center of the dot to the gaze estimation point is calculated. A distance equal to the radius of the dot is considered "accurate" as it indicates the user's point of gaze is within the on screen dot.

Limitations

Targeting an adult population for this study means the results may not be valid for the intended audience of children ages 5-8. However, as this study is meant to evaluate the appropriateness of a particular method of gaze estimation rather than the effectiveness of eventual screening tools themselves, this is not a limitation of the study.

Chapter IV – Experimental Results

Demographics

The group of participants was predominantly male, ages 30-39, with glasses. There were 16 participants aged 20-29, 18 participants aged 30-39, and 6 participants aged 40 or older. There were 11 females and 29 males. 32 participants wore glasses regularly and 8 did not. All participants aged

40 or older wore glasses. Not all participants who wear glasses wore them while viewing the game mechanic simulation, as several participants needed glasses for distance vision only. Figure 13 details the distribution of participants by age, gender and glasses use – excluding one participant who declined to provide his age on the demographic questionnaire.

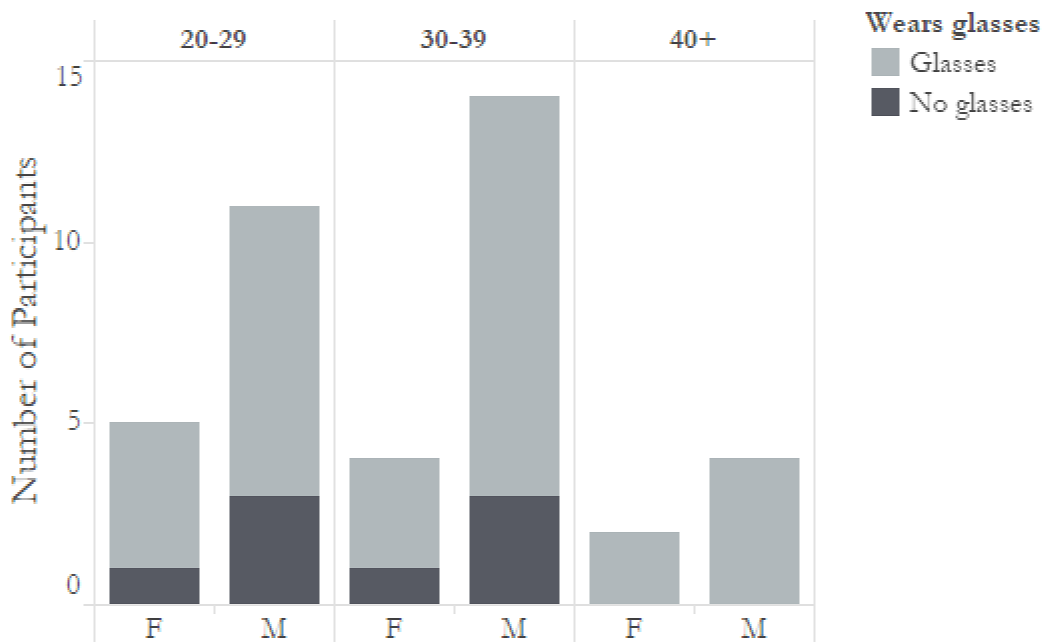


FIGURE 13 - STUDY PARTICIPANT DEMOGRAPHICS

Survey responses regarding tablet, smartphone and computer use show that tablet usage patterns do not mirror smartphone or computer usage pattern for these participants. All participants report every day use of smartphones and computers, as well as 55-62% of participants reporting use of these platforms for playing games at least 2-3 times per week. By contrast, only 25% of participants reporting daily use of a tablet, and only 20% for playing gamesat least 2-3 times per week. Full details of the survey responses are below in Figure 14.

Question asked	Never	1 time per month	1 time per week	2-3 times per week	Every day
How often do you use a tablet?	4	10	7	8	11
How often do you play games on a tablet?	16	10	6	4	4
How often do you use a smartphone?					40
How often do you play games on a smartphone?	5	7	6	10	12
How often do you use a computer?					40
How often do you play video games on any platform?	4	6	5	12	13

FIGURE 14 - DEMOGRAPHIC SURVEY RESPONSES

Given these responses represent the experience of adult professionals in a technological field, it remains to be seen if children in the age group that is a target of this software will have similar usage patterns. Factors such as technology available in the classroom and level of at home technology afforded them by their socioeconomic status will have an impact on each individual's exposure to tablets, smartphones, and computers.

Eye tracking

Eye tracking accuracy was estimated by direct observation of the EyeTab algorithm as it executed against each input video. EyeTab displays the video capture frame, as well as the ROI, eye center, eyelid, iris ellipse and estimated gaze points for each frame which allows real time comparison to the actual location of the eyes in each frame. Each video was classified into one of three categories: no eyes present in video, eyes present but not detected, or eyes detected. As illustrated in Figure 15, there were no usable gaze estimates from the video input collected in this study.

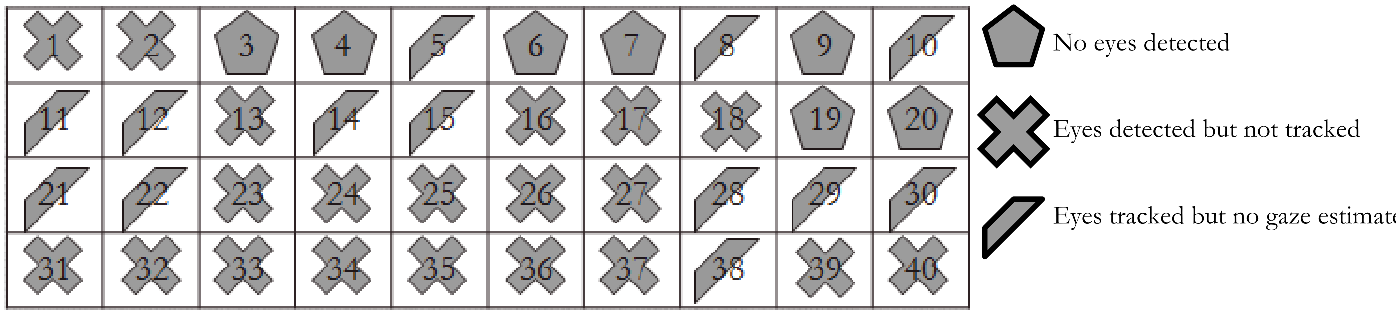


FIGURE 15 - RESULTS OF EYETAB ALGORITHM FOR EACH PARTICIPANT ID

For 7 participants, there were no eyes contained in the video frame, due to the angle at which the tablet was held. All 7 participants were members of the unrestricted motion group. For each of these participants, their eyebrows and forehead were in the camera frame, indicating the angle at which they held the tablet was almost acute enough to capture their eyes. Based upon subsequent reproductions using the tablet from the study, these participants held the tablet at 25-35° past perpendicular to the participant.

FIGURE 16 - ILLUSTRATION OF A 35° ANGLE CHANGE IN CAMERA FIELD OF VIEW

Figure 16 illustrates the impact of holding a tablet at a 35° angle past the perpendicular. The gray triangle represents the field of view for the tablet camera at perpendicular (on the left) and when angled an additional 35° away from the participant (on the right).

For 20 participants, eye tracking was not accurate. Either no eyes were detected or other features, such as eyebrows, were detected instead. This includes participants both with and without glasses.

For example, participant 24 did not have any eyes detected, despite capturing fully visible eyes in all frames of the image. Likewise, Participant 17 has eyes detected only for the last 28 seconds of footage, and during that time gaze estimation was provided for only one eye, making the average POG incalculable.

Eyebrows were detected in place of eyes for several participants. Anecdotally, this appears to occur most often with male participants with thick, dark eyebrows. Figure 17 shows screenshots of typical detection of an eyebrow rather than an eye.

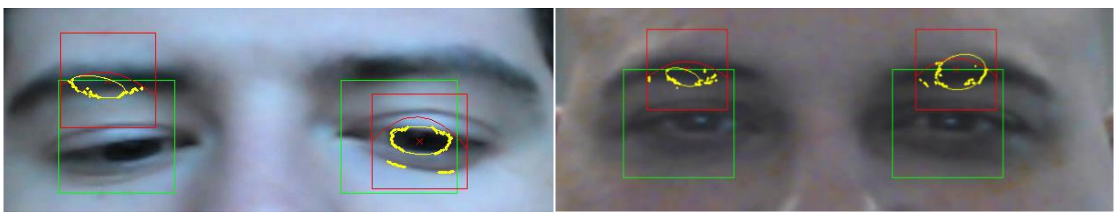


FIGURE 17 - SCREEN CAPTURE OF PARTICIPANTS 1 AND 18 ILLUSTRATING DETECTION OF EYEBROWS

Both eyes were detected for the remaining 13 participants. Again, this group included a mix of participants with and without glasses.

Gaze estimation

For the 13 participants in which eyes were accurately detected, no participant had gaze estimations for more than 25% of the frames in the video. Of the gaze estimations available, many were for a single eye or estimated to be far off-screen. No participant video resulted in gaze estimations that could be compared to the simulation to evaluate their accuracy.

Full details of the EyeTab algorithm results are available in Appendix F.

Performance Monitor results

Windows Performance Monitor's System Performance Data Collector Set was used during execution of EyeTab code on the study tablet. It identified the following resource usage:

Tablet:

- CPU – 37%
- Memory – 41%
- Disk I/O – less than 100 (read/write) per second

Eyetab.exe:

- CPU – 25.25%
- Memory– 131.768 MB or 6.5%

While operating system resource usage will need to be taken into account, based on these results, EyeTab could be executed on a tablet computer with one core and 1GB RAM.

Chapter V – Findings and Discussion

Recommendations for future work/studies

Use of EyeTab

The lack of usable gaze estimations in this study merits caution in choosing to utilize EyeTab in future studies. Previous correspondence with EyeTab's authors indicated low video resolution was the culprit for poor accuracy in initial testing, but the videos for the current study were explicitly captured in 720p resolution. Having elimination video resolution as the cause, an examination of the situations in which EyeTab might be utilized, and how the algorithm will potentially be affected by each situation, is warranted.

Considerations for the accuracy of EyeTab in different situations

Users with glasses: Eye detection failed for users with and without glasses, it does not appear to have been a determining factor in successful eye detection.

Users with one eye or closed eyes: EyeTab is trained on a data set that presumes two eyes are present in the video input. When one eye is closed or obscured, EyeTab will detect a second "eye", often the eyebrow or outside eyelid fold if shaded.

Users with different iris coloration: EyeTab detects the barrier between the sclera and iris – rather than the iris and pupil – and should be unaffected by differences in iris coloration.

Angle or rotation of user's face: The original pilot study on Eyetab suggests it should be robust to rotation of the face or changes in the angle of the face to the camera. The current study did not evaluate the accuracy of this assertion.

Users whose eyes vary in shape or size: Eye size and shape should only be a concern when the iris is obscured to the point that an ellipse cannot be accurately fit to the detected edge points. The population of the original EyeTab study and the current study did not contain a sufficient number of participants with narrow eyes to evaluate whether this is a concern.

Anecdotal data from further work by other team members produced encouraging results with EyeTab's algorithms. Graduate students working on game prototypes for the Education Young Eyes project successfully tracked their own eyes and those of volunteers while watching game simulations on tablet computer. Several differences between their results and the ones in this thesis bear consideration for designing future studies:

- The background of their game prototypes are images, like a sky or ocean scene, which may have reduced the reflection from the tablet screen in users' pupils

- The tablet was held at a close distance – approximately 20-25cm from the user
- Users were made aware that the tablet camera should be aimed toward their eyes

Design of games

The shortcomings of the results for this study offer several insights into the design of future simulations and games for use in vision screening and therapy.

Participants 3, 4, 6, 7, 9, 19 and 20 –representing 35% of the unrestricted movement group - held the tablet at an angle that did not capture their eyes in the camera frame. All of these participants held the tablet at a more obtuse angle. Any game developed may need a calibration screen, in order to educate the user on the angle to hold the tablet, or in-game logic that warns the user if the eyes are outside the frame for a set duration of time.

As can be seen in the image of participant 18 (on the right in Figure 17) the white background of the game mechanics simulation caused glared in several participants' glasses –and reflections in pupils – that may be the reason for eyebrows being detected rather than the pupils themselves. To mitigate this effect in the final games developed, designers should avoid the user of light, bright, solid background images. As several participants provided unsolicited feedback that the bright background had caused them eye discomfort, avoiding these backgrounds in the future is doubly advisable.

Methodology for future studies

Measuring the accuracy of the algorithm is a two-fold issue, in that it assumes that the participant is actually looking at the dot in the animation and that the algorithm is accurate. If the participant looks away during the animation, it will appear that the algorithm is inaccurate even if it is not.

Likewise, an accurate result does not necessarily mean the algorithm is accurate if the user is in fact looking away at that time. In future studies, it is advisable to compare results to a known good eye tracking software, such as one using an infrared camera that is mounted to the same tablet, so that a valid comparison can be done to evaluate the results of the algorithm.

The inability to estimate gaze for participants in the restricted motion group – in which the tablet was placed 40cm from the participants – corresponds to the earlier findings by Miluzzo et al that distances of about 45cm result in severe accuracy losses when estimating gaze, suggesting consideration of closer distances despite the recommendations for avoiding Computer Vision Syndrome by viewing tablet screens from this distance. (Miluzzo et al., 2010)

Additional insights into the environmental conditions that should be accounted for in development could be gained by taking details measurements using tablet instrumentation in later studies. Ambient light can be measured by the light meter for the built in camera. Angle and direction of tablet movement can be evaluated using the accelerometer and gyroscope that are commonly installed in tablet computers and smartphones. Recording the study sessions from a camera perpendicular to participants would allow estimation of the distance from the participant to the tablet screen. All of these potential measurements could be used to better inform the development of production systems in the future.

With sufficient data from a large participant group, analyzing the effect of visual differences on the accuracy of the gaze estimation is a vital step in the process. Such factors appropriate for subgroup analysis include: eye shape, eyebrow size and thickness, iris color, and presence of glasses in the frame.

Discussion

The study results show using unmodified tablet camera visual light spectrum input in gaze estimation in real time is not ready for use in commercial applications. While work can be done to refine the algorithms to be more robust to environmental conditions and noise, expedience in bringing a usable product to children in need to vision screening behooves the exploration of alternative methods in the near future.

The use of infrared camera input is well documented to be tolerant to the visual spectrum noise such as eyelashes and reflections, which are a paramount concern in algorithms like those used for this study. The reflections seen in users' pupils also reinforce the idea that an infrared input that is impervious to reflections in the visual light spectrum may be necessary to achieve accurate results in varied environments and user groups. Experimenting with ways to reduce the cost to deploy infrared cameras in the mobile space may make this a viable alternative. Perhaps a phone or tablet case could be designed like that of the PEEK case, which incorporates an infrared camera attachment for use with the onboard electronics.

Additionally, designing games that are validated to require healthy binocular vision to achieve higher scores could allow screening games to be designed wherein the score on the game is a proxy for binocular vision health such that lower scores warrant a professional eye examination. This approach would also eliminate the need for cameras to be present on screening tablets or computers.

Whatever the approach, collaboration between the technological innovation of computer scientists, the determination and insights of educators and the expert scientific guidance of eye care professionals offers the opportunity to address the unmet vision screening and therapy needs of children around the world.

Appendix A

Red Flags Screening Results - Oct 2013

103	total children	22
	Vertical tracking	6 of 22
	Horizontal tracking	6 of 22
	Teaming(convergence)	6 of 22
	Crawling	7 of 21
	Skipping	4 of 21
104	total children	12
	Vertical tracking	8 of 12
	Horizontal tracking	5 of 12
	Teaming(convergence)	4 of 12
	Crawling	0 of 9
	Skipping	2 of 10
107	total children	22
	Vertical tracking	9 of 22
	Horizontal tracking	8 of 22
	Teaming(convergence)	7 of 22
	Crawling	3 of 12
	Skipping	12 of 22
108	total children	24
	Vertical tracking	7 of 24
	Horizontal tracking	6 of 24
	Teaming(convergence)	8 of 24
	Crawling	5 of 21
	Skipping	6 of 22

TOTAL
80 children

	Vertical tracking	36 of 80 failed	45%
	Horizontal tracking	25 of 80 failed	31 %
	Teaming(convergence)	25 of 80 failed	31%
	Crawling	15 of 63 failed	24%
	Skipping	24 of 75 failed	32 %

Results provided by Katie Johnson

Appendix B

Email sent to recruit participants for this study

Hello CSS and IMD students!

A group of fellow students has spent the last year developing tablet-based games we hope will one day make vision screening and vision therapy available to children around the world. We have our first simulation ready and we need your help testing it!

We need approximately 10 minutes of your time to do the following:

1. Answer a short questionnaire

2. Watch a game mechanics simulation on a tablet (which will record your eyes while you play)

Participating in a study like this one is great experience for when you will likely conduct studies or trials during your time at UWB, and offers the chance to contribute to a program that could have significant positive impact for children everywhere. Participation is entirely voluntary, and there are no benefits or consequences associated with choosing whether or not to participate.

The study will take place in the CSS Grad Lab, located on the third floor of the UW-1 building (UW1-302) on Friday, October 24 from 12-5pm. Please reply to this email to schedule a time slot if you are interested.

Thank you,

Carisa Chang – graduate student, Masters of Science in Computer Science and Software Engineering

Appendix C

Demographic Survey

Participant ID: ___________

Please answer the questions below to the best of your knowledge. You may elect to skip any question. The answers provided will be kept anonymous.

Please provide the following demographic information:

Age: ____

Gender: _____

Do you wear prescription glasses or contacts? Yes No

If yes, what is your prescription (e.g. 20/20, 20/45, 20/200)?____________________________________

Have you been diagnosed any binocular vision issues? Yes No

If yes, which ones? _______________________

How often do you use a tablet? (circle one)

Never 1 time per month 1 time per week 2-3 times per week Every day

How often do you play games on a tablet? (circle one)

Never 1 time per month 1 time per week 2-3 times per week Every day

How often do you use a smartphone? (circle one)

Never 1 time per month 1 time per week 2-3 times per week Every day

How often do you play games on a smartphone? (circle one)

Never 1 time per month 1 time per week 2-3 times per week Every day

How often do you use a computer? (circle one)

Never 1 time per month 1 time per week 2-3 times per week Every day

How often do you play video games on any platform? (circle one)

Never 1 time per month 1 time per week 2-3 times per week Every day

Appendix D

Informed Consent

UNIVERSITY OF WASHINGTON

CONSENT FORM

Gaze Tracking on Unmodified Tablet Computers

Researchers: Carisa Chang – Researcher – 503-961-4729

Associate Professor William Erdly – Faculty Sponsor – 425-352-5370

Researchers' statement

We are asking you to be in a research study. The purpose of this consent form is to give you the information you will need to help you decide whether to be in the study or not. Please read the form carefully. You may ask questions about the purpose of the research, what we would ask you to do, the possible risks and benefits, your rights as a volunteer, and anything else about the research or this form that is not clear. When we have answered all your questions, you can decide if you want to be in the study or not. This process is called "informed consent." We will give you a copy of this form for your records.

PURPOSE OF THE STUDY

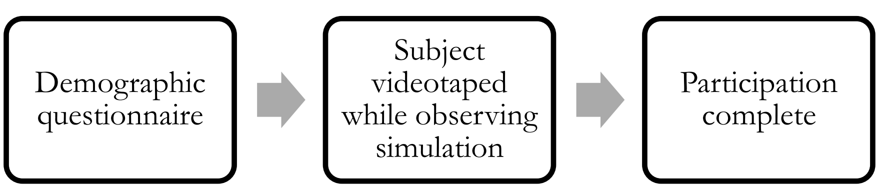
The purpose of this study is to evaluate the feasibility of capturing video and tracking the user's gaze accurately, using the unmodified camera component of a tablet computer. If the results of the study indicate tablet computers can track a user's gaze, vision screening and therapy games may be developed that will provide children around the world access to vision care that is not currently available.

STUDY PROCEDURES

Study participation will consist of the following measures:

Measure	Time required to complete
Demographic Survey	2 minutes
Game play and video recording	6 minutes

The following flow chart illustrates the order of study procedures:



RISKS, STRESS, OR DISCOMFORT

You may be uncomfortable sharing information on the demographic questionnaire, which pertains to known vision issues and tablet/desktop computer use. You may find the game mechanic simulation boring.

BENEFITS OF THE STUDY

There are no foreseeable benefits for participants as a result of this study. There is a considerable potential benefit to society if the results of this study enable the development of vision screening and therapy games for children.

CONFIDENTIALITY OF RESEARCH INFORMATION

All of the information you provide will be anonymous. It will be referenced by the "Participant ID" assigned to you during the study. We will not record or retain personally identifiable information (such as your name, Social Security Number or address) other than the video recordings.

Still images from the video captured during this study may be used in academic publications. Any images used in publication will be restricted to the area of the face immediately surrounding and including the eyes. It may be possible to identify a participant from these images although no personally identifiable information will be published.

Government or university staff sometimes review studies such as this one to make sure they are being done safely and legally. If a review of this study takes place, your records may be examined. The reviewers will protect your privacy. The study records will not be used to put you at legal risk of harm.

OTHER INFORMATION

You may refuse to participate and you are free to withdraw from this study at any time without penalty or loss of benefits to which you are otherwise entitled.

Printed name of study staff obtaining consentSignature Date

Subject's statement

This study has been explained to me. I volunteer to take part in this research. I have had a chance to ask questions. If I have questions later about the research, or if I have been harmed by participating in this study, I can contact one of the researchers listed on the first page of this consent form. If I have questions about my rights as a research subject, I can call the Human Subjects Division at (206) 543-0098. I will receive a copy of this consent form.

Printed name of subject Signature of subject Date

Copies to: Researcher, Subject

Appendix E

Source code for study

MainPage.xaml:

```
<Page
    x:Class="Pilot.MainPage"
    xmlns="http://schemas.microsoft.com/winfx/2006/xaml/presentation"
    xmlns:x="http://schemas.microsoft.com/winfx/2006/xaml"
    xmlns:local="using:Pilot"
    xmlns:d="http://schemas.microsoft.com/expression/blend/2008"
    xmlns:mc="http://schemas.openxmlformats.org/markup-compatibility/2006"
    mc:Ignorable="d">

    <Grid Background="{StaticResource ApplicationPageBackgroundThemeBrush}">
        <Button x:Name="Button_A" Content="A" HorizontalAlignment="Left"
Margin="522,507,0,0" VerticalAlignment="Top" Height="128" Width="128" FontSize="48"
Click="Button_A_Click"/>
        <Button x:Name="Button_B" Content="B" HorizontalAlignment="Left"
Margin="717,507,0,0" VerticalAlignment="Top" Height="128" Width="128" FontSize="48"
Click="Button_B_Click"/>
        <TextBox x:Name="ParticipantID" HorizontalAlignment="Left"
Margin="522,306,0,0" TextWrapping="Wrap" Text="Enter Participant ID here, then click
A or B, as instructed" VerticalAlignment="Top" Height="56" Width="323"
FontSize="16"/>
    </Grid>
</Page>
```

MainPage.xaml.cs:

```
using System;
using System.Collections.Generic;
using System.IO;
using System.Linq;
using Windows.Foundation;
using Windows.Foundation.Collections;
using Windows.UI.Xaml;
using Windows.UI.Xaml.Controls;
using Windows.UI.Xaml.Controls.Primitives;
using Windows.UI.Xaml.Data;
using Windows.UI.Xaml.Input;
using Windows.UI.Xaml.Media;
using Windows.UI.Xaml.Navigation;
using System.Threading.Tasks;
using Windows.Media.Capture;
using Windows.Storage;
using Windows.Storage.Streams;
using Windows.Media.MediaProperties;

namespace Pilot
{
```

```
    public sealed partial class MainPage : Page
    {
        public MainPage()
        {
            this.InitializeComponent();
        }

        protected override void OnNavigatedTo(NavigationEventArgs e)
        {
        }

        private void Button_B_Click(object sender, RoutedEventArgs e)
        {
            this.Frame.Navigate(typeof(PageB), ParticipantID.Text);
        }

        private void Button_A_Click(object sender, RoutedEventArgs e)
        {
            this.Frame.Navigate(typeof(PageA), ParticipantID.Text);
        }
    }
}
```

PageA.xaml:

```
<Page

    xmlns="http://schemas.microsoft.com/winfx/2006/xaml/presentation"

    xmlns:x="http://schemas.microsoft.com/winfx/2006/xaml"

    xmlns:local="using:Pilot"

    xmlns:d="http://schemas.microsoft.com/expression/blend/2008"

    xmlns:mc="http://schemas.openxmlformats.org/markup-compatibility/2006"

    xmlns:PlayerFramework="using:Microsoft.PlayerFramework"

    x:Class="Pilot.PageA"

    mc:Ignorable="d">


    <Grid Background="{StaticResource ApplicationPageBackgroundThemeBrush}">

        <CaptureElement x:Name="captureElement" HorizontalAlignment="Left"
Height="100" Margin="187,366,0,0" VerticalAlignment="Top" Width="100"/>

        <MediaElement x:Name="player" Source="Assets/movieA.mp4"
HorizontalAlignment="Left" Height="768" VerticalAlignment="Top" Width="1366"
MediaEnded="player_MediaEnded" MediaOpened="player_MediaOpened"/>

    </Grid>
```

```
</Page>
```

PageA.xaml.cs:

```
using System;
using System.Collections.Generic;
using System.IO;
using System.Linq;
using Windows.Foundation;
using Windows.Foundation.Collections;
using Windows.UI.Xaml;
using Windows.UI.Xaml.Controls;
using Windows.UI.Xaml.Controls.Primitives;
using Windows.UI.Xaml.Data;
using Windows.UI.Xaml.Input;
using Windows.UI.Xaml.Media;
using Windows.UI.Xaml.Navigation;
using Windows.Devices.Enumeration;
using System.Threading.Tasks;
using Windows.Media.Capture;

using Windows.Storage;
using Windows.Storage.Streams;
using Windows.Media.MediaProperties;


namespace Pilot
{
    public sealed partial class PageA : Page
    {
        public PageA()
        {
            this.InitializeComponent();
        }

        String outputID;
        MediaCapture capture = new MediaCapture();
        MediaCaptureInitializationSettings settings = new
MediaCaptureInitializationSettings();

        protected override void OnNavigatedTo(NavigationEventArgs e)
        {
            this.initCamera();
            //start and stop recording is managed by event handlers on the
MediaElement that plays the simulation
            string name = e.Parameter.ToString();

            if (!string.IsNullOrWhiteSpace(name))
            {
                outputID = "output_" + name;
            }
            else
            {
                outputID = "output_";
```

```
            }
        }

        async Task enumerateCameras()
        {
            DeviceInformationCollection deviceInfo = await
Windows.Devices.Enumeration.DeviceInformation.FindAllAsync(Windows.Devices.Enumeratio
n.DeviceClass.VideoCapture);
            if (deviceInfo.Count > 0)
            {
                settings.VideoDeviceId = deviceInfo[1].Id;
            }
            else
            {
                settings.VideoDeviceId = deviceInfo[0].Id;
            }
        }

        async Task StartCapturingVideo()
        {
            //specify 720p - required resolution for algorithm
            MediaEncodingProfile profile =
MediaEncodingProfile.CreateWmv(VideoEncodingQuality.HD720p);

            StorageFile output = await DownloadsFolder.CreateFileAsync(outputID +
".mp4", CreationCollisionOption.GenerateUniqueName);
            await this.capture.StartRecordToStorageFileAsync(profile, output);
        }

        async Task StopCapturingVideo()
        {
            await this.capture.StopRecordAsync();
        }

        async void initCamera()
        {
            await this.enumerateCameras();
            await this.capture.InitializeAsync(settings);
        }

        //stop recording when video ends
        private async void player_MediaEnded(object sender, RoutedEventArgs e)
        {
            await this.StopCapturingVideo();
            this.Frame.Navigate(typeof(MainPage));
        }

        //start recording when video starts
        private async void player_MediaOpened(object sender, RoutedEventArgs e)
        {
            await this.StartCapturingVideo();
        }
    }
}
```

PageB.xaml:

```
<Page
    x:Class="Pilot.PageB"
    xmlns="http://schemas.microsoft.com/winfx/2006/xaml/presentation"
    xmlns:x="http://schemas.microsoft.com/winfx/2006/xaml"
    xmlns:local="using:Pilot"
    xmlns:d="http://schemas.microsoft.com/expression/blend/2008"
    xmlns:mc="http://schemas.openxmlformats.org/markup-compatibility/2006"
    mc:Ignorable="d">

    <Grid Background="{StaticResource ApplicationPageBackgroundThemeBrush}">
        <CaptureElement x:Name="captureElement" HorizontalAlignment="Left"
Height="100" Margin="699,364,0,0" VerticalAlignment="Top" Width="100"/>
        <MediaElement x:Name="player" Source="Assets/movieB.mp4"
HorizontalAlignment="Left" Height="768" VerticalAlignment="Top" Width="1366"
MediaEnded="player_MediaEnded" MediaOpened="player_MediaOpened"/>
    </Grid>
</Page>
```

PageB.xaml.cs:

```
using System;
using System.Collections.Generic;
using System.IO;
using System.Linq;
using Windows.Foundation;
using Windows.Foundation.Collections;
using Windows.UI.Xaml;
using Windows.UI.Xaml.Controls;
using Windows.UI.Xaml.Controls.Primitives;
using Windows.UI.Xaml.Data;
using Windows.UI.Xaml.Input;
using Windows.UI.Xaml.Media;
using Windows.UI.Xaml.Navigation;
using Windows.Devices.Enumeration;
using System.Threading.Tasks;
using Windows.Media.Capture;

using Windows.Storage;
using Windows.Storage.Streams;
using Windows.Media.MediaProperties;

namespace Pilot
{
    public sealed partial class PageB : Page
    {
        public PageB()
        {
            this.InitializeComponent();
        }

        String outputID;
```

```
        MediaCapture capture = new MediaCapture();
        MediaCaptureInitializationSettings settings = new
MediaCaptureInitializationSettings();

        protected override void OnNavigatedTo(NavigationEventArgs e)
        {
            this.initCamera();
            //start and stop recording is managed by event handlers on the
MediaElement that plays the simulation
            string name = e.Parameter.ToString();

            if (!string.IsNullOrWhiteSpace(name))
            {
                outputID = "output_" + name;
            }
            else
            {
                outputID = "output_";
            }
        }

        async Task enumerateCameras()
        {
            DeviceInformationCollection deviceInfo = await
Windows.Devices.Enumeration.DeviceInformation.FindAllAsync(Windows.Devices.Enumeratio
n.DeviceClass.VideoCapture);
            if (deviceInfo.Count > 0)
            {
                settings.VideoDeviceId = deviceInfo[1].Id;
            }
            else
            {
                settings.VideoDeviceId = deviceInfo[0].Id;
            }
        }

        async Task StartCapturingVideo()
        {
            //specify 720p - required resolution for algorithm
            MediaEncodingProfile profile =
MediaEncodingProfile.CreateWmv(VideoEncodingQuality.HD720p);

            StorageFile output = await DownloadsFolder.CreateFileAsync(outputID +
".mp4", CreationCollisionOption.GenerateUniqueName);
            await this.capture.StartRecordToStorageFileAsync(profile, output);
        }

        async Task StopCapturingVideo()
        {
            await this.capture.StopRecordAsync();
        }

        async void initCamera()
        {
            await this.enumerateCameras();
```

```
            await this.capture.InitializeAsync(settings);
        }

        //stop recording when video ends
        private async void player_MediaEnded(object sender, RoutedEventArgs e)
        {
            await this.StopCapturingVideo();
            this.Frame.Navigate(typeof(MainPage));
        }

        //start recording when video starts
        private async void player_MediaOpened(object sender, RoutedEventArgs e)
        {
            await this.StartCapturingVideo();
        }
    }
}
```

Appendix F

Eyetab gaze estimation results

ParticipantID	No eyes in frame	No eyes tracked	<25% gaze estimated
1		x	
2		x	
3	x		
4	x		
5			x
6	x		
7	x		
8			x
9	x		
10			x
11			x
12			x
13		x	
14			x
15			x
16		x	
17		x	
18		x	
19	x		
20	x		
21			x
22			x
23		x	
24		x	
25		x	
26		x	
27		x	
28			x
29			x
30			x
31		x	
32		x	
33		x	
34		x	
35		x	
36		x	
37		x	
38			x
39		x	
40		x	

Appendix G

List of students involved in Educating Young Eyes project, as of December 2014:

Olajumoke Fajinmi

Carisa Chang

Harshada Hole

Sindhuri Bolisetty

Tuan Tran

Amrita Kaur

Prachi Singh

Anshu Priyadarshini

Ashley Bailey

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