Age Estimation of Adolescents Using Eye Measurements from Various Angles in Videos

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Abstract

Due to the prevalence of social media and devices like smartphones, photographs of oneself, or "selfies", have become extremely popular, especially with teenagers and pre-teens. Their appearance may be natural, but it may also be due to make-up, posing, clothing choice, or filter technologies available. By relying on measurements of features of the face, including the eyes and pupils, rather than appearance age, the age of an individual can be estimated with fewer hindrances. These "selfies" and other images can be taken at any camera angle relative to the front of the face and could be part of evidence in a criminal investigation. As a result it is necessary to have a way to estimate an individual's age while taking the angle into account. Institutional Review Board (IRB) approval was obtained in order to use human subjects. The target age group of participants was 11-19 years old. Because the pupil is affected by many variables, including mood, medication, and lighting, images were taken under controlled conditions with the illumination of the room documented. Participants were asked for their birthday and other general demographic information as well as basic questions regarding mood, medication, and eye problem history. A set of photographs and a video were taken using a Nikon® D3100 digital camera and an Apple® iPad® iOS Version 7.1.2. The photographs and stills from the videos were analyzed using Adobe® Photoshop® CS6, while videos were additionally analyzed using Adobe® After Effects®. Twelve of the twenty-one total participants participated in all four aspects of the study. While these spanned the entire age range and were evenly divided between male and female, most of them had irises that made confident distinction of the pupils difficult or impossible with Photoshop®. The few participants whose measurements could be determined did not align with the published equations from MacLachlan and Howland (2002). Measurements from the Nikon® videos indicated that the angle of camera yaw mattered, but the measurements did not consistently increase or decrease with increasing angle. Further research on this topic includes determining how various factors affect the measurements. These factors range from the presence of glasses and the camera quality to the movement of the camera in either of the other rotational directions or in any of the three possible planes. Any combination of movement should also be examined.

The relationship between the distance from the camera and eye measurements should also be examined. While the effect of lighting on pupil measurements is already known, verifying the relationship between lighting and measurement at various angles would be beneficial.

Literature Review

Forensic investigations regularly employ biometric analyses. Biometrics are based on biological or behavioral characteristics of people (Jain, 1999). The typical forensic biometrics are considered hard biometrics because they specifically identify an individual and, generally, only one. These include DNA and fingerprints. Other hard biometrics include face recognition and iris patterns. Other biometrics, like age estimation, are considered soft biometrics, which help identify individuals by providing extra information about them, but cannot be used for identification on their own (Fu, Guo, Huang, 2010).

For any biometric measure to be useful, it has to have certain properties. These properties include universality, uniqueness, permanence, collectability, acceptability, and low circumvention. Universality means everybody has this feature while uniqueness means nobody is exactly the same as anyone else. Permanence means it does not change with time. Collectability is the ability to measure the feature. Acceptability refers to the public's acceptance of it as an identifier. Low circumvention means it is hard to trick whatever system is measuring the feature (Jain, 1999). Soft biometrics, like age, are lacking in several of these characteristics. For instance, age is shared with many people and changes every year. It is also easy to alter the appearance age which is the age the visual appearance of a person implies (Fu, Guo, Huang, 2010).

Age is one of the many human traits that can be seen in the face. As a result there are two primary forensic approaches to using digital images with respect to age. The first approach, age synthesis, involves taking an image of a person and aging them according to the general natural aging process (Fu, Guo, Huang, 2010). This is done with missing children pictures in an effort to provide a more current picture of their appearance and help locate them. The second approach, age estimation, involves looking at an image and giving an exact age or an age group based on the visual information in the face. The actual age of an individual is his or her real age in years since birth. The perceived age is what a person thinks an individual's age is based on visual information (Fu, Guo, Huang, 2010).

The interesting thing about the aging process is that we all go through it at different rates. This is partly due to genetics and partly due to habits and the environments in which we put ourselves (Fu, Guo, Huang, 2010). This can complicate the age estimation processes. Another complication for age estimation using the whole face is variation in shape and texture. This applies both for an individual as he or she ages and among individuals of the same age (El Dib & Onsi, 2011).

Age estimation is not just a topic of forensic interest. It is also used in entertainment and security control and surveillance monitoring (Fu, Guo, Huang, 2010; Guo, et al., 2009). Surveillance monitoring can be used to help keep underage individuals from entering age-restricted movies or purchasing products like alcohol and tobacco (Fu, Guo, Huang, 2010). A study of human performance with the age estimation process found that it was easier for people to estimate the ages of children than of adults. The reasoning given for this was that, generally, facial profiles do not change after age 18 (Zeng, et al., 2012). For both humans and automated age estimation methods, the gender of the subject in a photograph affects the accuracy of age estimation. Humans have greater difficulty estimating the age of a male subject than a female (Zeng, et al., 2012). The gender that is more difficult for an automated method to estimate the age of depends on the particular method used (Guo, et al., 2009). Ethnicity of the subject has also been found to play a role in age estimation, both for humans and for automated methods (Guo & Mu, 2011; Zeng, et al., 2012).

There are numerous automated methods for age estimation with various levels of accuracy. Generally, the accuracy of these methods is measured in mean absolute error (MAE) or the average of the absolute value of the difference between the estimated age and the true age. Some of these methods include kernel partial least squares (KPLS or kernel PLS), active shape model (ASM) used to measure face shapes, and active appearance model (AAM) used to provide a statistical model of face shape. Machine learning methods include support vector machine (SVM) and support vector regression (SVR). There are also supervised manifold learning methods, including orthogonal locality preserving projections (OLPP), marginal Fisher analysis (MFA), and locality sensitive discriminant analysis (LSDA). Biologically-inspired features (BIF) is a method that performs well on its own and can also be combined with another method, such as the manifold learning methods (El Dib & Onsi, 2011; Fu, Guo, Huang, 2010; Guo, et al., 2009; Guo & Mu, 2011; Zeng, et al., 2012).

Rather than using the full face, some age estimation procedures use a particular component of the face or head. The change of cranial volume with age has been analyzed, from birth to 18 years of age (Purkait, 2011). This study was focused more on what percentage of the adult volume is present at each age. As a cross-sectional study, the estimate of what the cranial volume is at any given age does not fully account for individuals whose heads are larger or smaller than average in the same way a longitudinal study would. The author found that by the time of maturity, age 16 in females and age 17 in males, the cranial volume was 95% of the volume at age 18. Measurements of various portions of the ears have been used for general facial approximation, including age considerations (Guyomarc'h & Stephan, 2012). These measurements were found to be largely inconsistent with respect to other facial features and only slightly correlated with age.

The eyes have also been used for age estimation and general biometrics. The primary parts of the eye used for automated biometrics systems are the iris and the retina. The iris is an internal organ (Daugman, 1999; Poonguzhali & Ezhilarasan, 2013). It is protected from most of the environment by the cornea and the aqueous humor. The only component of the environment that affects it is light, resulting in dilation and constriction of the pupil. Even when the environmental light conditions are not changing, the iris causes the pupil size to oscillate at about 0.5 Hz. This steady-state oscillation is called hippus and is generally small. It is also easy to tell a program to track the hippus (Daugman, 1999). The iris pattern, like fingerprints, is determined during fetal development and can be used to distinguish between identical twins and between the eyes of the same person (Daugman, 1999; Poonguzhali & Ezhilarasan, 2013). This unique pattern is what iris biometrics systems scan and compare. Pupil size has been found to affect the accuracy of iris biometrics (Hollingsworth, et al., 2009). The retina is not studied in this project.

While the pupil is affected most notably by light, there are many other things that can affect its dilation. A person's mental or emotional state, his or her medications, and how well the eye is focused on an object all affect the pupil as well (Hollingsworth, et al., 2009; Lavezzo, et al., 2009; Watson & Yellott, 2012). These effects have to be taken into consideration in research in ophthalmology where numerous studies have examined pupil diameter. One of these studies studied the relationship between the pupil diameter and the corneal white-to-white distance (Cakmak, et al., 2012). The focus in that study was on the pupil diameter under mesopic (low lighting) conditions. A moderate correlation was found between the pupil diameter and the horizontal white-to-white distance. The authors also found that there was not a significant difference between genders for the horizontal white-to-white distance.

Other studies have examined the relationship between pupil diameter and age. Most of these studies have not looked at the relationship in children and young adults, but there are two notable studies with children. The first of these was a longitudinal study following participants ranging in age from one month to 19 years (MacLachlan & Howland, 2002). The participants' eyes were photographed each year under mesopic, or low lighting, conditions. Pupil diameters and interpupillary distances were measured from these photographs. Both of these were found to have a significant correlation with age, consistently increasing over the entire age range. The data for individuals aged 12-19 was less abundant due to dropout of participants as they got older.

The second study focused on children aged 4 to 6 (Lavezzo, et al., 2009). In this study, videos were taken of the children. The videos were considered to contain two different kinds of gazes: attentive and spontaneous, based on the amount of time elapsed. The attentive gaze corresponded with the child being less accustomed to the environment while the spontaneous gaze was considered to be after the child had adjusted and began exploring the room with his or her eyes. In general they found that the pupil diameter was larger for the attentive gaze than for the spontaneous gaze. The researchers also found that the diameters for both eyes were approximately the same and both were within the error of the measurement.

Introduction

This is the age of the Internet of Things, with digital devices, including cameras, all around us, possibly even constantly on us – and all capable of sending and receiving information including remote access commands across a network. Devices like smartphones and tablets have become nearly ubiquitous. Most smartphones and tablets are equipped with digital cameras allowing us to take pictures of anyone or anything at any time. As a result digital images have become common pieces of forensic evidence. While most of the images might be pictures from vacations or interactions with family and friends, some may have criminal content, such as child pornography. Many of the problems associated with facial recognition biometrics can also be found in these potentially criminal images. The lighting conditions are often unknown; facial expressions vary depending on the cooperation level of the subject or incentives behind the image; make-up may be used to make someone appear older; position and orientation are variable; and/or only part of the face may be visible (Weng & Swets, 1999). The angle at which the face is registered can also cause problems with facial recognition biometrics since most biometrics systems are not designed to account for various poses (Kato, et al., 2012).

One particularly common activity using smartphone and tablet cameras is the act of taking a picture of oneself, generally referred to as a selfie, which are generally shared with others, often via social media. The individual taking the selfie may be wearing make-up or fancy clothes or displaying an unusual facial expression. Photographic filters can be applied before or after taking the picture. All of this can alter the appearance and perceived age of the individual in the photograph. While facial expression may affect pupil size to some degree, the pupil can stabilize to its natural light-response size. As a result the pupil size and the distance between them can be used as an indicator of age. Since selfies and other digital images of people can be taken at any given angle, an examination of how various angles affect these measurements is necessary.

Materials and Methods

Due to the number of things that can affect pupil size, it was decided that photographs of individuals needed to be taken in a controlled environment. The target population was adolescents aged 11-19. Since minors are a protected population for research purposes, Institutional Review Board (IRB) approval was needed. Since this was a continuation of an earlier study, an extension of IRB approval was necessary. Once the necessary parent permission, child assent, and informed consent forms were updated, the IRB extension was granted for one year.

Participants were recruited through personal contacts of the research staff and through an emailed advertisement. Participants and their parents were brought into the room where the photographs would be taken to fill out the relevant consent forms. The consent forms were stored in random order and were the only place where participant names were recorded. The participants were then assigned a participant number and asked basic questions such as age, birthday, ethnicity, and mood. In addition, they were asked if they had any eye problems, such as needing glasses or contacts, and if they were on any medications.

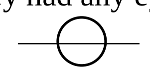

Figure 1. Symbol marking sensor plane.

Each participant was asked to sit all the way back in a chair such that the eyes would be 1.5 meters (59.06 inches) from the sensor in a camera that was mounted on a tripod. The sensor position is marked on the camera by a specific symbol, seen in Figure 1. The lux reaching the participant was measured using a Dr. Meter®

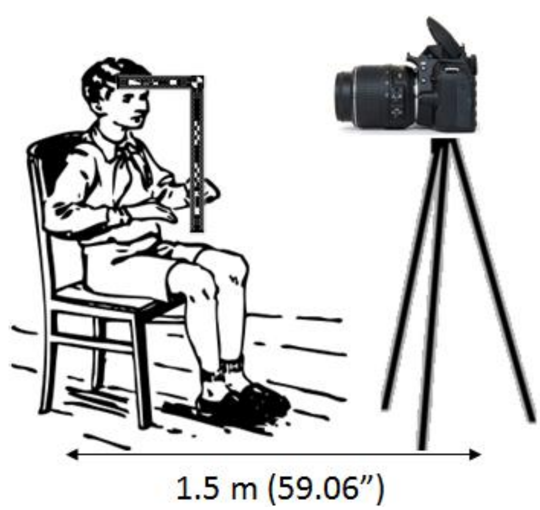

Figure 2. Nikon® camera set-up.

Digital Illuminance Meter (model LX1330B) and this reading was logged with the other participant information. The reading was taken with the sensor directed toward the camera at the position of the participant's eyes. One reading was taken for each participant. The participant was given crime scene ruler to hold in the plane of their eyes. This set-up can be seen in Figure 2.

A series of reference pictures was then taken using a Nikon® D3100 digital camera: one with the participant looking directly at the camera with an attentive gaze and one with them looking at a point past the camera for a spontaneous gaze. For participants with glasses, this series was repeated twice, once with glasses and once without. A short video was then taken using the Nikon® camera doing an approximate 60º pan to capture multiple angles of the face. The pan was started with the camera directly facing the participant and then panned left and right until one eye was out of frame. The participant was allowed to do this with or without glasses, whichever made him or her most comfortable.

The participant was then handed an Apple® iPad® with iOS version 7.1.2 to use to take a selfie and a short, approximately 15 second, video while moving the iPad® around the face, following the camera with their eyes. This video provided additional views of the face from various angles. The distance at which the iPad® was held from the face was also recorded. This set-up can be seen in Figure 3. The participant was also allowed to choose whether they wore glasses for the iPad® procedures.

Figure 3. iPad® camera set-up.

Once the images and videos were taken, they were transferred to a single password-protected computer in the MISDE lab at the Marshall University Forensic Science

Center (MUFSC). The SD card from the digital camera was attached via a USB write-blocking card reader and the files were copied. The iPad® files were copied using the generic USB iPad® connector. The files were placed in folders identifying the device used to collect them. They were also given names indicating participant number, participant age, gaze, and the presence or absence of glasses.

Video files were opened in both Adobe® Photoshop® CS6 Extended Version 13.0.1 (32-bit) and Adobe® After Effects® CS6 Version 11.0.4.2. In After Effects®, each video was processed using the 3D Camera Tracker to find the position and orientation of the camera for any given frame. For the Nikon® videos, the tracker was set to detect a tripod pan. Once the tracking process was completed, the 3D camera was created within After Effects®. Videos were then advanced frame-by-frame in Photoshop® to find good resolution frames that could be used for measurement purposes. These frames were then identified in After Effects® and the position and orientation of the camera was logged. Individual frames were saved as JPEGs identifying the participant number, age, and still number for that camera. All Nikon® and iPad® still photographs were automatically saved as JPEGs.

Each JPEG was then opened in Photoshop® for analysis. Images were given a custom measurement scale based on a 10 mm length of the crime scene ruler. If the image was at a noticeable angle, the pixel length of a 10 mm stretch above each eye was logged and used for the appropriate eye. The average of the two was used for measuring distances between them. The images were then cropped to show just the eye region of the face. The Channel Mixer was used and set to monochrome. The red, blue, and green channels were then adjusted as needed to clearly identify the pupil of both eyes while still keeping the appearance of a face. Circles or ovals were drawn around the pupils using the Ellipse Tool. The exact center of each was found by using a vertical line and a horizontal line drawn with the Line Tool, positioned with the Smart Guides on. The Line Tool was then used to draw a line from the center of one pupil to the center of the other. The Ruler Tool was used to measure the diameters and the distance between the centers using the appropriate custom measurement scale. All measurements were logged with the participant's number and age for analysis purposes.

Results

There were twenty-one (21) total participants in the study. Of these, twelve (12) were female and nine (9) were male. There were five (5) African-Americans, fifteen (15) Caucasians, and one (1) Mayan. Of the participants, only twelve (12) participated in the Nikon® video study and eleven (11) of those twelve also did the iPad® video with a scale. All data analysis was done focusing on these twelve participants, six (6) male and six (6) female. The breakdown of participant ages is shown in Table 1, while the breakdown of vision problems is shown in Table 2. Since medications and moods can affect pupil diameter, the general breakdown of these are shown in Tables 3 and 4, respectively. Medications taken were primarily for asthma or attention disorders.

Initial measurements were done using the Nikon® attentive photographs. The measurements of the pupil diameters and interpupillary distances for the females are shown in Figures 4 and 5, respectively. The measurements for the males are shown in Figures 6 and 7. The

Table 1. Participant Ages.

11	12	13	14	15	16	17	18	19
2	1	2	3	0	2	0	1	1

Table 2. Participant Vision Problems.

Glasses	Contacts	None
2	3	7

Table 3. Participant Medication Status.

Yes	No
6	6

Table 4. Participant Moods.

Excited	Content	Tired	Bored	Hungry	Mixed
1	4	1	2	1	3

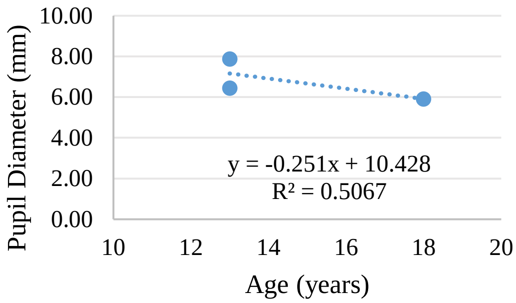

Figure 4. Female Pupil Diameters. The best fit equation and the R^2 value are displayed on the graph.

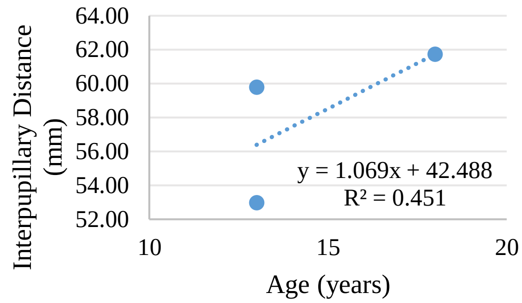

Figure 5. Female Interpupillary Distances. The best fit equation and the R^2 value are displayed on the graph.

equations represented were as follows, with x representing participant age in years:

$$\text{Female pupil diameter (in mm)} = 10.428 - 0.251x$$

$$\text{Female interpupillary distance (in mm)} = 42.488 - 1.069x$$

$$\text{Male pupil diameter (in mm)} = 27.719 - 3.6525x + 0.1482x^2$$

$$\text{Male interpupillary distance (in mm)} = -132.52 + 27.963x - 0.9948x^2$$

Only three (3) of the Nikon® videos allowed visualization of the pupil anywhere other than the initial frame. All three (3) of these were male participants. The data for the clearest frames is shown in Table 5. The camera positions are relative to center and are determined by which direction the camera was turned and are based solely on the yaw motion, or rotation around the vertical axis through the camera.

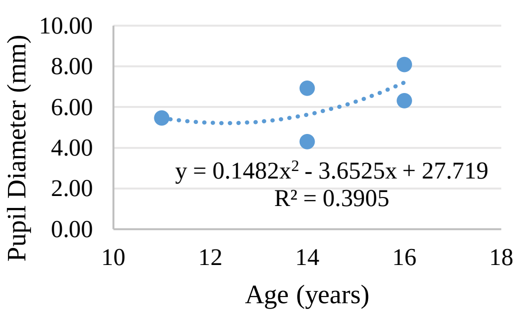

Figure 6. Male Pupil Diameters. The best fit equation and the R^2 value are displayed on the graph.

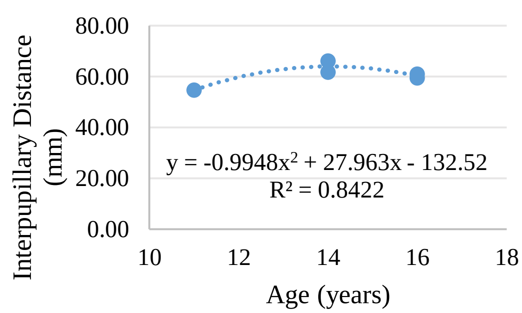

Figure 7. Male Interpupillary Distances. The best fit equation and the R^2 value are displayed on the graph.

Table 5. Pupil Diameter and Interpupillary Distances Resulting from Camera Yaw Rotation.

Age	Angle (°)	Pupil (mm)	Interpupillary Distance (mm)	Camera Position
14	0.0	5.95	59.88	Center
14	5.0	5.42	60.72	Right
14	11.7	6.33	58.60	Right
14	23.6	5.94	61.29	Right
14	28.4	5.10	60.91	Right
14	5.0	6.34	57.82	Left
14	22.8	5.59	60.90	Left
14	0.0	4.69	58.71	Center
14	6.8	5.00	61.84	Right
14	16.9	5.20	58.19	Right
14	25.5	5.28	61.12	Right
14	4.7	4.69	58.68	Left
14	19.9	5.37	60.48	Left
16	0.0	6.15	59.59	Center
16	5.5	5.94	60.31	Right
16	17.0	5.28	56.39	Right
16	24.8	5.53	58.86	Right
16	5.7	4.69	59.69	Left
16	11.8	5.59	58.53	Left

Discussion and Conclusions

Most of the participants had brown eyes. In general, if the pupils could be distinguished from the irises, it was only possible in the Nikon® photographs and not the video stills or the iPad® photographs. This could be, in part, because of the differing camera qualities. The D3100 is a 14.2 megapixel camera in its traditional photograph mode. When doing video, however, it is only a 2 megapixel camera. The iPad® front camera, by comparison, is a 1.2 megapixel camera with 0.9 megapixel video. An examination of the images and stills from the iPad® confirmed that the pupils of brown eyes could not be distinguished. Another possible explanation is the position of the setup relative to the lights caused interference at the pupil/iris boundary. An example of

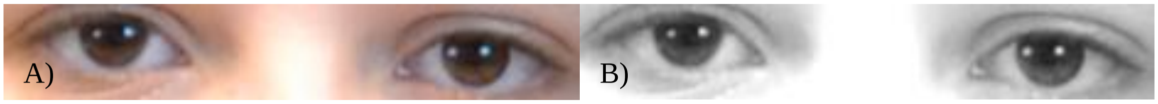

Figure 8. Eyes Showing the Difficulty of Distinguishing Pupils from Brown Irises. A) The original coloration. B) After setting the image to monochrome.

Table 6. Smartphone Camera Qualities.

Brand	Model	Front	Front Video	Rear	Rear Video
Asus®	ZenFone™ 6	2 MP	--	13 MP	--[1]
Nokia®	N8-00	0.3 MP	QCIF (176*144) (0.02 MP)	12 MP	720p (1280*720) (0.9 MP)[2]
Nokia®	Lumia™ 535	5 MP	FWVGA (848*480) (0.4 MP)	5 MP	FWVGA (848*480) (0.4 MP)[3]
Nokia®	Lumia™ 1520	1.2 MP	720p (1280*720) (0.9 MP)	20 MP	1080p (1920*1080) (2 MP)[4]
Motorola®	Moto G (2nd Gen)	2 MP	--	8 MP	--[5]
Sony®	Xperia™ T2 Ultra	1.1 MP	--	13 MP	1080p (1920*1080) (2 MP)[6]
Sony®	Xperia™ Z2	2.2 MP	--	20.7 MP	1080p (1920*1080) (2 MP)[7]
Samsung®	Galaxy Note 4	3.7 MP	--	16 MP	--[8]
Samsung®	Galaxy S®6 edge	5 MP	--	16 MP	UHD 4K (3840*2160) (8 MP)[9]
Apple®	iPhone® 4S	0.3 MP	--	8 MP	1080p (1920*1080) (2 MP)[10]
Apple®	iPad® (3rd Gen)	0.3 MP	VGA (0.3 MP)	5 MP	1080p (1920*1080) (2 MP)[11]
Apple®	iPhone® 6/6 Plus	1.2 MP	720p (1280*720) (0.9 MP)	8 MP	1080p (1920*1080) (2 MP)[12]

-- indicates that the data was unavailable. All data comes from the relevant manufacturer's website.
[1]https://www.asus.com/Phone/ZenFone_6_A600CG/specifications/. [2]http://www.microsoft.com/en-us/mobile/phone/n8-00/specifications/#head_camera. [3]http://www.microsoft.com/en/mobile/phone/lumia535/specifications/#head_camera.
[4]http://www.microsoft.com/en-us/mobile/phone/lumia1520/specifications/#head_camera.
[5]http://www.motorola.com/us/smartphones/moto-g-2nd-gen/moto-g-2nd-gen.html#specs-moto-g-titan.
[6]http://www.sonymobile.com/global-en/products/phones/xperia-t2-ultra/specifications/.
[7]http://www.sonymobile.com/global-en/products/phones/xperia-z2/specifications/.
[8]http://www.samsung.com/global/microsite/galaxynote4/note4_specs.html. [9]http://www.samsung.com/us/explore/galaxy-s-6-features-and-specs/. [10]https://support.apple.com/kb/SP643?viewlocale=en_US&locale=en_US.
[11]https://support.apple.com/kb/SP647?locale=en_US. [12]https://www.apple.com/iphone-6/specs/.

this difficulty is shown in Figure 8. Given this difficulty, the specifications of other smart devices were examined to see how the camera qualities compared. Some of these are shown in Table 6. In general, the older devices had poorer quality cameras. Even though the iPad® used in this study was older, the front camera quality of Apple® devices has not improved, as can be seen by the iPhone® 6 specifications.

In part because of the difficulty in distinguishing pupils from irises, the iPad® videos were not fully explored. It was observed that the videos provided six forms of camera motion, left and right, up and down, toward and away, pitch (rotation about the side-to-side axis), yaw, and roll (rotation about the front-to-back axis). This combination of motion allowed the same overall angle to be formed multiple ways and complicated analysis. Each individual form of motion may have a different effect on the measurements from a given still.

The measurements that were obtained from the Nikon® photographs were taken in order to compare them with published data. The equations found in the study by MacLachlan and Howland (2002) were gender dependent. The equations were as follows, with k representing participant age:

$$\text{Female pupil diameter (in mm)} = 5.40 + 0.285k - 0.0109k^2$$

$$\text{Female interpupillary distance (in mm)} = 41.76 + 1.891k - 0.052k^2$$

$$\text{Male pupil diameter (in mm)} = 5.83 + 0.181k - 0.0053k^2$$

$$\text{Male interpupillary distance (in mm)} = 43.36 + 1.663k - 0.034k^2$$

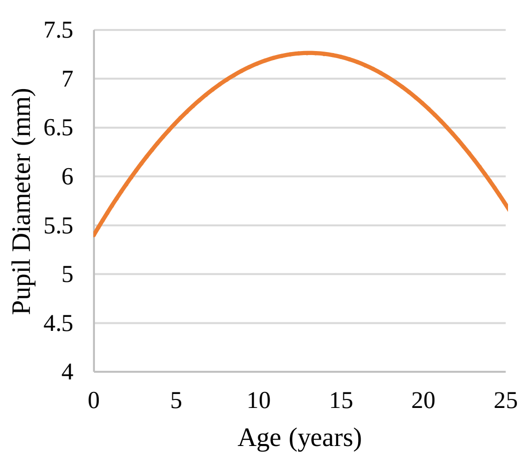

Figure 9. Female Pupil Diameter based on MacLachlan and Howland (2002).

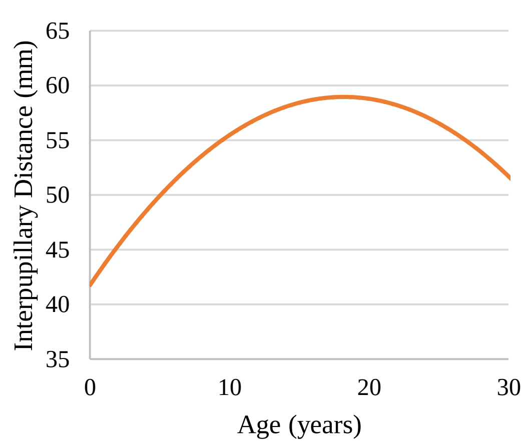

Figure 10. Female Interpupillary Distance based on MacLachlan and Howland (2002).

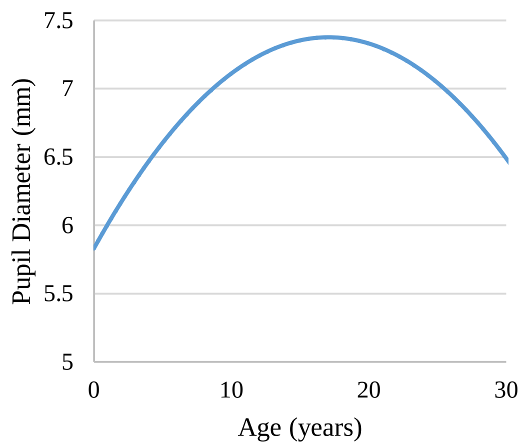

Figure 11. Male Pupil Diameter based on MacLachlan and Howland (2002).

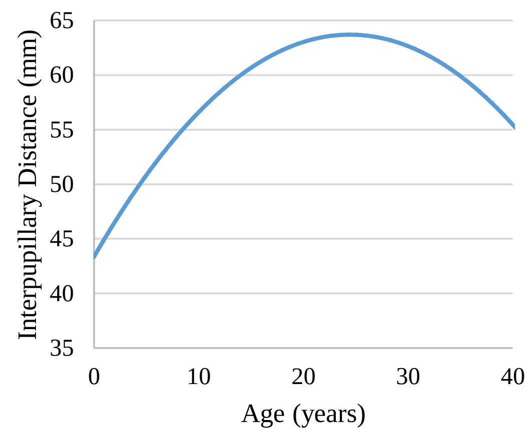

Figure 12. Male Interpupillary Distance based on MacLachlan and Howland (2002).

The graphs representing these equations are shown in Figures 9 and 10 for female measurements and Figures 11 and 12 for male measurements. When these were compared with Figures 4-8 and the equations they represent (above), there were noticeable differences. First, the equations for females in this study were linear instead of parabolic. This was because there were only two ages represented by three individuals. Second, the male equations, while parabolic did not have the correct values. The male pupil diameters in the study yielded a positive parabola as opposed to the negative parabola from the literature. This could also have been due to the poor participation in the study. Another possible explanation was that MacLachlan and Howland used lower lighting conditions for making their measurements. Lower lighting conditions should cause the pupils to be larger, although some of the measurements from this study were larger than the measurements from MacLachlan and Howland's study.

It was also observed that between the Nikon® photographs and the first frame of the video the pupil diameter and interpupillary distance were not necessarily the same. There were several possible explanations for this. First, the lower quality of the video may have made the boundaries of the pupils and the markings on the scale more blurred. Second, since thought patterns affect the size of the pupil, the participant may have had something suddenly come to mind that caused a change. Third, the natural hippus oscillation of the pupil may have played a role. If the photograph and the first frame of the video were taken at opposite extremes of the oscillation, the measurement would have been somewhat different.

There was no readily observable pattern between the angle from the starting point and the measurements made. Both the pupil diameters and the interpupillary distances increased and decreased regardless of angle. The changes may have been the result of the angle or the factors mentioned above. It was also observed that the camera was pitching and rolling in some of the frames. Each of these was less than 2° in any given frame.

Future Studies

One consideration that arose during the course of this study was the inability to analyze images without a known scale in roughly the same plane as the eyes. An analysis of a video with a scale revealed that a scale based on another object of known measurement behind the participant would not provide the same result. There may be a way to use another object as a scale, but the relationship between scales at various points in the image is unknown at this time.

Since this study focused primarily on the effect of angles related to the yaw motion of the camera, the effect of angles related to pitch and roll as well as translational motion or position should also be examined. These should be examined individually and in various combinations. Even among children there are many people who wear glasses on a regular basis. The effect of the lenses on the measurements of the pupil has not been examined. Since it was found that the quality of the iPad® images was not always sufficient for identifying pupils, cameras of varying quality should be examined to see what the minimum quality is for always identifying pupils.

Features that can be reasonably measured even in low quality images should be examined for a relationship to age.

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