Automated Pupillometer Using Edge Detection in OpenCV for Pupil Size and Reactivity Assessment

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***Abstract*—Measuring pupil size and reactivity in Pupillary assessment is a vital part of preliminary checkup among hospital patients, as it helps in determining neurological disorders. This measurement can be done by either manual or automated. In a manual assessment, which is often performed using a penlight and pupil gauge, there is no standardized protocol used for reactivity. Thus, results can vary due to room conditions and inter-examiner variability. This subjective assessment can lead to misconclusion between clinicians on classifying the health condition of patients. Whereas with automated, which can provide objective measuring through the use of electronics technology with complex algorithms. But automated pupillometers are still currently being used for research purposes. In line with this, the proposed automated pupillometer would like to aid medical personnel in conducting an objective assessment in order to avoid inter-examiner variability. In addition, the said device would procure test data for partnered doctors to assess subjectivity of pupil speed as brisk, sluggish, or non-reactive.**

Keywords—Raspberry Pi; NoIR; Infrared; Pupillary assessment; Pupillometer; Inter-examiner variability; Digital Image Processing; Pupil Contour

I. INTRODUCTION

A. Background of the Study

One particular way to assist healthcare personnel in distinguishing patients' condition is through their pupil size. As of date, manual and automated pupillometer assessments are used in the medical field, although manual assessment is more rampant. Studies have proven that manual assessment is observed to have some variations on diagnosis of pupil size and reactivity. Disagreements in the gathering of data through manual assessment in pupillary reaction pegged as high as 39 percent, thus, automated assessment is preferred to use for it involves the usage of pupillometer [1]. The pupillometer provides a reliable and objective measurement of pupillary size through pupil light reflex, which ejects subjectivity from the pupillary evaluation. The pupil's reactivity to light helps medical personnel assess the condition of the patient. The pupils are generally equal in size which varies from 2 to 4 mm in diameter in bright light and 4 to 8 mm in dark for adults. When light shines directly on the left eye, normally the left pupil should constrict. By virtue of consensual pupillary light reflex, when a light shines on the right eye, the left pupil would also constrict. Otherwise, the pupil is said to be unusual if it fails to constrict to light or dilate to dark. Unequal pupil size of more than 1 mm and do not return to equal size indicates a sign of an eye, brain, blood vessel or nerve disease [2]. According to the study done by the National Institute of Technology of Mexico, the analysis of the pupillary response with light stimulus shows a possible diagnosis of diseases such as Alzheimer's, Diabetes, Melancholia, Neurological Disorders, and other physiological disorders. Likewise, the pupil response is an involuntary indicator to some phenomenon occurring in the human brain, as such in psychophysiological processing of cognition and emotion [3]. However, a study conducted by past researchers, about 2,329 manual pupillary exams showed low inter-examiner reliability which was performed simultaneously among clinicians [4]. With this, it is indeed that a measuring device for the pupils is necessary to lessen the inconsistencies in pupillary assessments.

The objective of the research is to develop an RPi-based automated pupillometer using edge detection in OpenCV. Particularly, the study aims (1) to measure the pupil size of both eyes in comparison to the manual method of pupillometry and (2) to produce a data that may possibly recommend the range of values in categorizing the pupil reactivity as sluggish, equally reactive, brisk or non-reactive at a measured pupil speed.

The proposed device will detect and measure the pupil size and reactivity benefitting the medical health personnel particularly in the medical field as a pre-assessment for disorders such as neurological, ophthalmological and psychological to be studied for further analysis.

The main focus of this proposal is to design a device that will measure the size and reactivity of the pupils in quantitative parameters which are in terms of millimeters for the diameter or pupil size and in millimeters per second for the pupil reactivity respectively as it reacts to the light stimulus. The device will not consider other parts of the eye except for the pupil, so a clear view must be provided. Also, it will only cover those who are non-visually impaired and having an iris color within the shades of brown. Lastly, the study will not cover the full diagnosis of the patient's

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condition since it will only provide quantitative values to aid medical health personnel for diagnosis.

B. *Review of Related Literature*

There are plenty known automated pupillometer made up to today. Pupillometer is a name for two different devices. One used in critical care medicine, which measures reactivity through measurement of the pupil light reflex, and the other used in ophthalmology, which measures the distance between pupils through visual stimuli [5]. The NPi-100 Pupillometer accurately measures pupillary size, latency, constriction velocity, and dilation velocity. The Neurological Pupil index (NPi) algorithm grades the pupillary light reaction on a scale between 0 and 5, providing a number for clinicians to track and trend. It requires no calibration by the user and is extremely easy to use. It takes over 30 pictures per second of the pupil's response to light stimulus. It displays the reading in both numerical and graphic form. It stores up to 3,000 readings on the device. It prints via infrared to a portable printer for hard-copy documentation. The limitation of this version is that the storage data are limited. The accessibility of the information gathered by this device is limited and can be easily compromised since it will print a hard copy of the data of the patient. The device itself cost around $2,000.00 [6]. The NPi®-200 pupillometer system developed by the NeurOptics Company is the improved version of NPi®-100. It is completely accurate, reliable and objective pupil size and reactivity data, independent examiner [7]. However, these devices are only available for research purposes still, to 20 countries which do not include the Philippines. Also, this type of technology can only be operated perfectly in private hospitals and the device itself cost around $8,000.00.

Nowadays, great interest for vision-centered researches aims for progressive developments in the medical field. Studies that aids patients and medical assessments such as "Implementation of eye gaze tracking technique on FPGA-based on-screen keyboard system using Verilog and Matlab" by Padilla, D. A. et al. [8], "Detection of three visual impairments: Strabismus, blind spots, and blurry vision in rural areas using Raspberry Pi by implementing Hirschberg, visual field, and visual acuity test" by Paglinawan, A. C. et al. [9], and "Color vision deficiency compensation for Visual Processing Disorder using Hardy-Rand-Rittler test and color transformation" by Balbin, J. R. et al. [10].

Diagnosing pupillary reactivity in relevance to neurological illnesses done by neurological nurses is essential in determining the root cause of the illnesses of patients and to further analyze where is the impact and how does it affect the health condition of a patient. The types of pupillary reactivity which is being done by neurological doctors during manual assessment to classify how they react on the presence of light are, (i) Non-Reactive/Fixed, which refers to the abnormal reaction of the pupil in which it does not constrict or expand in the presence or absence of light, (ii) Sluggish which refers to the abnormal reaction of the pupil in which it has a slow response to constrict when exposed to a light or expand when exposed to reduction of light, and (iii) Brisk which refers to the normal reaction of the pupil to constrict when exposed to light or expand when exposed to reduction of light [11].

As of date, manual pupillometer assessment is still more widely used in the medical field as a pre-assessment in determining neurological, ophthalmological and psychological disorders. Manual assessment, being subjective, is found out to be prone to inaccuracies and inconsistencies in measuring pupil size as well as a diagnosis on pupillary light reflex on patients which have always been a problem in the neurological field. According to NeurOptics, factors that cause inaccuracies in manual assessment includes (1) poor light condition, (2) examiner's visual observation, (3) strength, distance, and orientation of the penlight which showed an inter-examiner disagreement between medical health personnel in manual assessment as high as 39% [1]. Furthermore, neurological nurses tend to misgauge pupil size and unable to identify anisocoria and diagnose pupillary light reflex properly [4]. Moreover, the research done by Couret et al. on the reliability of standard pupillometry practice in neurocritical care showed that there was poor correlation between the gathered data on manual assessment and automated assessment on pupil size specifically between 2 mm and 4 mm and found out that nurses in the NCCU missed 50% cases of anisocoria and wrongly detected 16 cases of anisocoria while on the assessment of pupillary light reflex, there was an overall 18% error rate which is indeed alarming since pupillary light reflex is one of the most important examinations done by nurses on brain-injured patients [1]. The study of Kerr et al. on the underestimation of pupil size by critical care and neurosurgical nurses showed that subjective assessment on the pupil in terms of size and reactivity were not accurate since the medical health personnel underestimated pupil diameters hence were not able to detect anisocoria and failed to assess pupil reactivity as well [12]. Also the research done by Department of Neurology and Neurotherapeutics and Neurological Surgery of University of Texas Southwestern Medical Center on Interrater Reliability of Pupillary Assessments among Physicians and Nurses showed that there was a large degree of disagreement between trained observed in assessing the pupil which includes the pupil size and pupil reactivity [4].

II. METHODOLOGY

A. *Process Flow*

From Figure 1, the process starts with the display of the graphical user interface, which shows the live feed, the user data input, and the windows to display data for the captured pupils. The name and age of the patient must first be typed into the information column, the assessment for measuring pupil size under dark and light conditions comes after. Once the button is pressed, the image from the camera feed would be processed to undergo image processing, then display the captured image and pupil size in millimeters. There is no restriction as to whether which pupil or condition to go first, and once the pupil size assessment is satisfied, proceed to measure pupil reactivity. The video would undergo the same image processing, the change in pupil size as the light stimuli

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are applied would be recorded to calculate for the average speed of the constriction of the pupil. Once the pupil reactivity assessment is satisfied, the data is saved, and the process is terminated.

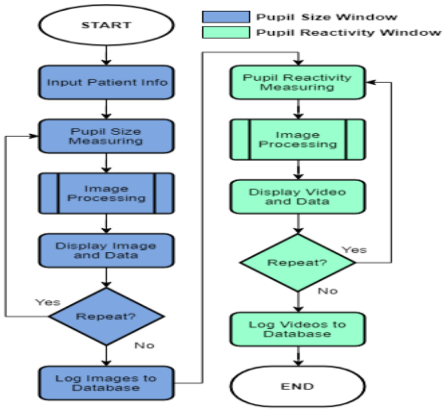

Figure 1. Process flow diagram

B. Block Diagram of the System

The block diagram of the device as shown in Figure 2 composed of three modules namely the accessibility module, database module, an image processing module. Each module comprises different electronic devices to implement the function of that specific module in which all of the modules are interconnected to the Raspberry Pi as the main device. The accessibility module comprises of the modules necessary in enabling the Raspberry Pi. Meanwhile, the image processing module are the modules needed to obtain captured pupil to be processed in determining pupil size and speed.

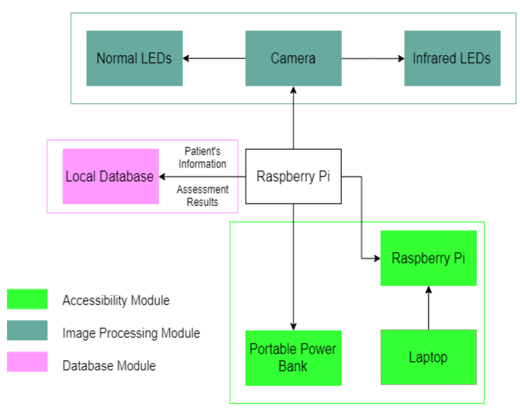

Figure 2. System block diagram

C. The Prototype

As shown in Figure 3 and Figure 4, the device features the use of an infrared Pi Camera, IR LEDs, and a 16 LED Ring Strip which is connected and powered by the Raspberry Pi microcontroller that runs on Raspbian OS. The system is enclosed inside a 3D printed casing and is powered by a removable power bank supported at the back of the casing. A 3D printed covering is also installed for the LEDs, which can be seen within the peephole to act as a light diffuser.

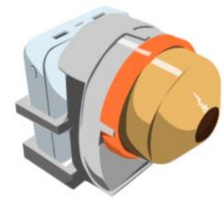

Figure 3. Overview of the prototype

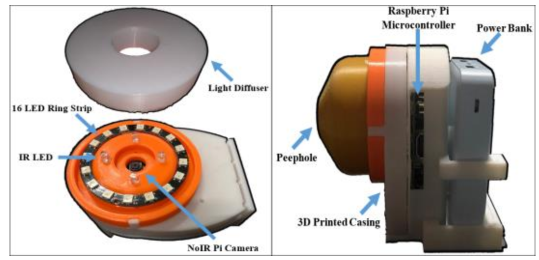

Figure 4. Internal and side view of the prototype

Figure 5. Pupil size assessment window

The initial window as shown in Figure 5 composed of the information box and the assessment for the pupil size for both left and right eye in dark and normal condition.

Figure 6. Pupil reactivity assessment windows

Meanwhile, the succeeding window as shown in Figure 6 focuses on the pupil reactivity on both eyes. It shows the average pupil speed of the eye being measure in millimeters per second (mm/s) as well as the basic information of the patient. An additional pop-up window automatically appears once the assessment for the pupil reactivity done to aid the medical health personnel in manually assessing the pupil reactivity condition of the patient whether brisk, equally reactive, sluggish, or nonreactive. Furthermore, the particular window also displays the save button to save all the gathered data to the local database.

D. Image Processing

The image captured in the live feed undergoes a series of image processing in order to detect and measure the pupil. The pre-processing begins with the capturing of a single frame from the video live feed displayed in the left side of

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the GUI. Once the frame is captured, it is further cropped into the guiding rectangle of the ROI (Region of Interest) in order to minimize the data to be processed.

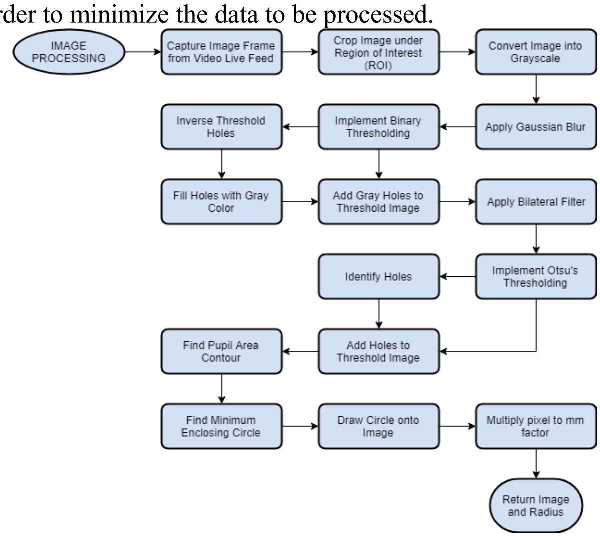

Figure 7 Image processing diagram

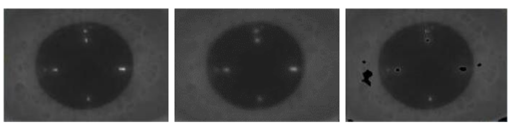

Figure 8. From left to right: (a) Grayscale Image, (b) GaussianBlur, (c) Threshold

To distinguish the pupil from the rest of the image, converting the 3-channeled colored image into a single channeled grayscale image is applied to reduce the processing time then apply Gaussian Blur onto the gray image to smoothen and reduce noise from the image as shown in Figure 8.a and Figure 8.b respectively. Then, thresholding is implemented as shown in Figure 8.c to output only a certain range of intensity, thereby capturing only the iris, pupil, and eyelashes and remove the sclera, skin, and visible white spots caused by the catch lights of the LEDs.

Figure 9. From left to right: (a) Inverse holes, (b) Gray holes, (c) Gray filled

To eject unnecessary holes, the image is first inverted using the previously used threshold as shown in Figure 9.a to identify the holes. The holes are then filled with gray color at a pre-determined intensity. The gray colored holes as shown in Figure 9.b is then added to the current threshold pupil image Figure 9.c.

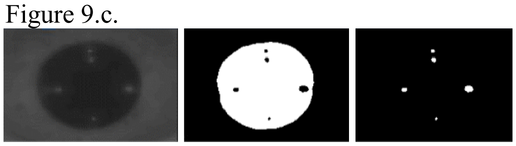

Figure 10. From left to right: (a) Bilateral Filter, (b) Otsu Threshold, (c) Pupil holes

To further smoothen out the crypts in the iris, bilateral filtering is applied as well as Otsu Thresholding to distinguish the pupil from iris by means of difference in histogram values as shown in Figure 10.a and Figure 10.b respectively. Further holes due to light coming from the IR LEDs are identified and ejected which are added to the result of the Otsu Threshold as shown in Figure 10.c

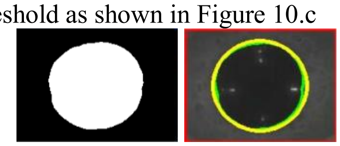

Figure 11. (a) Pupil Surface Area Figure (b) Pupil Enclosing Circle

The resulting binary image would resemble the detected pupil surface area. This image would then undergo Contour Detection which can determine the area of the pupil as shown in Figure 11.a allowing only a certain range of area to consider, with the intent of bypassing detection of other black elements in the image like the eyelashes. minEnclosingCircle algorithm is the applied to finally determine the center and radius of the detected pupil, which would then be used to draw the circle on the final output image as shown in Figure 11.b.

III. Results and Discussion

A. Calibration

To determine if the device is calibrated using statistical analysis, the device calibrated in which the obtained diameter using the device is compared to a black circle with a predetermined diameter and to any black circle-shaped object respectively for controlled and uncontrolled testing. In determining the t-value, the following equation is used:

$$t = \frac{\bar{x} - \mu_0}{\frac{s}{\sqrt{n}}} \tag{1}$$

where: t = t – value
$\bar{x}$ = sample mean
n = sample size
s = standard deviation

TABLE I. Controlled and Uncontrolled Testing

Trial	Controlled Testing		Uncontrolled Testing	
	Diameter	3 mm	Estimated Diameter of a Screw	4 mm
	Acquired Diameter Using the Device	Difference	Acquired Diameter Using the Device	Difference
1	3.09057 mm	-0.09057	3.91971 mm	0.08029
2	3.08193 mm	-0.08193	4.01986 mm	-0.01986
3	2.9499 mm	0.0501	3.98287 mm	0.01713
4	2.96874 mm	0.03126	4.04651 mm	-0.04651
5	3.09006 mm	-0.09006	4.05731 mm	-0.05731
6	3.02032 mm	-0.02032	4.06003 mm	-0.06003
7	2.99791 mm	0.00209	4.02403 mm	-0.02403
8	3.06255 mm	-0.06255	3.99941 mm	0.00059
9	3.0372 mm	-0.0372	4.07322 mm	-0.07322
10	2.99737 mm	0.00263	4.02588 mm	-0.02588
Average	-0.029655		-0.02088	
Standard Deviation	0.05103353		0.045256	
t- value	-1.83756334		-1.45919	

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Table 1 shows the values acquired by the device for the 3 mm given diameter in ten trials together with its computed difference, average, standard deviation and t-value and an estimated 4 mm diameter using a measuring tape for the controlled and uncontrolled testing respectively. Having t-value of -1.83756334 and -1.45919 for both testing, the resulting t-value is within the acceptance region between the Null Hypothesis (H_0), -2.262 and +2.262. Thus, the sample values are calibrated within certain degrees of error.

B. *Pupil Size Assessment*

In this part, the objective is to measure the pupil size of both eyes in comparison to the manual method of pupillometry. From the actual data obtained by the doctors in the manual assessment, it shows that the pupil size of each on both dark and normal conditions were estimated and ranged instead of estimating the size to a single unit. Meanwhile, the automated assessment using the device produces exact values on both left and right eye on both dark and normal condition. Hence, the average size in the manual assessment was determined using the following equation for comparison purposes:

$$\text{Sample Average} = \frac{\text{Lower Value} + \text{Higher Value}}{2} \quad (2)$$

Based from Table 2 and Table 3 pertaining to dark and normal condition respectively, it shows that values for pupil size obtained from the device in comparison to the average size from manual assessment respectively in both normal and dark conditions have close values together with very minimal difference to each other. Henceforth, it can be furtherly be evaluated that the device is consistent in providing pupil size values with very negligible difference from the manual assessment.

TABLE II. SAMPLE PUPIL SIZE ASSESSMENT UNDER DARK CONDITION

Pupil Size in Dark Condition (mm)								
Sample	Left				Right			
	Sample Average from Manual			Automated	Sample Average from Manual			Automated
	Doctor 1	Doctor 2	Doctor 3		Doctor 1	Doctor 2	Doctor 3	
1	5.5	5.5	5.5	5.9388	5.5	5.5	5.5	5.79422
2	4.5	4.5	4.5	4.46736	4.5	4.5	4.5	4.30111
3	4.5	4.5	4.5	4.14206	4.5	4.5	4.5	4.21107

TABLE III. SAMPLE PUPIL SIZE ASSESSMENT UNDER NORMAL CONDITION

Pupil Size in Normal Condition (mm)								
Sample	Left				Right			
	Sample Average from Manual			Automated	Sample Average from Manual			Automated
	Doctor 1	Doctor 2	Doctor 3		Doctor 1	Doctor 2	Doctor 3	
1	3.5	3.5	3.5	4.03371	3.5	3.5	3.5	3.85127
2	2.5	2.5	2.5	2.44964	2.5	2.5	2.5	2.74403
3	3.5	3.5	3.5	3.71348	3.5	3.5	3.5	3.75015

C. *Pupil Reactivity Assessment*

In this part, the objective is to produce a range of values in categorizing the pupil reactivity as sluggish, brisk, non-reactive and equally reactive based on the gathered data and the use of statistical analysis.

On the automated assessment, the pupil will be recorded through video while it is illuminated briefly by the LED. The speed would be determined by analyzing the rate of change of the size of the pupil before and after illumination. The video would undergo image processing frame-by-frame to measure its size. These pupil sizes would be logged to an array accordingly to its time frame. The maximum and minimum size would then be identified through the algorithm of the program, together with its respective time. The average speed of the pupil size can be computed using the formula:

$$v = \frac{\Delta d}{\Delta t} = \frac{d_2 - d_1}{t_1 - t_2} \quad (3)$$

where: v = velocity in mm/s
d_2 = maximum size at time t_2
d_1 = minimum size at time t_1

TABLE IV. PUPIL REACTIVITY ASSESSMENT ACTUAL

Pupil Reactivity					
Sample	**Manual Assessment**			**Automated Assessment**	
	Sluggish	**Equally Reactive**	**Brisk**	**Left (mm/s)**	**Right (mm/s)**
1			✓	4.98506	4.83487
2		✓		4.35003	4.44609
3		✓		3.64131	3.85037
4		✓		3.67374	3.71948
5			✓	4.99703	4.8266
6			✓	5.101	4.9968
7			✓	4.84694	4.98562

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8		✓		3.48472	3.53711
9		✓		4.11655	4.30403
10		✓		3.52366	3.5803
11			✓	5.04471	4.98163
12		✓		3.9611	4.10265
13		✓		3.11333	3.39572
14			✓	5.09583	4.93317
15		✓		2.80438	2.82224
16		✓		3.2866	3.04711
17		✓		4.38567	4.07094
18		✓		2.5102	2.56188
19		✓		3.97479	3.61036
20		✓		3.24029	3.19562
21			✓	4.92738	4.99473
22		✓		3.53623	3.3013
23		✓		3.67058	3.46913
24	L ✓	R ✓		1.72259	1.58939
25	L ✓	R ✓		1.19899	1.23955
26	R ✓	L ✓		0.96648	1. 06931

Table 4 shows the gathered data by the three doctors stating the pupil reactivity condition of the samples whether sluggish, equally reactive or brisk and the quantitative value of the pupil reactivity in mm/s obtained using the device on both eyes. Samples gathered are limited to normal and patients with known pathologies (e.g. previous history of stroke). No samples were gathered under non-reactive to light as this woulsd most likely be seen among deceased patients according to the doctors.

The gathered data by the device is then categorized and tabulated based on the condition evaluated by the medical personnel resulting to 33 equally reactive, 14 brisk, and 3 sluggish samples. Test for normality were done in each condition using the following equation:

$$g = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{(n-1)(SD)^3} \tag{4}$$

where: $\sum x$ = sum of all samples

$\bar{x}$ = sample mean

SD = standard deviation,

n = sample size

g = sample skewness

x_i = ith sample.

TABLE V. TEST FOR NORMALITY TABLE FOR EACH CONDITION

Parameters		Equally Reactive	Brisk	Sluggish
Skewness		-0.152081	-0.24367	0.352208
Standard Deviation		0.5049	0.08697	0.38729
Significance Level	α/2	0.025	0.025	0.025
Number of Samples	n	33	14	3
Degrees of Freedom	v	32	13	2
mean		4.96796	4.96796	1.29602
t 0.025		2.16	2.16	4.303
Confidence Limit	Upper Bound	3.74191	5.02483	2.25816
	Lower Bound	3.38384	4.91108	1.07996

The resulting value of the skewness for Equally Reactive condition is -0.152081, for brisk condition is -0.24367, and for sluggish is +0.352208. Thus, it is assumed that there is symmetry on normality on the distribution of the data since the skewness falls on the range of -0.5 to +0.5 validating the sample size of each condition.

T-test statistical treatment with 95% confidence interval is the determined to know the significant difference of each condition using the following equation in determining the upper and lower bounds of each condition:

$$\bar{x} - t_{\alpha/2}\frac{SD}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2}\frac{SD}{\sqrt{n}} \tag{5}$$

where: $t_{\alpha/2}$ = significance level,

$$\bar{x} - t_{\alpha/2}\frac{SD}{\sqrt{n}} = \text{lower bound} \tag{6}$$

$$\bar{x} + t_{\alpha/2}\frac{SD}{\sqrt{n}} = \text{upper bound} \tag{7}$$

TABLE VI. CONFIDENCE RANGE PER PUPIL REACTIVITY CONDITION

Condition	Pupil Speed Range Range (mm/s) Lower bound to Upper Bound
Non-reactive	0
Sluggish	1.07996 to 2.25816
Equally Reactive	3.38384 to 3.74191
Brisk	4.91108 to 5.02483

Table 6 shows the obtained range on each condition using the confidence interval formula. Meanwhile, on values falling under the gap between computed ranges, shall apply the condition closest to the corresponding bounding range.

IV. CONCLUSION

The pupil size assessment shows that the average pupil size per annually assessed sample is relatively close to the obtained size using the device for both dark and normal condition provided that the environment is dim. Hence, the device is capable of measuring pupil size at both conditions. Furthermore, the pupil reactivity assessment calculated the possible range of values for reactivity by treating the sample data size onto a T-test with a 95% confidence interval. The reactivity measured by the device is in terms of millimeters per second r second, namely: the nonreactive having a speed

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of 0 mm/s by default since nonreactive pupils denotes that the sample is already deceased and thus the pupils no longer react to light; brisk condition which fall under the range of 4.91108 mm/s to 5.02483 mm/s, equally reactive condition falling from 3.38384 mm/s to 3.74191 mm/s, and sluggish condition from 1.07996 mm/s to 2.25816 mm/s. On values falling under the gap between computed ranges, the condition closest to the corresponding bounding range.

V. RECOMMENDATION

The researchers would recommend a further study if the device can still capture the pupillary response given patients with varying iris pigmentation and incorporate a second camera to simultaneously capture the pupil size and reactivity for both pupils, in hopes of reducing the time it takes to complete the assessment. Increasing the sample size to have a more apparent range of values categorizing the pupil reactivity is also recommend and preferable to have more samples with abnormal cases. In addition, it is also recommended to conduct sample tests for varying age groups, to consider the factor of age in the variations of pupil size and reactivity.Alternative algorithms are also recommended to improve the image processes to better distinguish the pupil even in undesired room conditions and increase the processing speed.

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