Health and Technology (2020) 10:437–441
https://doi.org/10.1007/s12553-019-00366-9

ORIGINAL PAPER

Developing a visual perimetry test based on eye-tracking: proof of concept

Eduardo A. Martínez-González[1,2] · Alfonso Alba[1,2] · Martin O. Méndez[1,2] · Jorge Fernández-Wong[3]

Received: 15 January 2019 / Accepted: 22 August 2019 / Published online: 29 August 2019

Abstract
Computerized Perimetry (CP) is one of the clinical tests commonly used to evaluate peripheral vision and monitor the progress of eye diseases such as glaucoma. The aim of CP is to determine retinal sensitivity using luminous stimuli of variable intensity at different positions of the visual field. In modern campimetry devices, patients must respond to each perceived stimulus by pressing a button; however, this characteristic makes the test more susceptible to spurious and erroneous interpretations due to tiredness, lack of concentration, or device design flaws. This work presents an alternative paradigm for automatically assessing stimulus perception through a low-cost eye tracker and a computer monitor. We tested the preliminary version of the paradigm among eight subjects and obtained favorable results. In conclusion, our eye-tracking paradigm tool could help design more reliable visual field tests using low-cost portable equipment.

Keywords Computerized Perimetry · Eye tracker · Glaucoma · Visual field

1 Introduction

Human body deterioration is a natural and inevitable process, which negatively affects the health and lifestyle of most people. The sense of sight, which involves complex processing of signals in the nervous system, is one of the systems that are commonly affected by senescence [1]. According to 2017 statistics from the World Health Organization (WHO), approximately 253 million people suffer from visual disability, 36 million of which are completely blind. Adults aged 50 years or older account for a high percentage of the blind people, thus suffering mostly from cataracts (35%), refractive correction errors (21%) and glaucoma (8%) [2]. Similarly to many degenerative diseases, glaucoma is incurable and characterized by a gradual loss of the visual field, with no other symptoms such as pain. However, multiple clinical tests are nowadays available to diagnose, evaluate, and monitor the progress of glaucoma and other diseases of the retina and the optic nerve. One of these tests is computerized campimetry (CC) or computerized perimetry (CP) [1].

CC employs luminous stimuli of variable size and intensity, located at different points within the visual field. The goal of the test is to evaluate the sensitivity of the retina to the different light intensities by asking the subject to respond to the stimuli by pressing a button each time a stimulus is perceived. Under this paradigm, CC demands a considerable amount of concentration from patients, who must also focus their sight toward a specific area (usually the centre of the screen) during the test. After a few minutes, patients often become easily tired and/or distracted, which may lead to spurious responses and thus unreliable results.

An eye-tracker (ET) is a device that registers gaze location within a certain area, often using an infrared light source and a high-speed camera. Currently, ETs are successfully used in different areas of research and entertainment [3]. In the medical field, they have been used for a wide range of purposes, including the assessment of visual adaptability of glaucoma patients in daily activities such as walking [4], determining the impact of cataracts in eye sensibility [5], or proposing new campimetry paradigms to overcome the difficulty that some people have in fixating their gaze in the central luminous stimulus during a visual field test. This work proposes a

✉ Eduardo A. Martínez-González
arturomtz.2012@gmail.com

[1] Facultad de Ciencias, Universidad Autónoma de San Luis Potosí, San Luis Potosí, S.L.P, Mexico

[2] Laboratorio Nacional CI3M & CICSaB, Universidad Autónoma de San Luis Potosí, San Luis Potosí, S.L.P, Mexico

[3] Hospital de Especialidades Médicas de la Salud, San Luis Potosí, S.L.P, Mexico

low-cost system based on an ET to test the visual field as a proof of concept. The system analyses and classifies gaze trajectories without the need of a motor response from the subject.

2 Materials and methods

Our paradigm for visual field testing requires showing patients a moving visual stimulus on a computer, and then making them follow the stimulus with their eyes at all times. Initially, the stimulus appears at a reference position (i.e. the centre of the screen), yet once the system detects users fixating their gaze at the point of interest, it abruptly moves the stimulus to some peripheral point. If the stimulus lies within the healthy visual field, the patient will direct their sight toward the stimulus, resulting in a nearly straight trajectory between the center of the screen and the stimulus location. On the other hand, if the patient cannot see the stimulus, the resulting gaze trajectory will be random (as the subject searches for the stimulus across the screen) or will be fixed near the reference point. With this in mind, we hypothesize that gaze trajectory analyses performed by the ET will allow us to determine which of the peripheral stimuli were observed and which ones were not seen. This goal is achieved by extracting two features from each trajectory: angle difference with respect to the stimulus trajectory, and shortest distance between stimulus and gaze trajectory. Finally, we used two cascaded classifiers to categorize each stimulus as either observed or not observed.

2.1 Prototype specifications

We implemented the prototype in Processing language (v3.0.1 for Windows 64 bits), which is an open-source language derived from Java that simplifies the development of interactive graphical applications. Similarly, we employed a low-cost ET from The Eye Tribe, with a frame rate of 30 fps and an operating range of 45–75 cm. The system was implemented in an HP ProBook 4430 s laptop with the Windows 7 operating system running under a 64-bit Core i3 processor, an Intel HD Graphics 3000 video card, and USB 3.0 ports (required for the eye-tracker). Finally, we also employed a 20" LCD computer monitor (model Dell P2011HT) with a resolution of 1600 × 900 pixels.

2.2 Test subjects

Eight healthy subjects (one woman and seven men) from a public university, between 24 and 30 years old participated in the experimental tests. We obtained informed consent from all of them. Four of the subjects needed glasses to correct nearsightedness but were asked to perform the test without them.

2.3 ET calibration

Prior to the test, it is necessary to calibrate the ET for each subject. To do this, a short animation is employed by our system. The animation shows a sequence of nine little red circles for approximately two seconds each, as depicted in Fig. 1, and the subject is asked to fixate their gaze at each circle. The ET registers the patient's gaze direction for each of the nine targets and from this data determines the calibration parameters.

2.4 Implementation of the proposed paradigm

Before performing the test, each participant was given instructions and then performed the calibration stage. Those subjects who used glasses for nearsightedness were asked to perform the test without glasses to avoid interference from reflections in the glasses. Each participant sat 45 cm away from the screen to be comfortable during the experiment. Similarly, we placed a customized chin-rest to avoid undesirable head movements and reduce fatigue. Figure 2 depicts the prototype system.

Figure 3 introduces a block diagram of our paradigm. A reference stimulus (RS) is presented at the center of the screen. When the subject fixates their gaze on this stimulus for at least one second, the stimulus is abruptly moved towards the periphery. This peripheral stimulus (PS) is shown for 600 milliseconds, and then, it is moved back to the reference position to prepare the subject for the next PS. If the RS is shown for more than three seconds without the subject staring at it, a simple animation, consisting of a ring of decreasing radius, is displayed to attract the subject's sight to the center of the screen.

During our experiment, we used two types of PS: visible peripheral stimuli (VPS) and non-visible peripheral stimuli (NVPS). In terms of implementation, the only difference between VPS and NVPS is that NVPS have a null intensity contrast; that is, they are shown in the same color as the background; hence, it is impossible for the subject to see them. On the other hand, VPS offer a high contrast with the background. Specifically, VPS were shown in violet, corresponding to

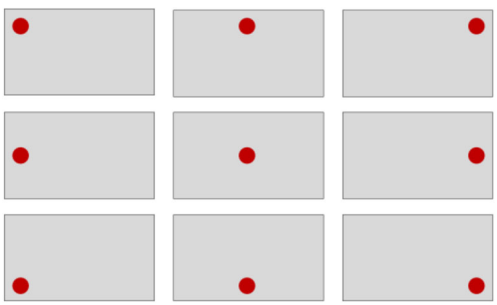

Fig. 1 Target locations during calibration. The targets appear in sequence from left to right, top to bottom

Fig. 2 Subject executing the proposed visual test

(182, 0, 255) on an eight-bit RGB scale, whereas the background and NVPS were shown in gray (200 on an eight-bit grayscale). All stimuli consisted of filled circles with a diameter of 16 pixels.

The PS positions were distributed in a polar grid, as shown in Fig. 4. The grid is depicted here for reference but was never shown to the subjects. An artificial blind zone comprising NVPS was randomly chosen for each patient by selecting one position on the grid and all of its immediate neighbors. Hence, the blind zone consisted of up to nine grid positions. Each PS was shown exactly twice in a random sequence. Since there were 126 positions, a total of 252 peripheral stimuli were shown during the test.

2.5 Classification stage

A PS is classified as seen if two conditions are met: first, the trajectory direction of the subject's gaze is sufficiently similar to the PS direction, and second, the gaze trajectory passes close enough to the PS. Given that a gaze trajectory is composed of a sequence of 2D points, we applied least squares

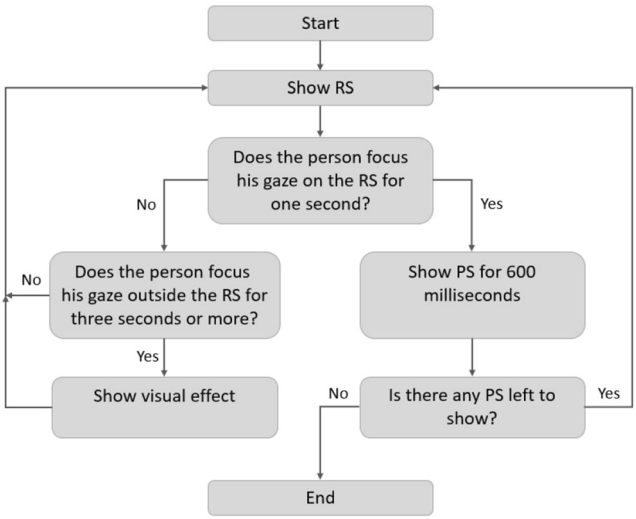

Fig. 3 Block diagram of the proposed paradigm for the evaluation of the visual field

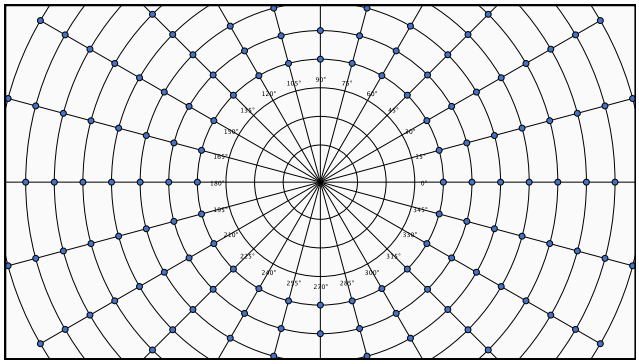

Fig. 4 Distribution of the 126 positions of the peripheral stimuli in a polar grid

regression on each trajectory to obtain the trajectory's direction, and then obtained the absolute difference between the trajectory's direction and the PS direction. We also calculated the shortest Euclidean distance between each point in the trajectory and the PS. In this way, we characterized each trajectory by two features: the angle between the trajectory and the PS, and the shortest distance between the trajectory and the PS.

Once the features for all PS were computed, we used a classifier to separate the PS that were seen by the subject from those that were not seen. The classification stage involved two cascading classifiers: first, we relied on a k-means classifier to obtain a pre-classification of the data. From this pre-classification, we developed Gaussian models for each class (seen / not seen) by computing their corresponding mean and covariance matrices. Then, we relied on a Bayesian classifier to reclassify the data according to the models, based on the Mahalanobis distance. Once we reclassified the data, we recomputed the models and applied the Bayesian classifier once more. This process was iterated until convergence. Figure 5 depicts the result of the classification process using the two characteristics mentioned before. In this case, blue points correspond to the stimuli classified as seen, whereas green points correspond to stimuli classified as not seen. The gray rings correspond to the mean of the not-seen class. Finally, note that we computed the classification models independently for each subject to account for perceptual differences between the participants.

3 Results

An expert visually analyzed all the trajectories acquired during the experiment in order to obtain the true class (seen/ nor seen) for each PS and perform a quantitative evaluation of the proposed classifiers. Table 1 summarizes our results for each subject and the average results. The first two columns list the number of seen peripheral stimuli (SPS) and not seen peripheral stimuli (NSPS) per subject, according to the expert visual

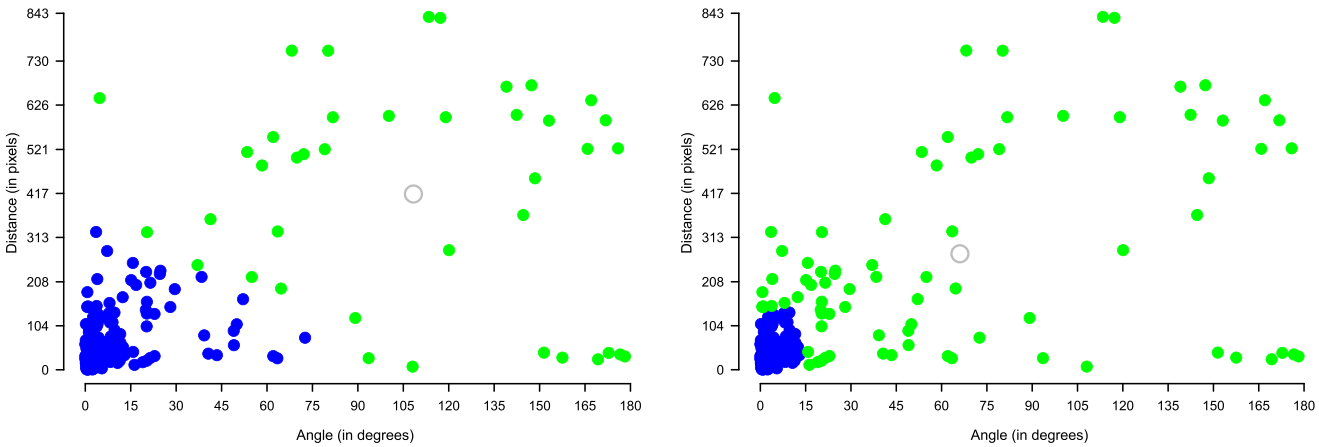

Fig. 5 Classification stage. (Left) Pre-classification of the data using a K-means classifier. (Right) Classification of the data using a Bayesian classifier

analysis; this information is considered as ground truth. The following four columns show the percentages of true positives (TP – SPS that were correctly classified as such), false negatives (FN – SPS that were wrongly classified as not seen), false positives (FP – NSPS that were wrongly classified as seen), and true negatives (TP – NSPS that were correctly classified) obtained from the classification stage. Finally, the last column lists the time taken for each subject to complete the test.

We used the trajectory analysis results to reconstruct the visual field map for each subject. Figure 6 illustrates the reconstructed map for subject 5, where the blue circles represent those stimuli that the classifiers detected as seen by the subject both times (as a reminder, a stimulus was shown twice at each position), whereas the red triangles correspond to those PS that were classified as seen only once. The black squares correspond to stimuli classified as not seen on both occasions. Finally, the positions marked with a black circle correspond to the artificial blind zone; that is, non-visible stimuli that should be classified as not seen. In this case, our system correctly detected the blind zone.

Table 1 Experimental results

Subject	SPS	NSPS	TP (%)	FN (%)	FP (%)	TN (%)	Time (min: s)
1	229	23	93.01	7.99	0.0	100	09:21
2	221	31	88.68	11.32	3.23	96.77	08:18
3	231	21	87.44	12.56	0.0	100	08:25
4	208	44	81.73	18.27	2.28	97.72	08:33
5	193	59	87.56	12.44	10.17	89.83	12:23
6	224	28	87.05	12.95	7.15	92.85	07:57
7	229	23	81.22	18.78	0.0	100	11:35
8	104	148	95.192	4.808	14.19	85.81	8:59
Average	204.88	47.12	87.73	12.39	4.63	95.37	9:21

4 Discussion

The results from the computational analysis of gaze trajectories revealed the expected behavior of the ET trajectories with respect to the two types of PS. That is, the system detected the subject's inability to see an NVPS, as well as their ability to see the VPS within their visual field. The reconstruction of the visual field map in Fig. 6 indicates that the subject in question struggled to see stimuli on the upper-left and upper-right regions of the polar grid, which deserves further investigation. As expected, each subject showed different behavior. During visual field tests, such as CC, it is important to correctly detect those regions where patients struggle to perceive relevant objects. In this sense, we consider that our classification method provides good results, with an average true negative rate of 95.37%, while also maintaining a relatively high true positive rate of 87.73% on average.

5 Conclusion

In this work, we demonstrate that it is possible to reconstruct the binocular visual field map by analyzing the trajectories obtained from an ET under a novel assessment paradigm, in which patients are not required to manually respond after each

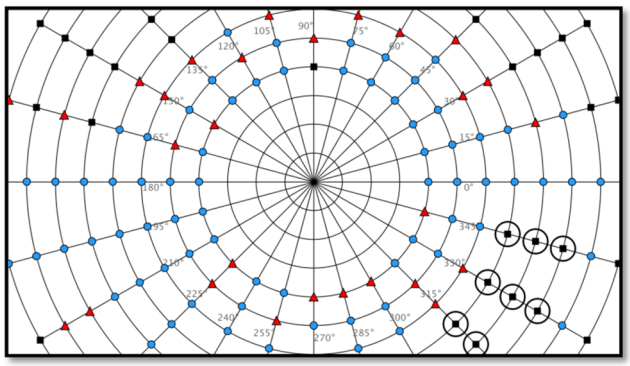

Fig. 6 Visual field reconstruction for Subject 5

stimulus. Similarly, our visual field assessment alternative can reduce patient fatigue, it does not require patient attention at all times. In other words, patients can blink, close their eyes, or look at somewhere else without affecting the results of the test. Instead, our system simply waits for patients to focus their attention on the reference stimulus to carry on the evaluation. Other advantages of our system include its low-cost, portability, and adaptability. That is, the software is implemented in an open-source platform and is easy to maintain and modify. As its main limitation, our system relies on an ET that needs both eyes open to detect gaze position. Consequently, the system can assess only the binocular field, whereas most perimetry devices evaluate the monocular field. To address this limitation, we are currently investigating different schemes for monocular field assessment using low-cost ETs. Future work will also focus on modulating PS intensity to make our system able to detect not only whether stimulus is observed, but also the intensity threshold value required for the patient to observe each stimulus.

Funding There is no funding source.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The study presented in this article was conducted following the ethical standards of the institution (Universidad Autonoma de San Luis Potosi) and the Helsinki Declaration of 1975 as revised in 2000 and 2008. The study only involves a non-invasive visual test where a visual stimulus (a moving circle) on a computer screen is presented to the subjects.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Barton JJS, Benatar M. An introduction to Perimetry and the Normal visual field" in field of vision: a manual and atlas of Perimetry, Ed. Humana Press Inc, 2003, 1–6.
2. World Health Organization. Blindness and visual impairment. 2017.
3. Gent E. For your eyes only [gadgets eye tracking]. Eng Technol. 2015;10(9):56–9. https://doi.org/10.1049/et.2015.0920.
4. Kasneci E, Black AA, Wood JM. Eye-tracking as a tool to evaluate functional ability in everyday task in Glaucoma. J Ophthalmol. 2017;2017:10. https://doi.org/10.1155/2017/6425913.
5. Thepass G, Pel JJM, Vermeer KA, Creten O, Bryan SR, Lemij HG, et al. The effect of cataract on eye movement Perimetry. J Ophthalmol. 2015;2015:9. https://doi.org/10.1155/2015/425067.
6. Murray I, Perperidis A, Brash H, Cameron L, McTrusty A, Fleck B, Minns R. Saccadic vector optokinetic Perimetry (SVOP): a novel technique for automated static perimetry in children using eye tracking" in 35th annual international conference of the IEEE EMBC, Osaka, Japan, 2013, 3186–3189. doi: https://doi.org/10.1109/EMBC.2013.6610218.