ORIGINAL ARTICLE

A New Approach for Lie Detection Using Non-Linear and Dynamic Analysis of Video-Based Eye Movement

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Received: 11 June 2022 / Accepted: 12 October 2022

Abstract

Purpose: This study aimed to evaluate a lie-detection system by non-linear analysis of video-based eye movement.

Materials and Methods: The physiological signals, as well as video-based eye movement in horizontal and vertical channels, were recorded based on a Control Question Test (CQT). The dynamics of eye movement signals were then analyzed by Recurrence Quantification Analysis (RQA). Statistical analysis was performed by ANOVA and Linear Discriminate Analysis (LDA).

Results: In this study, 40 subjects participated. The statistical analysis results of vertical eye movement indicated that Entropy (ENT) measures increased significantly for relevant questions in comparison to other questions. Moreover, a significant increase was observed in all RQA parameters except L_{max} and Determinism (DET) for horizontal eye movement. The results of LDA using psychophysiology features. The accuracy percentage of 78.4% and 81.86% were obtained for lie detection using physiological signals and optimal RQA parameters of video-based eye movements, respectively.

Conclusion: The accuracy of lie detection by significant RQA parameters was more than the accuracy of physiological signals. So, the results of this study illustrate that the dynamic technique is well suited to analyze eye movement signals under stress and it could be recommended as a useful method in lie detection.

Keywords: Recurrence Quantification Analysis; Eye Movement; Physiological Signals; Control Question Test.

DOI: https://doi.org/10.18502/fbt.v10i1.11516

1. Introduction

Lie detection has been used to identify the guilty for the past 75 years. It used psychological techniques [1]. The scientific community and applied research widely discuss the field of detection [2]. Several behavioral, linguistic, and psychophysiological clues have been investigated to uncover possible indicators of human lying, as dishonesty is thought to play an essential role in a variety of interpersonal interactions [3]. Scientists and forensic professionals have done their best to develop tools and procedures for detecting deception [4].

Physiological response measurements, particularly those associated with the polygraph, are frequently used for lie detection. In the case of lying, with the help of a procedure designed to increase automatic reactivity, this method is used [5]. Respiration, cardiovascular measures, and Electro Dermal Response (EDR) are among the most commonly used physiological measures in polygraph systems [6]. Many approaches to the psychophysiological detection of lies have been developed in recent years [7]. Voice and speech analysis [8], thermal imaging [9, 10], functional Magnetic Resonance Imaging (fMRI) [11, 12], event-related potentials [13], and changes in ocular parameters have been examined as possible alternative markers of deception [14, 15]. With the help of structures interacted with the automatic nervous system, these measures are derived. In such automatic measures, the emotional effects of deception are taken into account. One of the most widely used psychophysiological tests is called Control Question Test (CQT), which is extensively debated in the scientific literature and is used in criminal investigations in some countries [16, 17]. In the CQT, subjects (or suspects) are requested to answer three kinds of yes or no questions: control, relevant, or irrelevant to the crime. Detectors use different types of questions to detect deception [16]. The examiner can discover the offender using these physiological indications during the examination.

Change in eye movements due to the fight-or-flight is one of the responses of the body against stress. As a deceptive subject is questioned, he/she undergoes stress which activates the automatic nervous system. Afterward, the systematic nervous system starts responding to increase the eye blood flow to facilitate rapid eye movement in preparing for the fight-or-flight response [10]. Psychologists employ strategies such as rapid eye movements to recognize and cure stress. Because we almost use our eyes in all situations, eye movements may provide useful information for diagnosis and understanding of our activities. Rapid and abrupt eye movements necessitate viewing these motions as a time series obtained from a non-linear dynamic system [5]. The purpose of this research is to assess a lie-detection system using a non-linear analysis of eye movement in a polygraph exam. In a Control Questions Test, the person's comments are investigated by analyzing video-based eye movement as well as psychophysiology signals.

2. Materials and Methods

2.1. Data Collection in CQT

In this study, 40 students (20 men and 20 female) participated. Their mean age was 29.41 years (SD = 4.53 years). They were generally undergraduate students. None of the people had mental illness or psychophysiology problems and also eye diseases. CQTs were used for 40 students who were examined with a polygraph about a mock crime that all of them had committed. There are three general types of questions in the CQT including Relevant Questions (directly crime-related questions), Control Questions (focusing on general, non-specific misconducts of nature as similar as possible to the issue under investigation), and Irrelevant Questions (focusing on completely neutral issues) [16]. During the examination stage, a series of questions is presented to the examinee while continuously measuring several physiological reactions. In this study, physiological reactions such as photoplethysmography, electrodermal activity, respiratory changes, and eye movement were recorded. In the CQT, people were requested to randomly select one object among the five objects (such as a ring, money, bracelet, coin, and watch) and gave negative answers to all questions during the test time. As a result, the participants lied about one of the questions, which was about the selected object, and it caused to increase in their stress. Also, the presentation of these questions was performed by naming the objects, and participants answered NO to all questions, even the one they selected. At least 20 seconds time interval was considered between each question in order to record the provocations. The first question was an irrelevant question (neutral question). The data were collected in a laboratory with a temperature equal to 25°C and far away from noise and visual pollution by a standard polygraph system (CPSpro Plethysmograph 87010 Small Size, Stoelting

Co, USA). Data were saved on a computer with a sampling frequency equal to 256 Hz. Three physiological signals were used: changes in respiration (obtained from a tube attached around the abdomen), changes in electrodermal activity (obtained from two electrodes placed on the palmer surface of two fingers), changes in relative blood volume (obtained from an infrared photoplethysmograph sensor placed on the finger). The eye movement images were recorded by using the 60 frames per second camera (mobile camera, Samsung Galaxy S9). In the data recording protocol, when the question started, the video recording was started, and the videos were labeled according to the time file of the questions. Based on this, using the labeled file, the eye movements in each question are determined. According to this, we defined "t_2" as the ending time point for each question. The eye movement and corresponding physiological signals were recorded at "t_2". The eye movements in each question and corresponding signals were recorded three times (3 charts) for each subject.

A pre-test interview was conducted, the main stress level was produced, and their psychological conditions were arranged such that any variations in stress level throughout the questions were solely due to lying. The primary purpose of the interview was to gather demographic information and to enlighten individuals about encouragement. The study was carried out in compliance with the Helsinki Declaration; it was approved by the Local Ethics Committee (North Khorasan University of Medical Sciences), and all subjects provided written informed permission before inclusion.

2.2. Physiological Signals Analysis

For physiological signals, the first step is to eliminate the noises in signals to refine the signal from the disturbances. For this reason, special filters were used to remove high-frequency artifacts and power line interference [16, 17]. Min-Max normalization was applied to each subject in order to remove subject-dependent properties. In the proposed approach, three normalized physiological signals were evaluated based on extracted features in CQT [17]. The extracted features were as follow:

For the respiration channel, there are four empirically confirmed features that are considered diagnostic. Three features are suppression of respiration amplitude, reduction in the respiration rate (which includes changes in the inhalation/exhalation ratio if they result in respiration rate decreases), and apnea occurring near the exhalation cycle. The fourth respiration criterion is a temporary rise in the baseline of the tracing. For the electrodermal channel, scores are based primarily on a comparison of the peak amplitude. Amplitude is measured from the pre-stimulus baseline to the highest peak achieved within the scoring window. The ratio of the relevant and comparison question is calculated. For the photoplethysmography channel, the relative strength of the reactions is assessed by comparing the reduction in pulse amplitude.

2.3. Eye movement Signals Analysis

Many image processing techniques have been developed for eye pupil and iris segmentation [18]. Most of the iris and eye pupil segmentation methods use an Integro differential operator to localize the iris and eye pupil boundary accurately. Applying video-based techniques and an image processing system, the border between the iris and the sclera (limbus tracking) is detected and tracked. Measurements within ±15° can be achieved with an accuracy of 0.1°. Daugman proposed an Integro differential operator in order to detect the eye pupil and iris boundary [19]. Eye tracking by this method has some limitations. The biggest limitation is the subject's head movement, so five infrared sensors were located on the head to estimate the head movements. During the experiment, the subjects were requested to fix their head, and vertical and horizontal eye movements were tracked. The sudden vertical and horizontal head movements were estimated by an infrared network and eye tracking was optimized. The ratio of vertical iris coordinate changes to the iris center is obtained. To transform these changes into distance, the eye size is measured. In order to calibrate the eye tracking method, before starting the test, the person was asked to move his/her eyes to the right and left as well as up and down twice in a row to evaluate the changes in eye movements.

The dynamics of eye movement signals were then analyzed by Recurrence Quantification Analysis (RQA). Recurrence plots are indeed visualization of phase space trajectories using a two-dimensional graph. As the state of a system usually changes in time, the vector in phase space describes a trajectory that represents the dynamics of the system. In fact, recurrence plots are a mathematical technique that allows visualization of the recurrence of dynamic systems. From the recurrence plots, some characteristic typologies such as homogeneity, periodicity, and the presence of drifts or disrupted patterns of the dynamic system can be visually inspected. Many researchers have developed the recurrence quantification analysis to quantify recurrence plots [20]. They defined measures using the recurrence point density and diagonal structures in the recurrence plot [21]. In this study, six recurrence variables were extracted for quantifying the recurrence plot. The first recurrence variable was Determinism (DET). DET measures the proportion of recurrent points forming diagonal line structures. The second recurrence variable was line max (L_{max}), which was simply the length of the longest diagonal line segment in the plot, excluding the main diagonal line of identity (i = j). Recurrence Rate (RR), which is the percent recurrences and density of recurrence points, was extracted as the third recurrence variable. The fourth recurrence variable was Entropy (ENT), which is the Shannon information entropy of all diagonal line lengths distributed over integer bins in a histogram. The fifth and sixth recurrence variables were Laminarity (LAM) and Trapping Time (TT). LAM is analogous to DET except that it measures the percentage of recurrent points comprising vertical line structures rather than diagonal line structures. TT is simply the average length of vertical line structures [21]. Each of the above parameters was calculated for all the questions from the reconstructed phase space of each two seconds eye movement. The feature extraction process was performed by Matlab (The Math Works, Natick, MA, USA). RQA parameters were calculated using the cross-recurrence plot toolbox 5.14 (R27.1) of Matlab.

2.4. Statistical Analysis

The Kolmogorov–Smirnov test was used to check for normality. A one-way ANOVA was used to test for differences between questions in CQT. A Post Hoc multiple comparisons with equal variances assumed (Tukey) were also performed to evaluate the extracted variables in Irrelevant-Control, Relevant-Control, and Relevant-Irrelevant. Linear Discriminate Analysis (LDA) was used to classify the data and separates relevant questions from the others. All statistical analyses were performed with the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL). A significance level of $p < 0.05$ was considered to be significant. Figure 1 shows the setup of the experiment and how to place the sensors for recording the signals. Figure 2 shows the schematic representation of signals analysis.

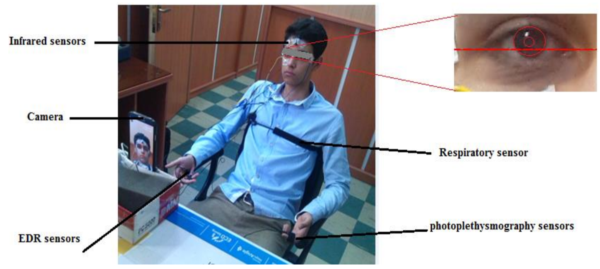

Figure 1. Setup of the experiment with photoplethysmograph, respiration, and electrodermal sensors for recording physiological signals and also camera and IR sensors for detecting eye movements

3. Results

After pre-processing and signals normalization, the variables were extracted from the signals in CQT. Fifteen out of 40 cases that had severe head movement were excluded from the study because of the subsequent problem in eye tracking detection using the IR sensor and camera. So, 25 cases (15 men and 10 females) were included for eye movement analysis in the study.

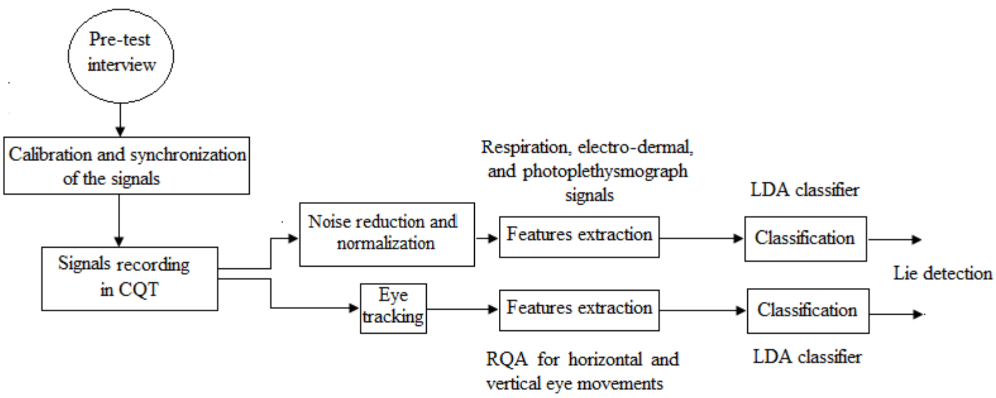

Figure 2. Schematic representation of recording and analysis of physiological signals as well as eye movement signals in CQT

There were 375 questions for the 25 participants in the 3 charts (25 * 5 * 3), 300 of which were irrelevant and control (used as non-relevant questions) and only 75 of which were relevant. Table 1 shows the results of LDA using psychophysiology features. Among 300 Non-relevant questions, 236 cases are identified correctly. Also, among 75 relevant (lie) questions, 58 cases are identified correctly. So, an accuracy percentage of 78.4% was obtained for lie detection classification.

The six measures of RQA include L_{max}, LAM, TT, ENTR, DET, and RR were calculated to analyze the eye signals in relevant questions compared to other questions. The three main parameters were required for RQA analysis. The time delay was considered 1, which was determined by initial minimum points in the mutual information function. The embedding dimension m was fixed to 1 using the false nearest neighbor method. The parameter ε was 10% of the maximum phase space diameter. After estimating the reconstruction dimension and delay time, the recurrence plot was created for all the questions from the reconstructed phase space of each 2 seconds eye movement.

Figures 3 and 4 illustrate the recurrence plots in 2 sec and 2-types questions for horizontal and vertical eye signals. The differences were found in the structure of patterns within recurrence plots in different questions, especially in horizontal signals. A higher proportion of points were grouped into diagonals in relevant questions. More points are predominant in the relevant question compared to the non-relevant questions.

RQA results from the different questions of CQT showed that all RQA parameters were normally distributed. Tables 2 and 3 represent the mean and standard deviation of RQA parameters for relevant, irrelevant, and control questions in two types of eye movement signals. The results from one-way ANOVA for horizontal eye movement time series indicated that no significant changes were observed between three types of questions for all RQA parameters ($p > 0.05$). Post Hoc analysis for horizontal eye movement showed significant differences for all RQA parameters except DET and L_{max} between relevant-control and relevant-irrelevant questions. For the RR, LAM, TT, and ENT parameters, a significant change was found between relevant and other questions but not between control and irrelevant questions.

The statistical analysis results for vertical eye movement indicated that there were no significant differences in the three types of questions. Post Hoc analysis for vertical eye movement showed significant differences between the relevant question and the others in ENT parameters.

Table 1. Lie detection by LDA classifier from extracted features of Psychophysiology signals in CQT

Type of Features	Type of Questions	Non-Relevant	Relevant	Accuracy (%)
Psychophysiology Features	Non-relevant	236	64	78.4
	relevant	12	58	

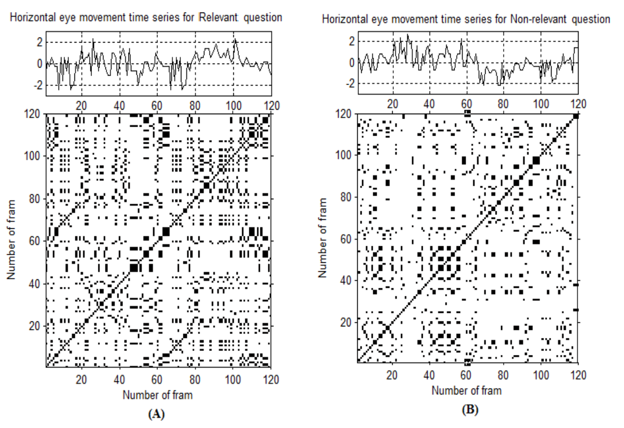

Figure 3. The recurrence plots of the 2-sec horizontal eye movements in (A) relevant and (B) non-relevant questions

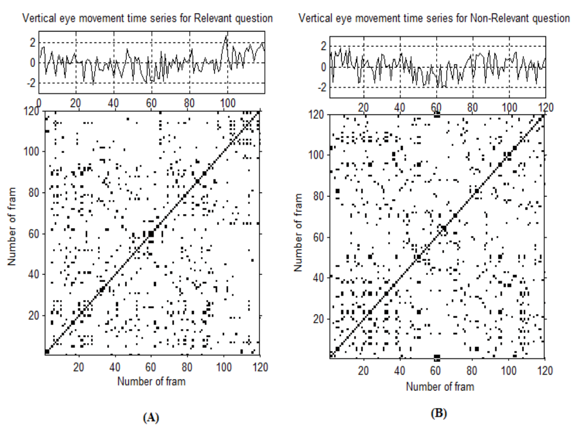

Figure 4. The recurrence plots of the 2-sec vertical eye movements in: (A) relevant and (B) non-relevant questions

Table 4 shows the results of LDA using RQA parameters of eye movement signals. By using optimal RQA parameters, among 300 Non-relevant questions, 244 cases are identified correctly and the others incorrectly and among 75 lie questions, 63 cases are identified correctly. So, the accuracy percentage of lie detection classification was obtained at 81.86%.

4. Discussion

This study examined the dynamics of video-based eye movement during different psychological states to see whether there were any changes in the ocular processes as a result of stress (lie) stimulation. There are noticeable variations in the recurrence plots for horizontal eye movement in 2-type questions. Results of RQA measures showed that significant differences were observed between the relevant and non-relevant questions in RR, LAM, TT, and ENT for horizontal eye movement and ENT for vertical eye movement signals. The statistical analysis results of the vertical eye movement time series indicated that ENT measures increased significantly for relevant questions in comparison to other questions. Moreover, a significant increase was observed in all RQA parameters except L_{max} and DET for horizontal eye movement.

The value of ENT was significantly higher in relevant questions compared to the non-relevant question in horizontal and vertical eye movements, which indicates more complexity and less deterministic behavior in relevant questions. The RR parameter quantifies the percentage of points that return to the same local neighborhood in the reconstructed phase space [22]. Relevant questions for horizontal signals showed a greater recurrence rate, indicating that the signal trajectory returned to the same phase-space regions more frequently. The measures LAM and TT mark a time interval during

Table 2. RQA parameters in 3-types question for horizontal eye movement

RQA parameters of horizontal signals	RR	DET	ENT	Lmax	TT	LAM
Irrelevant question	0.063 ± 0.065	0.28 ± 0.17	0.48 ± 0.15	2.23 ± 0.16	2.36 ± 0.47	0.48 ± 0.19
Control question	0.054 ± 0.069	0.25 ± 0.18	0.43 ± 0.13	2.29 ± 0.21	2.38 ± 0.55	0.34 ± 0.21
Relevant question	0.088 ± 0.082	0.37 ± 0.13	0.77 ± 0.14	2.36 ± 0.11	2.78 ± 0.47	0.62 ± 0.18
P-value	0.086	0.091	0.073	0.096	0.121	0.059

Table 3. RQA parameters in 3-types question for vertical eye movement

RQA parameters of vertical signals	RR	DET	ENT	Lmax	TT	LAM
Irrelevant question	0.057 ± 0.009	0.15 ± 0.06	0.31 ± 0.13	2.07 ± 0.16	2.11 ± 0.16	0.21 ± 0.06
Control question	0.061 ± 0.014	0.12 ± 0.07	0.32 ± 0.09	2.07 ± 0.21	2.08 ± 0.28	0.17 ± 0.12
Relevant question	0.052 ± 0.008	0.11 ± 0.13	0.55 ± 0.12	2.12 ± 0.11	2.09 ± 0.21	0.17 ± 0.07
P value	0.186	0.406	0.088	0.379	0.953	0.506

Table 4. Lie detection by LDA classifier from extracted features of eye movement signals

Type of features	Type of questions	Non-relevant	Relevant	Accuracy (%)
RQA parameters for horizontal eye movement	Non-relevant Relevant	160 31	140 44	54.4
RQA parameters for vertical eye movement	Non-relevant Relevant	203 23	97 52	68
All RQA parameters	Non-relevant Relevant	217 19	83 56	72.8
Optimal RQA parameters (RR, LAM, TT, ENT for horizontal and ENT for vertical)	Non-relevant Relevant	244 12	56 63	81.86

which a state does not change or changes very slowly [23]. Therefore, the higher their values, the more stable are the system.

With respect to changes over time, moreover, levels of the relevant and non-relevant questions exhibited significant differences for the first-time windows (2-second) in all RQA parameters of both eye movements but no significant differences in RQA parameters appeared during the other time windows. This result could be related to the onset of stress, which would appear more readily in the initial time of relevant questions. A significant increase was observed in RR, ENT, TT, and LAM between the 2 types of questions for eye signals. The physiologic reasons behind these performances could be rapid eye movement, which was probably caused by stress activation.

The details of the proposed classification method showed that the accuracy of lie detection by optimal RQA parameters was more than the accuracy of physiological signals. While polygraph approaches have produced classification accuracy of 65 to 95% [24], our results were in good agreement with the aforementioned report.

This study was conducted in laboratory settings and was experimental work. The disadvantage of experimental work is that passing or failing a test is not real and the participants may not take the test seriously. This will reduce reliability and increase error. In this study, this problem was improved by encouragement. The test used in this study is CQT. The reason for using this test is the lack of a person's head movements and the focus on improving the quality of the visual signals. Also because of changes in the eye, it is not only the changes caused by the chaotic eye movements. This study is an experimental work and by increasing and improving its results can be implemented in real systems. So, one of the important areas that should be considered in future studies in this area is the accuracy improvement of results and the actual implementation of the study on stress analysis and polygraph tests. Thus, the evaluation of nonlinear changes in eye movements indicates that these changes can make the difference between a lie and the right questions when compared with classic polygraph signals. It can be used as a method to enhance accuracy in testing stress and lie detection.

5. Conclusion

The goal of this study was to assess the dynamics of video-based eye movement during CQT in order to gain a thorough knowledge of the eye movement patterns that were present. The dynamic parameters used in this study were effective in uncovering concealed information in eye movement signals. The variations in eye movement signals obtained using dynamic factors in the relevant question versus the other questions might be attributed to underlying alterations in fast eye movement. This might be due to an abrupt shift in eye movements during stress. So, using dynamic parameters, one may graphically uncover hidden patterns and structural changes in eye movement, as well as detect commonalities across time series under stress. Furthermore, the accuracy of lie identification by major RQA factors was greater than the accuracy of physiological signals, indicating that the dynamic methodology is well adapted to analyzing eye movement signals under stress and might be suggested as a valuable tool in lie detection.

Acknowledgment

The authors would like to thank all the people who participated in this study. This study was supported by the Research and Technology Deputy, North Khorasan University of Medical Sciences. [Grant Number No. 4010165] & [Ethic Code: IR.NKUMS.REC.94.135].

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