Assessment of electrocardiogram visual interpretation strategy based on scanpath analysis

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Abstract: The automated ECG interpretation systems are supposed to follow the human expert reasoning. Despite of well established standards, the visual interpretation strategy of the human is still undisclosed today. The paper presents a new approach to the interpretation process research based on eyetrack features captured from a human expert during biosignal visual inspection. This approach required a set of visual tasks consisting in ECG interpretation by volunteers of different degree of expertise. The recorded eyeglobe trajectories were analysed in context of medical data represented in the displayed ECG traces and revealed interesting information on diagnostic data distribution and principles of interpretation strategies. The scanpath-derived data make benefit of oculomotoric habits gathering in everyday practice, unconscious mutual perception-recognition interactions and are not affected by human memory or verbalization limits. For these reasons they provide more objective assessment than any other method willingly controlled by the human. Beside of new information about the ECG contents and quantitative description of medical data distribution, our experiment reveals some eyetrack parameters as distinctive for interpretation skills estimation.

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1. Introduction

One of the common features of biosignals and an intrinsic property of the electrocardiogram is the irregular distribution of diagnostically important components in time. This widespread belief is commonly accepted, but rarely investigated. Consequently, rare are quantitative, signal content-related descriptions of irregularities that would be applicable for automatic estimation of instantaneous bandwidth. The control of adaptive biosignal and data transmission in distributed monitoring networks is the emerging area of prospective applications for general rules of data stream variability relating the medical content of the signal and its expected statistical parameters. Searching for the signal meaning beyond its technical parameters and the involvement of medical knowledge would not be feasible without the co-operation of experienced people. In this case, however results are very sensitive to human factors: prejudging, verbalization and others. Referring to human experts pool usually involves statistical processing of their outcome, very effective in suppression of inter-subject variability, but inadequate for systematic errors.

An original alternative to a standard questionnaire, is a visual experiment performed on cardiology experts aiming at capturing and investigation of local variations of the ECG trace conspicuity. Assuming proper observer engagement in the trace inspection, the gaze is controlled instinctively and the eyeglobe movements objectively represent the information gathering sequence. The analysis of experts' eyeglobe trajectories captured during the manual interpretation not only reveals regions of particular importance in the signal trace, but also reconstructs the human reasoning involved in the interpretation process. Therefore, except for our main interest in prediction of required transmission channel parameters from the automatic rough estimation of medical contents, the eyetrack features captured during the visual inspection of biosignals may be applicable in:

- implementation of human reasoning and non-verbalized rules in machine interpretation algorithms,
- objective assessment of cardiologist interpretation skills,
- teaching of the visual interpretation using the guided repetition of expert's scanpath,

For various scenes their perceptual models (PM) have been recently recognized as valuable tool for improving interaction of a human with sophisticated devices (Dick 1980, Ober 2002). The PM of the ECG is an outcome of statistical processing of scanpaths, analysed in context of background visual information. The fixation time and gaze order correspond to the amount of data gathered visually by the observer and represent the diagnostic importance of particular regions in the scene (Boccignone 2001). In case of the ECG, the waves' positions represent subsequent events in the cardiac cycle and in this context the concentration of foveation time along the horizontal axis express the local density of medical data.

The scanpath features are representative for quantitative measurement of data stream gathered from a particular point of the visual scene only when considering the physiology of human perception and oculomotoric system (Pelz 2001). Three groups of issues were identified as affecting the visual perception time:

- the randomness of observation start and finishing moments,
- the dynamics of seeking new target and the accuracy of eyeglobe positioning,
- the ambiguity of binocular perception

Automatic extraction of local conspicuity estimate from recorded polygonal curves requires proper detection of all these phenomena and correction of foveation time for each section of electrocardiogram. For this purpose, we developed a heuristic-driven pre-processing algorithm correcting observer-dependant issues influencing the relationship of gaze time and localization of the observer's interest.

The reported research aimed at the analysis of experts' eyeglobe trajectories captured during the visual ECG interpretation in following three aspects:

- identification of particular importance regions in the signal trace in context of represented medical information,
- examining and generalization of visual information pursuit strategies,
- selecting the eyetrack parameters discriminating the experienced and the untrained observers.

2. Materials and Methods

2.1 Visual task methodology

The research on the perceptual model of the electrocardiogram was based on a series of visual experiments. Each experiment was carried out with participation of a human volunteer performing sequentially a set of visual tasks. Every new observer answered a questionnaire specifying his or her degree of expertise, professional interest and sight defects if any. Next, the observer was instructed as he or she would be expected to give an interpretation of the displayed ECG's. Moreover, before each visual task, the observer performed a calibration procedure providing an individual scanpath transposition matrix. The matrix is calculated from differences between standard calibration rectangle coordinates and corresponding scanpath trace and used for correction of geometrical issues as far the eyeglobe capturing conditions are maintained. Each visual task consisted of three stages:

1. the observer received a certain standardized knowledge and was motivated to complete the information from the scene,
2. the observer scrutinized the scene in an unrestricted manner, however only 8 initial seconds of scanpath signal were analysed,
3. the observer announced the completion of the task.

At each stage, the scanpath may be influenced by unexpected observer's behaviour or other human factor, therefore high degree of co-operation is essential. During the experiment the diagnoses were not evaluated mainly for the lack of methods available.

2.2. Eyetracking device

In visual experiments we used the infrared reflection-based eyetracker OBER-2 (Ober 1997). The goggles illuminate each eyeglobe with four adjacent spots of total power of 5 mW/cm^2 in infrared pulses (wavelength 940nm) lasting for 80μs repeated at the sampling frequency. Four IR sensors per eye work in a pairwise space-differential configuration and capture two-dimensional trace of each eye at the speed of 750 samples per second during the ECG presentation lasting for 8s. Since the sensor captures the visual light as well, a double sampling method is used for the sidelight discrimination. This specific time-differential measurement relates the actual infra-red reflection readout to the sidelight background captured ca. 80μs before the LEDs become active. This measurement method eliminates the influence of all common light sources except for high frequency fluorescent bulbs, and allows the device to achieve the angular resolution of 0.02 deg. This value is equivalent to the ECG time interval of 30 ms if a standard chart plot (25mm/s) is viewed from a typical reading distance (40 cm). The position of both eyes was recorded simultaneously, however only the dominant eye was used to determine the electrocardiogram conspicuity. Figure 1 displays the physical background of the differential infrared reflection-based eyetrack acquisition.

2.3. Observers population

The recordings of scanpaths were made in similar laboratory conditions in volunteers during manual interpretation of ECG traces. For the visual experiment we invited 17 experts (12 +/- 4 years of experience) and 21 students having only basic knowledge about the ECG. Before attempting the visual task, all observers completed a questionnaire specifying their professional specialisation, practise and skills in ECG interpretation as well as describing the eyesight defects they eventually have. As the experts in majority wear glasses, we had to check the side effect it has to the scanpaths. We found no significant difference in traces but only if the positions of the glasses and of the eyetracker goggles remain unchanged from the calibration to the measurement phase.

2.4. Reference traces

As visual targets we used randomly selected CSE recordings (Willems 1990). The reference wave borders were not displayed but provided the cardio-physiological background for the scanpaths signal processing. Considering the borders of electrocardiogram waves in the scanpath analysis was a key point of finding the relationship between a cardiac event and the amount of information its representation contributes to the final diagnosis.

Each observer was asked for interpretation of 8 traces. Each trace from the dataset 3 appeared 2 to 4 times (2.43 on average). Pacemaker-stimulated recordings no. 67 and no. 70, were excluded for the lack of waveform measurement points in the database.
Since the scanpath analysis aimed at the features of a spontaneous expert action and the knowledge he or she uses to search the visual information from the chart, only the initial 8 seconds of the interpretation was recorded. We assumed that initial interpretation stages, common for all presented traces, end with wave morphology recognition, for which the presentation of one full heartbeat is sufficient. The ECG recordings used for the experiment were standardized in the length to 800 samples (1.6 s at the sampling frequency of 500Hz) and centred on the representative QRS complex. Waveforms were presented on a computer display simulating a typical 12-leads paper recording. The reading distance was set to 40 cm and controlled with use of a chin support. Each presentation of the ECG trace was interlaced with the fixation point in the middle of the display.

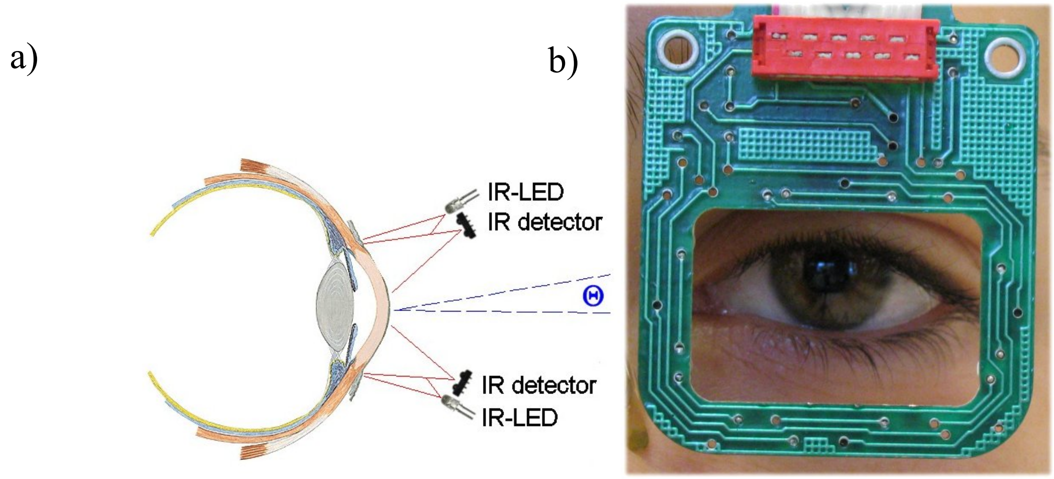

Figure 1. a) Physical principle and b) technical details of the infrared reflection-based eyetracker OBER-2

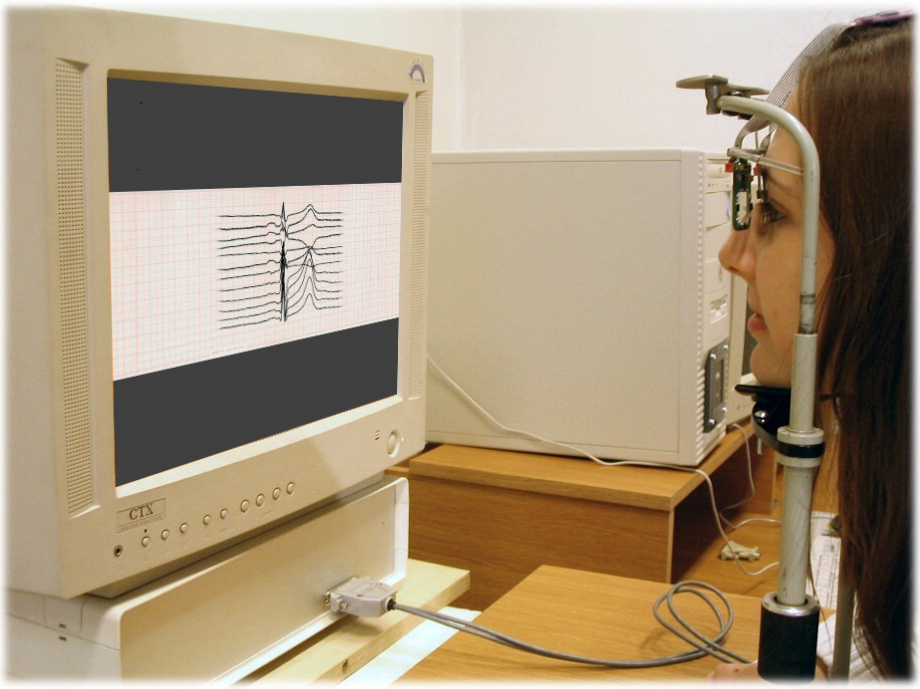

Figure 2 The expert volunteer performing a visual task on ECG interpretation. During experiments the ECG was displayed at the speed of 25mm/s in order to simulate typical paper charts. For the reason of clarity, the ECG in the figure is exceptionally represented at 100mm/s

2.5. Scanpaths signal processing

Each visual experiment provides a four-column matrix representing raw eyeglobe coordinates at the evenly spaced time points (Salvucci 2000). Prior to the ECG traces investigation, the observer is asked to gaze at the corners of displayed calibration rectangle. Identification of these gaze points in the eyetrack allows to calculate display-relative coordinates from the A/D converter output.

All signal processing routines were developed in Matlab with regard to the aims of visual experiments. Main stages of this calculation include:

- detecting the true confines of visual perception in the scanpath: the end of initial idle time and the interpretation task completion time,
- qualification of each foveation point in the scanpath as belonging to the particular ECG section (i.e. P, QRS and T) with use of a set of reference wave borders provided in the CSE database
- averaging of the number, duration and order describing foveation regions, separately for each ECG section in all ECG displays,
- referring of the contribution of each section's conspicuity to the true visual engagement time.

Since the foveation points are not directly referred to the ECG time, the intrinsic variability of waves' length does not influence the result.

Apart of the waves conspicuity statistics, the duration and order describing foveation regions reveal the perceptual strategy related to main stages of the ECG interpretation process. The principle of strategy description is the identification of most attractive points coordinates and their gaze order aiming at relating the foveation regions to the ECG events and displayed ECG leads.

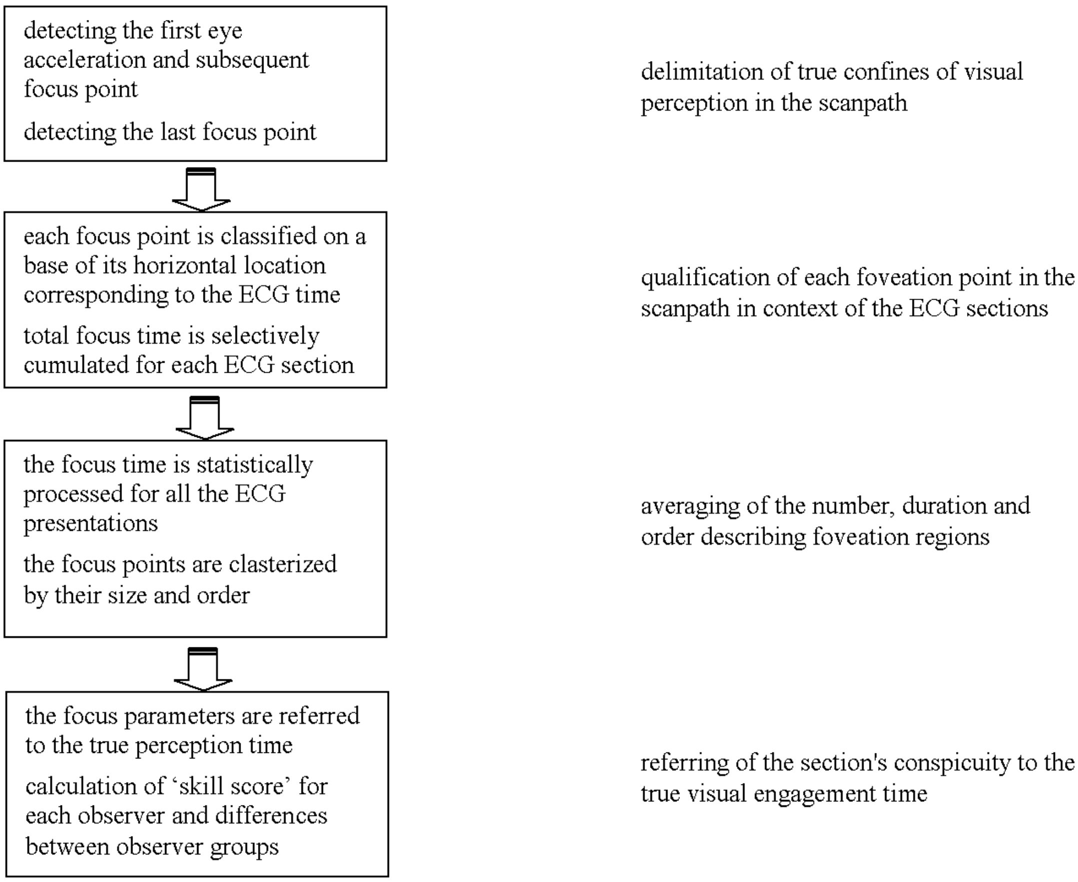

Figure 3 Scanpaths signal processing diagram

3. Results

3.1. Quantitative description of medical data distribution

Statistically processed results of all visual experiment are summarized in table 1. Figures 4 and 5 display examples of the eyeglobe trajectory over a 12-lead ECG plot and the corresponding bar graph of the attention density[1] representative for two groups of observers: experts and students.

Assuming that students behave as untrained observers, the only reason for the difference of attention density variations between two groups are experts perceptual habits developed during the years of practice. Therefore highlighting the attention density variations is of particular interest in aspect of objective skills assessment. The local difference in attention density between two groups is particularly important within the QRS wave borders, indicating the information represented in the QRS shape as principal for the diagnostic decision.

Table 1. Results of ECG inspection scanpaths analysis

Parameter		Unit	Observers	
			Experts	Students
observers population			17	21
idle time		ms	73 ± 55 [a]	88 ± 105
interpretation time		s	5.5 ± 1.5	6.2 ± 1.7
local foveation	within P wave	%	23 ± 12	17 ± 12
	within PQ section	%	7 ± 5	11 ± 10
	within QRS wave	%	38 ± 15	26 ± 19
	within T wave	%	18 ± 10	21 ± 10
	within TP section	%	14 ± 5	25 ± 14
attention density	maximum	s/s	21.0	16.0
	minimum	s/s	1.9	3.9

[a] Average value ± standard deviation

3.2. Pursuit of the Visual Interpretation Strategy

The second group of results were derived by the analysis of perceptual strategy. The strategy is attributed by the focuss points coordinates and time and by the gaze order. Figures 6 and 7 display examples of the strategy over a 12-lead ECG plot. The focus point origins are represented by the circle centers and focus time – by their diameters. Small flashes represent gaze movements to the next focuss point and helps to follow the observer gaze order. Table 2 summarizes the corresponding strategy description parameters.

Studies of the scanpath examples given in figures 6 and 7 reveal main principles of perceptual strategy typical for both groups:

- experts (figure 6) scan purposely selected traces for expected waveforms,
  - 1-st circle is the main focus point and represents 31% of total focus attention,
  - subsequent points order may be justified by: (2) rhythm detection, (3) QRS-verification, (4) rhythm verification (5) T-segment assessment.
- students (figure 7) scan every trace for anything interesting,
  - chaotic or systematic scan,
  - 7-th circle is detected as main focus point (perhaps because is a turning point),
  - main focuss point represents 17% of total focus attention,
  - subsequent points order corresponds to traces order,

[1] Attention density represents the time the eyeglobe spends over a time unit in the ECG plot (recorded typically at 25mm/s) and thus is expressed in second per second ([s/s]). It should be noticed that although scanpath time and ECG time are both temporal variables given in seconds, the eyesight and ECG record are not simultaneous processes.

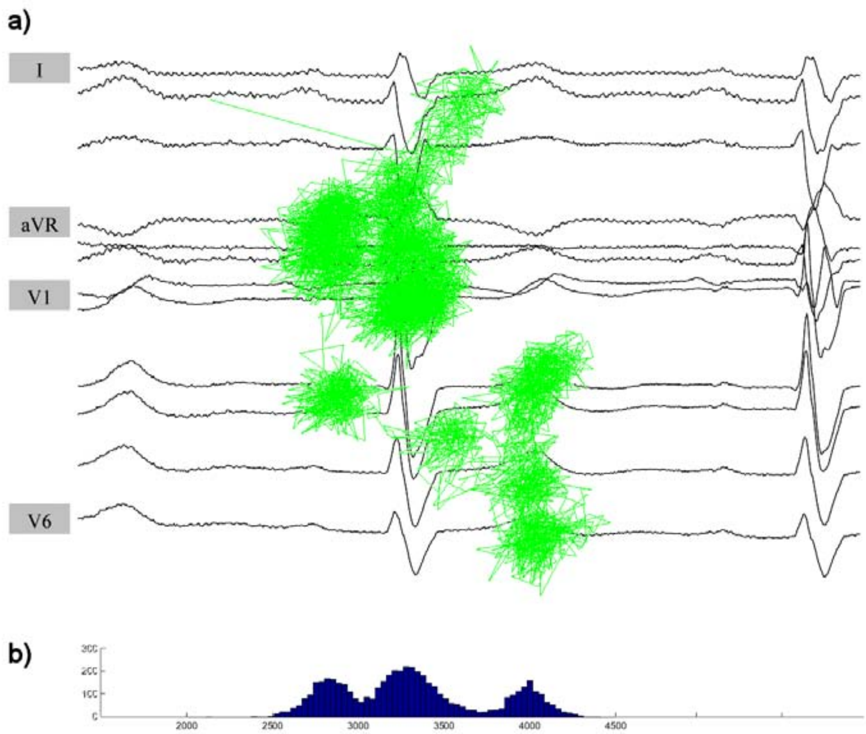

Figure 4. a) The example of expert's eyeglobe trajectory over a 12-lead ECG plot (CSE-Mo-001) b) corresponding bar graph of the attention density

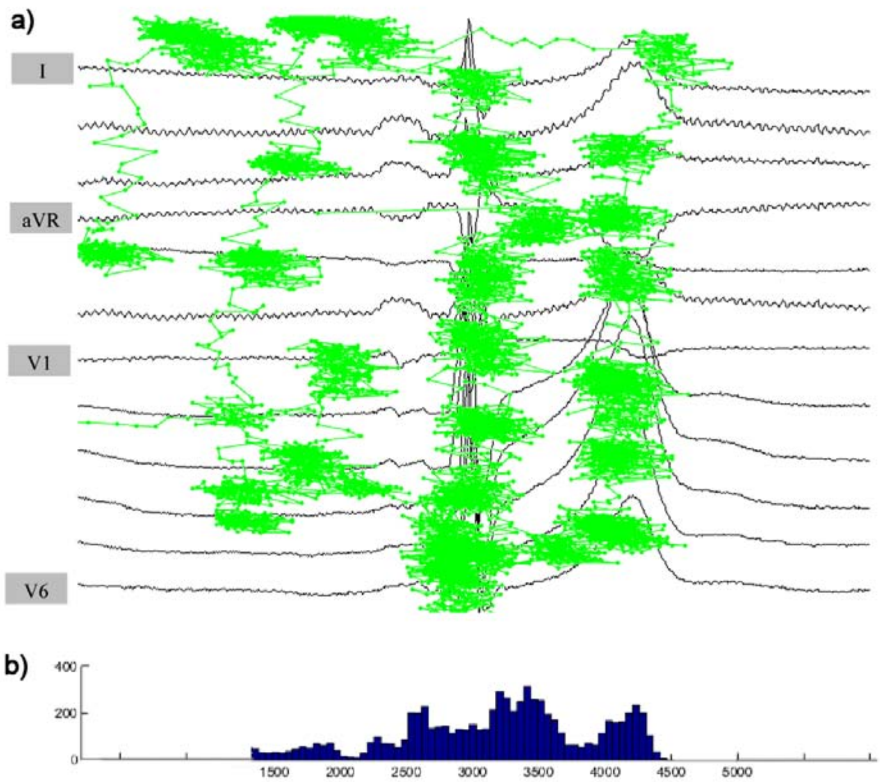

Figure 5. a) The example of student's eyeglobe trajectory over a 12-lead ECG plot (CSE-Mo-021) b) corresponding bar graph of the attention density

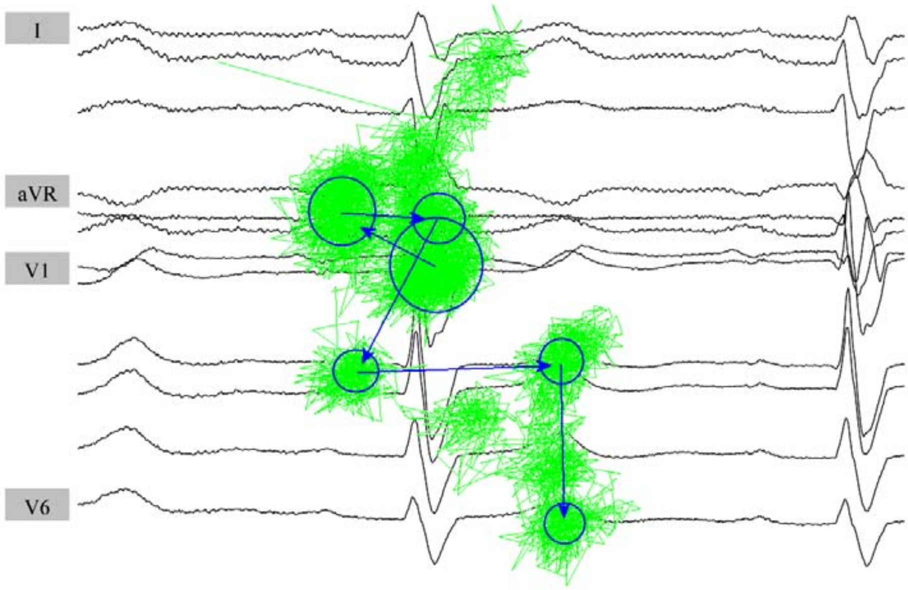

Figure 6 The example of expert's perceptual strategy over a 12-lead ECG plot (CSE-Mo-001); the circle diameter represents foveation time.

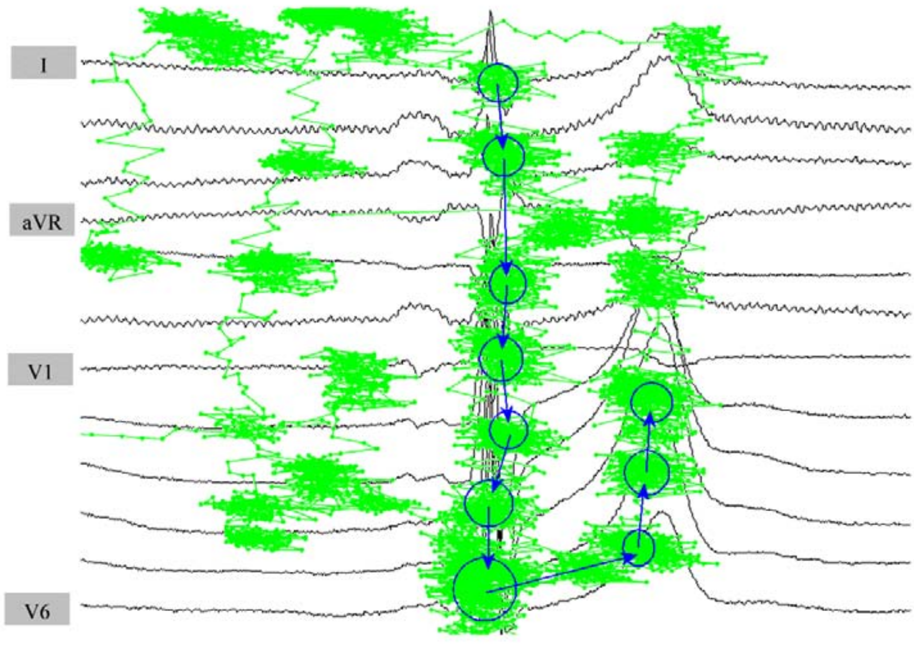

Figure 7 The example of student's perceptual strategy over a 12-lead ECG plot (CSE-Mo-021); the circle diameter represents foveation time.

For the further studies aimed at perceptual strategy repeatability we selected electrocardiogram images interpreted by at least two observers from the same group. By comparing the positions and gaze order of five most important foveation points in the scanpaths we found that similarity between two experts is much more probable (37%) than between two students (17%). As students acts as untrained observers applying general conspicuity rules to the ECG plot, their perceptual strategy is chaotic and thus the repetability is weak. The experts apply medically-justified conspicuity rules and scrutinize the ECG scene in more consistent way, therefore the probability of similar scanpath increases. This result proves the proper representation of the ECG interpretation process and personal skills of observer in the visual strategy.

Table 2. Quantitative description of perceptual strategy

Parameter	Unit	Observers	
		Experts	Students
observers population		17	21
relative foveation time for the main focus point	%	31 ± 12 [a]	17 ± 10
number of foveation points [b]		6.1 ± 1.7	9.2 ± 3.9
foveation points distance	deg.	5.7 ± 2.4	3.1 ± 1.2
scanpath length to the last foveation point [c]	deg.	34.7 ± 5.1	28.5 ± 6.6
scanpath duration to the last foveation point [b]	s	3.6 ± 1.3	5.7 ± 1.5

[a] Average value ± standard deviation
[b] Including points having at least 5% of relative foveation time
[c] To the last point having at least 5% of relative foveation time

The eye tracks gathered during the visual experiments need further exploration and contextual analysis with regard of CSE database records and the medical significance of the data. The example of unexplored area is the correctness of medical diagnoses made on a background of visually inspected traces.

3.3. Objective assessment of personal interpretation skills
One of the motivation of reported research and very promising field of application is the objective assessment of personal interpretation skills for a given class of scenes. Comparing certain parameters of scanpath between the experts and the students groups highlights the experience-justified differences and provides a quantitative measure of observation skills. Focussing this approach on interpreting the ECG, particular difference in fixation time (expressed as percentage of the total observation time) was found within the QRS wave (38% - experts, 26% - students) and within the T-P section (14% - experts, 25% - students). Both groups showed irregularity in fixation time per ECG plot time unit, however in experts it varies in a range from 21 s/s at the QRS to 1,9 s/s at the baseline and in students only from 16 s/s to 3.9 s/s respectively.
In the perception of a typical image by an untrained observer some features in the scene are particularly conspicuous. The example given in (Tadeusiewicz 2004) indicates the edges as elements attracting most foveation time. In the electrocardiogram, although the QRS complex having the highest contribution of high frequency components is at the same the most conspicuous for both group of observers, the P wave, hardly distinguishable from the baseline, and the very smooth T wave are lower, but not far from the QRS result. For these waves, the information is more difficult to extract and the visual pursuit requires more time.
For the group of students behaving like untrained observers in front of the ECG plot, we found some typical relationships of the scanpath and the local quantitative features of the scene (e. g. frequency). Similar relationships are significantly weaker for the group of experts. The difference of perception between students and experts can only be explained by perceptual and oculomotoric habits developed during the years of practice. These differences are particularly important in the QRS wave foveated up to 50% longer by experts than by students. That indicates the information represented in the QRS shape as principal for the diagnostic decision.

4. Discussion

4.1. Challenges in scanpath analysis
Visual experiments provide a quantitative description of the trace conspicuity in context of cardiac events represented in the signal. The advantages of scanpath analysis place it among most useful tools for investigation of human mental processes, surrounding perception and interaction as well as man-machine interfacing.
Although very informative, the scanpath is also very sensitive to the voluntary observer cooperation during visual tasks and thus has to be interpreted carefully. Some parameters show high inter-observer variability of unexplained origin. Being aware of the difficulties and familiar with other visual

experiments, we eliminated 18% of records from the scanpaths statistics for the reason of poor co-operation or misunderstanding of visual task rules. Unfortunately, the result is still influenced by psycho-physiological factors beyond of control during the visual experiment:

- observer-dependent features varying from one person to another, including eyesight defects influence, anatomy, perceptual and motoric skills etc.
- observer status-dependent properties for each particular person varying from one day to another: psycho-physiological status, drugs, climate influence etc.

The identification of basic phenomena interfering the relation of scanpaths and visual perception information flow needed the analysis of various visual experiments results. Another challenge was the development of scanpaths pre-processing software towards standardizing and minimum operator assistance in recognition of desired trace features.

4.2 Exploiting the scanpath information

The dedicated signal processing, scanpath interpretation and statistics revealed many differences between cardiology experts and untrained observers concerning the ECG inspection methods and perceptual strategies. The most discriminative parameters of the scanpath are:

- attention density variability is significantly higher in the expert group,
- number of foveation points is lower in the expert group, similarly to the results obtained from 'fast reading' people in one of our previous research.
- distance of foveation points is higher in the expert group
- total scanpaths duration to the last significant foveation point is shorter indicating the expert is searching for the most important data at first.

All these parameters indicate a very precise and consistent way of information search in experts. Moreover, high variation of first foveation points focus time and distance suggest the hierarchical information gathering reflecting the parallel decisive process. The knowledge gathered from a given point of the scene is interpreted and not only approaches the final diagnosis, but also influences subsequent steps of visual search, determining the position and gaze time of focus points ordered by descending importance.

The research addresses also the issue of objective assessment of cardiologist interpretation skills.

4.3. Potential application domains

The cardiologist's scanpaths were acquired initially in a framework of studies on irregular distribution of diagnostic content in the ECG signal issuing a medical background for nonuniform ECG sampling (Augustyniak2004) and distortion assessment methods. Besides the main research, we observed significant variations of qualitative scanpaths parameters and perceptual strategy. Therefore, considering the importance of the initial observers knowledge, we found interesting to correlate these variations with the cardiologist's experience.

As a reference we selected the control group from students featuring the initial knowledge standardized by their study course. The comparison result revealed new applications area for the ECG scanpath, extending far beyond the effective signal compression. Examples of such application include, but are not limited to:

- objective assessment of human interpretation skills,
- acceleration of cardiologist training by scanpath repetition as a method of oculomotoric habits cultivation.

4.4. Future considerations

The reported research demonstrates that the common belief on irregular medical data distribution is fully justified for the electrocardiogram. With the use of scanpaths analysis, the local data distribution can be effectively measured and expressed as attention density.

In the future, these research would be continued towards:

- extraction of heart disease-typical perceptual strategy, optimization and implementation in machine-interpretation algorithms;
- proposition of perception-based teaching and learning progress assessment rules;
- objective assessment of cardiologist interpretation skills,

– pursuit for the interpretation-related mental processes, which can not be controlled and reported knowingly without affecting the perception process.

The proposal of using scanpaths as an objective assessment tool for interpretation skills does not fully exploit the potential of scanpaths. Several wider aspects should be considered as application of expert's scanpaths analysis:

– The perception is representative for mental processes, difficult to express knowingly.
– The visual image interpretation learning through development of oculomotoric habits by expert scanpath repetition is believed to overcome the problem of precise verbalisation of knowledge.

5. Conclusion

The presented work demonstrates that the common belief on irregular medical data distribution in the electrocardiogram is justified. Moreover, the local data distribution can be effectively measured through scanpaths analysis and expressed as attention density. Initially the perceptual model of the ECG was conceived for effective non-destructive acquisition system with non-uniform sampling (Augustyniak 2002). The inverted attention density is suitable as a time-tolerance relation for the non-uniform sampling procedure.

The scanpath analysis provides not only image-assessment, but also observer-assessment tool. The experts and students eyeglobe trajectories captured during the visual inspection of the record issues a reliable quantitative measure indicating the observer's interpretation skills. Similar visual experiment-based methods may be applicable to other signals and images.

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