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AWARENESS EVALUATION OF PATIENTS IN VEGETATIVE STATE EMPLOYING EYE-GAZE TRACKING SYSTEM

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Application of eye-gaze tracking system to awareness evaluation is demonstrated. Hitherto awareness evaluation methods are presented. The assumptions of proposed method based on analysis of visual activity of patients in vegetative state are demonstrated. The eye-gaze tracking system "Cyber-Eye" developed at the Multimedia Systems Department employed to conducted experiments is presented. Research described in the paper indicates that awareness level of 13 of 15 tested patients was misdiagnosed before the new method of awareness evaluation is introduced .

Keywords: Vegetative state; minimally conscious state; gaze tracking; eye activity; awareness evaluation; consciousness study.

1. Introduction

Each year, a considerable number of patients in a vegetative state die with incorrectly recognized level of consciousness. Other people experienced by acute brain injury (especially: stroke, hypoxia or critical drop of blood pressure) fall into a coma. The coma is a temporary state which can be finished by: fast recovery or a vegetative state, a locked-in syndrome or the brain death[1]. The vegetative state and the locked-in syndrome might be distinguished by evaluation of awareness level. There are different methods and technologies supporting this kind of evaluation. Some of them were characterized in Section 2. In the case of vegetative state the awareness is at zero level while awareness of patients in locked-in syndrome is at the highest level[2]. In some cases the vegetative state can be temporary state as well. Some patients remain in this state until death. Nevertheless, there are patients who recover their awareness slightly and go into minimally conscious state. Awakening from a coma is the process that can last for many years. Signs of awareness characterized of the minimally conscious state are prerequisites of the awakenings process. Therefore, differentiating between vegetative state and minimally conscious state is very important and responsible task of therapists. It is difficult because some signs of consciousness can easily be missed due to sensory and motor disabilities[3] or can be regarded as accidental. Research results concerning the misdiagnosis of awareness level of patients in vegetative state are terrifying. Recent study conducted by Schnakers and coworkers in 2009[4] shows that a misdiagnosis rate equals 41%. According to previous research patients' awareness was diagnosed incorrectly in case of 37 to 43% of subjects[5,6]. These statistics clearly indicate that enhancement of diagnosis' reliability and accuracy is necessary. The scheme presented in Fig. 1 shows that awakening of patient in vegetative state is possible but it happens gradually. Differentiating between vegetative and minimally conscious state announces a chance to recovery of consciousness.

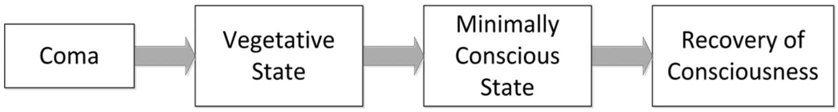

Fig. 1. The process of gradual awakening of patient in vegetative state

This paper focuses on easy, effective and relatively inexpensive method of awareness evaluation. The proposed approach allows for classifying of patients' clinical state between vegetative or minimally conscious state. The method is based on analysis of patients' visual attention exploiting eye-gaze tracking system. The system called "Cyber-Eye" and relevant application which enables tracking of patient' gaze activity was developed at the Multimedia Systems Department of Gdansk University of Technology. More detailed description of the system and the proposed methodology were presented in Section 3.

2. Review of awareness evaluation methods

The basic method of consciousness assessment is a neurological observation of patient's clinical state. The procedure was proposed by Teasdale and Jannet in 1974[7]. They developed the Glasgow Coma Scale (GCS) which consists in evaluation of eye opening, the best verbal answer and the best motor reaction caused by the external stimuli. Each type of activity is assessed according to defined in advance criteria with the corresponding point scale. Nevertheless, the GCS is not reliable procedure of consciousness evaluation. Its limitations reveal particularly in case of patients with ocular trauma, tracheostomy or respiratory support[8]. There are other rates pointing on consciousness of patients in vegetative state such as: *Full Outline of UnResponsiveness scale* (FOUR)[9], *Wessex Head Injury Matrix* (WHIM)[10] or *Sensory Modality Assessment and Rehabilitation Technique* (SMART)[11]. However, due to the nature of this paper their detailed characteristics would be omitted.

Methods characterized by a more reliability are associated with advance technologies. The first method is based on event-related potentials (ERP) research. It is a non-invasive electrophysiological investigation exploiting external stimuli independent on sense. The ERP research evaluates some of the high level characteristics of information processing in the central nervous system (CNS). Thus, ERP reflects an intellectual and emotional patient brain' response to relevant stimulation[12]. In most cases of ERP traces P3 wave (or P300, the third positive wave, the wave with a 300 ms latency) is analyzed[13]. The energy of the stimulus does not impact on the amplitude or latency of the P3 wave, thus it is called the endogenous potential as well. It is known that the latency of the P3 wave is directly related to the speed of cognitive processing[13,14]. Kok indicated the amplitude of the P3 wave shows the allocation of brain energy resources[15]. Laureys conducted the experiment with patient in vegetative state recording ERP[1]. The stimuli were uttered names and ERPs were recorded for patient's name and other names. Laureys noticed significant change of the P3 wave' amplitude when the stimulus was patient's name or other name. The change of amplitude value referring to the P3 latency was included between 1–10 μV. This experiment allowed for changing the diagnosis of this patient. The confirmed in an objective way patient's response to his/her name enables regarding his/her as the patient in minimally conscious state.

Other methods are related to neuroimaging techniques. Their serious disadvantage is cost and availability. It is worth mentioning about positron emission tomography (PET) and a functional magnetic resonance imaging (fMRI). Boly *et al.*[16] studied patients in minimally conscious state in the context of pain perception employing PET technique. PET scans found increased blood flow in areas of the brain corresponding to the subjective experience of pain. Schiff *et al.*[17] employed fMRI technique in order to research activation in auditory center of patients in minimally conscious state. Schiff's experiment showed characteristic activation in auditory center when patients heard familiar voice reading personally meaningful content. The activation was not seen when the narratives were reading backwards.

It is noteworthy that advanced methods such as ERP, PET and fMRI show the brain's electrical activity as a result of specific stimulation. Nevertheless, their functionality is associated merely with monitoring of the brain state. The method proposed by the Authors does not monitor electrical activity of CNS. It enables the therapist to observe patient's behavior by tracking his/her eye-gaze activity when the patient is presented various visual contents. Therefore, the method provides not only a diagnostic support but a therapeutic as well.

3. Cyber-Eye system employed in awareness evaluation

3.1. *Cyber-Eye system*

The Cyber-Eye provides an eye-gaze tracking system. Eye-gaze tracking technology consists in determining the user's fixation point on the computer screen. Gaze direction estimation is based on processing of frames captured from the system camera. Despite that first eye-gaze tracking techniques have been developed over 100 years ago, current video-based technology appeared in the early 90s. Modern eye-gaze tracking systems are non-invasive, contactless, user-friendly and highly accurate. They are employed in many different domains – market research, websites usability determination or communication. Authors exploited the eye-gaze tracking system in awareness evaluation, providing original and much needed application.

The Cyber-Eye system is based on infrared (IR) illumination like most eye-gaze tracking systems available in the market. IR illumination does not disturb the user because it is invisible. Exploiting IR illumination enhances effectiveness of the image processing algorithm. First, contrast between the pupil and the iris is much higher in the processed frame in comparison to the standard grayscale image. Second, the IR LEDs generate characteristic corneal reflections called glints. A better contrast and four reflections on the cornea increase precision of fixation point determination. A sample of the image processed by the system is shown in Fig. 2.

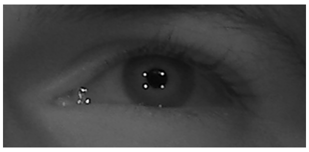

Fig. 2. Sample of processed eye image with four corneal reflections

The algorithm of image processing and determination of gaze direction consists of several important stages. Each frame acquired by the camera is segmented into regions of 40x40 pixels. The brightest points are determined in each 40x40 area. The region in which the brightest points form a quadrangle shape is regarded as a part of image including the first user's eye. Detection of the second eye region is limited to the areas located on the left and on the right side of found eye region. In the next step coordinates of each glint of both eyes are determined based on the center of gravity calculation. Then, the region of pupil is detected in the eye image using the ellipse fitting algorithm. Coordinates of the ellipse center directly correspond to coordinates of the pupil center. Subsequently, the fixation point is estimated for each eye independently. The relative location of glints and the pupil center and layout of glints on the cornea influence gaze direction' estimation. The functional scheme of this algorithm is presented in Fig. 3.

In case of presented research the angular resolution (accuracy) of the Cyber-Eye system is not the most important parameter. Nevertheless, it is noteworthy that the Cyber-Eye' angular resolution was evaluated assuming the user is positioned in the optimal distance of 60 cm from the system monitor. In the experiment devoted to system resolution' determination 115 students of the Gdansk University of Technology were engaged. They were focusing their gaze on the 48 points displaying evenly in 8 columns and 6 rows. It was assumed the system resolution would be calculated in three steps. First, values of maximum deviations of determined fixation points from the displayed points in horizontal and vertical plane were evaluated. Then, horizontal and vertical angular resolution based on deviations' values was calculated for each subject independently. In the last step, the proper angular resolution was determined based on average of all obtained outcomes. The angular resolution in horizontal plane equals 3.32°

and in vertical plane: 3.38°. It means that the system effectively distinguishes areas with a width of 3.48 cm and a height of 3.54 cm. This accuracy is quite sufficient for the purpose of conducted research.

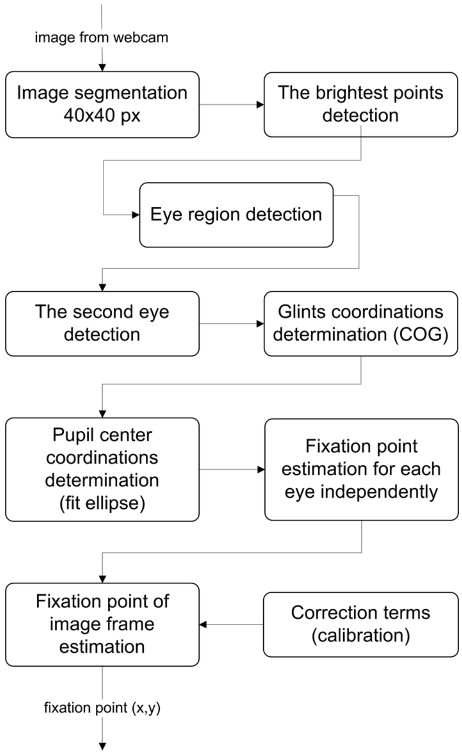

Fig. 3. Functional scheme of the gaze direction' estimation algorithm

The hardware part of the Cyber-Eye system consists of the 19" LCD display with four sections of IR LEDs at the corners, the modified USB camera sensitive to the infrared range, the IR LEDs driver which controls activating of IR emitting sections and the computational unit – a standard PC. It should be noted that the character of carried out experiments requires the use of a special monitor arm. A lot of patients are immobilized thus the Cyber-Eye monitor' position should be adjusted adequately. Fig. 4 shows the testing setup of the Cyber-Eye system during the experiment. More information on the Cyber-Eye hardware and software is to be found in some earlier publications of the Authors[18,19,20,21].

Fig. 4. The Cyber-Eye monitor equipped with a special arm used during the experiment

3.2. *Methodology*

The diagnosis of patients in vegetative state based on awareness evaluation exploits the developed application called the Cyber-Eye Multimedia Training (COMT). The purpose of this software was the objectivization of methods used previously by therapists through transferring them to the eye-gaze tracking system. The COMT application enables preparing of any multimedia content in a similar way to some standard tools for creating presentations. The basic difference consists in the feature of displaying the user's gaze fixation point on the computer screen and recording its coordinates. Due to this functionality the visual content can interact with the user by highlighting the selected image and playing the predefined sound sample. There are three types of audio content. The application can play some default sounds chosen by the therapist. It is possible to play the audio file according to the specified path, providing the most useful option. The COMT software employs the speech synthesis engine which enables 'reading' any verbal phrase[22,23]. During the diagnosis/therapy process the therapist should tell the patient simple commands.

Experiments of awareness evaluation assume that the content presented to the patient is related to him/her past experiences. It is called a 'personal picture'. Therapists prepare slides in the COMT application including two pictures – in most cases – photos. The personal picture presents a member of patient's family or himself/herself. The second picture shows other unknown person. There is an important assumption these different pictures in semantic context should be visually similar (color, saturation).

Another important aspect of the employed methodology is a layout of displayed pictures. They are exhibited in different configurations: in the left/right, top/bottom part of the screen. During the experiments therapists swap them as well. This allows for objectivization of therapists' observations by avoiding cases when patient's gaze is involuntarily focused on a single point. In each localization of the picture associated with the patient the therapist tells the command: “Find yourself / mom/ dad / your boyfriend / *etc.*”.

The Cyber-Eye system records coordinates of patient’s fixation points reflecting his/her visual activity while working with the COMT application. It is possible to generate a heat map with gaze plot superimposed on displaying content. An example of such a heat map and a gaze plot was shown in Fig. 5.

4. Experiments

4.1. *Conditions*

Verification of minimally conscious state’ diagnostic criteria specified by Giacino[24] is the main assumption of the conducted research. According to those criteria, response to verbal order, object localization and sustained visual fixation and pursuit are symptoms of patient’s awareness. It is worth mentioning that the therapists repeat this experiment frequently to exclude randomness of the observation. Taking into account the fact patients in vegetative / minimally conscious state get tired relatively quickly, a test session is carried out two-three times a week for about 20 minutes. Research described in this article has been conducted involving 15 patients of the Therapeutic Care Center in Torun, Poland. All of them were diagnosed as patients in a vegetative state.

4.2. *Results analysis*

Each patient demonstrates a specific way of watching displayed pictures. Nevertheless, the common feature is a visual scanning of the presented content. It means the patient looks at the ‘personal picture’ then at the second one and *vice versa*. However, after the stage related to the familiarization with the pictures, the patient focus finally his/her gaze on the ‘personal picture’. It is supposed that the time of such a visual scanning corresponds to the patient’s level of consciousness. This observation requires an additional research. Table 1 includes results summarized for one randomly selected test session. Parameter in the second column of table (n_s) is the number of gaze points recorded during the visual scanning before focusing the gaze on the ‘personal picture’ (it relates to the first configuration of pictures’ presentation). Parameter t_1 represents the relative time of focusing patient’s gaze on the ‘personal picture’ (it also corresponds to the first configuration of pictures’ presentation). The parameter of the fourth column (n_c) is the number of configuration changes (it relates to pictures presentation configurations during the whole test session). The parameter T_t in the last column represents the mean value of the relative time of patient’s concentration on the ‘personal picture’ during the whole experiment. Thus, the parameters n_s and t_1 are associated with the first configuration of pictures layout and the parameters n_c and T_t are referred to the total time session for each patient.

The results summarized in Tab. 1 are characterized by specificity. Nevertheless, it is possible to observe an important common feature. Namely, most of tested patients focused their gaze on pictures related to their past life. Relatively high visual attention of patients was observed in case of ‘personal pictures’ during the first presentation as well as during the whole test session. A sample pictures layout with superimposed heat map and a corresponding gaze plot were shown in Fig. 5.

Table 1. Summarized results of awareness evaluation during random test session

Patient ID	n_s	t_l [%]	n_c	T_t [%]
01	4	83	6	72
02	3	88	8	80
03	6	70	8	58
04	3	85	7	67
05	2	92	8	83
06	5	31	9	23
07	4	94	7	85
08	4	24	10	29
09	3	90	8	75
10	3	85	7	69
11	2	62	8	55
12	4	88	6	81
13	5	86	8	78
14	2	79	8	74
15	3	93	7	82

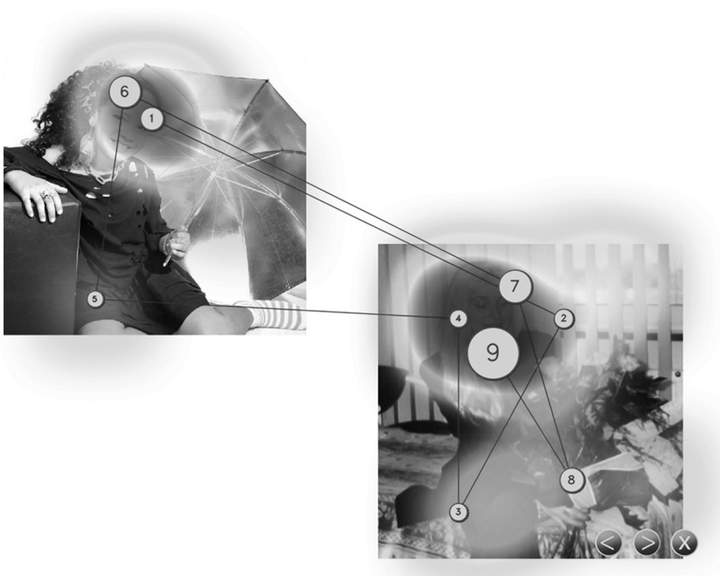

Fig. 5. Example picture displaying configuration. The ‘personal picture’ is located in the right part of the screen

Those are results of one of many experiments conducted by therapists. However, outcomes of patients 06 and 08 indicate that voluntary eye movements are problematic. It was mentioned that results of one experiment are not representative and it should be repeated many times. The results of subsequent studies confirmed the observed tendency related to the presented experiment. The summary result of this research is surprising. It turns out that the preceding diagnosis of vegetative state for 13 of 15 (~87%) patients was wrong. Patients 06 and 08 actually are in vegetative state. Currently, the other ones were diagnosed as patients remaining at least in minimally conscious state.

5. Conclusions

Awareness evaluation in case of patients remaining in vegetative state is a challenge for science. There are many advanced technologies employed in research concerning patients in vegetative state. Simultaneously, introducing an eye-gaze tracking system to this domain looks like innovative and promising approach. It is worth noting that scientists used to research patients' eye-gaze activity[25]. However, they did not apply any eye-tracking system, previously. The proposed methodology objectively confirmed what the therapists have suspected working with their patients, namely that the standard diagnosis can lead to wrong conclusions in many cases.

It should be emphasized that the proposed methodology based on eye-gaze tracking technique supports both: level of consciousness diagnosis and therapy as well. The Cyber-Eye system allows for presenting any multimodal content which can be regarded as relevant stimulus. Moreover, it enables communicating by gaze using the virtual keyboard with speech synthesis module. There are many applications of the eye-gaze tracking system in the area of diagnosis and therapy of patients in vegetative state.

The meaning of conducted and presented research is can be important for therapists, for patients' families and for themselves. Diagnosis of minimally conscious state can make a first step leading towards patients' awakening and their returning to normal life.

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