Under normal circumstances, the pupillary light reflex (PLR) causes the pupil diameter to decrease as larger amounts of light are sensed by the retina. However, the Autonomic Nervous System (ANS) controls the muscles in the iris through both its Sympathetic and Parasympathetic Divisions and modifies the diameter of the pupil in response to other forms of autonomic activation, in addition to light stimulation of the retina. In particular, it has been shown that the pupil diameter also responds to cognitive and emotional processes. We are interested in using the real-time measurement of pupil diameter to assess affective responses during human-computer interaction. However, this will only be possible if signal processing techniques can be used to identify and remove the component of pupil diameter changes due to PLR. In this report, we propose a solution to that prerequisite by practically modeling the PLR system through an Adaptive Interference Canceller (AIC) defined by the changes in measured PD caused exclusively by a step change in illumination, which was simultaneously recorded by a light sensor. Our results confirm that the AIC was able to converge, minimizing its error to acceptable levels. Furthermore, the impulse response model implicitly formed in the weights of the adapted AIC can be extracted as an approximation to the transfer function mediating between changes in illumination and changes of pupil diameter.

Keywords: Pupillary light reflex (PLR), adaptive interference canceller (AIC), pupil diameter (PD), illumination intensity level (IL), least mean square (LMS), step response, impulse response.

INTRODUCTION

The size of the human pupil is known to be determined by a balance between dilation and constriction, which are controlled by the Sympathetic and the Parasympathetic Divisions of the Autonomic Nervous System (ANS) [1,2]. For years, the change of the illumination level has been considered as the predominant factor determining the diameter of a person’s pupil. However, recent studies indicate that the pupil diameter (PD), as an important indicator of emotional processing activity, has significant potential for the evaluation of affective states [3]. Therefore, it is of interest to identify (and then remove) the contribution of the pupillary light reflex (PLR) in PD variations, to enhance the application of PD measurements for affective monitoring of a computer user.

The Pupillary Light Reflex (PLR) designates the mechanism by which the human pupil changes its diameter inversely to the amount of light striking on the retina [4]. For example: under normal conditions, when the light intensity increases, an increased activation of the parasympathetic division of the ANS will cause the constriction of the circularly arranged pupillary sphincter muscle, which will result in a compensatory decrease of the pupil diameter [5]. Consequently, the reduced PD will cause a smaller pupil area, which will also reduce the light flux impinging upon the retina. The basic scheme of this behavior is shown as a negative feedback system in Figure1.
We hypothesize that the responses of the ANS to illumination and affective changes are superimposed in the externally measured PD signal. Accordingly, we propose the diagram shown in Figure 2 to practically model and remove the PLR-driven component of PD variations. This figure is a typical adaptive interference canceller (AIC) arrangement, in which, if the transfer function of the block that transforms illumination to pupil diameter changes (blocked marked “?”) could be emulated by an adaptive transversal filter (ATF), it may be possible to remove the variations of PD caused by illumination changes (IL) from the measured pupil diameter signal (PD). Similar AIC systems have been successfully used to remove an unwanted interference component that pollutes a measured signal if an independent measurement of the interference is available to the AIC [6].

In the case at hand, the measured signal $s$ is the PD signal as reported by an eye tracking system (T60, Tobii Technology, Church Falls, VA), at a sampling rate of 60 samples/sec. We propose to treat the PLR-driven PD variations as the polluting component, $n_0$, and an independent measurement of illumination in the neighborhood of the eye of the subject (IL) as the correlated $n_1$ noise sample, and we assume that there is a deterministic system turning $n_1$ into $n_0$ (It should be noted that, in this study no affective stimulation is being considered yet, so, for this study $n_0 = s = d$). Ideally, the error, $e$, should be minimized (in a least-squares sense) by the AIC when the adaptation of the ATF has been completed. Under those conditions, PLR-driven components of PD variations ($n_0 = d$) should be matched by the output, $y$, that the adapted ATF creates from the additional illumination signal, $n_1$, and, at that point, the weights of the ATF will be an estimate of the impulse response of the transfer function mediating between changes of illumination and PD changes.

FIGURE 2: Block Diagram of Adaptive Interference Canceller (AIC) for PLR Identification

MATERIALS AND METHODS

Our experiments implemented the block diagram shown in Figure 2, by measuring the pupil diameter in the subjects (PD) while simultaneously recording the illumination levels detected with a sensor placed in their foreheads. Since no affective stimuli were provided during the short recordings, the “Affective Contribution to PD” is assumed to be zero. A desk-mounted Tobii T60 eye tracking system was used to measure pupil diameter signals from both eyes of the subjects, and the average of the two was recorded, at 60 samples/sec, as the “Measured PD” signal. Additionally, a synchronized illumination measurement system was used to record the illumination level present in the area around the eyes of the subject. This system consisted of a BS500B0F photo-diode (Sharp...
Electronics, Mahwah, NJ), placed on the forehead of the subject and connected to an amplification circuit capable to provide an analog output voltage that is linearly proportional to illumination level [7]. The linearity of this transduction was verified by plotting the analog voltage levels obtained vs. readings from a calibrated luminance meter (Mod. 401036, Extech Instruments, Waltham, MA) at different illumination levels, yielding a scaling factor of approximately 0.0043 V/Lux. The analog output of the illumination measuring system was sampled at 60 samples/sec to provide the “Measured IL” signal shown in Figure 2, and stored in the same file as the PD signal.

In this study, participants were asked to remain seated in front of the Tobii T60 screen, looking at a fixation point in the center of the screen, for about 30 seconds, while wearing a head band with the photo-diode. Initially the environment was illuminated only by a dim lamp placed above the eye level of the subject, then, an additional high level of illumination provided by all the lights in the room was switched on after 10 seconds in order to implement a step increase in the IL signal, eliciting a step response in the system responsible for the pupilary light reflex.

RESULTS

The AIC block diagram illustrated in Figure 2 was implemented off-line in MATLAB. Initially, only 500 PD and IL samples that were recorded following the application of the illumination step were processed by the AIC, and the origin (relative zero level) for the PD signal was set to be the value of the first sample in the reduced interval (Figure 3, top panel). The resulting PD signal was processed by the AIC system as the primary input signal $s_n = n_0$. Moreover, the reference input signal $n_I$ was the illumination intensity data, shifted to start with a zero value as well (Figure 3, middle panel). The numerical derivative of the PD signal, passed through a median filter (Figure 3, bottom panel), was considered a useful estimate of the impulse response of the unknown system and therefore loaded as initial weights to the Adaptive Transversal Filter (ATF). The adaptation process was performed with the standard Least Mean Square (LMS) algorithm (as detailed in [6]), using an adaptation rate $\mu$ equal to 0.001. The process continued through multiple epochs. After each epoch the newly adapted ATF weights were re-loaded as starting weights for the next epoch. The mean square error (MSE) value for each epoch was observed to decrease. The process was stopped when the MSE value of the error was approximately 0.0002.

It was expected that a successful adaptation, capable of minimizing the error signal, $e$, would require that the ATF transformed $n_I$ in the same way as the unknown transfer function (marked “?” in Figure 2), therefore obtaining a functionally equivalent model, at least with respect to the type of variations in $n_I$. Since the ATF is a non-recursive filter, the sequence of its adapted weights would also reveal an approximation to the impulse response of the unknown transfer function, which would constitute a practical model for that transfer function.
Figure 4 confirms these expectations. It shows (top plot) that in the adapted AIC the evolution of $y$, the output of the ATF, is very close to the measured PD (both traces are almost completely overlaid). The middle plot in Figure 4 shows that the error $e$ (difference between PD and $y$), has been minimized. The lower plot in Figure 4 shows the ATF weights obtained after the successful adaptation, which represent the approximation obtained for the impulse response sequence of the unknown system. In the example displayed 300 epochs of adaptation were performed.

**DISCUSSION AND CONCLUSION**

The usefulness of the AIC model obtained was verified by feeding the AIC (with the previously adapted weights) a longer segment of the PD and IL signals. Figure 5 shows the results. In particular, the top panel shows that the 500-weight ATF continues to produce an output $y$ (overlaid with PD) that closely approximated the PD values recorded after sample number 500. This is confirmed by the error values displayed in the bottom panel of Figure 5, which are small throughout. For this simulation the adaptation rate $\mu$ was 0.005 and the resulting MSE value was 0.1985.

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