Reconstruction and Analysis of the Pupil Dilation Signal: Application to a Psychophysiological Affective Protocol

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***Abstract*—Pupil dilation (PD) dynamics reflect the interactions of sympathetic and parasympathetic innervations in the iris muscle. Different pupillary responses have been observed with respect to emotionally characterized stimuli. Evidences of the correlation between PD and respiration, heart rate variability (HRV) and blood pressure (BP) are present in literature, making the pupil dilation a candidate for estimating the activity state of the Autonomic Nervous System (ANS), in particular during stressful and/or emotionally characterized stimuli. The aim of this study is to investigate whether both slow and fast oscillations of the PD can be addressed to characterized different affective states. Two different frequency band were considered: the classical autonomic band [0-0.45] Hz and a very high frequency (VHF) band [0.45-5] Hz. The pupil dilation signals from 13 normal subjects were recorded during a psychological protocol suitable to evoke particular affective states. An elaborate reconstruction of the missing data (blink events and artifacts) was performed to obtain a more reliable signal, particularly in the VHF band. Results show a high correlation between the arousal of the event and the power characteristics of the signal, in all frequencies. In particular, for the "Anger" condition, we can observe 10 parameters out of 14 significantly different with respect to "Baseline" counterparts. These preliminary results suggest that both slow and fast oscillations of the PD can be used to characterize affective states.**

I. Introduction

The pupil dilation (PD) mechanisms allow for the continuous fluctuation of the size of the pupils, even when a subject is gazing at a fixed object, and they are partly the result of the action of the Autonomic Nervous System (sympathetic and parasympathetic innervation in the iris muscle) [1]; different pupillary responses were observed with respect to cognitive stimuli [2]. The most widely studied and reported phenomenon related to PD is the physiological response of the pupil to impulsive light stimuli, i.e. the pupillary light reflex. Although there are many studies about modeling pupillary response to explain signal behavior, improved recording devices and an easier access to signal processing tools have led PD to serve as a new helpful mean also in psychology and communication laboratories [3], [4].

As a results, increasing interest has been recently raised on the dynamics of pupil size variations in response to emotionally characterized stimuli: using auditory emotional stimulation during human-computer interaction, Partala and Surakka [5] reported that the variation of PD can provide indication of affective processing; more recently, Bradley et al. [6] found a direct correlation between the level of emotional arousal to different types of pictures, in terms of positive, neutral and negative valence, and the pupil diameter.

On the other hand, pupil size variability (PSV), i.e. the fluctuation of pupil size without accommodation and light response, is still not fully understood: in literature it is reported that the fluctuations of the PD has some relations with other physiological signals, i.e. respiratory signal [7] and HRV [8], but few works explore the signal at higher frequencies [9].

We intend to study the spectral information carried by the PD signal to find out whether both slow and fast oscillations of the PD can be addressed to characterize different affective states with respect to a baseline condition. Basically, we suppose that PD could be a candidate for estimating the activity of the Autonomic Nervous System (ANS), in particular during stressful and/or emotionally characterized events.

When analyzing PD, a typical problem is eye blinking, which results in missing data. Eye blinking affects both temporal and spectral parameters of PD: Nakayama [10] examined the relationship between eye blinking and some indices of the pupil; results showed that eye blinking significantly affects a wide frequency range of the power spectrum of pupil variations. Lately, in presence of eye blinking, researchers have proposed methods such as cubic interpolation [11]. These methods, although preferred for their simplicity and speed of computation, are not able to accurately reconstruct the missing dynamics of the signal. To overcome these limitations, we revisit [12] a method of reconstruction based on Iterative Singular Spectrum Analysis (Iterative-SSA) [13], for the filling of missing data during eye blinking events. As further contribution, we present the results of the analysis of PD signals recorded during a psychological protocol suitable to evoke particular affective states; after reconstruction, we perform spectral analysis and explore power distribution in two frequency bands, i.e. the classical autonomic band and a higher frequency band. Lastly, we perform statistical analysis and discuss the overall results.

II. Methods

A. Experimental procedures

Taking inspiration from a protocol by Rainville et al. [14], 13 normal subjects were voluntarily recruited from the student body of IULM University of Milan. After filling consent forms and self-reports, the students were first interviewed to recall and tell the psychologist one or possibly two recent episodes for target emotion (happiness, sadness, anger and fear). Subjects not able to recall a vivid recent episode for each of the four emotions were excluded from the study.

During the second appointment, each subject was asked to sit down in front of the Eye-tracking monitor and, after a baseline of 3 minutes, psychologist helped him/her in recalling the most intense episode described in the interview. When the subject reported to feel again the target emotion, the psychologist asked the subject to keep still, silent and to gaze at the center of the Eye-tracker monitor for 3 minutes. The sequence of the emotions was randomly assigned. For each subject five conditions were registered, namely "Baseline" "Happiness", "Fear", "Anger" and "Sadness". PD signals were recorded using the RED250™ eye-tracker by SensoMotoric Instruments, at a sample frequency of $\mathrm{f_s} = 250$ Hz; prior to start each recall, a calibration of the eye-traker was performed; in addition to PD, we recorded also physiological signals, using Flexcomp Infinity™ encoder (Thought Technology Ltd.; Montreal, Canada) with a sampling rate of 2048 Hz: ElectroCardioGraphic (ECG) activity; Abdominal and Thoracic Respiration; Blood Volume Pressure (BVP); Skin Conductance (SC); ElectroMioGraphic (EMG) activity over the *Currogator Supercilii* muscles; ElectroEncephaloGraphic (EEG) activity at the Cz position. A preliminary analysis of cardio-respiratory patterns has been carried out [**?**].

The PD raw signals[1] were low-passed and resampled at 50 Hz. Off-line, we reviewed all the intervals the eye-tracker labeled as blink events, and a neighborhood of 100 ms before and after the onset of each eye blinking event was considered as part of the event [15]. A final visual check of the signal was also performed in order to detect the blink events and the artifacts the eye-tracker couldn't recognize.

B. Reconstruction of PD signal during blink events

An Iterative-SSA method was implemented to fill the gap obtained on a PD signal from blink events [12], [13].

The SSA is a powerful signal processing technique introduced by Broomhead [16]. The aim of SSA is to make a decomposition of the original series into a sum of independent and interpretable components such as a slowly varying trend, oscillatory components and a structureless noise.

The only parameter we had to determine was the embedding dimension M. Once M is chosen, the M-lag correlation matrix $\mathbf{C}_x$ is computed as

$$\mathbf{C}_x = \frac{1}{N - |i-j|} \sum_{n=1}^{N-|i-j|} x(t_n) x(t_{n+|i-j|}), \qquad (1)$$

[1]We define PD raw signal as the signal split out by the eye-tracker.

Then, singular value decomposition (SVD) is carried on $\mathbf{C}_x$ for computing its eigenvectors, $\mathbf{E}_l$. Projecting the time-series onto each $\mathbf{E}_l$ produces M principal components (PC). PCs are shorter $(N - M + 1)$ and filtered version of $x(t_n)$. The original time series can be expanded in an optimal way as the sum of its M reconstructed components, $\mathcal{R}_l(t_n)$ [17].

M defines the order of the system which generated the signal, and therefore also the number of the components. The choice of M is a key problem, since dynamics with periods longer than M can't be solved [17]: therefore, the greater M is, the longer periods can be observed and reconstructed; however, a M too large would cause the equivocation of a single component in two or more components. In practice, it's useful to remember an empirical rule, i.e. SSA analyzes successfully periods between $M/5$ and M [17].

We decided to reconstruct the PD signal, previously filtered and resampled at 50 Hz, in order to be able to analyse frequencies up to 5 Hz. We chose $M = 150$ as a compromise, to explore the high frequency components, and also to preserve the low frequency components. All the M components were used in the reconstruction of the PD signal. In Figure 1 we show an example of the reconstruction performed using the I-SSA algorithm.

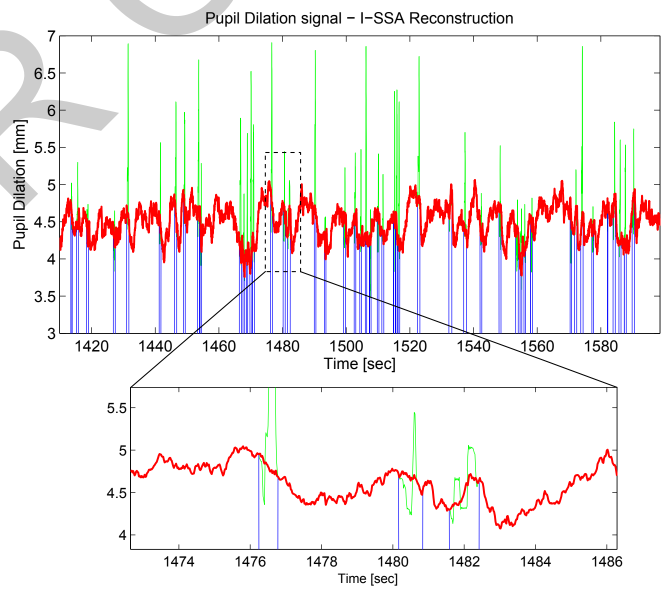

Fig. 1: An example of the reconstruction of Pupil Dilation signal with the I-SSA algorithm for the subject "sbj05", during "Anger" event.

C. Spectral Analysis an Feature Selection

As previous studies reported a spectral content for the PD signal up to 4-5 Hz [9], we low-passed and resampled the reconstructed PD signal at 10 Hz.

For the estimation of the spectral components, we performed a parametric spectral analysis via autoregressive (AR) model coefficients estimation. The order of the model was chosen according to the Akaike Information Criterion (AIC) [18]. A spectral decomposition procedure was applied to calculate the power of the oscillations embedded in the series [19].

For the investigation of the classic autonomic bands, we referred to the standard measurements of heart rate variability (HRV) in both psychophysiological and clinical uses [20]. The power of each PD rhythm was allocated to the corresponding frequency bands (low frequency, LF, [0.04-0.15] Hz; high frequency, HF, [0.15-0.45] Hz), and the central frequencies of LF and HF, as well as the LF/HF ratio, were obtained.

To explore the frequency contributions from 0.45 Hz up to 5 Hz, referred to as very high frequency (VHF), an high-pass filter was performed with a cutoff frequency at $f_c = 0.2$ Hz, to eliminate the high power low frequency content. We chose to consider [0.45-1] Hz, [1-2.5] Hz and [2.5-5] Hz (respectively "Low" VHF, "Middle" VHF and "High" VHF) as frequency bands, based on the observation of the PSD high frequency contents. In Figure 2 an example of the analysis is shown.

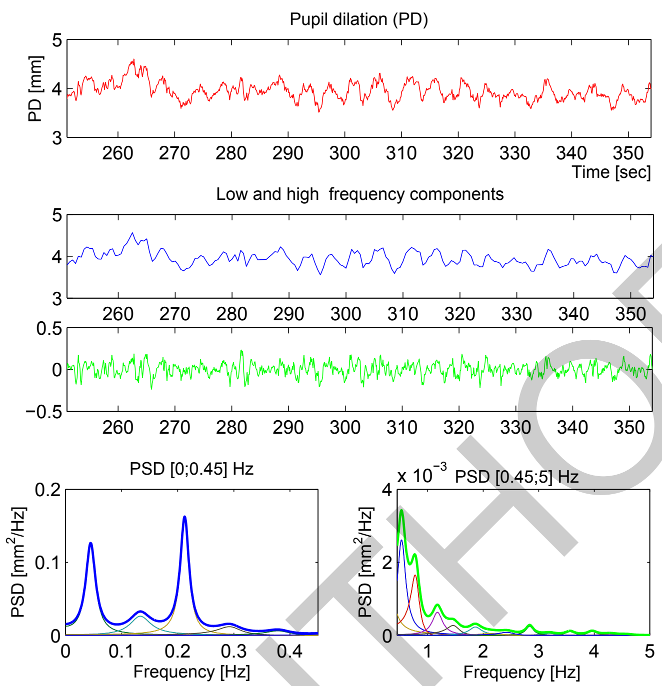

Fig. 2: Example of the analysis of the pupil dilation signal of the subject "sbj22" during "Baseline" event.

Of note, we also computed the mean value of PD, its standard deviation, the ratio of mean and standard deviation, the total variance, the total power in [0-0.45] Hz and the total power in [0.45-5] Hz.

III. Results

As the hypothesis of normality according to a Lilliefors test could not be rejected, we further performed a Grubb's test, and identified a frequent outlier derived from "sbj40". The subject is included in boxplots and figures, but it was excluded for the statistical analysis. An unpaired two-tailed Student's t-test was performed to test the statistical significance of the differences among the parameters of "Baseline" with respect to the counterparts of any other emotional event. In Table I the mean values and the standard deviations of the parameters are presented: bold type identifies statistically significant differences, $*$ is for p-value$<$0.05 and † for p-value$<$0.01.

In Figure 3 we report the boxplots of the HF component and the "High" VHF component. The red asterisks designate the conditions that showed significant differences with respect to "Baseline".

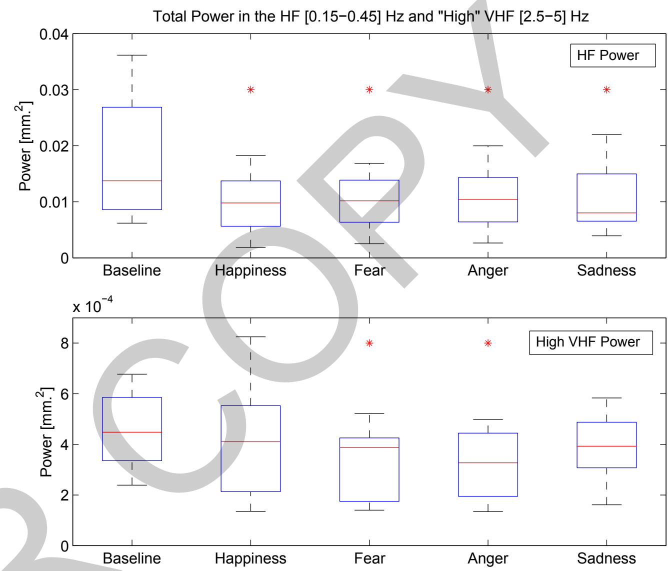

Fig. 3: Boxplot of the total power in the HF band [0.15-0.45] Hz, and the "High" VHF band, [2.5-5] Hz, for all the conditions. The red asterisks designate the conditions that showed significant differences with respect to "Baseline".

IV. Conclusions

The presented results confirm the hypotheses motivating our research. In particular, they show, within the boundaries of this protocol, that the "Anger" condition, the most triggering event, results in 10 parameters out of 14 result significantly different from "Baseline" counterparts.

As it was expected, since sympathetic activation is usually accompanied by a reduction in total power [20], we can observe a decrease in variance from "Baseline" to all emotionally characterized conditions. In this regard, we report in Figure 3 the boxplots of the total power in the HF band. For this parameter, every condition is significantly different from "Baseline", and a clear decrease in HF power can be noticed. Although not statistically significant, the LF/HF ratio has a similar pattern, increasing for the most triggering conditions ("Anger" and "Fear"). Of note, as we noticed during the experiment and later examining the signals, values for "Sadness" were affected by a different breathing behavior than in all other states.

Going back to Table I, it can also be observed that the central frequencies shift towards higher frequencies both in LF and HF. This behavior, present in every condition, is

TABLE I: Mean and Standard Deviation for all the parameter; unpaired two-tailed Student's t-tests were performed between the "Baseline" condition and the emotionally characterized ones; statistically significant differences were bold typed.

	Baseline	Happiness	Fear	Anger	Sadness
μ_{PD}	3.963 ± 0.379	4.022 ± 0.453	4.007 ± 0.4348	3.967 ± 0.4878	3.997 ± 0.4667
σ_{PD}	0.2685 ± 0.067	0.2319 ± 0.0517	0.2536 ± 0.1098	0.2313 ± 0.0749	0.2355 ± 0.0682
μ_{PD}/σ_{PD}	15.54 ± 3.67	18.04 ± 4.03	17.38 ± 4.63	$\mathbf{18.48 \pm 5.03}^*$	17.93 ± 4.25
σ^2_{PD}	0.0761 ± 0.0360	$\mathbf{0.0560 \pm 0.0242}^*$	0.0753 ± 0.0838	$\mathbf{0.0585 \pm 0.0388}^*$	0.0595 ± 0.0370
Power$_{[0-0.45]}$	0.0632 ± 0.0354	0.045 ± 0.022	$\mathbf{0.0554 \pm 0.0623}^*$	$\mathbf{0.0465 \pm 0.0344}^*$	0.0488 ± 0.0339
Power$_{[0.45-5]}(*10^{-2})$	0.673 ± 0.371	0.657 ± 0.564	0.553 ± 0.303	$\mathbf{0.515 \pm 0.4}^\dagger$	0.67 ± 0.463
Power$_{LF}$	0.0208 ± 0.0144	0.0113 ± 0.00662	0.0118 ± 0.00707	$\mathbf{0.0099 \pm 0.00533}^*$	0.0168 ± 0.0161
Central Freq.$_{LF}$	0.0653 ± 0.0251	$\mathbf{0.1078 \pm 0.0236}^\dagger$	$\mathbf{0.0904 \pm 0.0228}^\dagger$	$\mathbf{0.0987 \pm 0.0186}^\dagger$	$\mathbf{0.0958 \pm 0.0273}^\dagger$
Power$_{HF}$	0.0174 ± 0.0129	$\mathbf{0.00917 \pm 0.00512}^\dagger$	$\mathbf{0.0107 \pm 0.00636}^*$	$\mathbf{0.0097 \pm 0.00510}^*$	$\mathbf{0.0102 \pm 0.00565}^*$
Central Freq.$_{HF}$	0.2436 ± 0.0291	0.264 ± 0.0212	$\mathbf{0.2589 \pm 0.0326}^*$	0.2568 ± 0.0293	0.2566 ± 0.0352
LF/HF Ratio	1.6246 ± 1.5856	1.4684 ± 0.8038	1.3289 ± 0.8514	1.1835 ± 0.6461	1.617 ± 0.932
Power$_{[0.45-1]}(*10^{-2})$	0.505 ± 0.359	0.436 ± 0.382	0.391 ± 0.224	$\mathbf{0.315 \pm 0.202}^*$	0.432 ± 0.325
Power$_{[1-2.5]}(*10^{-2})$	0.17 ± 0.088	0.152 ± 0.106	0.14 ± 0.0654	$\mathbf{0.118 \pm 0.08}^*$	0.167 ± 0.116
Power$_{[2.5-5]}(*10^{-3})$	0.484 ± 0.269	0.397 ± 0.205	$\mathbf{0.315 \pm 0.132}^*$	$\mathbf{0.338 \pm 0.215}^\dagger$	0.414 ± 0.21

$*$: p-value$<$0.05; $\dagger$: p-value$<$0.01

also significantly different with respect to "Baseline". We hypothesize that this result could be related to an increase in respiratory rate for triggering conditions.

Finally, in the VHF bands we also find significant differences, mostly in the "High" VHF band, whose results are shown in Figure 3. In particular, "Anger" and "Fear" show a statistically significant decrease in spectral power in the "High" VHF band in comparison to "Baseline". Although not as significant, we can observe the same behavior in every emotionally characterized condition and for every VHF band we have considered. The changes observed in fast PD dynamics could be possibly attributed to central autonomic control activation in response to triggering events, such as the recall of the emotions we used in our protocol. Our findings, and relative hypotheses, require further tests and *ad hoc* designed experiments in order to be validated. Successful outcomes in favor of the capability of PD dynamics to reveal important brain mechanisms might be of great importance not only for social disciplines involving communication and psychology studies [21], but also in a broader range of applications in medical, civil, or military environments.

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