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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 PD dynamics can be addressed to characterized different affective states. Two different frequency bands 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 indices out of 13 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].

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 indices 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 main higher frequency band. Lastly, we perform statistical analysis and discuss the overall results.

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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, the students were first interviewed to recall and tell the psychologist one or possibly two recent episodes for each 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 emotion connected with the episode, he/she was asked to keep still and silent, gaze at the center of the Eye-tracker monitor for 3 minutes, and retain the feeling as long as possible. 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$^{\text{TM}}$ eye-tracker by SensoMotoric Instruments, at a sample frequency of $\text{f}_\text{s} = 250$ 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$^{\text{TM}}$ 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 [15].

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 [16]. 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

The Singular Spectra Analysis (SSA) is a powerful signal processing technique introduced by Broomhead [17]. The aim of SSA is to make a decomposition of the original series into a sum of independent and interpretable components, for example a slowly varying trend, discrete oscillatory components and structureless noise. We have implemented an Iterative-SSA method to fill the gaps of the PD signal due to blink events [12], [13]. In summary, the algorithms transforms the one-dimensional PD time series in and M-dimensional vector series by choosing overlapping windows to delimit each vector (embedding). The only parameter to be determined is the embedding dimension M. Once M is chosen, the M-lag correlation matrix $\mathbf{C}_x$ is computed as

$$\mathbf{C}_x = \tfrac{1}{N-|i-j|} \sum_{n=1}^{N-|i-j|} x(t_n)x(t_{n+|i-j|}) \quad \text{with } 0 \leq |i-j| < M. \tag{1}$$

Singular value decomposition (SVD) is further computed from $\mathbf{C}_x$, with eigenvectors $\mathbf{E}_l$. Projecting the time-series onto each $\mathbf{E}_l$ produces M principal components of lenght $(N - M + 1)$. It was demonstrated that the original time series can be reproduced with minor errors as the sum of its M reconstructed components, $\mathcal{R}_l(t_n)$ [18].

The choice of M is a key problem: the greater M, the longer the periods that can be observed and reconstructed; however, M too large would cause the fallacious description of a single oscillation into two or more components. An empirical rule was proposed by Vautard et al. [18], pointing at optimal reconstruction results for periods between $M/5$ and M. We chose $M = 150$ to reconstruct our PD recordings, previously filtered and resampled at 50 Hz, as the best choice to be able to analyze high frequency components up to 5 Hz, and preserving at the same time frequency components as low as 0.04 Hz. In order to retain the entire information content in the reconstruction of the PD signal we have decided to consider all the M components. In Figure 1 we show an example of the reconstruction performed using the I-SSA algorithm.

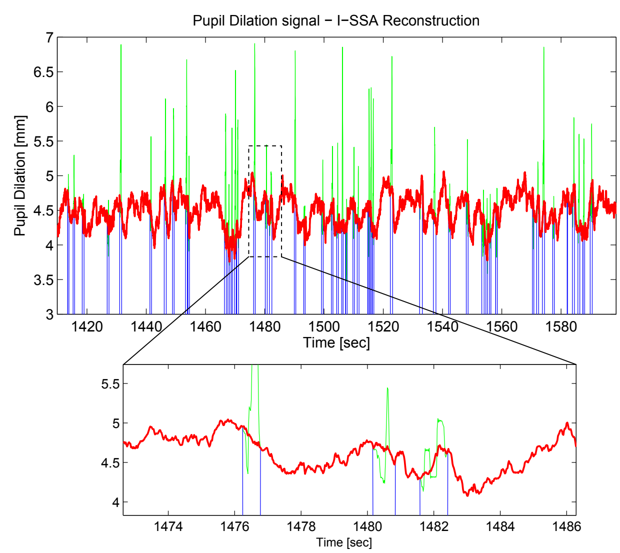

Fig. 1: An example of the reconstruction of Pupil Dilation signal with the Iterative-SSA algorithm for the subject "sbj05", during "Anger" event. In red the reconstructed signal, in green the original signal and in blue the blinking events.

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

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

(AR) model coefficients estimation. The order of the model was chosen according to the Akaike Information Criterion (AIC) [19]. A spectral decomposition procedure was applied to calculate the power of the oscillations embedded in the series [20].

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 [21]. The power of each PD rhythm was allocated to the corresponding frequency bands, low frequency (LF), from 0.04 to 0.15 Hz, and high frequency (HF), from 0.15 to 0.45 Hz. The central frequencies in LF and HF were computed, too.

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 three bands at higher frequencies, respectively VHF$_{[0.45\text{-}1]}$, from 0.45 to 1 HZ, VHF$_{[1\text{-}2.5]}$, from 1 to 2.5 HZ, and VHF$_{[2.5\text{-}5]}$), from 2.5 to 5 HZ. The choice was based on the observation of the PSD high frequency contents across all the subjects. In Figure 2 an example of the analysis is shown.

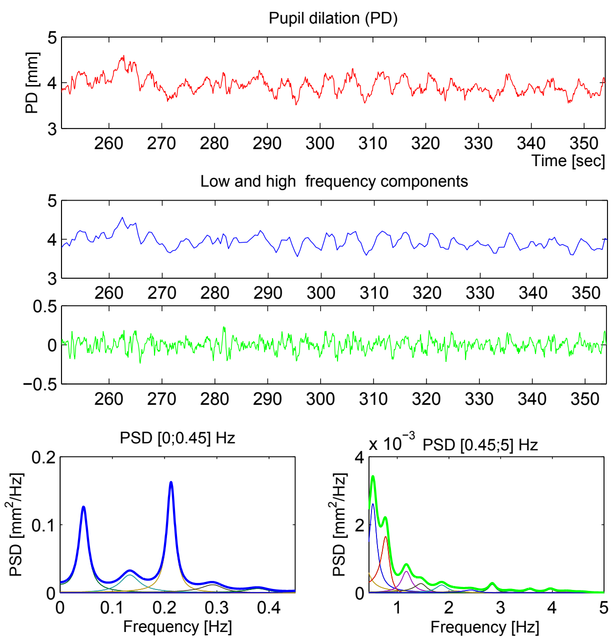

Fig. 2: Example of the analysis of the pupil dilation signal of the subject "sbj22" during "Baseline". In red the signal sampled at 50 Hz, in blue and in green respectively the low (0-0.45 Hz) and high (0.45-5 Hz) frequency oscillation.

We also computed the mean and standard deviation of PD, the ratio of mean and standard deviation, the total variance, and the total power in [0-0.45] Hz and in [0.45-5] Hz. 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". This subject was previously flagged for high presence of artifact noise and is therefore excluded from statistical analysis. An unpaired two-tailed Student's t-test was performed to test the statistical significance of the differences among the indices of "Baseline" with respect to the counterparts of any other emotional event.

III. RESULTS

Table I reports the mean and standard deviation of all the indices: bold type identifies statistically significant differences, $*$ is for p-value<0.05 and $\dagger$ for p-value<0.01.

Figure 3 shows the boxplots of the power in HF and in VHF$_{[2.5\text{-}5]}$ for all the experimental conditions. The red asterisks designate significant differences with respect to "Baseline".

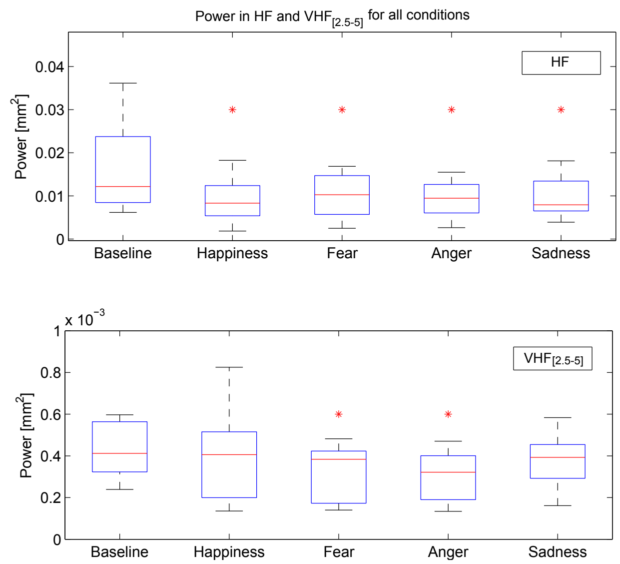

Fig. 3: Boxplot of the total power in HF and in VHF$_{[2.5\text{-}5]}$, for all the conditions. The red asterisks designate the conditions that showed significant differences with respect to "Baseline".

We can observe an overall decrease in variance for all emotionally characterized conditions. Particularly, the total power in the HF band (Figure 3) is significantly different from "Baseline" for each emotional events. In 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 also significantly different with respect to "Baseline". In VHF bands we also find significant differences, mostly in VHF$_{[2.5\text{-}5]}$ (Figure 3). In particular, "Anger" and "Fear" show a statistically significant decrease in spectral power in VHF$_{[2.5\text{-}5]}$ with respect to "Baseline". Although not significant, we can observe the same behavior in every emotionally characterized condition and for every VHF band we have considered. "Anger", which is the most triggering event, is significantly different from "Baseline" in 10 out of 13 indices.

IV. DISCUSSIONS & CONCLUSIONS

We have presented a new method for the reconstruction of PD to analyze its statistical properties and its spectral content as related to ANS dynamics in a psychophysiological paradigm designed to induce affective responses. We have

TABLE I: Mean and Standard Deviation for all the indices; 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
$\mu_{\text{PD}}/\sigma_{\text{PD}}$	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
$\text{Power}_{[0\text{-}0.45]}$	0.0632 ± 0.0354	0.045 ± 0.022	$\mathbf{0.0554 \pm 0.0623}^*$	$\mathbf{0.0465 \pm 0.0344}^*$	0.0488 ± 0.0339
$\text{Power}_{[0.45\text{-}5]}(*10^{-2})$	0.673 ± 0.371	0.657 ± 0.564	0.553 ± 0.303	$\mathbf{0.515 \pm 0.4}^\dagger$	0.67 ± 0.463
LF	0.0208 ± 0.0144	0.0113 ± 0.00662	0.0118 ± 0.00707	$\mathbf{0.0099 \pm 0.00533}^*$	0.0168 ± 0.0161
f_{LF}	0.0653 ± 0.0251	$\mathbf{0.1078 \pm 0.0236}^\dagger$	$\mathbf{0.0904 \pm 0.0228}^\dagger$	$\mathbf{0.0987 \pm 0.0186}^\dagger$	$\mathbf{0.0958 \pm 0.0273}^\dagger$
HF	0.0174 ± 0.0129	$\mathbf{0.00917 \pm 0.00512}^\dagger$	$\mathbf{0.0107 \pm 0.00636}^*$	$\mathbf{0.0097 \pm 0.00510}^*$	$\mathbf{0.0102 \pm 0.00565}^*$
f_{HF}	0.2436 ± 0.0291	0.264 ± 0.0212	$\mathbf{0.2589 \pm 0.0326}^*$	0.2568 ± 0.0293	0.2566 ± 0.0352
$\text{VHF}_{[0.45\text{-}1]}\ (*10^{-2})$	0.505 ± 0.359	0.436 ± 0.382	0.391 ± 0.224	$\mathbf{0.315 \pm 0.202}^*$	0.432 ± 0.325
$\text{VHF}_{[1\text{-}2.5]}\ (*10^{-2})$	0.17 ± 0.088	0.152 ± 0.106	0.14 ± 0.0654	$\mathbf{0.118 \pm 0.08}^*$	0.167 ± 0.116
$\text{VHF}_{[2.5\text{-}5]}\ (*10^{-3})$	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

observed a general decrease in the power, both at HF and VHF. This results is not surprising, as a sympathetic activation could be accompanied by a general reduction of the variability of the signals [21]. We further hypothesize that the shift of LF and HF central frequencies could be related to an increase in respiratory rate for triggering conditions. In particular, during "Sadness" the PD dynamics could be influences by the observed different breathing behavior, and this will be the subject of future works. PD frequency content beyond 1 Hz, rarely explored by the scientific community, has shown significant changes for the emotional events characterized by high arousal, i.e. "Fear" and "Anger". These fast changes could be possibly attributed to central autonomic control activation in response to triggering events, such as the emotion-recall paradigm we used in our protocol. Also here, 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 [22], but also in a broader range of applications in medical, civil, or military environments.

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