A Novel Protocol for the Quantification of Cardiovascular and Autonomic Responses to Urban Environments Through Physiological Signals

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Abstract

Objective physiological measures like heart rate variability (HRV) and electrodermal activity (EDA) can provide valuable insights into autonomic processes related to emotional responses. We present a novel protocol aimed at evaluating emotional responses to urban design choices via combined analysis of psychological and physiological data recorded during a guided walk throughout a urban environment. Statistically significant differences were found in the cardiovascular and autonomic responses of tested subjects across different points of interest along the route, suggesting that the evaluation of psychophysiological responses through analysis of cardiovascular signals can indeed offer insights into the perception of urban design implementations and how they ultimately promote well-being.

1. Introduction

Urban design choices can have a substantial impact on both mental and physical well-being of citizens by promoting physical activity, reducing stress, and facilitating social cohesion[1][2]. Ultimately, these factors significantly contribute to improving and maintaining the cardiovascular health of residents and users of urban areas.

The joint efforts of our multidisciplinary team of biomedical engineers, urban planners and environmental psychologists are aimed towards the goal of developing a novel platform that can aid urban planners in the decision-making phase of urban renovation projects, via the combined analysis of psychological and physiological data.

Physiological variables like Heart Rate Variability (HRV) and Electrodermal Activity (EDA) are objective measures of emotion-related autonomic responses; therefore, the protocol we devised employed metrics derived from these measures to evaluate subjects' reaction to urban environments.

This presents results from a pilot study carried out at the Università di Milano Bicocca campus that tested the validity and feasibility of the protocol.

2. Materials and Methods

2.1. The Protocol

The experimental protocol consisted of a guided walk throughout the Università di Milano Bicocca campus along a predefined path that was specifically devised to simulate the experience of students walking from the nearby Milano Greco Pirelli train station towards the classroom buildings in Piazza della Scienza.

Seven Points of Interest (POIs) were selected along the route, each characterized by either one or two directions of view that subjects were instructed to look at when reaching each POI (see Fig. 1 and Table 1).

The participants' physiological responses were continuously recorded throughout the walk via EDA and ECG electrodes connected to a multichannel signal acquisition system set to a sampling frequency of 256 Hz.

An initial baseline acquisition point at the beginning of the walk was used to record the subjects' physiological activity in rest conditions.

Psychological responses were collected at each POI via the exp-EIA (experiential Environmental Impact Assessment) survey embedded into the CitySense® mobile application developed specifically for our platform[3].

An operator carrying an array of environmental sensors (such as illumination, temperature, and humidity) followed the experimental subjects throughout the walk to collect environmental data.

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Ethics Committee of Politecnico di Milano.

In total, 69 people selected among the general student population participated in the experimental protocol. All subjects signed an informed consent form prior to the beginning of the experiment.

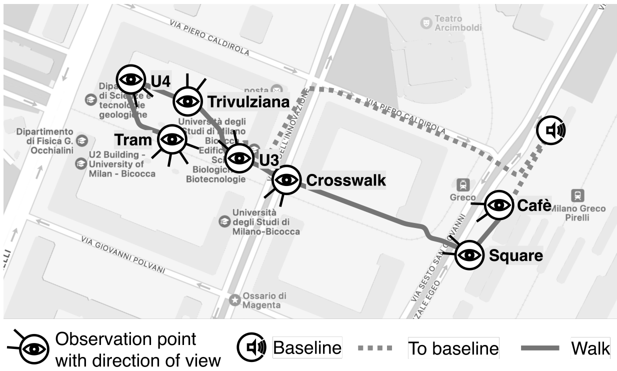


Figure 1: The guided walk consisted of one initial baseline acquisition points, and seven observation points. Note that the final point, denoted as 'Tram', includes two directions of view that the subjects were asked to treat as two separate observation points.

Table 1: Points of Interest (POI) and Directions of View (DOW)

POI	Name	Directions of View
1	Cafè	1
2	Square	1
3	Crosswalk	1
4	Building U3	1
5	Trivulziana	1
6	Building U4	1
7	Tram	2

2.2. Signal Processing

The ECG signal was filtered with a 3rd order Butterworth filter with passing band of 5 to 26 Hz, to remove power line interference, baseline drift and other superimposed noise.

Beats were extracted via the Pan-Tompkins algorithm. The results were manually inspected and erroneous annotations were corrected. The segments of the signal recorded while the subject was walking were particularly difficult to automatically annotate; in several subjects heartbeats in these sections required manual selection.

The RR signal was extracted as the distance in seconds between subsequent beats. Ectopic and misdetected beats were corrected via shape-preserving piecewise cubic interpolation. Heart rate (HR) was computed as the reciprocal of the RR series after resampling signal at a constant sampling frequency of 8 Hz.

A Point Process statistical approach that models beat-to-beat intervals as a history dependent inverse Gaussian (HDIG) process was used to estimate both time domain (RR series) and spectral indices (Low Frequency Power LF, High Frequency Power HF, Ultra High Frequency Power UHF, and Sympathovagal Balance LF/HF) in continuous time[4].

The Point Process approach was chosen over traditional methods as it tends to outperform such techniques when analyzing fast-changing signals like RR series acquired while alternating walking and standing still[5][6].

Spectral indexes were computed as continuous-time signals sampled at 20Hz; A time domain average of each signal was calculated for each subject and for each POI segment of the recording to obtain punctual indexes.

Poincaré indexes of HRV were computed on the non resampled RR series; in particular, SD1 (length of the minor semi-axis of the Poincaré ellipse), SD2 (length of the major semi-axis), SD1SD1 (ratio of the semi-axes lengths) and ARR (area of the ellipse) were derived for each segment of the recording.

The Electrodermal Activity signal was deconvoluted into its tonic and phasic components via the cvxEDA algorithm. The Phasic Driver of Electrodermal Activity (PDA) was estimated too: this signal represents the spikes of neural activity throughout the nerve fibers innervating sudomotor glands, and it's known from literature to correlate to ANS arousal[7].

Furthermore, the Emotional Index was computed as described by Vecchiato et. al.[8] The Emotional Index (EI) is a combined index of arousal and valence that's calculated using both the Heart Rate and the tonic EDA signals, after normalization with respect to baseline.

Both tonic EDA, PDA and EI were averaged for each POI to obtain punctual indexes.

Finally, Principal Component Analysis was carried out to identify the linear combination of features that explained the greatest amount of variability within the dataset.

3. Results

Friedman multiple comparison analysis of the metrics revealed statistically significant differences in the cardiovascular and autonomic responses of test subjects across the different points of interest (see Fig. 2 and Fig. 3).

In particular, mean PDA values steadily increased throughout the walk, with statistically significant differences ($p < 0.015$) being observed between POIs 2 and 3 ('Square' and 'Crosswalk') and POIs 4 to 7 ('Building U3', 'Trivulziana', 'Building U4' and 'Tram').

The EI showed significant differences ($p < 0.03$) between POIs 1 and 2 ('Cafè' and 'Square'), and POI_6 ('Building U4'). Although not statistically significant, a 'peaks and valleys' trend was observed throughout the POIs, with POI_4 ('Building U3') exhibiting a mean EI indicative of a general happy state, while the subsequent POI_5 ('Trivulziana', a point characterized by the view

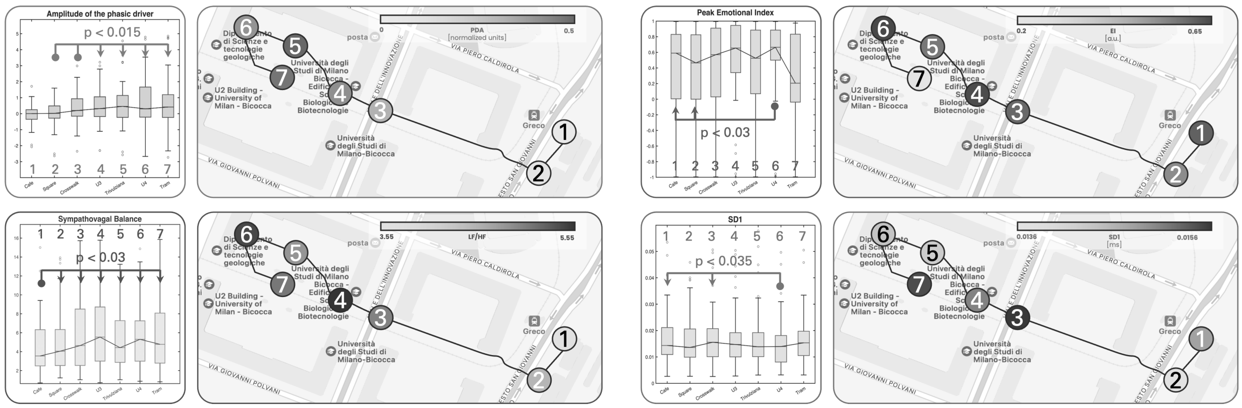
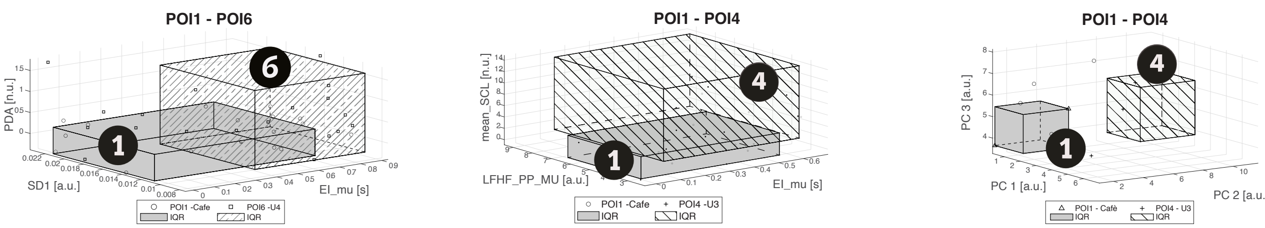


Figure 2: The computed metrics. On the maps, intensity of the shaded circles indicates magnitude of the median index computed across all experimental subjects at the specific point of interest.



(a) (b) (c)

Figure 3: 3D plot comparison of some POI pairs. The boxes represent the $25\% - 75\%$ interquantile range distribution along each of the three directions corresponding to the three physiological variables of SD1, LF/HF, and PDA (in plots (a) and (b)), or to the three principal components obtained by PCA of the physiological dataset (in plot (c))

over the construction site towards Piazza Trivulziana) being characterized by a more alert response. SD1 displayed significant changes ($p < 0.035$) between POI_6 (‘Building U4’) and POIs 1 and 3 (‘Cafè’ and ‘Crosswalk’).

Regarding LF/HF, statistical significance was observed when comparing POI_1 (‘Cafè’) to the rest of the POIs (POI_2 to POI_7). The trend of this variable throughout the walk showed a steady increase from POI_1 (‘Cafè’) to POI_4 (‘Building U3’), suggesting increasing sympathetic activity. A sudden decrease in sympathovagal balance in correspondence of POI_5 (‘Trivulziana’) was then followed by a second peak at POI_6 (‘Building U4’).

Finally, the Principal Component Analysis approach achieved a relevant separation between specific positions using appropriate combinations of metrics that most contributed to the variability of the dataset, most importantly the mean Tonic EDA and mean and standard deviation of the Sympathovagal Balance. The three principal components obtained as linear combinations of the aforementioned metrics showed significant separation between POIs 1 and 2 (‘Cafè’ and ‘Square’, located at the very beginning of the walk), and the other five POIs. An exemplary PCA separation is shown in Figure 3c.

4. Discussion

The above presented results allow us to draw some important considerations about the general autonomic activation levels during the guided walk.

In particular, POIs 4 and 6 (‘Building U3’ and ‘Building U4’) appear to be characterized by the highest sympathetic activation, as suggested by the trend in the LF/HF distribution; conversely, vagal activation seems to be prevalent at the ‘Crosswalk’ POI_3 as indicated by SD1[9].

The PDA assessment points at a general increase of overall arousal levels, with POIs located close to the classroom buildings exhibiting higher arousal levels than POIs near the train station. Of note, PDA arousal assessments showed similar differences in transient responses to arousing stimuli across POIs.

Considering the overall trends of the four most significant metrics, the initial two POIs (POI_1, ‘Cafè’, and POI_2, ‘Square’) are characterized by the lowest arousal levels, and neutral valence. On the other hand, POIs 3 to 7, located in close proximity to the classroom buildings are those with highest arousal. As a matter of fact, POI_1 and POI_2 are situated in the square in front of the Milano

Greco Pirelli train station, an open space that offers a less obstructed view of the sky than the tall buildings that characterize the main university campus. This substantial environmental difference could explain the distinct variation in arousal between the two sections of the walk.

Furthermore, POI_4 ('Building U3') seems to be the observation point that elicits the highest sympathetic activation and an emotional response suggesting a state of happiness. POI_6 ('Building U4') is characterized by a similar physiological response: the two POIs are at opposite ends of the main square around which classroom buildings are located, and offer a similar view. Conversely, POI_5 ('Trivulziana'), located in between POI_4 and POI_6, faces a passage through buildings towards Piazza Trivulziana, partially blocked by a construction barrier due to ongoing renovation work. Such duller view is supposedly influencing the observed decrease in sympathetic activity, reflecting a shift of emotional responses to a more negative valence in correspondence of POI_5.

These finding point at a relevant effect of the environment perception on the physiological states of the urban dweller. As the experimental protocol included the collection of psychological and environmental responses that were analyzed by the environmental psychologists and urban planners on the team, our next goal for the advancement and continuation of the project is therefore the merge of the results obtained from the analyses of the three datasets, to achieve a multifaceted and more detailed view of how urban environment affects its inhabitants.

5. Conclusions

The results of the experimental walk conducted throughout the Università di Milano Bicocca campus provide first evidence on how autonomic activity is subject to changes during urban exploration contexts.

Our findings suggest that the evaluation of psychophysiological responses through analysis of cardiovascular and electrodermal signals can indeed offer insights into the perception of urban design implementations: these findings, augmented by the inclusion of other variables such as psychological responses and environmental factors, can therefore be employed to guide decision making during the planning stages of urban renovation projects, with the ultimate goal of maximizing citizens' well-being both on a mental and on a physical level.

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