Effect of EDA-driven sympathetic responses on the central processing of faces cued by hedonic odors: a preliminary ERP study

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***Abstract*—Olfactory stimuli are powerful cues modulating behavioral and physiological responses to the emotional perception of human faces. In this context, although both central and autonomic dynamics have been investigated, the potential integration of autonomic information on the responses at the central level has never been considered. In this work, we acquired both the electrodermal activity (EDA) and EEG signals from a group of 20 healthy volunteers during a passive viewing task consisting of a contextual presentation of neutral faces and emotional odors. We applied a novel approach based on the processing of EDA to identify event-related potentials (ERPs) with and without a concomitant sympathetic response. Then, we investigated the modulatory effect of both their sympathetic responses and contextual odors on ERP components involved in the processing of faces. We observed an enhancement of the N170 amplitude in the left parieto-temporal region when a sympathetic response was present, compared to ERPs associated with no sympathetic responses, irrespective of odors' valence. Our preliminary results suggest that sympathetic responses identified from EDA have an effect on the early central processing of faces with background odors, possibly reflecting enhanced arousal triggered by salient features of the stimuli.**

***Keywords*—Face processing, ERP, sympathetic responses, hedonic olfaction**

I. Introduction

Facial expressions are powerful non-verbal means through which the emotional state or the identity of a person can be efficiently decoded [1]. However, when expressions are ambiguous, their interpretation relies on the integration with other sensory modalities [2]. Previous research indicated contextual odors as powerful emotional triggers for the processing of faces, with odors' valence and arousal playing a key role as modulatory factors [3]–[5]. Moreover, their influence is not limited to subjective ratings but extends also to the physiological response as measured by EEG event-related-potentials (ERPs).

ERPs are EEG changes time locked to sensory, motor or cognitive events that provide a noninvasive approach to study psychophysiological correlates of mental processes. These waveforms are characterized by some key features, namely components, that can reflect early "sensory" or late "cognitive" responses [6]. Previous studies highlighted a contextual effect of emotional odors occurring at different stages of face processing, including the N1/P1 [7], N170 [8], VPP [9], and LPP [10] components.

Parallel to ERP analyses, other studies focused on the autonomic response elicited by contextual visual/odor stimulation [11], [12]. Particularly, enhanced peripheral sympathetic activations have been observed following the presentation of either visual or olfactory stimuli and that reflected the perceived level of arousal [11]–[13]. In this light, it would be of particular interest integrating the sympathetic responses with ERP measures for analyzing the multimodal integration of visual-odor processing.

Here, we investigate the effect of peripheral sympathetic responses on the central processing of neutral faces modulated by hedonic odors. We combine standard ERP analysis with the information provided by electrodermal activity (EDA). EDA is the most commonly used index to assess peripheral sympathetic activity, as the eccrine sweat glands generating it are mainly controlled by afferent sudomotor sympathetic fibers [13]. Accordingly, we apply a rigorous deconvolution procedure based on [14] to estimate the EDA underlying sudomotor nerve activity (SMNA), and identify the occurrence of significant sympathetic responses associated with the presentation of the stimuli. We exploit these events to compare ERPs with and without a sympathetic response [15]. Moreover, we evaluate the influence of contextual odors on both types of ERPs.

II. Material and methods

A. Subjects

The study was conducted according with the guidelines of the Declaration of Helsinki, and approved by the Bioethics Committee of the University of Pisa Review No. 14/2019, May 3rd, 2019. Twenty healthy volunteers (age 27 $\pm$ 3, 5 females) with equivalent olfactory threshold according to the double-blind forced-choice olfactory test [16] were enrolled in the study. Volunteers were not allowed to have any food nor drink in the 30 minutes preceding the experiment.

B. Stimuli

We selected three different odorants: i.e., banana (isoamyl acetate), isovaleric acid, and n-butanol, to convey positive,

negative, and neutral valence, respectively [17], [18]. We additionally used clean air as a control condition. For each subject, we prepared $1ml$ isointense solutions diluting pure odorant substances in distilled water according with the ratios of 1/20 (banana, n-butanol) and 1/10 (isovaleric acid) respectively. Odorants were delivered through an in-house built computer-controlled olfactometer at a flow rate of $60ml/min$.

Visual stimuli were obtained from the Chicago Face Database [19]. Particularly, we balanced the stimuli across gender, age, and ethnicity, to mitigate potential confounding effects related to the intrinsic characteristics of the actors. The pictures were shown on a 15" laptop screen with a refresh rate of 60Hz and a resolution of 1920x1080. The pictures' size was 15cm in width and 10cm in height, and they were displayed at about 50cm from the eyes of the participants.

C. Experimental protocol

Before starting the experiment participants rated the odorants in terms of valence (from -2 to +2) and arousal (from 1 to 5) according with the Self-Assessment Manikin (SAM) test [20]. In this phase, odors were randomly presented for a duration of 10s. Then, subjects underwent to an experimental protocol made of 128 trials of concurrent odor/image administration. A schematic representation of each trial is reported in Fig 1, which consisted of: (1) 3s of gray background; (2) 3s of fixation cross; (3) 1.5s of neutral face image presentation; (4) 6s of inter-trial rest during which subjects rated the facial expression in terms of valence and arousal according to the SAM test. Odorants were administered from phase (1) to (3), while during (4) clean air was used to washout the odor. Each odor condition comprised a total of 32 trials. The experimental protocol for olfactory/visual stimulation was designed and implemented using the PsychoPy software [21].

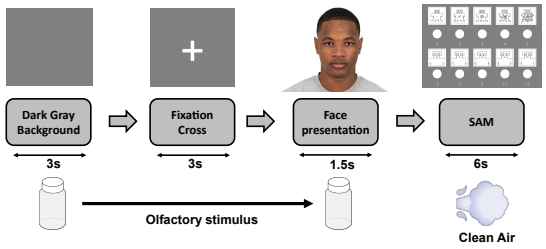

Fig. 1: Experimental protocol. For each trial a random odor among banana, n-butanol, isovaleric acid and clean air was delivered starting from *Dark Gray Background* to *Face presentation*. A wash-out with clean air was performed during *SAM*.

D. EDA acquisition and sympathetic activity estimation

EDA was acquired at a sampling frequency of 250Hz with a Shimmer3 GSR+ unit (Shimmer, USA) and a pair of Ag/AgCl electrodes placed on the proximal phalanx of the first and second fingers of the non-dominant hand, respectively. For each odor condition, we estimated the trials associated with an enhanced peripheral sympathetic response through a novel approach based on the analysis of the EDA signal. For each subject, we undersampled the EDA to the sampling frequency of 50Hz and performed a Z-scoring on the data. Then, we applied cvxEDA to obtain an estimate of the SMNA [14]. We identified discrete events of sympathetic activation associated with the presentation of visual stimuli as those epochs having non-zero SMNA bursts occurring in the (1-5)s after stimulus onset.

Additionally, to study potential differences in the sympathetic response to different odor conditions, we extracted: (1) the number of epochs with/without a sympathetic response (nSymp), (2) the latency of sympathetic responses, (3) the average amplitude of the SMNA across epochs, and (4) the subject-average SCR generated by the SMNA bursts.

E. EEG acquisition and preprocessing

EEG was acquired at the sampling frequency of 500Hz using a high-density 128-channel geodesic EEG System 300 from Electrical Geodesic, Inc. (EGI). Electrodes were grounded through two additional channels placed between Cz and Pz and referenced through Cz. We always kept electrode impedances below $20k\Omega$ during the acquisitions. We preprocessed the EEG signal using EEGLAB [22] with a pipeline comprising: (1) zero-phase antialiasing filter (filter cut-off = 30hz) and downsampling to a sampling frequency of 100Hz, (2) a zero-phase high-pass filter (cut-off = 0.1Hz) to improve data stationarity, (3) bad channel removal with poor correlation with their neighboring channels (i.e., ρ <0.8) [23], (4) channel recovery through spherical spline interpolation, (5) re-referencing to average. Then, preprocessed EEG was segmented into epochs ranging from -200ms to +1000ms around face-stimulus onset. For each epoch we removed a baseline estimated in the (-200,0)ms time-range. Epochs contaminted by irreducible artefacts were identified by visual inspection and removed. Finally, we decomposed EEG data through ICA [24], and we removed components resembling noise sources (e.g., EMG, eye blinks). Clean epochs were averaged together based on both the odor condition and the presence or absence of peripheral sympathetic activation (hereinafter referred to as *Odor* and *Symp* conditions, respectively). Accordingly, we obtained subject-average ERPs for each combination of *Odor* and *Symp*.

We analyzed ERP components based on specific regions of interest (ROIs) of the scalp with the guidance from previous literature [7]–[9], [25]–[28]. More specifically, we extracted (1) the P1 component in the 120-160ms interval after stimulus onset in the occipital region around O1 and O2 (10 electrodes); (2) the N1 component at the same latency as P1, in the central region around Cz (15 electrodes); (3) the N170 component in the 160-200ms interval at both the left and the right occipito-temporal regions (7 electrodes near P7 and P8, respectively); (4) the Vertex Positive Potential (VPP) in the 160-200ms interval in the same ROI of the N1 component; (5) P2 component at 220-300ms in the same occipital region of P1; (6) the Late Positive Potential (LPP), a sustained positivity occurring in the 300-500ms range around Pz (9 electrodes). For each subject and for each component, we extracted the mean amplitude within the respective time interval and ROI.

F. Statistical analysis

We analyzed SAM ratings of the odorants through multiple Wilcoxon sign-rank tests on the valence and arousal ratings, respectively. P-values were adjusted for multiple comparison testing with Bonferroni correction. We applied the same statistical procedure to test for the effect of *Odor* on the SAM ratings of faces.

We applied a 1x4 within-subject ANOVA on the average SMNA amplitude to test for an effect of *Odor* on the sympathetic responses. Multiple comparison testing was controlled with false-discovery rate (FDR) for multiple testing under dependency [29]. The same statistical testing procedure was applied to the latency of such responses. We investigated the effect of *Odor* on subject-average SCRs through a repeated-measures 1x4 ANOVA (corrected with FDR). Moreover, we performed a 2x4 ANOVA on the number of EDA epochs (i.e., *nSymp*) grouped by *Odor* and *Symp*, to test for an interaction between the factors (FDR-corrected).

We tested for a significant effect of *Odor* on the amplitude of each component through a 1x4 within-subject ANOVA (FDR-corrected). Post-hoc comparisons were conducted with a t-test (corrected with Bonferroni). In addition, for the odors that elicited an ERP response statistically different from clean air, we ran a 2x2 ANOVA with Odor (i.e., clean air vs odorant) and *Symp* as within-subject effects, to test for a significant difference between ERPs associated with/without a peripheral sympathetic response.

III. Results

A. SAM statistical analysis results

1) Odor rating: Subjects rated isovaleric acid as significantly more unpleasant (mean $\pm$ standard error (SE); valence = -0.62 ± 0.18) and more arousing (arousal = 2.81 ± 0.22) with respect to banana and n-butanol. We did not find any significant difference between the valence and arousal ratings of banana (valence = 0.38 ± 0.20; arousal = 2.33 ± 0.21) and n-butanol (valence = 0.10 ± 0.18; arousal = 1.86 ± 0.17).

2) Face rating: We did not find any significant difference in the subjective ratings of faces among odors for both the valence (clean air = -0.05 ± 0.05; banana = -0.14 ± 0.06; n-butanol = -0.03 ± 0.05; isovaleric acid = -0.09 ± 0.07) and arousal (clean air = 2.17 ± 0.16; banana = 2.23 ± 0.17; n-butanol = 2.18 ± 0.16; isovaleric acid = 2.15 ± 0.17).

B. EDA statistical analysis results

We did not find any significant effect of *Odor* on the SMNA average amplitude, SMNA latency, and subject-average SCRs. Conversely, we found a significant effect for *Symp* on nSymp ($F_{6,64} = 5.76, p < 10^{-5}$; FDR-corrected). More specifically, we found a lower number of stimuli associated with a sympathetic response, compared to those without sympathetic response, irrespective of *Odor*.

C. ERP statistical analysis results

We found a significant effect for *Odor* on the N1 ($F_{6,64} = 6.65, p < 10^{-4}$; FDR-corrected) and VPP ($F_{6,64} = 3.63, p < 10^{-4}$; FDR-corrected) components at the ROI centered on Cz (Fig. 2). Post-hoc analysis highlighted a more negative N1 component during the administration of isovaleric acid, with respect to clean air. Moreover, the VPP amplitude during the administration of both isovaleric acid and n-butanol was signficantly lower with respect to clean air.

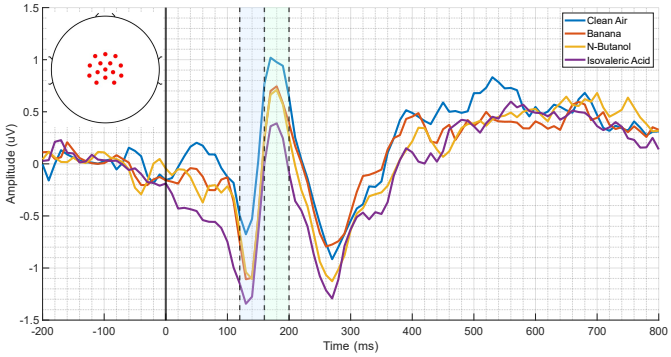

Fig. 2: ERP grand-averages for the Clean Air (blue), Banana (red), N-Butanol (yellow), and Isovaleric Acid (purple) conditions in the time range from -200ms to 800ms with respect to the stimulus onset. ERPs were averaged across 15 electrodes around Cz, as schematically represented by the scalp map on the top-left of the plot. We found a greater N1 amplitude during Isovaleric Acid, with respect to Clean Air (blue area). Conversely, we found a lower VPP amplitude during both Isovaleric Acid and N-Butanol, with respect to Clean Air (green area)

In light of the results obtained from the SAM and ERP analyses, we focused on the effects of isovaleric acid compared to clean air. Accordingly, we run a 2x2 ANOVA with *Odor* and *Symp* as within-subject effects, to further test for an effect of peripheral sympathetic responses on ERP components. Consistently, we found a significant effect for *Odor* on both the N1 ($F_{1,17} = 12.95, p = 0.001$) and VPP ($F_{1,17} = 14.81, p < 10^{-3}$). Moreover, we observed a significant effect for *Symp* on the N170 at the left parieto-temporal ROI ($F_{1,17} = 5.10, p = 0.03$) (Fig.3). Particularly, the presence of a sympathetic response resulted in the increase of the N170 amplitude. We did not find a significant interaction between *Odor* and *Symp* for any of the ERP components investigated.

IV. Discussion

In this work, we provided a novel methodological approach based on the analysis of the EDA signal to integrate peripheral sympathetic activity information onto ERP analysis of key components associated with the processing of faces and contextual hedonic odors. Although preliminary, our results showed a significant difference between ERPs with and without a SMNA response at the early stages of face processing.

We did not find any significant difference in the ratings of faces for both valence and arousal among odors. Yet, we

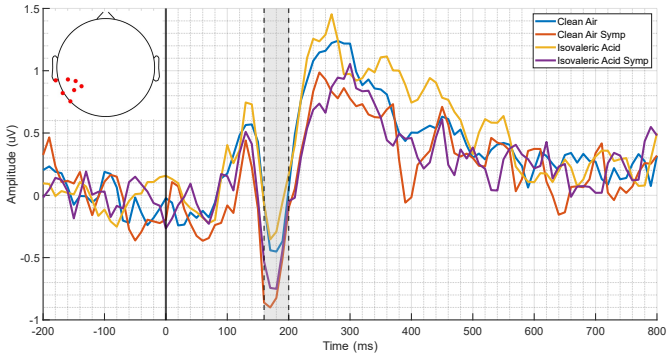

Fig. 3: ERP grand-averages for the Clean Air (blue), Clean Air Symp (red), Isovaleric Acid (yellow), and Isovaleric Acid Symp (purple) conditions in the (-200,800)ms time around stimulus onset. ERPs were averaged across 7 electrodes around P7, as schematically represented by the scalp map reported on left. The gray area highlights the time range for which we obsrved a significant difference between the amplitudes of the N170 component of epochs with and without a sympathetic activation.

observed an effect of olfactory stimulation on the N1 e VPP ERP components. Particularly, the amplitude of the VPP was lower during the administration of both isovaleric acid and n-butanol, with respect to clean air. This is in line with previous studies reporting an overall effect of olfactory stimuli, irrespective of their valence [9]. Considering N1, we observed a more negative amplitude during the administration of isovaleric acid, with respect to clean air. Greater amplitudes of the N1/P1 component have been associated with the enhanced allocation of attention towards faces [7]. In this light, we may suggest that isovaleric acid had a greater arousing effect on the early processing of visual stimuli, compared to the other odorants. This is further corroborated by our findings on the subjective ratings of odors, showing isovaleric acid as being perceived as more arousing and unpleasant compared to banana and n-butanol.

The amplitude of the N170 increased for the P7 cluster in the presence of a sympathetic response. Previous studies have found a significant correlation between the N170 amplitude and the perceived level of arousal associated with faces, irrespective of their valence, such that arousing stimuli were associated with increased ERP responses [30]. Further, during the N170 window, it is hypothesized that multiple cortical processes underlie the fine-graining categorization of faces based on their main characteristics, such as expression, eye gaze, and identity [27]. In this light, we may suggest that the higher N170 amplitude observed during sympathetic responses reflects enhanced arousal associated with salient features of the stimuli.

Of note, banana was rated neutral rather than positive. In this light, we cannot exclude that this was reflected also at the ERP level, where we did not observe any significant difference between positive and neutral conditions. However, we should also consider the low flow rate at which odors were delivered (i.e., $60ml/min$), which is lower than flow rates commonly used in the literature (e.g., 1-$6l/min$) [31]. In this light, future works could evaluate the effects of low flow rates influence on key features of perceived odors.

Although preliminary, our results suggest that integrating peripheral sympathetic information in the analysis of the central responses to the contextual presentation of visual and olfactory stimuli may be of interest for future studies investigating potential effects at the source level through the application of more sophisticated techniques.

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