Characterizing emotional response to olfactory, auditory and visual stimulations in a virtual reality environment

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Running head: Olfactory emotion in multisensory virtual environment

i. Summary/Abstract

Food stimuli are multisensorial: eating potato chips is associated with a particular sound, odor, taste, color, form, texture, *etc*. The understanding of consumer emotional experience requires the study of each sensory component isolated from each other's or combined, in different contexts and conditions. Virtual reality recent development offered a unique tool allowing the complete and highly controlled study of consumer experience. It bridges the gap between real-life and laboratory investigations by providing rich, complete and adjustable environment that can be combined with the increasing number of methods developed to measure psychological, behavioral and physiological effects of emotion. The protocol presented here was developed to investigate implicit behavioral and physiological emotional responses related to the encountering of emotional olfactory, auditory and visual stimuli in a rich virtual environment. It was developed without any reference to food consumption behavior but can be easily transferable to all kind of stimuli.

ii. Key Words

Breathing; Electrodermal response; Emotion; Heart rate; Multisensory; Odor; Virtual Reality

1 Introduction

The method we developed aimed at investigating emotional responses to olfactory, auditory and visual stimuli in an ecological and fully controlled virtual reality (VR) environment. It consisted in an association between a VR software, a device allowing rigorous olfactory stimulation called "an olfactometer" and a physiological recording belt giving access to physiological emotional processing. Albeit this method was conceived for fundamental research, it could inspire industry players or laboratory, working in the scope of food science, olfactory design or cosmetology to test the emotional response to environmental or object-specific odor (Note 1).

When characterizing cognitive or emotional processes, whether for the purpose of fundamental or applied research, it is interesting to consider the multisensory environment in which this cognitive process takes part. It allows for the experimental conditions to be closer to real life and the conclusions to be more plausible than in impoverished experimental contexts ***(1–3)***. While real-life ecological situations might be difficult to control and to manipulate, VR offers the opportunity to explore a cognitive process in a multisensory environment without these disadvantages. And, importantly, it enables the determination of the interactions between the main process of interest and its environment. While VR commonly offers auditory stimulation in addition to the visual context ***(4–6)***, it has been rarely coupled to olfactory stimulations. In some studies, environmental smells ***(7)*** or food odors ***(8)*** have been simply added to the ambient air by being diffused through commercial electronic scent diffusers in the experimental room while participants explore a virtual environment. In other studies, specific installations that are much more complex have been developed, enabling various scents to be diffused during different virtual scenarios, at a precise time and space with the possibility to synchronize the delivery of the odorant with pictures, videos or sounds ***(9)*** and even in combination to haptic stimulation ***(10)***. In the former, the development is easy but the possibilities are limited to environmental odors diffusion and independent of the participants behavior. In the later, the development is complex and necessitates a combination of specific technological developments but the possibilities are much larger. Odors may be delivered specifically to the nose of the participants and their delivery is triggered by the participant himself. The method we developed is intermediate in complexity. It necessitates limited developments in comparison to dedicated installations, since it combines existing technique of olfactory stimulation ***(11)*** to VR software, but offers similar possibilities in addition to be readily transportable.

In our approach we aimed to study the implicit and objective emotional responses to olfactory, auditory and visual stimuli in two different ways, that were developed in the method section: 1) By recording the number of time the participants voluntarily activated the presentation of each stimulus during the exploration of the virtual environment, a behavior reflecting their attraction or repulsion toward them; 2) by recording participants' physiological parameters reflecting the response to emotional stimuli (respiratory and heart signals, and electrodermal responses) during virtual environment exploration. No development was needed for this purpose, suitable equipment being commercially available.

2 Materials

2.1 Participants

Participants had to report normal sense of smell and no visual or auditory impairments.

2.2 Computer equipment

The experiment required the use of a computer linked to two screens, one on the participant's side and the other on the experimenter's side (Figure 1 A-B). The computer characteristics must be sufficient enough to support the RV software. For example, the computer used in the experiment had the following characteristics: a RAM of 12 Go, a processor of 64 bits, and a graphical card Nvidia Quadro K420.

2.3 Virtual reality software

The software was developed using Unity 5.6.5 (Unity Technologies, USA) by a local technical platform NeuroImmersion (CRNL). It allowed the presentation of a virtual 3D house in a first-person view (non-immersive VR) that can be actively explored using a trackball (Kensington, Redwood Shores, CA, USA) (Note 3). As is it widely the case in VR, the software involved visual stimulations that compose the surrounding environment, and auditory stimulations of synthetic footsteps paced on the rhythm of participant's speed. The house was composed of three rooms, a bedroom, an office and a living-room, connected to a corridor by closable doors (Figure 1 C-E). Each of these rooms was defined by its furniture, its decorative elements, the nature of the floor and its wallpaper. For example, the bedroom included a queen-size bed, a chest of drawers, two night-tables, three matching carpets and four paintings. In addition, three clickable elements were placed in each room at specific locations, allowing to send specific sensory stimulations: a fragrance diffuser (glass bottle with capillary stems) delivered olfactory stimulus, a radio receiver delivered auditory stimulus and a small portable picture frame delivered visual stimulus (Note 4). These elements were highlighted by an arrow that appeared when participants were nearby.

The software was designed to adapt to different protocols. For this purpose, it opens on a floating window allowing its configuration. In the *Graphics* tab, screen resolution, graphics quality and monitor for display were determined, allowing its adaptability on different types of screens and computers. In the *Input* tab, the coding of the movement was defined (either keys of the keyboard or mouse/joystick/trackball). Then the *home page* allowed to select the name of the session, the participant identifier, and to load the input file presenting the parameters for sensory stimulations. The date and time were automatically filled in. An *Option page* allowed to specify any other potentially important variables (*e.g.*, minimal duration of the experiment). A *Start* button allowed to launch the experiment *per se*. An *Exit* button allowed to close the software.

Input file defined which stimulation was associated with each clickable element, and the duration of each stimulation (Note 5). Output file reported the significant timings of the experiments, with time 0 being the click on the start button. It was composed of the total duration of the exploration and of the time of each sensory stimulation sending.

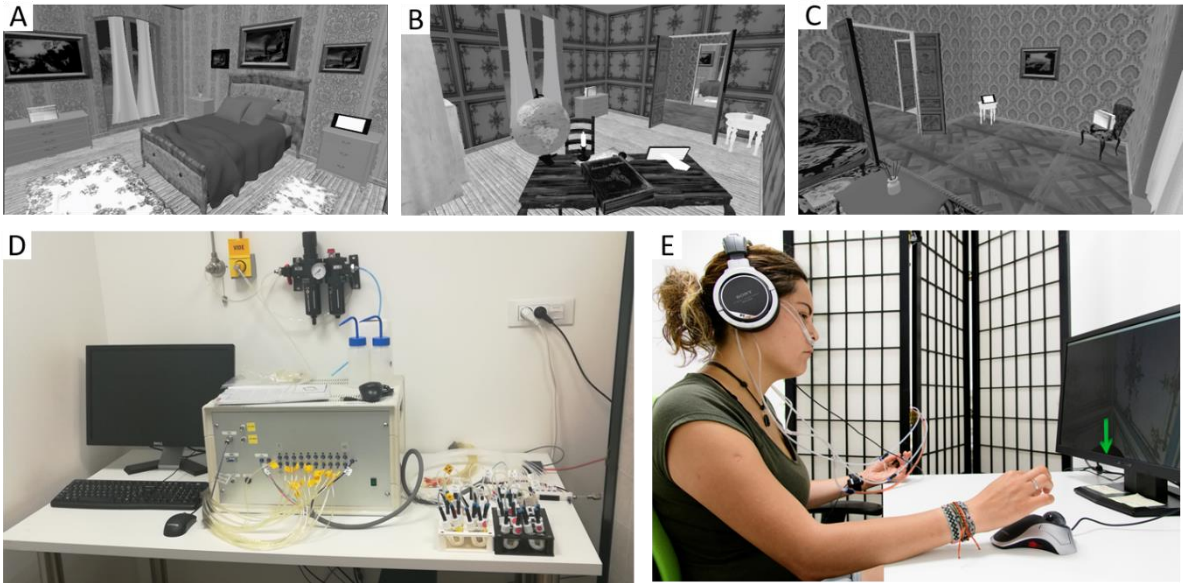

Figure 1. Experimental setup. The experimental setup was split by a screen into two parts: A) In the experimenter side, on the desk, a computer, the olfactometer and the odorants were positioned from left to right; and B) in the participant side, a participant wearing nasal cannulas and earphones was investigating the virtual environment. The virtual reality software represents a house made of three rooms: C) a bedroom, D) an office; E) a living-room.

2.4 Sensory stimulations

Sensory stimulations were selected to differ according to the emotional category, negative, neutral and positive, based on previous research ***(12, 13)***. Their *a priori* pleasantness was only used for stimulus selection, as the subjective emotion evoked by each stimulus in each participant was recorded in a separate experimental session.

2.4.1 Olfactory stimulations

Odorants consisted of essential oils, single or mixtures of monomolecular chemical compounds, and fragrances. Negative odorants were composed of Carrot (Givaudan-Roure®, Vernier, Suisse), Musk

(Givaudan-Roure), Pastry (Perlarom 93, Grasse, France), Stemone (Créations aromatiques), Vetiver (Davenne, Montfavet, France), and Yeast (Givaudan). Neutral odorants were composed of Basil (Créations aromatiques, Neuilly-Sur-Seine, France), Black Olive (Meilleur du Chef®, Bassussarry, France), Cis-3-hexenyl salicylate (Créations aromatiques), Dill (Pharmacie Croix Blanche, Dijon, France), Honey (Givaudan-Roure), and Ylang Ylang (Givaudan). Positive odorants were composed of Bien-Être (EmoSens), Blackberry (Givaudan®, Vernier, Suisse), Cosy (EmoSens), Lovely Ion (EmoSens®, Lyon, France), Osmose (EmoSens), and Tomato (Givaudan-Roure, Vernier, Suisse). The undiluted odorants were placed in 10 ml U-shaped Pyrex® tubes (VS Technologies, Saint-Priest, France) filled with microporous beads of polyether block amide (PEBAX®, Arkema, Puteaux, France; ref 33 SA 01 MED) and closed with O-rings (Radiospare; ref 129-050) and customized drilled TEFLON caps. In preliminary tests, absorption of the odorous substance by the microporous beads were performed in Petri boxes. While filled with beads, a 1-cm empty space was preserved in each arm of the U-tube. The tubes were ordered and placed vertically in a homemade rack (printed with 3D printer; Figure 1A). When not in used, odorant tubes were closed with a flexible tube joining the two drilled caps hermetically sealing them, and kept in ventilated panel.

The odorants were presented with a 20-channel computer-controlled olfactometer designed in our team (Figure 1A, for more details, please see ***(11)***). This odor diffusion system was developed to allow computer-controlled rigorous olfactory stimulations and to adjust odorant presentation with nasal respiration. The participants' nasal respiratory signals were acquired using a nasal cannula positioned in both nostrils (Teleflex, Le Faget, France; ref 1103) and connected to an airflow sensor. Respiratory signal was used to trigger the odor stimulation. During the odor stimulation, the olfactometer waited for the participants' subsequent expiration to deliver the odor, allowing it to be perceived at the beginning of the subsequent inspiration. When an expiration was detected, an unodorized airflow was sent to one of the U-shaped odorous tubes. Unodorized vector air directly comes from the laboratory distribution network or a portable air compressor. Odorized airflow was sent to and mixed with air carrier in a homemade drilled mixing head made of PTFE (polytetrafluoroethylene) through low-absorption (Teflon® Fluorinated Ethylene Propylene) tubes. The concentration of the odorant and of air carrier was established through pilot experiments for each odorant, such as the final physical intensity seem comparable between stimuli. The mixing-head output, the odorized airflow, was sent to the nostrils though two flexible tubes (Soft Polyurethane Tubing; SMC France, Marne La Vallée, France; ref TUS0425N-20), fixed to the nasal cannula with tape, opening out under the nostrils (Figure 1B). Odorized airflow was not sent directly into the nostrils in order to limit discomfort and mechanical stimulation by the airflow. The olfactometer was controlled by an in-house LabView software (National Instruments, Austin, TX, USA) and interacted with the VR software to synchronize odor stimulation with box opening via a TCI-IP connection. Input files defined the concentration and duration of each odor.

2.4.2 Auditory stimulations: Musical pieces

Eighteen musical pieces were selected and modified from the materials used in Vieillard *et al.* (2008)***(14)*** (Copyright, Bernard Bouchard, 1998) (http://www.peretzlab.ca/knowledge_transfer/). Negative excerpts were P01, P05, P06, P10, P11, and P12. Neutral excerpts were M03, M06, M09, M10, M11, and M16. Positive excerpts were G03, G06, G07, G10, G11, and G13. They were modified in MIDI (Digital Performer®, MOTU, Cambridge, USA) aiming to reduce or enhance potentially evoked emotional features. The modifications included changes of tempo, mode (major/minor), and/or a few notes, depending on the clip. The musical clips were played with an acoustic piano timbre (Cubase®, Steinberg Media Technologies, Hamburg Germany) at a comfortable loudness level. Their average duration was 7.70 ± 1.30 s. Musical pieces were presented with regular headphones covering ears.

2.4.3 Visual stimulations: Pictures of face

Eighteen pictures of Caucasian faces were selected from the Compound Facial Expressions of Emotions Database ***(15)*** (http://cbcsl.ece.ohio-state.edu/dbform_compound.html). They were composed of nine women and nine men faces. These faces were virtualized with CrazyTalk®8 software (Reallusion Inc., California, U.S.A.). The same non-gendered hairstyle and outfit were chosen for each face. Pictures of this virtualized faces were then modified in order to create six negative, six neutral and six positive face pictures. They were turned into black and white, presented on a white background, and their relative position and dimensions were similar (Photoshop®, Adobe, Dublin, Ireland). The 2863 x 1718-pixel pictures were presented in jpeg format on the center of the screen for 6 s.

2.5 Physiological responses recording: Sensor belt

Participants physiological response was acquired using Equivital EQ02 LifeMonitor (AD Instruments, Paris, France; ref HIDA3330-IFU-26-1 0A). It was composed of a Sensor Belt allowing to wear a module placed on the body, named the Equivital Sensor Electronic Module (SEM), and to communicate with it through wireless communication. The belt contains electrocardiogram (ECG) electrodes and respiratory sensors, *i.e.* chest expansion based respiratory belt transducer. The Equivital Galvanic skin resistance (GSR) Add-On (ref EQ-ACC-034) connects to the module to enable recording of Galvanic Skin Response signals (or electrodermal response) with two MLA1010 disposable electrodes. Data acquisition device (PowerLab 16/30, ADInstruments) and analysis software (LabChart 7, AD Instruments, Paris, France; ref HIDA3330-IFU-26-1 0A ADInstruments) were used for data acquisition, display and analyses.

2.6 Emotional evaluations of the sensory stimuli

Participants rated each stimulus that were presented within the VR environment using non-graduated scales (Note 6). The evaluations concerned three complementary facets of the emotional response 1) Pleasantness (unpleasant – neutral – pleasant; the pleasantness scale was divided into two equal parts by a “neutral” value separating the ratings of unpleasantness and pleasantness); 2) Emotional Intensity (very weak – very intense); and 3) Motivation (also called Wanting) (very weak – very intense).

3 Methods

3.1 Exploration of the virtual environment

Participants were first equipped with the physiological responses recording belt and the two electrodes, and were placed in front of a screen. In order to not bias the participants’ behavior, the exact aim of the experiment was hidden and the participants were told that the study aimed at investigating the perception of various environments involving odors, music and pictures. The instructions were the followings:

“*You are going to visit a house with three rooms. We want you to feel as if you were in this house, as for real, we want you to immerse yourself in this house. You are free to explore this house at your own pace. You can move around the house with the trackball (*Note 3*), and observe the rooms of the house, its furniture, the ambient light, and the landscape through the windows. In each room you will find particular objects that you can interact with by clicking on them. They all look the same in any room. They are [*show pictures*]: a perfume diffuser that allows you to smell a scent, a radio that allows you to listen to music, and a photo frame that allows you to see a picture of face. The smells, music and picture of faces will be different for each room. You will have a minimum of 10 minutes to discover the house. You can click as many times as you want on the interactive objects. For the odors, here are some precautions. When you click on the diffuser, you will hear a "click": do not pay attention to it. It is due to the sending of the smell. It takes time for the scent to reach your nose, so it's normal for this click to occur as you are exhaling. But don't hesitate to tell me if you don't smell anything, since each diffuser is associated with a smell. We also advise you to allow a little time to pass (about 20 seconds) between two smells, so that your nose is not saturated and you can smell anything. Finally, keep in mind that you must continue to breathe normally through your nose when sending the scent as well as throughout the experience. Do you have any question? Is everything clear to you*?”.

After having ensured that the participants understood everything, they put on the nasal cannula, and the headphones. After checking the quality of the breathing signal and determining the level of the sound properly for participants, the self-paced free exploration begun.

3.2 Emotional evaluations of the sensory stimulations

After the exploration of the virtual environment, participants were told to evaluate their emotional responses for each sensory stimulation encountered in the virtual house (Note 6). Each unimodal stimulus was presented for 6 s (excepts for music, where the duration depends on the music piece). The instructions were the followings: " *This is the last part of the experiment. We want you to characterize the odor, music and face stimuli that you discovered in the experiment. For each stimulus you will be asked three questions: 1) "How much do you like or dislike this stimulus?"; this is the pleasantness; it might go from very unpleasant to very pleasant, the middle value being neutral. 2) "How strong is the emotion evoked by this stimulus?"; this is the emotional intensity; it might go from very weak to very intense. 3) "How much would you like to be sent this stimulus again?"; this is the motivation; It might go from very weak to very intense. After each stimulus presentation, you will answer the questions making a precise mark on the scales presented to you on the sheet. There are no good or bad answers, this is your own feeling*."

As an example, Figure 2 presented pleasantness evaluations of the stimuli used in the experiment. These emotional evaluations may be further correlated or regressed with behavioral and physiological measures, with for example the JASP (https://jasp-stats.org/) or R (https://www.R-project.org/) softwares.

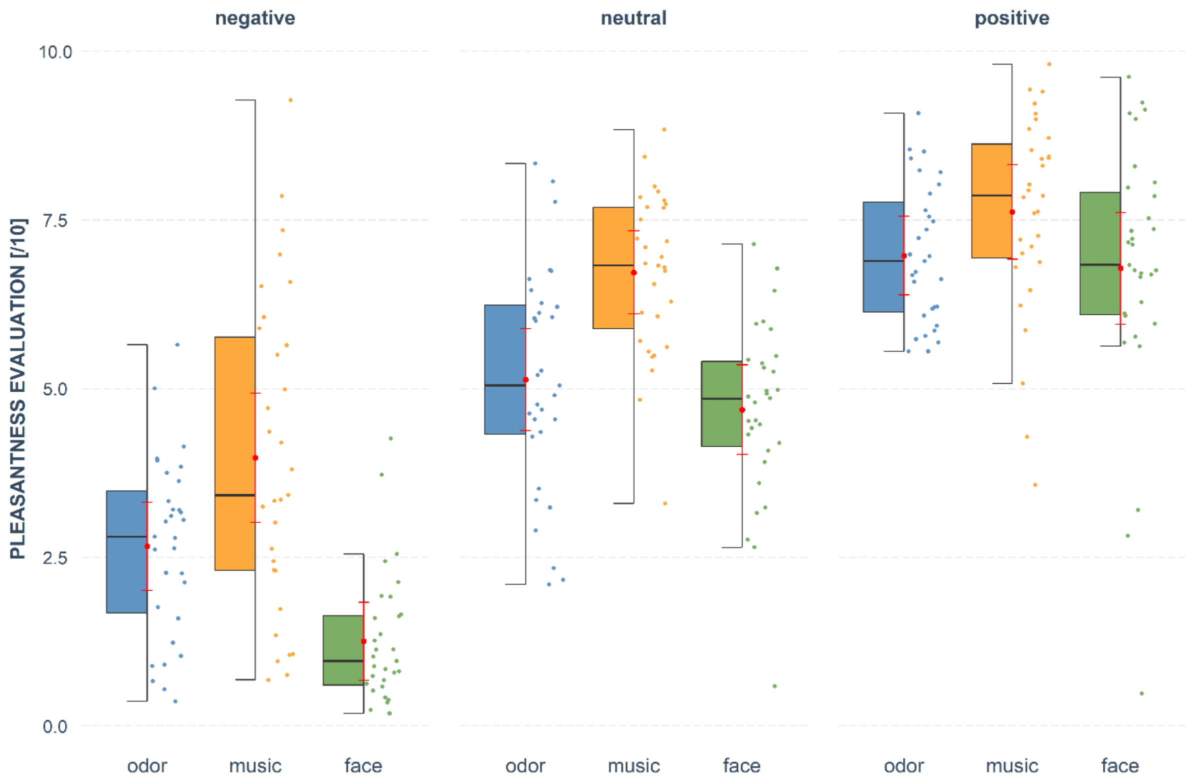

Figure 2. Emotional sensory evaluations. Mean ratings of pleasantness of odor, music and face stimuli a priori selected as being part of negative, neutral and positive emotional categories. Individual raw data are represented with dots. The distribution of data is displayed with boxplot (minimum, first quartile, median, third quartile, maximum). The model estimated means and their dispersion (SEM) are represented on the right side of each boxplot.

3.3 Attraction/Repulsion behavior

Emotional responses were investigated by the number of times the participant clicked on each clickable object in order to perceive the stimulus it delivered during the exploration of the virtual environment. This behavior reflected an attraction/repulsion behavior toward each stimulus. In our experiment, the number of clicks had been shown to depend on the subjective emotional evaluation, as the example shown in Figure 3.

Figure 3. Attraction/Repulsion behavior. Mean number of click for each odor, music and face as a function of mean motivation evaluations (z-score, arbitrary units). Here, the higher the motivation, the more often the participants tended to click on the objects in order to perceive the stimuli.

3.4 Emotional physiological responses

Breathing, ECG and GSC signals were recorded to access to covert, physiological manifestations of the emotional response. These signals were displayed and extracted in text files with LabChart software, as presented in Figure 4. Breathing signals were considered in their inspiratory part, their expiratory part, and both parts together forming a breathing cycle. The amplitude of the signal (maximum), its duration and its volume were measured. The ECG signals reflected the electrical activity of the heart. From this signal, duration between two beats were extracted to calculate heart rate variability (HRV). The GSC signals reflected the skin conductance (or electrodermal) response. The peaks of this signal and their parameters (*e.g.*, onsets, peak amplitude, *etc.*) were extracted. When external or internal stimuli occurred that are physiologically arousing, breathing, HRV and GSC signals might show variations. Figure 5 represents the variation of breathing with pleasantness that we observed with odor but not with music nor picture of face stimulations.

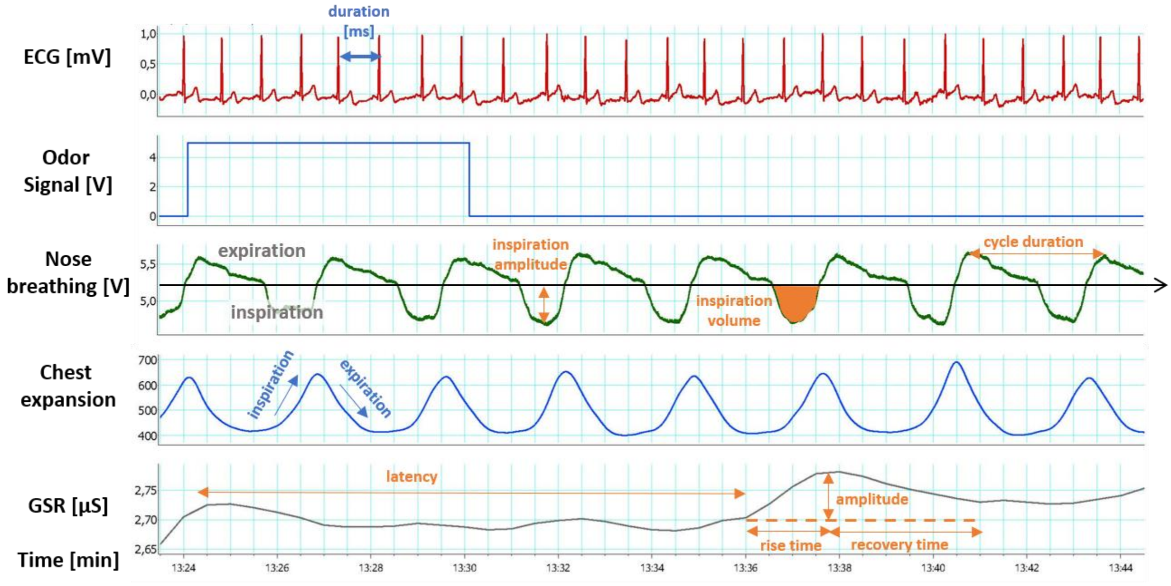

Figure 4. Physiological signals from LabChart. An example of a 20 s time window where an odor (second raw) was sent. ECG signal from the Sensor Belt (first raw), Respiratory signal from the olfactometer (third raw), Respiratory signal from the Sensor Belt (fourth raw) and GSR from the Sensor Belt (fifth raw) were displayed.

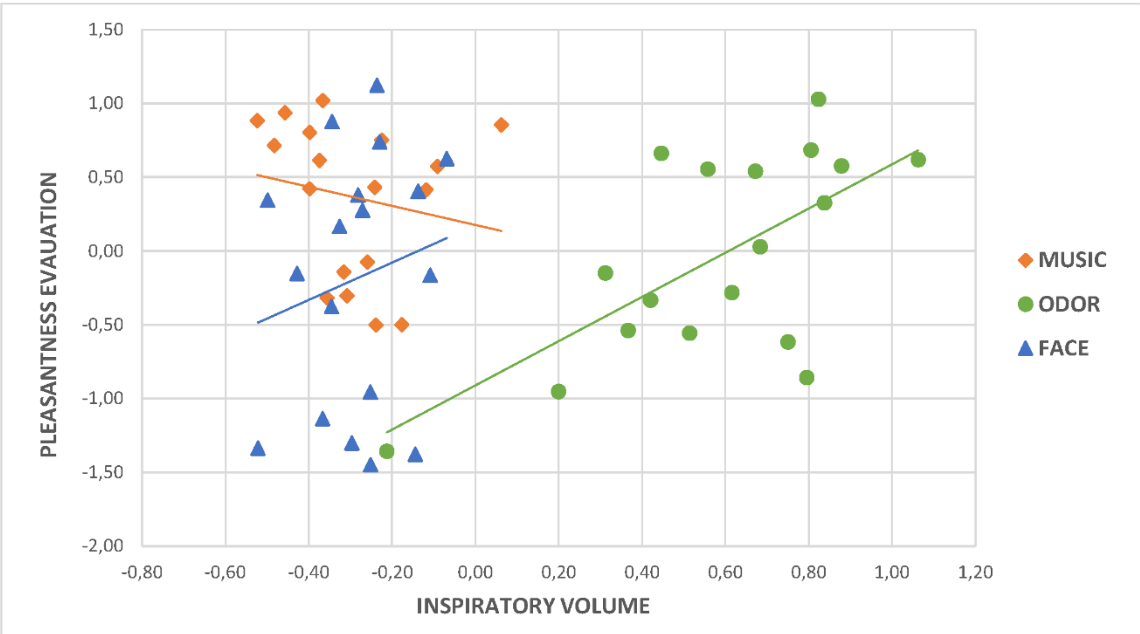

Figure 5. Breathing modulations with emotion. Mean inspiratory volumes as a function of mean evaluation of pleasantness (z-scored, arbitrary units) for odors, music and face pictures. In this example, the more pleasant the odors, the bigger the inspiratory volume.

4 Notes

Note 1. Examples of potential applications

Methods used in this chapter may be applied to address a vast number of questions. For example, it may be useful to study whether the odor or the sound of a food product may be more important in emotionally guided decision behavior or on subsequent product memory. It may also be used to study the effect of many different contexts on the emotion evoked by the product. For cosmetic industry, this protocol can be used to choose which packaging matches the best with a fragrance; for example, by studying which packaging-fragrance association is more emotional or more memorized, as a function of the social or environmental context (see ***(16)*** for other applications).

Note 2. Non-immersive vs immersive virtual reality (VR) set-up

Immersivity defines the degree to which the user is isolated from the real-world environment and is reach by introducing a sense of presence with rich sensory-motor perception and interactivity in the VR environment. The degree of immersivity can change the perception and response latency ***(8, 16)***. However, the choice of an immersive environment depends on other variables:

- Financial cost: Immersive VR set up requires purchasing specific materials (room, googles...), while non-immersive VR needs only common computer devices (screen, mouse…)
- Feeling of discomfort: Immersive VR might generate feeling of disease, while it is not an issue for non-immersive VR. Accordingly, the presence of virtual characters, may provoke the famous uncanny valley effect, explaining the feeling of strangeness felt when an object, a robot or a character resemble to a real human while keeping non-human attributes ***(17, 18)***.
- Matching with the real-life environment: An issue with the non-immersive VR can be the mismatch between the reality and RV condition. For example, if the house is presented with a nigh environment while the experiment is run in the middle of the day. This problem would not exist with immersive VR set-up.

Note 3. Trackball vs other devices

In a semi-immersive VR, participants can move and explore an environment with many different devices, such as a mouse, a trackball, a joystick or a wheel. This interactivity with the environment is crucial, as it distinguish VR from watching a video. The choose of this device is of importance as a function of the experiment. For example, if running an fMRI study the trackball is a better choice than a mouse. Its use limits the movements of the participants in the scanner in comparison with computer mouse, since only fingers moves but the hand is stable.

Note 4. Emotional contagion

Emotional contagion might happen in the virtual environment (emotional spread of one stimulus on another), and the spatial repartition of the stimuli in the environment might be considered. This is of great importance since odors seem to be particularly prone to be influenced by other stimuli ***(19, 20)***. For example, in our experiment we choose to place in the same room stimuli with similar emotion.

Note 5. Simultaneous multisensory stimulation

In the current version of the software, only one stimulation was sent per clickable element, but this input file configuration allowed the simultaneous delivery of an olfactory stimulation, an auditory stimulation and a visual stimulation. While it might be interesting to deliver simultaneously stimulations from different sensory modalities, it raised several questions from which the congruence between these sensory stimulations and the attentional competition.

Note 6. Sensory Evaluation Scales

In this protocol, scales were printed on paper and ratings were *a posteriori* transformed into scores from 0 to 10. Scales might also be presented using other methods such as the self-assessment manikin ***(21)***. The use of a software to assess subjective emotion might be also of interest, allowing to restrict the response time, and to measure physiological responses evoked at rating time.

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