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Investigating the human chemical communication of positive emotions using a virtual reality-based mood induction

Running head: VR-based communication of positive emotions

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Abstract

Humans can communicate their emotions to others via volatile emissions from their bodies. Although there is now solid evidence for human chemical communication of fear, stress and anxiety, investigations of positive emotions remain scarce. In a recent study, we found that women's heart rate and performance in creativity tasks were modulated by body odors of men sampled while they were in a positive vs. neutral mood. However, inducing positive emotions in laboratory settings remains challenging. Therefore, an important step to further investigate the human chemical communication of positive emotions is to develop new methods to induce positive moods. Here, we present a new mood induction procedure (MIP) based on virtual reality (VR), that we assumed to be more powerful than videos (used in our previous study) to induce positive emotions. We hypothesized that, consequently, given the more intense emotions created, this VR-based MIP would induce larger differences between the receivers' responses to the positive body odor versus a neutral control body odor, than the Video-based MIP. The results confirmed the higher efficacy of VR to induce positive emotions compared with videos. More specifically, VR had more repeatable effects between individuals. Although positive body odors had similar effects to those found in the previous video study, especially faster problem solving, these effects did not reach statistical significance. These outcomes are discussed as a function of the specificities of VR and of other methodological parameters, that may have prevented the observation of such subtle effects and that should be understood more in-depth for future studies on human chemical communication.

Keywords

Chemical communication, virtual reality, positive emotions, body odor, perfume, emotional contagion

Introduction

Humans are able to communicate information of social nature to people surrounding them via complex signals of chemical nature (chemosignals¹) emitted by the body². Information from a *donor* (or *emitter*), perceived by a *receiver* via the olfactory channel, may concern for example identity³, sex⁴, age⁵, diet⁶, sickness⁷, aggression⁸, or competition⁹. Transient negative emotional states can also be communicated in this manner, such as sadness¹⁰, disgust¹¹, and especially fear and anxiety^{12–18}. This has been confirmed in a recent meta-analysis¹⁹. For the chemical communication of positive emotional states, however, evidence remains much more scarce and disparate results were found²⁰.

In a recent study, we investigated humans' ability to communicate a range of positive feelings via their axillary odor (Richard Ortegón et al., 2022)²¹. We found converging evidence for the transmission of positive emotions from male donors to female receivers, and that this phenomenon escaped receivers' conscious awareness, as is often observed in chemical communication studies^{16,22}. Rather than a mere transmission, it is an emotional contagion that seems to have taken place (i.e., a partial replication of the state of the donor in the receiver²³). Indeed, the receivers exposed to the body odor of donors having experienced positive feelings (i.e., positive body odors), showed signs of being in a positive emotional state themselves, such as reduced heart rate^{24,25} and improved performance on behavioral tasks known to be modulated by positive affect (i.e., creativity/creative problem-solving tasks^{26,27}). A secondary aim of that study was to investigate perfume's interaction with this chemical communication of positive emotions. Indeed, although body odors are rarely found alone in ecological situations²⁸ and the use of fragrance is nearly universal since antiquity²⁹, the possible modulation of interpersonal chemical communication of emotions remains unexplored to date. In Richard Ortegón et al.²¹, adding perfume did not suppress the effect of positive body odors

on heart rate, and acted in synergy with positive body odors for some of the variables studied (increased perceptual differences between positive and neutral body odors).

Although these findings feed the meager existing literature with new arguments in favor of a chemical communication of positive emotions in humans, a methodological challenge persists. Indeed, the contrasted results of previous studies may be due to the fact that inducing positive emotions in the laboratory remains challenging: for example, in our study described above²¹, the positive mood induction implemented with videos was successful in only 38% of the odor donors. Developing new and more effective methods to induce positive mood is thus an important step to better understand the human chemosignalling of positive emotions. This is the main aim of this article.

Emotion elicitation in laboratory settings can be considered as lacking ecological validity³⁰ and is not fully equivalent to that experienced in daily life. Controlled mood induction procedures (MIP) used in the laboratory implement a variety of means, varying in realism. These means, inter alia, include: autobiographical recall³¹, music^{32,33}, pictures (IAPS³⁴), short clips/movies^{35,36}, and self-referential statements such as the Velten procedure^{37,38}. A comparison of several of these MIPs suggests that the more senses are engaged, the more effective MIPs are^{39,40}. As a consequence, a promising pathway to increase MIPs efficacy could be the use of virtual reality (VR). This tool is indeed pertinent because it is closer to everyday life stimulations than many of the pre-existing MIPs, due to the fact that it can recruit visual and auditory channels but also provide tactile return via controllers as well as vestibular sensations for example. VR allows deeper feelings of “immersion” and “presence” (see^{41,42}) which have been reported as important for being closer to real-life daily situations. Furthermore, it has been shown to be a successful tool for inducing emotions, including positive ones⁴³⁻⁴⁷. It thus makes it a promising instrument for studies in the field of human chemical communication of emotions, in which it has never been implemented before.

In the present study, we thus tested a new method to induce positive emotions, namely a VR-based MIP. Apart from the type of MIP (VR activities instead of 2D video clips, to allow for a more realistic setting), the design of the experiment was similar to our previous experiment²¹. We collected axillary sweat from donors after a positive and a neutral VR-based MIP, the former being designed to elicit positive emotions and the latter to not create any vivid emotion. Then, receivers were exposed to these body odors and their responses were monitored at different levels: autonomic nervous system responses, verbal conscious ratings, and behavioral tasks involving creative problem-solving and divergent thinking tasks, based on the “broaden-and-build” theory⁴⁸. This theory links creativity to positive affect, an association robustly found in the literature^{26,27,49–52}. We first hypothesized that compared with the Video-based MIP we previously used, a more realistic and immersive procedure using VR-based MIP would elicit stronger emotions in donors. Second, we hypothesized that, as a consequence, a stronger emotional contagion would occur in receivers exposed to body odors sampled during a VR-based MIP. Especially, it can be expected that this emotional contagion is expressed as previously through the receivers’ physiological responses (decreased heart rate after having smelled the positive body odor), but also through their verbal, motor (sniffing behavior, facial EMG), and behavioral responses (better performance in creative tasks when exposed to the positive body odor). Finally, in the physiological session, a condition where perfume was added to the sampled positive and neutral body odors was implemented. In line with our previous study, no disruptive effect of perfume is anticipated.

Methods

Part 1. Odor collection

Participants (donors)

Donors were 10 males (mean age \pm SD: 24.0 \pm 4.4 years old) who declared being heterosexual, of European descent, and non-smokers. Male donors were preferred over female donors because they have larger apocrine glands⁵³ and thus have the potential to produce more emotion-related chemicals. Sexual orientation and ethnicity were controlled because these parameters have been shown to influence body odor perception⁵⁴⁻⁵⁶. All participants (donors and receivers hereafter) provided written informed consent prior to participation and received monetary compensation. This research was conducted in accordance with the Declaration of Helsinki and was approved by the local Sud Méditerranée III ethical review board (May 13, 2019).

Virtual environment and stimuli

Donors took part in two sessions each, one with a positive MIP and one with a neutral one, on two different days. Two virtual environments were created in Visual Studio with Unity 2017.4.20f1. For the *positive condition*, participants stood in a virtual homely and warm living room surrounded by mountains and lakes. In this home environment, they were given the possibility to take part in one or more activities successively, among 3 games available from Steam store (<https://store.steampowered.com/>: Google Earth VR by Google – a game to explore the world through Google Earth in virtual reality, TiltBrush – a 3D painting game by Google, and Guided Meditation by Cubicle Ninjas – an application that allows to meditate in virtual environments) and ten 360° videos (including landscapes of beaches, mountains, videos of puppies or northern lights for example). For the *neutral condition*, participants stood

in a virtual room, which was an empty replication of the real experimental room. This virtual room was equipped with a screen where the participants were given the opportunity to watch 2D clips (those used as a neutral MIP in our previous research²¹) and/or to participate in a not very interesting construction game (developed in-house) in which they had to stack wooden blocks to build a pre-defined architectural structure. In both conditions, participants were allowed to perform as many different activities as they wanted for 30 minutes. They were free to repeat or interrupt them according to their wishes, as to give them a personalized experience.

Body odor collection

From two days before the first odor collection, donors followed a protocol to prevent odor contamination (details can be found in Supplementary Methods). Body odor collection took place on mornings only, so as to minimize potential emotional events before the collection. Additionally, donors had to take a shower just before coming to the laboratory. After having washed their armpits with odorless soap (Le Petit Marseillais, Johnson & Johnson, Issy-les-Moulineaux, France), they were asked to put on cotton t-shirts (Decathlon, Villeneuve d'Ascq, France), previously washed with a non-perfumed detergent (Le Chat Sensitive 0%, Henkel, Düsseldorf, Germany), instead of their personal clothes to prevent odor contamination. On these t-shirts, 10x10cm sterile gauze pads (Sylamed) were affixed to the armpit zone via stainless steel snaps. At the end of the emotional induction, pads were removed from the t-shirt, snaps were removed from the pads, and the pads were cut into 1x3cm strips taken from their central area, placed in aluminum foil and then in one ziplock bag per donor and per emotional condition (positive/neutral), before being stored at -32°C.

Manipulation check of emotion induction

Donors' facial EMG recordings.

To get an objective measure of positive affect, donors' facial muscular responses were measured during each MIP session (neutral, positive), converted and amplified via an 8-channel Procomp+ amplifier (Thought Technology, Montreal, Canada). Recordings (256 Hz sampling rate) were done via Ag/AgCl electrodes on the *zygomaticus major* muscle, because this muscle has been extensively used in psychophysiological research as a marker of positive emotions⁶². The analyzed window was 30 minutes long (i.e., the duration of the induction session), after having observed 2 minutes of rest during which the experimenter ensured that there were no electrical artifacts. A high-pass filter was added along with smoothing algorithms to eliminate artifacts. The number of peaks for each time window was computed by means of in-house Python scripts, and the area under the curve (AUC) was calculated for the detected peaks.

Donors' emotional ratings.

To measure the subjective emotional response of the donors during the MIP, they were asked after each excerpt or activity to rate how amused, afraid, happy, sad, surprised, disgusted, angry, neutral and calm they felt during the activities using continuous virtual visual analog scales ranging from "not at all" to "extremely" (then converted to 0-100 scores). Note that high scores on the "neutral" scale were defined by the experimenters as the absence of emotion.

Procedure

Donors attended the two MIP sessions (neutral/positive) in a random order one day apart (within-subjects design) (Figure 1). Upon their arrival, they put the prewashed cotton t-shirt on. The experimenters then placed facial EMG electrodes on the right *zygomaticus major*. Then, participants put the VR headset (HTC Vive, HTC France Corporation, Paris, France) and headphones on to undergo the emotion induction procedures. After each excerpt or activity, they provided emotional ratings (see previous section) directly inside the virtual home environment. For each condition, an internal timer limited the session to 30 minutes, at the end of which participants were informed to exit the virtual activities, to go back to the home environment again and to end the session.

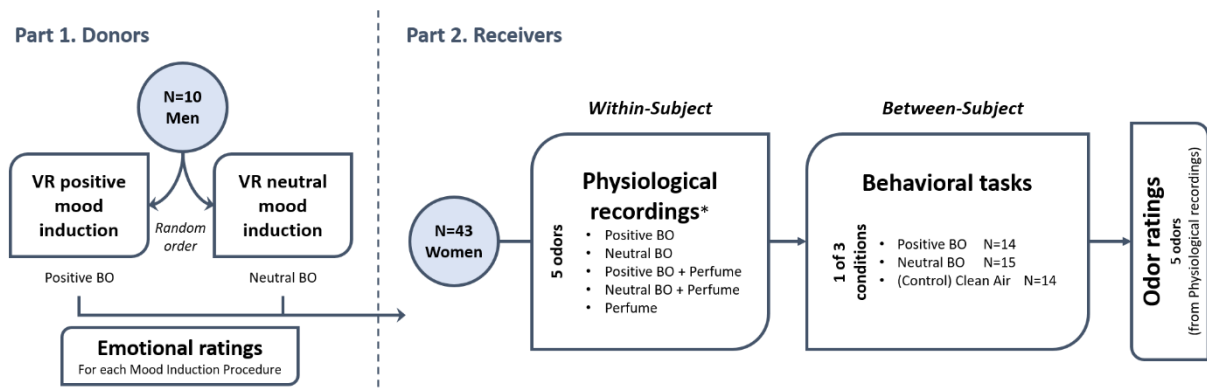


Figure 1. Summary of the experimental procedure. Donors (N=10) underwent a positive mood induction procedure and a neutral one, in a random order two days apart, during which their body odor was sampled. Receivers (N=43) took part in physiological recordings during which they were exposed to both positive and neutral body odors, then in behavioral creativity tasks in one of the odor conditions, and finally in verbal evaluations of all odors. BO: Body Odor. (*) Skin conductance data of 10 participants was lost due to technical issues.

Data analysis

Donors' facial EMG recordings.

The facial EMG activity (*zygomaticus*) was analyzed with linear mixed-effects models, using the `glmer` (for the number of peaks) and the `lmer` (for peaks AUC) functions of the `lme4` package⁶⁵ in R (R Core Team 2019⁶⁶, RStudio version 3.6.1). Condition (Positive/Neutral MIP) was used as a Fixed factor and Subject was used as a Random factor. In this and the other linear mixed model analyses used in this article, visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality, and when it did, outliers were removed based on visual inspection of the Cook's distances to improve the quality of the model. For models obtained with `lmer`, P-values were obtained using Kenward–Roger approximation in the `anova` function of `lmerTest` package in R⁶⁷ and for the model obtained with `glmer`, by using the `Anova` function. Post-hoc contrasts were performed using the `emmeans` package in R⁶⁸.

Donors' emotional ratings.

Two analyses were conducted. First, to evaluate VR MIP's efficacy compared a Video-based MIP²¹, we used linear mixed-effects models on the emotional ratings of the donors during the MIPs, with Study (VR/Video) and Question (“happy”/“neutral”) as fixed factors and Subject as a random factor. This was performed separately for the Positive and the Neutral MIPs, and we focused on the Study×Question interaction. Second, the manipulation check for the present (VR) study was performed by running a mixed-effects model on the “happy” ratings with Condition (Positive/Neutral MIP) as a fixed factor and Subject as a random factor. In addition, note that as in our previous study²¹, the mood induction procedure was considered successful for each participant if the criteria of i) average happiness ratings >50 in the positive MIP and ii) average happiness ratings ≤50 in the neutral MIP, were met.

Missing and removed data.

For donors, saving issues resulted in the loss of the EMG recordings of 2 participants for the neutral MIP, and 1 for the positive MIP.

Part 2. Odor presentation

Participants (receivers)

Receivers were 43 women (mean age \pm SD: 22.2 \pm 2.7 years old) who declared being heterosexual, of European descent, non-smokers, and using hormonal contraception. They reported not suffering from any psychological, cardiac, respiratory, or olfactory diseases. Female receivers were preferred over male receivers because they have a better sense of smell and greater sensitivity to emotion chemosignals^{13,57}. Sexual orientation and ethnicity were controlled for the same reasons as in donors, and hormonal contraception was also added to limit olfactory variations due to the menstrual cycle in spontaneously ovulating women⁵⁸. Each receiver took part in a 3.5-hour individual session, which included: physiological recordings, behavioral tasks, and odor ratings (Figure 1).

Stimuli

In the physiological recording session, all receivers were presented with 5 conditions (positive body odor, neutral body odor, perfume alone, positive body odor with added perfume, and neutral body odor with added perfume; within-subjects design). The stimuli were presented 3 times each, in 3 blocks comprising the 5 stimuli in a pseudo-randomized order (interleaved with a clean air condition, never in first or last position, to limit olfactory fatigue and cleanse the tubing). In the behavioral tasks, receivers were exposed either to positive body odor samples, neutral body odor samples, or clean air (condition attributed randomly, between-

subjects design). Due to time and material limitations, no condition with perfume was included in the behavioral tasks. For the odor ratings, all odors previously used in the physiological session were rated by all receivers (Figure 1).

Preparation of the body odor samples was performed by putting the frozen 1×3cm sweat pad strips obtained in donors at room temperature one hour before the start of the receivers' session. To reduce the effects of interindividual variability between the 10 donors, 4 strips from 4 different donors (chosen in a pseudo-randomized manner), combining left or right armpit chosen at random⁵⁹, were used. Each 4-strips composite sample was used only once, and a new (different) composite sample was used for each receiver. This stimulus was placed into a U-shaped Pyrex® tube (VS technologies, France; volume: 10 ml; length: 50 mm; external diameter: 14 mm). Each positive composite body odor and neutral composite body odor sample was prepared twice, to allow for the addition of 2 drops of a male perfume in one of the duplicated samples. For the perfume-only condition, 2 drops were dropped into an unused 1x3cm sterile gauze pad strip. The perfume (concentrate of a commercially available fine fragrance diluted in Dipropylene-glycol, 10% concentration) was chosen among other perfumes because it received the highest scores of pleasantness in a preliminary test (N=24, 16 women). Olfactory stimuli were diffused at an airflow of 1.5 L/min using a computer-controlled olfactometer with time-controlled stimulus onset and were delivered to the participant's nose via a nasal cannula.

Measures

Receivers' physiological recordings.

Receivers' heart rate, skin conductance response, and facial muscular responses were measured with Equivital EQ02+ Lifemonitor system (Equivital, Cambridge, UK), and amplified by a Dual Bio Amp from AD instruments (Dunedin, New Zealand). The acquisition software was LabChart v8.1.5 (AD Instruments, Dunedin, New Zealand). Signals were analyzed in a range of 10-seconds pre- and 10 seconds post-stimulus for the heart rate and 10-second post-stimulus for the skin conductance. High-pass, low-pass filters were added along with smoothing algorithms to eliminate artifacts. A local mean of the points during these 10-second windows was calculated using scripts developed in-house with Python (v.3.7;⁶⁰).

For *heart rate*, the mean values of the frequency were computed and the difference between the 10-second post-stimulus and the 10-second pre-stimulus windows was calculated (beats per minute, post- minus pre-).

For *skin conductance (SC)*, the SC peak was calculated as the maximum amplitude of the electrodermal response during the 10-s post-stimulus minus the value of the signal at stimulus onset. In addition, the number of detected SC responses during this 10s-post-stimulus window was determined using the algorithm described in Kim et al. (2004)⁶¹ combining event-related and non-specific responses during the 10-s post stimulus window using a 0.1 μ S amplitude threshold.

The *EMG recordings* (1000 Hz sampling rate) were performed via Ag/AgCl electrodes on the *zygomaticus major* and the *corrugator supercilii* muscles, because these muscles have been extensively used in psychophysiological research as markers of positive and negative emotions, respectively⁶². Since the aim of EMG measure in donors and receivers was not the same, the analyzed time windows were also different: while for donors, the window was 30 minutes long (see Donors section above), for receivers it was the 10 seconds post stimulus.

The number of peaks for each time window was computed by means of in-house Python scripts, and the area under the curve was calculated for the detected peaks.

The *sniffing behavior* of the receivers was also recorded by means of a nasal cannula positioned in both nostrils and connected to an airflow sensor (AWM720, Honeywell, France). This system was developed in-house to allow us i) to synchronize odor delivery with the participants' respiration, and ii) to record sniffing behavior. The sniffing signal was amplified and digitally recorded at 256 Hz using LabVIEW software®. The area under the airflow curve (volume inspired, arbitrary unit) and the duration of the sniff (time in seconds between the inhalation starting point and the point where the flow returned to zero) were computed for the first sniff following odor presentation.

Creativity and problem-solving tasks.

All receivers took part in two different behavioral tasks. The first task was the Guilford's Alternate Uses Task⁶³. In this test, the participants are asked to list as many non-obvious uses as possible for common objects in a limited time and their answers are given scores in terms of fluency, originality, elaboration, and flexibility (for details about scoring and examples, see Supplementary Method). Here, receivers were given 2 minutes per object, which were: brick, barrel, pencil, shoe, car tire, hanger. The AUT scores were attributed in a double-blind fashion by two independent judges. As the scores of both judges on each variable were highly correlated ($r = 0.70$ to 0.96), they were averaged.

The second task was Duncker's Candle Problem⁶⁴. The receivers were brought in front of a table where they could find a box of tacks, a candle, and a box of matches. They were asked to find a way, with the available objects, to affix the candle to the wall (on a corkboard) in such a way that it would burn without dripping wax on the table or on the floor. The problem was considered as solved if the receivers emptied the book of matches, used the tacks to nail

the box to the corkboard and made the candle stand inside the empty box. They were given 10 minutes to solve this problem. The frequency of success and the time to solve the problem (only in case of success) were recorded and analyzed.

Odor ratings.

At the end of the experiment (after the creativity tasks, Figure 1), the female receivers were asked to provide subjective evaluations the experimental odors on 9-point Likert scales (1 = not at all, 9 = extremely) for how intense, pleasant and familiar they were, and to the extent to which they caused well-being.

Procedure

The physiological recording session took part first (Figure 1). The receivers were equipped with the measurement sensors and the nasal cannula and were seated in a comfortable chair in a quiet and well-ventilated room with standardized conditions of light (no windows) and temperature. They were also given white noise through sound-canceling headphones. The experiment started with 2 minutes of rest during which the experimenter ensured that the physiological signals were stable with no artifacts (from electrical or biological sources) before starting the session, and to provide a baseline. Then the first odor was sent with the olfactometer for 5 seconds, on an expiration to ensure that it would enter the nostrils at the beginning of the next inspiration. The next 60 seconds were odorless to return to a baseline and to avoid olfactory adaptation. Then, the next odor was delivered and so on (in a pseudo-randomized order) until all odors were sent (first block out of three). After unhooking the receivers' psychophysiological sensors, participants had a 5-minute break before the behavioral tasks started. In these tasks, the odor condition was attributed randomly, in a double-blind fashion. During the whole duration of the behavioral session, the odor (or clean

air) was sent to receivers' noses by the olfactometer through a nasal cannula, for 5 seconds every 30 seconds. Finally, the receivers rated the odors on verbal scales and were thanked for their participation after a small brief about the purpose of the experiment.

Data analysis

Receivers' physiological responses.

The receivers' physiological variables that we analyzed were: i) Mean heart rate change compared to baseline (beats per minute), ii) Log-transformed skin conductance SC peak (in μS) and number of SC responses, iii) Log-transformed sniff volume (area under the curve AUC) and sniff duration in seconds for the first sniff during odor presentation, and iv) Facial EMG number of contractions and intensity of contractions (area under the curve AUC) for the *zygomaticus major* and *corrugator supercilii*.

Linear mixed-effects models were conducted using the `glmer` (for the number of SC responses and number of EMG peaks) and the `lmer` (for all other variables) functions of the `lme4` package in R (see also Donors' Data analysis section for more details). Condition (Positive/Neutral body odor) and Perfume (With/Without) were set as Fixed factors. Random factors were Subject and, only when it significantly improved the models, stimulus Repetition (i.e. presentation order, as stimuli were presented 3 times). A model selection procedure was conducted to select the best models, using the `anova` function of `lmerTest` package, where the non-significant interactions were removed to keep only the best model including the main effects. For models obtained with `lmer`, P-values were obtained using Kenward–Roger approximation in the `anova` function of `lmerTest` package and for the model obtained with `glmer`, by using the `Anova` function. Post-hoc contrasts were performed using the `multcomp` function of the `emmeans` package.

Receivers' performances in the behavioral tasks.

The receivers' performances in the creativity and problem-solving tasks were the Alternate Uses Task (AUT) scores of fluency, originality, elaboration and flexibility on the one hand, and the Candle Problem frequency of success and time to solve the problem in case of success (in sec) on the other hand.

We conducted one-tailed Welch t-tests because a clear *a priori* hypothesis was postulated before data collection and was already found in our previous research. Namely, smelling positive body odors is expected to increase positive affect and thereby creativity²⁷ compared with smelling neutral body odors. Our target comparison being the positive versus neutral conditions comparison, a preliminary analysis comparing performances in presence of the Neutral body odor with those in the control condition revealed no significant differences between Neutral condition (N=15) and clean air (N=14) (AUT fluency: $p=0.680$; AUT originality: $p=0.330$; AUT elaboration: $p=0.950$; AUT flexibility: $p=0.700$; Candle Problem: $p=0.209$). Consequently, thereafter we focus only on the target comparison between Positive (N=14) and Neutral (N=15) conditions. A Chi-square test was also conducted to compare the frequency of succeeded versus failed attempts during the Candle Problem in the positive versus the neutral condition.

Receivers' odor ratings.

The raw odor ratings of intensity, pleasantness, familiarity, and well-being collected after the behavioral tasks were analyzed using linear mixed-effect models with Condition (Positive/Neutral body odor) and Perfume (With/Without) as Fixed factors and Subject as a Random factor, using the same procedure as for the physiological responses (see above).

Missing and removed data.

Due to technical issues, the sensor measuring the receivers' SC responses did not allow us to record the signal of the first 10 participants. Additionally, technical faults of the acquisition system happened during some trials, and some trials were also removed if artefacts were found after visual inspection. In total: 22 trials for the SC (5%), 32 for the heart rate (6%), 25 for the sniff (4%) and 31 for the EMG (6%) were removed or not analyzable.

Results

In this section, we first tested whether the VR-based induction we developed was effective to induce positive emotions in the odor donors, and whether it would be more effective than the Video-based induction we used previously in Richard Ortégón et al.²¹. Second, we tested whether the different types of responses of the receivers (physiological, motor, verbal and behavioral) would vary as a function of the odors they were exposed to. Notably, we tested the effect of Condition (smelling body odors collected during the positive MIP versus during the neutral condition), and in some cases the effect of Perfume (body odor with or without perfume).

Donors: Emotion induction efficacy

The average happiness ratings per donor that were collected during the positive VR-based MIP were all above 50 on a 0-to-100 scale and ranged from 52 to 87 depending on the individuals. This means that, based on self-reports, the VR-based MIP was effective in inducing a positive state in all donors (N=10, 100%), which is a major improvement compared to our previous study with Video-based MIP, where mood induction was effective

in only 8 donors out of 21 (38%, ratings during the positive MIP ranging from 27 to 94). Note that donors were independent in both studies and had similar characteristics (all males, similar age range, same selection criteria). The significance of this progress was further evidenced by the fact that there was a significant interaction between Study (VR vs. Video) and Question (“neutral” vs. “happy”) in the Positive MIP ($F(1,521.40)=28.86, p<0.0001$; Figure 2B). Post-hoc contrasts revealed that this was due to the fact that donors provided, on the one hand, higher happiness ratings with the VR-based MIP than with the Video-based MIP (Mean \pm Standard Deviation: 74.42 ± 9.52 and 57.64 ± 17.93 respectively), and lower neutral ratings on the other hand (VR: 17.02 ± 17.10 ; Video: 29.47 ± 14.06). Note that the Study \times Question interaction was not significant in the case of the Neutral MIP ($F(1,470.11)=1.08, p=0.300$; Figure 2A). All together, these results indicate that the mood induction based on VR was better at inducing positive emotions when compared to the Video-based MIP used in our previous study²¹.

In the present study, the manipulation of our experimental conditions was successful since happiness ratings were higher in the positive VR-based MIP than in the neutral VR-based condition (Positive: 74.42 ± 9.52 , Neutral: 31.44 ± 17.91 ; Condition effect: $F(1,140.66)=162.72, p<.0001$). This result is supported by the participants' non-verbal behavior. Indeed, the donors had more EMG peaks for the zygomaticus muscle during the positive than during the neutral condition (Positive: 101.21 ± 103.39 , Neutral: 33.88 ± 45.48 ; Condition effect: $\chi^2(1)=1796.3; p<0.0001$). They also had higher AUC (Positive: 3589.96 ± 3399.95 , Neutral: 1009.80 ± 813.28 ; Condition effect: $F(1,102.06)= 38.67; p<0.0001$) for this muscle whose activity is known to correlate with positive emotion (see Supplementary Figure S1).

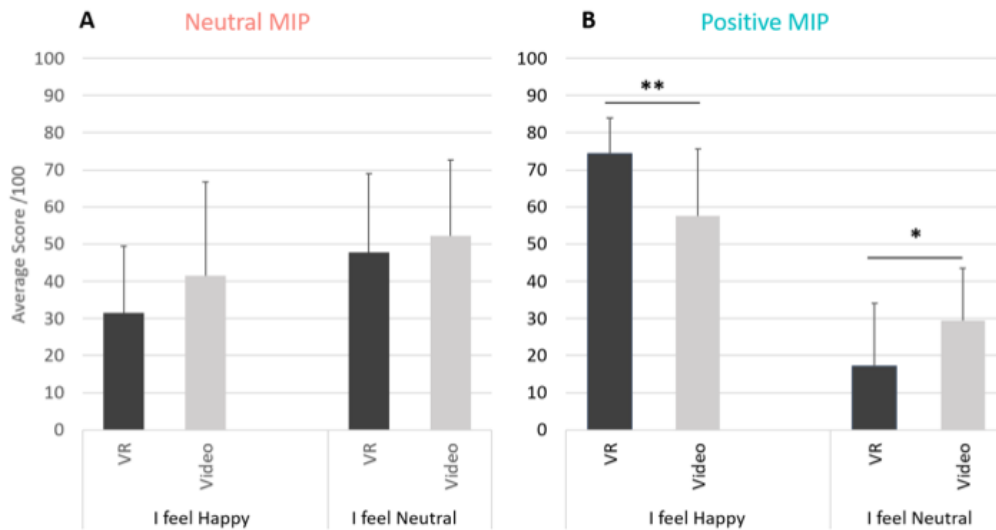


Figure 2: Male donors' emotional ratings (0-100) during the Neutral (**A**) and Positive (**B**) Mood Induction Procedures as a function of the Study (VR or previous study with Video) and of the Question (“I feel neutral”/“I feel happy”). Linear mixed models tested were Variable ~ Study + Question + Study×Question + (1|Subject). The Study×Question interaction was significant only for the Positive MIP ($p<0.0001$) but not for the Neutral MIP ($p=0.300$). Means ± Standard Deviations. Post-hoc contrasts: * $p<0.01$, ** $p<0.01$.

Receivers: Responses to the positive vs. neutral body odor

Physiological responses.

No main effects of Condition or Perfume on mean *heart rate* and no Condition×Perfume interaction were significant ($ps>0.05$, see Table 1 and Supplementary Figure S2).

The analysis of the log-transformed *Skin Conductance (SC) peak* (Table 1) revealed a significant effect of Perfume ($p=0.0002$, Figure 3A) but no effect of Condition nor of the Condition \times Perfume interaction. Higher SC peaks were found when perfume was present ($M_{\log\pm SD}= -0.331 \pm 0.59$) than when body odors were presented alone (-0.500 ± 0.60). Regarding the *number of SC responses*, we found a significant effect of Condition ($p=0.041$, see Table 1, Figure 4A) due to more numerous SC responses in the Positive than in the Negative condition. There was no significant effect of Perfume or of the Condition \times Perfume interaction for this variable.

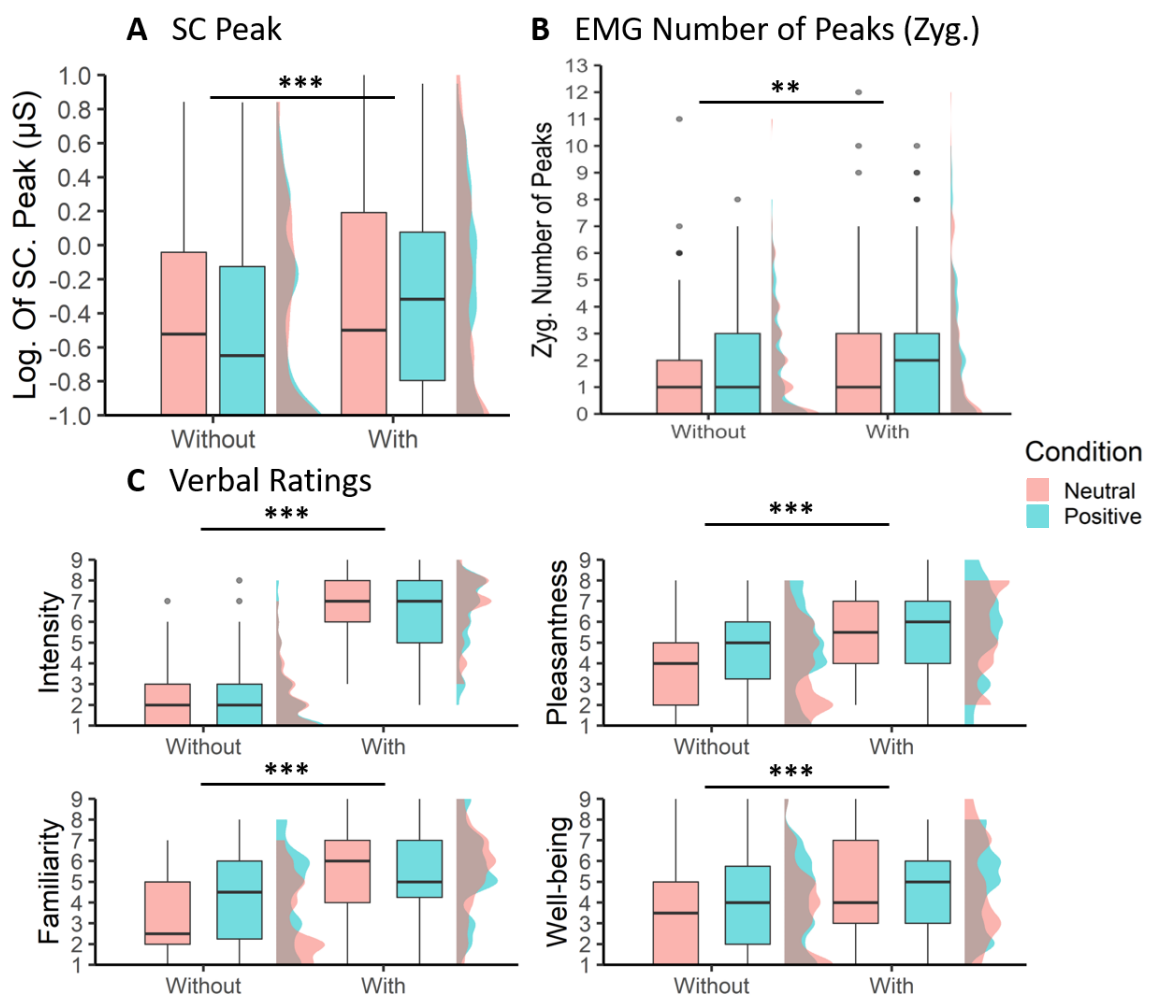


Figure 3. Effect of the factor Perfume on female receivers' responses (represented by Condition neutral vs. positive). **(A)** Skin conductance peaks (μS) in response to donors' body odors without and with perfume. **(B)** Number of Peaks detected for the *zygomaticus major* muscle in response to donors' body odors without and with perfume. **(C)** Odor ratings of intensity, pleasantness, familiarity, and well-being in response to donors' body odors without and with perfume. Linear mixed models tested were Variable \sim Condition + Perfume + (1|Subject) + (1|Repetition) for the physiological measures, and the same model without Repetition for the verbal measures. Main effects of Perfume: * $p < 0.05$, ** $p < 0.01$ *** $p < 0.001$.

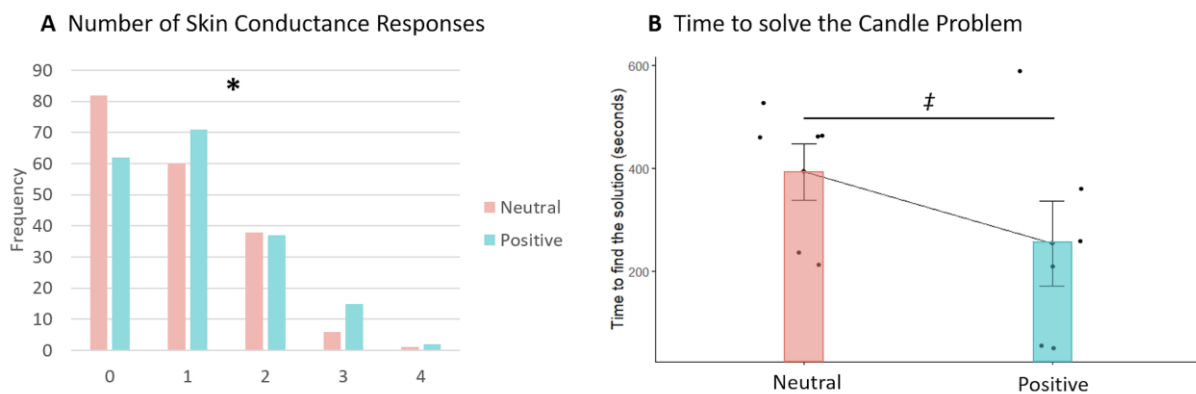


Figure 4. Effects of the factor Condition (neutral vs. positive) on female receivers' responses. **(A)** Number of skin conductance responses to the neutral and positive body odors (N=33 receivers, 374 trials; Linear mixed model tested was Condition + Perfume + (1|Subject); Condition effect $p < 0.05$). **(B)** Mean time to find the solution to the Candle problem, in seconds (Welch t-test: $p = 0.098$, in participants who successfully solved the problem, namely N=6 out of 15 in the Neutral condition and N=6 out of 14 in the Positive condition). Means \pm Standard Error of the Mean. ‡: $p < 0.10$; * $p < 0.05$.

Motor responses

There were no main effects of Condition or Perfume and no interaction on log-transformed *sniff volume* nor on log-transformed *sniff duration* ($p > 0.05$, see Table 1 and Supplementary Figure S3).

Regarding EMG responses, there was a significant main effect of Perfume on the number of peaks for the *zygomaticus* muscle ($p = 0.002$, see Table 1, Figure 3B), which was higher when the body odors were presented with perfume (2.05 ± 2.40) than without (1.64 ± 1.95). A marginal effect of Condition was found on the number of peaks and the peaks' AUC for this

muscle due to slightly higher values in the positive condition ($p=0.083$ and $p=0.069$, see Table 1), but there was no effect of the Condition×Perfume interaction. As for the *corrugator* muscle (Supplementary Figure S4), the analysis of the number of peaks revealed a main effect of Perfume ($p=0.023$, see Table 1; With perfume: 1.23 ± 1.70 ; Without: 1.01 ± 1.55), a marginal effect of Condition ($p=0.051$, see Table 1) and no interaction. Analysis of the *corrugator* peaks' AUC revealed no significant main effects or interactions ($ps>0.05$, see Table 1).

Table 1. Receivers' physiological and olfactomotor responses as a function of Condition (Positive vs. Neutral body odor) and Perfume (With vs. Without). Results of the linear mixed models with Condition and Perfume as fixed factors and Subject (and in some cases stimulus Repetition) as random factor (intercept). The effect of the interaction was never tested because it was not present in the best models (see Methods). *Zyg.*= *zygomaticus major*, *Corr.* = *corrugator supercilii*. *P*-values < 0.05 are in bold.

Variable	Main effects and interactions	Statistics	
Heart Rate	Condition	F(1,432.49)=0.284	P=0.594
	Perfume	F(1,431.22)=1.390	P=0.239
	Condition×Perfume	-	-
SC peak	Condition	F(1,252.84)=1.230	P=0.268
	Perfume	F(1,252.09)=13.997	P=0.0002
	Condition×Perfume	-	-
Number of SC responses	Condition	$\chi^2(1)=4.16$	P=0.041
	Perfume	$\chi^2(1)=2.13$	P=0.144
	Condition×Perfume	-	-
Sniff volume	Condition	F(1,429.09)=0.518	P=0.472
	Perfume	F(1,429.12)=2.596	P=0.108
	Condition×Perfume	-	-
Sniff duration	Condition	F(1,437.17)=0.007	P=0.934
	Perfume	F(1,437.27)=0.006	P=0.937
	Condition×Perfume	-	-
EMG Number of Peaks	Zyg. Condition	$\chi^2(1)=3.01$	P=0.083
	Zyg. Perfume	$\chi^2(1)=9.25$	P=0.002
	Zyg. Condition×Perfume	-	-
	Corr. Condition	$\chi^2(1)=3.80$	P=0.051
	Corr. Perfume	$\chi^2(1)=5.13$	P=0.023
	Corr. Condition×Perfume	-	-
EMG Peaks AUC	Zyg. Condition	F(1,431.48)=3.317	P=0.069
	Zyg. Perfume	F(1,431.33)=0.431	P=0.512
	Zyg. Condition×Perfume	-	-
	Corr. Condition	F(1,348.18)=0.268	P=0.605
	Corr. Perfume	F(1,348.33)=1.761	P=0.185
	Corr. Condition×Perfume	-	-

The best models were $Variable \sim Condition + Perfume + (1/Subject) + (1/Repetition)$, except for heart rate and number of SC responses for which the best model was $Variable \sim Condition + Perfume + (1/Subject)$.

Odor ratings

A significant effect of Perfume was found (no effect of Condition and no interaction) on all odor ratings (see Table 2, Figure 3C). When presented with perfume, body odors were perceived as more intense (6.45 ± 1.70 vs. 2.30 ± 1.60 without perfume; $p < 0.0001$; 95% CI = [3.71, 4.60]), more pleasant (5.48 ± 2.12 vs. 4.13 ± 2.06 without; $p < 0.0001$; 95% CI = [0.77, 1.93]), more familiar (5.38 ± 2.06 vs. 3.69 ± 2.08 without; $p < 0.0001$; 95% CI = [1.10, 2.28]) and as inducing more well-being (4.70 ± 2.21 vs. 3.69 ± 2.12 without; $p = 0.0009$; 95% CI = [0.43, 1.60]).

Table 2. Odor ratings as a function of Condition (Positive vs. Neutral body odor) and Perfume (With vs. Without). Results of the linear mixed models with Condition and Perfume as fixed factors and Subject as random factor (intercept). The effect of the interaction was never tested because it was not present in the best models (see Methods). P-values < 0.05 are in bold.

Variable	Main effects and interactions	Statistics	
Intensity	Condition	F(1,124)=0.138	P=0.711
	Perfume	F(1,124)=341.890	P<0.0001
	Condition×Perfume	-	-
Pleasantness	Condition	F(1,124)=2.023	P=0.157
	Perfume	F(1,124)=21.087	P<0.0001
	Condition×Perfume	-	-
Familiarity	Condition	F(1,124)=2.554	P=0.113
	Perfume	F(1,124)=32.182	P<0.0001
	Condition×Perfume	-	-
Well-being	Condition	F(1,124)=2.203	P=0.140
	Perfume	F(1,124)=11.623	P=0.0009
	Condition×Perfume	-	-

The best models were $Variable \sim Condition + Perfume + (1|Subject)$

Behavioral tasks

No differences were found between the group exposed to positive body odors and the group receiving the neutral body odor, in any of the behavioral tasks.

In the Alternate Uses Task, both groups did not differ on Fluency (Positive: 3.44 ± 1.08 , Neutral: 3.64 ± 1.21 , $t(26.94) = -0.480$, $p=0.682$; 95% CI = [-0.92, Inf]), Originality (Positive: 0.67 ± 0.22 , Neutral: 0.64 ± 0.17 ; $t(24.77)= 0.372$, $p=0.360$; 95% CI = [-0.10, Inf]), Elaboration (Positive: 0.47 ± 0.15 , Neutral: 0.56 ± 0.19 ; $t(26.40) = -1.530$, $p=0.931$; 95% CI = [-0.21, Inf]) or Flexibility (Positive: 3.27 ± 0.98 , Neutral: 3.51 ± 1.16 ; $t(26.74) = -0.592$, $p=0.721$, 95% CI = [-0.92, Inf]) (see Supplementary Figure S5).

In the Candle problem, the solution was found in the allotted time by six participants in the neutral condition (6/15, 40%) and in the positive condition (6/14, 43%). The difference between these two observed frequencies was not significant ($X^2(1) = 0.00$, $p = 1.000$). Among the participants who did find the solution, problem solving time did not significantly differ between the groups (due to one data point, Figure 4B), although there was a nominal trend for the positive group to find the solution quicker (Positive: 254.50 ± 202.40 seconds, Neutral: 393.16 ± 133.22 seconds, $t(8.648) = -1.402$, $p=0.098$; 95% CI = [-Inf, 43.52]).

Discussion

This research addresses an important challenge for the understanding of human chemical communication of positive emotions. Namely, it aimed at developing a new method to induce positive moods in participants whose body odor is collected to examine its behavioral effects on receivers. Indeed, although previous evidence suggests that positive emotional contagion can happen via volatile chemicals emitted by the body, it remains difficult to induce positive emotions in the laboratory. In Richard Ortégón et al. 2022 for instance²¹, the induction of positive emotions was possible only in 8/21 donors, thus preventing from using the axillary samples of the 13/21 remaining ones. Therefore, we used a similar design but replaced 2D

videos by VR activities. VR is an innovative and more immersive approach to induce intense emotions.

An important methodological finding was that the VR-based MIP was significantly more effective at inducing the desired positive emotional state in donors than our previously used video-based MIP. Such a comparison has never been done before in the context of chemical communication, but is consistent with previous research showing that VR is effective in inducing such states^{43,69}. However, although we expected that a stronger emotion would trigger stronger differences in receivers' responses to the positive versus the neutral condition, in the present study we could not replicate the findings of our previous work. Indeed, while we previously found that receivers exposed to an emotionally positive body odor had a reduced heart rate, were more performant on creativity tasks, and were able to verbally differentiate it from a neutral control²¹, here no significant differences were found for those variables. This was despite the efficacy of the VR-based MIP that was expected to even lead to stronger physiological and behavioral effects (but see⁷⁰ for a non-confirmation of this intuitive thought in the context of chemical communication of fear). The fact that this was not entirely the case, since the only significant effect we found was more skin conductance responses but only marginally significant effects were found on behavior (faster problem-solving in presence of the positive odor compared with the neutral one, Figure 4) could be explained by several factors.

It is possible that, instead of triggering more intense positive feelings, VR may rather have elicited a higher level of agreement between individuals than did videos in our previous research. When comparing the happiness ratings of the 8 donors selected in the video study (based on successful emotion induction) with the ones of all donors in the present VR experiment, no differences occur (Supplementary Figure S6). This means that, i) using a selection of donor samples, although not optimal due to loss of samples, can approximate the

results of a more effective MIP, and ii) instead of expecting stronger effects it would have been more reasonable to expect similar effects to our previous study. As this was however not the case, other factors specific to the VR experiment may have accounted for the near absence of effect of the odor condition.

One such factor may be related to the higher level of immersion that VR can offer relative to images or music alone, but it also constitutes what we can call a *supranormal stimulus*, with out-of-the-ordinary scenarios unattainable in real-life settings where participants fly in the air or paint in space, for instance (as it was the case here). These supranormal situations could trigger stronger emotions than necessary for chemical communication to happen optimally, especially since most of the participants had never used a VR headset before (anecdotal evidence from discussions with them). Indeed, as suggested by Isen⁷¹ intense positive affect may have a different impact on cognition (in kind, and not in magnitude) than mild affect, because an intense emotion could distract or demand too much attention. In our study, it could be that the VR situation was too intense for the donors overall, in the positive as well as the neutral condition. This hypothesis came to us after having examined the arousing ability of the body odor samples. Indeed, participants in the VR-based MIP doubled their skin conductance responses to the odor samples than in the Video-MIP (one or more SC responses in 61% of the trials versus 34% of the trials in the Video-MIP; $X^2(1)=35.7$, $p<0.0001$, Supplementary Figure S7A). Interestingly, this was applicable not only to the responses to the positive odor samples but also to the neutral ones (Supplementary Figure S7B). Although only a direct comparison of VR- and Video-based protocols in the same participants could provide reliable answers, we can formulate some speculations. With VR the contrast between the positive and the neutral condition might be insufficient to trigger clearly observable differences in the behavioral outcomes. Although this assumption is not supported by the explicit emotional ratings (Supplementary Figure S6), it cannot be excluded that other aspects

of the emotional response are in play, such as the donors' level of arousal (not recorded here). It could also be hypothesized, as evoked elsewhere (⁷⁰), that an increase in eccrine sweat due to a more intense emotion could dilute the active compounds responsible for the behavioral effects observed previously with a less powerful emotion induction. Finally, there is also a possibility that other compounds are produced during VR-induction compared to Video-induction and that these have a masking effect on the active compounds. In the future, a finer knowledge of the chemical bases of human chemical communication would help with interpreting these results.

Some methodological parameters of the experimental designs could also explain the discrepancies of results between our two studies. The time between body odor samples collection and their utilization for receivers was longer in the VR experiment (≈ 5.5 months) compared with the Video experiment (\approx between 1 week and 1.5 months), and although microbial transformation is significantly reduced at -32°C , it is not unlikely that this longer storage length led to modifications in the sample composition. Consistently with this hypothesis, there were four times more participants who reported being able to perceive something when presented with the body odor samples in the VR experiment (11.63% versus 3.33% in the video experiment). Although storage duration up to 6 months at this same temperature seems to have no effect on perceptual ratings of body odors sampled for 24 hours (pleasantness, attractiveness, masculinity⁷²) this does not exclude the possibility that chemical cues of emotional state may have been altered during storage, especially since our sampling was considerably shorter (30 min) and emotional cues are more subtle than less transient information such as masculinity. Two other experimental parameters may also have contributed to the different outcomes obtained in both studies. For the positive MIP in the Video experiment, participants took part in groups of 3 (which is believed to amplify the experienced positive emotion) but this was not technically possible to implement in the VR

experiment (individual sessions). Additionally, in our previous work, but not in the present study, the participants received a personalized gift during the positive MIP. This may have had an additional positive influence in the Video study, even though the gift was found to have mitigated success (anecdotal evidence from participants' post-experiment debrief interviews).

As to the possible effect of fragrance on the chemical communication of positive emotions, we found no interaction. When presented with added perfume, the body odors were rated as more intense, pleasant, familiar, and caused more well-being than when they were presented alone, as in our previous study. Although it cannot be excluded that differences in the ratings (collected at the very end of the experiment) may be modulated by the fact that non-perfumed conditions were encountered more often than perfumed ones throughout the experiment, these results were expected. Indeed, the perfume used was pre-selected to be pleasant, and was clearly perceivable by contrast with the body odors which most of the time were not consciously perceived. Presented with perfume, the body odors also were associated to a higher peak amplitude in the skin conductance recordings (in accordance with the overall odor's higher intensity⁷³), and a higher number of contractions of the major zygomatic muscle (in accordance with the more positive valence⁶²). In our previous study, we found a synergic effect of the fragrance (higher intensity and familiarity of the positive body odor vs. the neutral one when they were presented with perfume, while no difference occurred when presented alone). This was not observed here, in accordance with the absence of differences between conditions on the different variables investigated.

To conclude, although the present study did not reveal strong evidence of a chemical communication of positive emotion through human body emissions, it is very likely that some methodological choices in this study (or a lack of power due to low sample sizes, especially in the creativity tasks) account for its inability to reveal a phenomenon that truly exists. Several

previous works support this position. They provide evidence that body odors of positive emotion can be explicitly discriminated from body odors collected in a neutral state^{74,75}, that they differ in their chemical properties⁷⁶ and most importantly that they elicit different behavioral responses even if not consciously detected (e.g., happier facial expressions²⁰; higher creativity²¹). Importantly, the patterns of results for the creativity task obtained in our previous study²¹ and in the present one are extremely similar, which is an element of confirmation (Supplementary Figure S8). In addition, not only humans, but also other animal species display behavioral changes in response to human positive versus neutral body odors (more stranger-directed behaviors in dogs⁷⁷; less head lifting behavior in horses: ⁷⁸). Therefore, we believe that the chemical communication of emotion is characterized by physiological and behavioral effects that are difficult to observe in laboratory, and that some methodological choices prevented us from revealing these effects, which are subtle and probably modulated by the context, in the present study. This leads us to formulate some recommendations for future studies in this field. Given that inducing positive emotions in the laboratory is not easy, VR is undoubtedly interesting for its very consistent effects (less waste of time, energy, and money due to less odor sample loss than with videos that are not systematically successful). However, for its use to be optimal, it may *first* be worth controlling for previous experience of the donors with VR since in novices it might constitute an experience that is too much out of the ordinary, even in the neutral condition. *Second*, increasing the contrast between neutral and positive conditions by using videos in the former and VR in the latter is an option to be considered. *Third*, not only measuring the level of arousal of the odor donors during emotion induction (by recording electrodermal responses for instance) is recommended, but also future studies should investigate the respective weight of the effect of arousal (high, low) and valence (positive, negative, neutral) of the induced emotion, in order to better understand how these two major components of emotion⁷⁹ are

involved in human chemical communication. Finally and more generally, research on human chemical communication would benefit from further methodological investigations of parameters that are susceptible to affect the observability of a chemical communication, such as storage temperature and duration (see ⁸⁰ for first evidence), among others.

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Conflict of interest

All authors declare no conflicts of interest. This work results from a collaboration between the Lyon Neuroscience Research Center and the Shiseido company. The data collection and statistical analyses were exclusively led by the authors from the Lyon Neuroscience Research Center.

Access to data and program code

Data and program code that support the findings of this study are available from the corresponding author (CF) upon request.

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