

**Fear-related chemosignal modulates fear recognition in ambiguous  
facial expressions**

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**ABSTRACT**

Integrating emotional cues from different senses is critical for adaptive behavior. Much of the evidence on crossmodal perception of emotions has come from studies of vision and audition. An emotion from one sense modulates how the same emotion is perceived in another sense, especially when the input to the latter sense is ambiguous. Here we address whether olfaction too causes similar sensory modulation of emotional perception. We show in two experiments that the chemosignal of fearful sweat biases women toward interpreting ambiguous expressions as more fearful, but has no effect when the facial emotions are more discernable. Our findings provide direct behavioral evidence that social chemosignals can communicate emotions and demonstrate that fear-related chemosignals modulate visual emotional perception in an emotion-specific way -- an effect of olfaction in humans that has been hitherto unsuspected.

## INTRODUCTION

Whereas our knowledge of human chemosensory communication of emotion is still limited, it is known that humans do communicate social information through chemical signals. The most well-known case is the olfactory modulation of the female reproductive cycle (Stern & McClintock, 1998). There has been some indirect evidence that social chemosignals communicate emotions. Chemosignals generated by the body of people experiencing anxiety and fear produce a significant albeit subtle effect on implicit perception and cognitive performance. For instance, while people were more likely to see a neutral face as happy when it is preceded by a subliminally presented happy face in the absence of olfactory stimuli, this effect was weakened in women when they were exposed to the anxiety-related chemosignal (Pause, Ohrt, Prehn, & Ferstl, 2004). The anxiety-related chemosignal also augmented the startle reflex (Prehn, Ohrt, Sojka, Ferstl, & Pause, 2006), an indirect measure of emotion. The fear-related chemosignal led to greater cautiousness; it made women perform more accurately on a word-association task, and react more slowly to ambiguous word pairs (Chen, Katdare, & Lucas, 2006).

It is common to believe that the role of chemosensory communication is limited in a species like humans, in which vision and hearing play dominant roles. While the affective content of subliminal common household smells has been found to prime likability for neutral faces (Li, Moallem, Paller, & Gottfried, 2007), the effect of social chemosensory input on vision -- in particular, the extent to which emotional chemosignals modulate visual emotional perception -- is largely an open question. By contrast, extensive work exists on the cross-modal influence between facial and vocal cues (McGurk & MacDonald, 1976). For emotional perception, studies have found that the two emotional cues are evaluated and integrated from both modalities. Of particular importance to us is the recognition that the influence of one emotional modality has

the greatest effect on the other, when the latter is ambiguous (de Gelder & Vroomen, 2000; Massaro & Egan, 1996). It is therefore natural to predict that the strongest chemosensory modulation of visual emotional perception, if it exists, occurs when the visual emotional cues are most ambiguous.

We have addressed this issue in two experiments by focusing on the effect of a fear-related chemosignal (sweat collected from donors viewing horror videos) in an emotional identification task. We did so by using the same types of olfactory stimuli (emotional sweat collected on gauze pad and control gauze pad with no sweat) throughout but *varied* the effectiveness of the visual input by changing the ambiguity of the facial emotions from somewhat happy to ambiguous to somewhat fearful. The latter is achieved through morphing between prototypical happy and fearful faces of each actor. Gauze pad free of chemosensory social information provided a clean baseline for comparison.

## **METHOD**

### **Participants**

Informed consent was obtained from all subjects involved. We recruited only men as sweat donors for their larger apocrine glands in the underarm (Doty, 1981). We recruited only women as odor recipients for their superior sense of smell (Brand & Millot, 2001) and sensitivity to emotional signals (Brody & Hall, 2000).

Eight healthy male non-smokers (mean age  $\pm$  s.e.m. = 26.1  $\pm$  0.83 yrs) from a larger study were chosen as emotional sweat donors (see Olfactory stimuli selection and preparation below). Six of them served as sweat donors for the first experiment. Two of them served as sweat donors for the second experiment.

Twenty right-handed women (mean age  $\pm$  s.e.m. =  $19.7 \pm 0.26$  yrs) participated in a pilot testing in which they performed the emotional identification task in the absence of olfactory stimuli. None of them participated in the actual experiments.

In the first experiment, forty-eight right-handed female non-smokers (mean age  $\pm$  s.e.m. =  $19.6 \pm 0.25$  yrs) with a normal sense of smell (phenyl ethyl alcohol threshold mean  $\pm$  s.e.m. in binary dilution steps =  $10.78 \pm 0.61$ , corresponding to 0.0047% in propylene glycol), and regular menstrual cycles (mean  $\pm$  s.e.m. =  $28.7 \pm 0.24$  days) were tested. Threshold was assessed using Sniffin' Sticks (Burghart Instruments, Wedel, Germany). Eighteen subjects were on hormone contraceptives. The remainders were tested on the  $12.8 \pm 1.37$  day (mean  $\pm$  s.e.m., from the first day of their period) of their menstrual cycles.

In the second experiment, sixteen right-handed female non-smokers (mean age  $\pm$  s.e.m. =  $19.6 \pm 0.32$  yrs) with a normal sense of smell (phenyl ethyl alcohol threshold in binary dilution steps  $\geq 7$ , corresponding to 0.0625% in propylene glycol), and regular menstrual cycles (mean  $\pm$  s.e.m. =  $30.6 \pm 2.06$  days) were tested. Two of them were on hormone contraceptives. The remainders were tested on the  $14.6 \pm 2.34$  day (mean  $\pm$  s.e.m., from the first day of their period) of their menstrual cycles.

## **Materials**

### *Olfactory stimuli selection and preparation*

Donors were informed that the study was on physiological and psychological responses to sensory stimuli. They refrained from using deodorant/ antiperspirant/ scented products, and used scent-free shampoo/conditioner, soap, and lotion (provided by the experimenter) two days prior to the sweat collection experiment until after the experiment was over. They washed their sheets

with the scent-free detergent provided by the experimenter. They kept a diet diary and avoided odorous food such as garlic, onion, asparagus, and spices. Each donor went through the sweat collection sessions held at the same time of the day over three consecutive days (one session per day). On the day of each session, they wore next to their skin a new t-shirt (provided by the experimenter) to prevent odor contamination of their regular clothes. During each session, they kept a 4" x 4" pad (rayon/polyester for maximum absorbance) under their armpits while they watched each of the three 20-minute-long video segments intended to produce the emotions of fear, happiness, and neutrality, respectively. Meanwhile, their heart rate was recorded using disposable snap electrodes attached to the right collarbone and the left and right (ground) rib cage (BIOPAC Systems, Inc. Goleta, CA). The segment presentations were counterbalanced. A 5min segment of the same emotional content preceded each 20min segment, serving as an emotional transition. New pads were used for each segment. After each segment, the donors rated on a 100mm visual analogue scale how angry, fearful, happy, neutral, and sad they felt while watching the video segment. For each donor, only pads worn during the 20min segments that elicited the most self-reported happy and fearful feelings (based on their mood ratings) were chosen. Compared to the corresponding neutral videos, donors experienced increased heart rate during the horror movies ( $t(19) = 2.26$ ,  $p = 0.036$ , Cohen's  $d = 0.61$ ), but not during the slapstick comedies ( $t(18) = 0.69$ ,  $p = 0.50$ , Cohen's  $d = 0.21$ ; one donor's heart rate data during the selected happy video segment was excluded due to electrode detachment). We then identified eight donors who self-reported happiness and fear feelings the most and used their sweat pads in the current experiment (Figure S1).

The selected sweat pads were each cut into 8 pieces (sized 1"x2"), separated by video type, and stored at  $-80^{\circ}\text{C}$ . The control (gauze pad with no sweat) was cut and stored in the same

fashion. The pads were defrosted to room temperature 30min prior to the emotion identification tasks. During the computer-administered emotion identification task, a pad was taped underneath a subject's nostrils without directly touching the skin (it rested on a plastic wrap).

### *Visual stimuli selection*

To create ambiguity in facial emotions, we morphed prototypical examples of happy and fearful faces from 9 actors (5 females and 4 males) (Ekman & Frieser, 1976) with 2.5% increments and thus generated a continuum of 40 images (morphs) for each actor between his/her happy photo and his/her fearful photo (Morpher 3.1). The resulting 360 morphs represent gradual transitions from the prototypical happy expressions (0% fear) to the prototypical fearful expressions (100% fear). All morphs were included in our pilot testing, which employed the same task and procedure as the actual experiment but without applying any olfactory stimuli.

To locate the ambiguous morphs to be used in the actual experiment, we plotted the proportions of faces categorized as fearful separately for each actor and then performed a sigmoidal curve fit using the function  $y = a_0 + a_1 / (1 + \exp(-(x - a_2) / a_3))$  (Moradi, Koch, & Shimojo, 2005) ( $a_0$ ,  $a_1$ ,  $a_2$ , and  $a_3$  are coefficients for the y-offset, height, center, and width of the curve, respectively.  $x$  is the morphing step,  $y$  is the proportion of fear responses. See Figure S2). Based on the fitted curve, we were able to identify, for each actor, a morphing step that was judged as fearful around 50% (between 45%-55%) of the times. This morphing step, as well as morphs that were within 3 steps (each at 2.5% increment in terms of the degree of morphing) before or after it [a total of 7 intermediate images from each actor, assigned to applied morphing level 1 (somewhat happy), 2, 3, 4 (ambiguous), 5, 6, and 7 (somewhat fearful) respectively, see Figure 1a and Figure S2], were used in the first experiment. In the second experiment, we

selected two actors whose images produced greatest chemosensory modulation in the first experiment. Morphing levels 2 through 6 from each actor were included in order to provide subjects with the context of comparison. Each morphed image was independently presented for five times to each subject.

### **Experimental procedures**

In our emotion identification task, female subjects viewed a series of the morphed faces and were asked to respond accurately and quickly as to whether each face was happy or fearful. The faces were presented in a randomized sequence, each face for 250ms, and each preceded by 1000ms' fixation cross and followed by up to 2000ms' grey background (Figure 1b). If a response is received within 2250ms of the onset of a face, it will start the next trial. Otherwise, the next trial will begin 2250ms after the onset of the previous face. The tasks were performed at least 5 minutes apart from one another; each time, subjects were exposed to a different type of olfactory stimuli applied underneath their nostrils. The order of the olfactory applications was balanced. Care was taken so that the olfactory stimuli did not come into direct contact with the subjects' skin. Both the subjects and the experimenters were blind to the nature of the olfactory stimuli.

In the first experiment, two types of sociochemosignals (sweat of fear obtained from male donors watching horror movies, and sweat of happiness obtained from the same donors watching comedies; each carried on a gauze pad), and one non-social control (a gauze pad with no sweat) were tested. Each condition consisted of 63 trials. Subjects completed the Spielberger's State Anxiety Inventory (Spielberger, Gorsuch, & Lushene, 1970) after each emotion identification task, before the olfactory stimulus was removed. They re-smelled the three olfactory stimuli at

the end of the experiment, and described what each smelled like in an open-ended manner.

Thirty-six of the subjects also rated the olfactory stimuli by their intensity and pleasantness on a 7- point Likert scale.

Based on the results of the first experiment, the second experiment compared between two olfactory conditions: fearful sweat and control pad, focusing on women's perceptions of fear in the most ambiguous faces while being exposed to fearful sweat. Each condition consisted of 50 trials. The procedures were otherwise identical to the first experiment except that the anxiety questionnaire was not used (given that it was found in the first experiment not to be related to the olfactory conditions,  $F(2, 94) = 0.46, p = 0.63$ ).

## **Analyses**

Trials where the subjects did not respond, or responded in less than 200ms after the onset of a face ( $RT < 200ms$ ), were excluded from further analysis. When analyzing the response time (RT) data, we also excluded trials where the subjects responded more than 1s after the disappearance of a face ( $RT > 1250ms$ ). The trials excluded count for less than 5% of the total number of trials.

The key dependent variable -- proportion of faces identified as fearful -- was calculated as the number of fearful responses divided by the total number of responses at each level of applied morphing for each subject. Following our hypothesis that the strongest chemosensory modulation of visual emotional perception occurs when the visual emotional cues are most ambiguous, we examined the effect of chemosensory input for the most ambiguous faces by using repeated measures ANOVA (olfactory condition as the within subject factor with three levels: fearful sweat, happy sweat, and control pad) in the first experiment and paired sample t

test (fearful sweat vs. control pad) in the second experiment. The same tests were then performed for the less ambiguous levels to further test the hypothesis.

We conducted similar tests with the RT (at each level of applied morphing), intensity, pleasantness, and state anxiety [as measured with the Spielberger's State Anxiety Inventory (Spielberger et al., 1970) in the first experiment], respectively, to assess whether these variables differ across olfactory conditions.

In the first experiment, to confirm the effect of visual input on the proportion of faces categorized as fearful, we conducted a repeated measures ANOVA using applied morphing level (seven levels: from applied morphing level 1 to applied morphing level 7) and olfactory condition (three levels: fearful sweat, happy sweat, and control pad) as the within subject factors.

In the second experiment, subjects perceived the fearful sweat to be equally intense ( $t(15) = -0.48$ ,  $p = 0.64$ , Cohen's  $d = 0.18$ ) but less pleasant ( $t(15) = -2.91$ ,  $p = 0.011$ , Cohen's  $d = 0.81$ ) than the control (Figure S3b). To assess whether pleasantness differences contributed to the increased fear identifications (increased proportion of faces identified as fearful) at the most ambiguous level, we built a linear mixed model using fear identification at the most ambiguous level as the dependent variable, olfactory condition (fearful sweat vs. control) as the factor, and pleasantness ratings as the covariate. While olfactory condition had a significant effect on fear identifications ( $F(1, 16.40) = 10.15$ ,  $p = 0.006$ ) at this level, pleasantness did not affect fear identifications ( $F(1, 25.71) = 0.43$ ,  $p = 0.52$ ).

We classified the verbal descriptions of the olfactory stimuli into 9 categories (Table S1) based on the semantic similarity of the descriptions. We subsequently performed chi-square test to examine if the three olfactory stimuli in the first experiment and the two olfactory stimuli in the second experiment differ in any of the nine categories.

## RESULTS AND DISCUSSION

Figure 2 plots the proportion of subjects' fear responses for faces of each level of applied morphing under the three olfactory conditions of the first experiment: the fearful sweat, happy sweat, and control. Visual input clearly had a strong impact on their judgments ( $F(4.24, 199.05) = 158.70, p < 0.001$ ): morphs that were closer to the original fearful pictures were more likely to be judged as fearful. Under the control condition, the fear identification naturally grew monotonically with the level of the applied morphing. Nevertheless, olfactory input affected the identification when the visual cues became most ambiguous, as revealed by a significant effect of olfactory stimuli for the morphing level 4 ( $F(2, 94) = 3.17, p = 0.047$ , Partial Eta Squared = 0.063), but not for the other levels ( $ps > 0.50$ ). Post-hoc analysis showed that, at this level of applied morphing, subjects were more likely to judge a face to be fearful when they were exposed to the fearful sweat, as compared with the control (Tukey's  $p = 0.046$ , Cohen's  $d = 0.37$ ). No difference was found between the happy sweat and the control (Tukey's  $p = 0.82$ , Cohen's  $d = 0.09$ ). This may be because sociochemosensory modulation of visual cues is mainly controlled by negative affect. Such negativity bias – greater weight of negative over nonnegative events -- is widely observed in the contexts of emotion and cognition (Cacioppo & Gardner, 1999). It may be argued that happy sweat (generated in response to stimuli with socially acquired value) does not carry as much evolutionary salience as fearful sweat (generated in response to stimuli that threaten survival).

To further explore the observed effect, we conducted the second experiment focusing on perceptions of fear in the most ambiguous faces while being exposed to the chemosignal of fearful sweat from two new donors versus the control. When we exclusively analyzed the single most ambiguous morphing level, we found that the subjects were more likely to judge a face to

be fearful when they were exposed to the chemosignal of fearful sweat, as compared with the control ( $t(15) = 3.27$ ,  $p = 0.005$ , Cohen's  $d = 0.74$ ) (Figure 3). For each of the other levels, the difference was not significant ( $ps > 0.18$ ). Both are compatible with the results of the first experiment.

The effect of chemosignal of fearful sweat cannot originate from the speed of processing. Olfactory input did not significantly affect how fast the subjects responded to the faces at any morphing level ( $ps > 0.46$  in the first experiment,  $ps > 0.51$  in the second). In addition, the effect cannot be the result of its intensity or pleasantness. In the first experiment, subjects did not tell the three olfactory stimuli apart in either intensity or pleasantness rating ( $F(2, 70) = 1.84$ ,  $p = 0.17$ , Partial Eta Squared = 0.050, for intensity;  $F(2, 70) = 1.15$ ,  $p = 0.32$ , Partial Eta Squared = 0.032, for pleasantness) (Figure S3a). In the second experiment, subjects perceived the fearful sweat to be equally intense ( $t(15) = -0.48$ ,  $p = 0.64$ , Cohen's  $d = 0.18$ ) but less pleasant ( $t(15) = -2.91$ ,  $p = 0.011$ , Cohen's  $d = 0.81$ ) than the control (Figure S3b). Yet the difference in the pleasantness did not affect emotional perceptions of the ambiguous faces (Linear mixed model,  $F(1, 25.71) = 0.43$ ,  $p = 0.52$ ). In addition, the subjects did not distinguish the olfactory stimuli on the basis of odor quality [Table S1,  $\chi^2(2)s < 8.4$ , Bonferroni corrected  $ps > 0.13$  in the first experiment;  $\chi^2(1)s < 1$ , Bonferroni corrected  $ps > 0.9$  in the second experiment]. Finally, the effect cannot be due to fear- and anxiety- related arousal, since the subjects did not differ in self-reported anxiety in the first experiment ( $F(2, 94) = 0.46$ ,  $p = 0.63$ , Partial Eta Squared = 0.01).

Instead, we propose that the effect we have observed has its origin in evolution. Through learning, chemosensory input became associated with fearful visual information and acquired emotional value. Encountering fear-related chemosignals in the presence of ambiguous faces triggers that previously stored association, and leads to greater perceptions of fear in the

ambiguous face (err on the cautious side, much like freezing upon seeing a twig that looked like a snake (LeDoux, 1996)). This likely occurs on a subconscious level, as subjects reported the same level of fear-related anxiety across different olfactory conditions, and were verbally unaware of the nature of the conditions.

Chemosignaling of fear in the form of alarm pheromones is well documented in many animals. It serves warning purposes, produces heightened vigilance or escape behavior, and alters autonomic (stress-induced hyperthermia), and immune (analgesia) responses in the conspecific recipients (Wyatt, 2004; Zalaquett & Thiessen, 1991). Although the vomeronasal organ is usually implicated in the detections of alarm pheromones (Kiyokawa, Kikusui, Takeuchi, & Mori, 2007), the olfactory epithelium (input site of the main olfactory system) (Kobayakawa et al., 2007; Liberles & Buck, 2006; Rottman & Snowdon, 1972) has also been shown to respond to these social cues. Moving down the main olfactory pathway, the amygdala, a primary olfactory region which receives direct chemosensory input from the olfactory bulb, has been widely implicated in fear recognition and fear/sensory modality association learning (Dolan, Morris, & de Gelder, 2001; Otto, Cousens, & Herzog, 2000; Rosenkranz & Grace, 2002). It receives parallel subcortical and cortical visual input and processes fearful visual information (Morris, Ohman, & Dolan, 1999). It also processes fear-related chemosignals in rats (Yasushi Kiyokawa, Kikusui, Takeuchi, & Mori, 2005), sending the input from the olfactory bulb to the bed nucleus of the stria terminalis, which is then forwarded to the hypothalamus and the brain stem. Such main olfactory pathway for fear-related chemosignals likely applies to humans, who lack typical receptor cells in the vomeronasal organ (Bhatnagar & Smith, 2001). It is thus plausible that the amygdala is the site where the integration of the fearful visual and chemosensory information takes place. When facial expressions are ambiguous, the fear-related

chemosignal augments the recognition of fearful signals in the face, and pushes it above a threshold level.

Our results provide direct support to the view that human emotional chemosignals act upon our behavior and cognition in a manner that is consistent with their inherent emotional contents, as implicated in several previous studies (Ackerl, Atzmueller, & Grammer, 2002; Chen & Haviland-Jones, 2000; Chen et al., 2006; Pause et al., 2004; Prehn et al., 2006). Our work has focused on one negative emotion, fear. It motivates future studies to examine more than one negative emotions (e.g., also employ Happy- Angry and Angry-Fearful morphs). Such studies will be important to fully establish the extent to which the chemosensory modulation of emotional recognition is emotionally specific beyond fear.

Finally, we note that our findings on emotional chemosensory modulation of visual emotional perception add the olfactory dimension to the crossmodal integration of emotional cues that had been discussed in the context of visual and auditory stimuli (de Gelder & Vroomen, 2000; Massaro & Egan, 1996). The latter literature has established that the perception of an ambiguous sense is modified by the less ambiguous sense. Interestingly in our case here, emotional olfaction, while being the less ambiguous sense compared to the most ambiguous morphed faces, is itself still ambiguous. Its nature is not accessible through verbal descriptions, and its effects occur at the subliminal level. These features are also characteristics in studies involving nonsocial pleasant and unpleasant smells and neutral faces in the context of judging facial likeability (Li et al., 2007). In addition, we have shown that the intensity and pleasantness qualities of the olfactory stimuli do not contribute to the effect.

## **OVERALL DISCUSSION**

We examined in two experiments the modulation of the perception of facial emotions by emotional chemosignals. We demonstrated that chemosignal of fearful sweat, compared with the control pad, biased women toward interpreting ambiguous expressions as more fearful, but had no effect when the facial emotions are more discernable. Our findings provide direct behavioral evidence that social chemosignals can communicate emotions (as do visual and auditory signals), and demonstrate that fear social chemosignals modulate visual emotional perception in an emotion-specific way.

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### Figure legend

Figure 1a: Examples of the morphed faces of two actors displayed in the emotion identification task in the first experiment. Each actor has 7 morphs ranging from somewhat happy to somewhat fearful. These faces have been chosen because they were judged to be fearful 20%-80% of the times in our pilot experiment in the absence of any olfactory stimuli. Specifically, level 4 consists of the most ambiguous morphs: the corresponding pictures were judged to be fearful in the pilot study 45% to 55% of the times. b: Procedure of the emotion identification task. Subjects first saw a fixation cross for 1s. Then a picture was presented for 250ms, followed by the grey background for up to 2s. The next trial began immediately after the subject made a response. The visual angle for the faces is  $17^{\circ} \times 24^{\circ}$ , with heads fixed in a chin rest. Subjects were instructed to respond as accurately and as quickly as possible whether they saw a happy face or a fearful face. Half of the subjects used their left index fingers to press key 'z' for a happy face and used their right index fingers to press key '/' for a fearful face. The other half did the reverse.

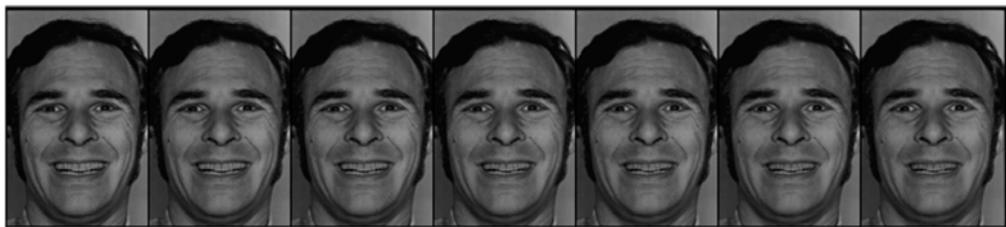
Figure 2a: Subjects' fear identifications for faces of incremental morphing under the three olfactory conditions in the first experiment. The dotted line is the sigmoidal curve fit for the fear identifications under the control condition. There is a significant effect of olfactory condition with the most ambiguous faces (level 4) ( $F(2, 94) = 3.17, p = 0.047$ ); the observed fear identification deviates from the fitted curve. No such effect is seen with the other faces. b: Bar graph showing the difference between the observed proportion of fear identification and the predicted value for each olfactory condition at applied morphing level 4. The predicted value is determined by the fitted curve. In all cases, error bars represent the standard error of the mean.

Figure 3a: Subjects' fear identifications for faces of incremental morphing under the two olfactory conditions in the second experiment. The dotted line is the sigmoidal curve fit for the fear identifications under the control condition. Again, fear identification for the most ambiguous faces (Level 4) is significantly higher when the subjects were exposed to fearful sweat as compared to the control pad ( $t(15) = 3.27, p = 0.005$ ). b: Bar graph showing the difference between the observed proportion of fear identification and the predicted value for each olfactory condition at applied morphing level 4. The predicted value is determined by the fitted curve. The fear identification under the fearful sweat condition is also significantly different from the predicted value at level 4 ( $t(15) = 2.54, p = 0.022$ ). In all cases, error bars represent the standard error of the mean.

Figures

Figure 1

**a**

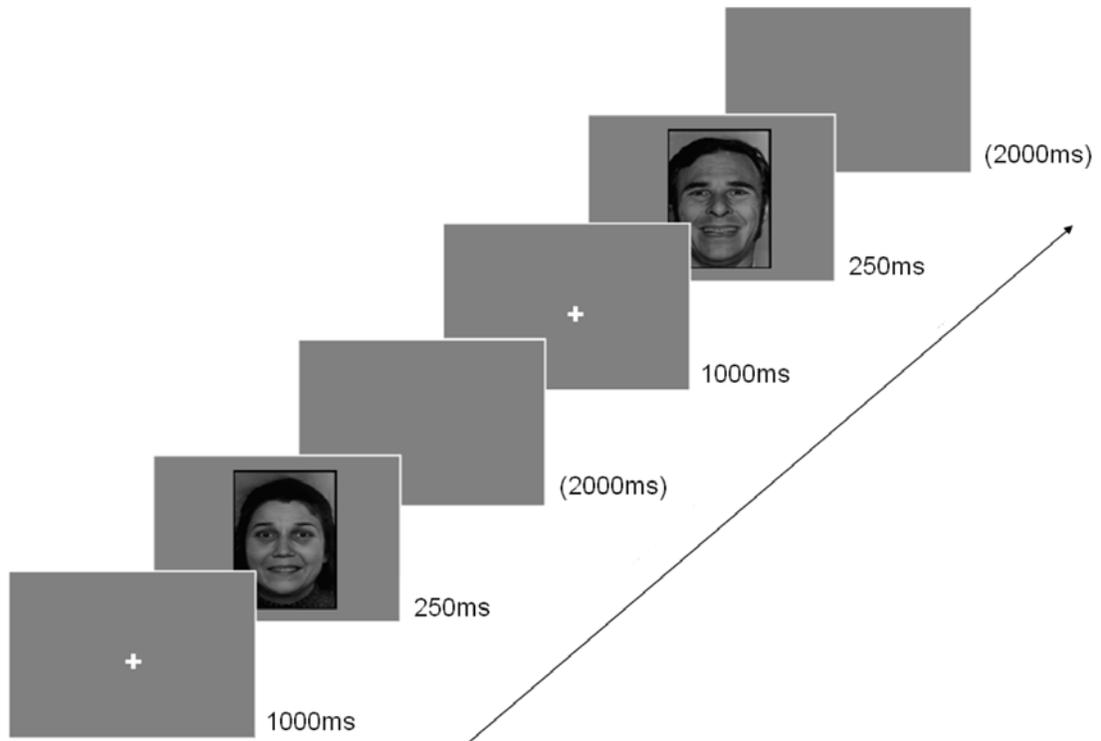


Levels of Applied Morphing

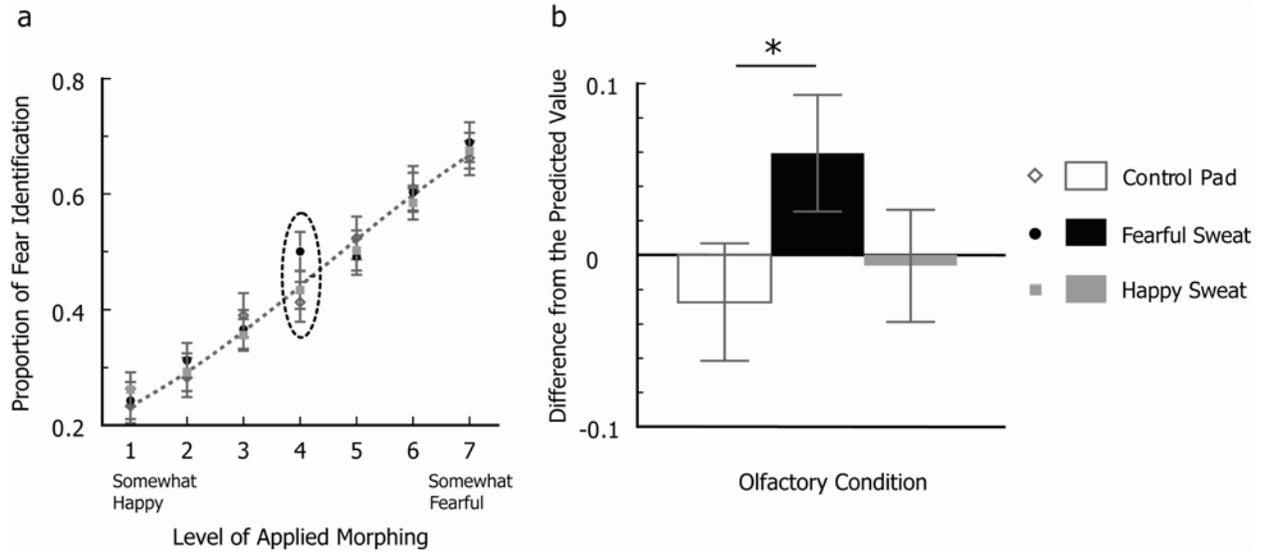
1 2 3 4 5 6 7

... ..

**b**



**Figure 2**



**Figure 3**

