Chem. Senses 31: 415–423, 2006

doi:10.1093/chemse/bjj046
Advance Access publication March 9, 2006

Chemosignals of Fear Enhance Cognitive Performance in Humans

Denise Chen, Ameeta Katdare and Nadia Lucas

Psychology Department MS-25, Rice University, 6100 Main Street, Houston, TX 77005, USA

Correspondence to be sent to: Denise Chen, Psychology Department MS-25, Rice University, 6100 Main Street, Houston, TX 77005, USA. e-mail: xdchen@rice.edu

Abstract

It is well documented across phyla that animals experiencing stress and fear produce chemical warning signals that can lead to behavioral, endocrinological, and immunological changes in the recipient animals of the same species. Humans distinguish between fear and other emotional chemosignals based on olfactory cues. Here, we study the effect of human fear chemosignals on the speed and accuracy of cognitive performance. In a double-blind experiment, female participants performed a word-association task while smelling one of the three types of olfactory stimuli: fear sweat, neutral sweat, and control odor carrier. We found that the participants exposed to the fear condition performed more accurately and yet with no sacrifice for speed on meaningful word conditions than those under either the neutral or the control condition. At the same time, they performed slower on tasks that contained ambiguous content. Possible factors that could introduce bias, such as individual differences due to anxiety, verbal skills, and perceived qualities of the smells, were ruled out. Our results demonstrate that human fear chemosignals enhance cognitive performances in the recipient. We suggest that this effect originates from learned associations, including greater cautiousness and concomitant changes in cognitive strategies.

Key words: cautiousness, cognitive performance, fear chemosignals

Introduction

Communication of affective and motivational state through chemical signals is well established in animals. Animals from sea anemones (Howe and Sheik, 1975), earthworms (Ressler *et al.*, 1968), minnows (von Frisch, 1941), and social insects (Regnier and Wilson, 1969; Suh *et al.*, 2004) to mice (Rottman and Snowdon, 1972), rats (Abel, 1991), and deer (Muller-Schwarze *et al.*, 1984) communicate fear through chemicals. Chemicals associated with fear and danger produce behavioral, physiological, and immunological changes in the recipient animals of the same species (e.g., Agosta, 1992; Wyatt, 2003). Humans have also been shown to distinguish between the sweat collected from the same individuals during fearful and neutral affective states (Ackerl *et al.*, 2002) and between fearful and happy states (Chen and Haviland-Jones, 2000).

Perceptions of threat can lead to changes in overall behavior. Chemicals released as warning signals can generate a global increase in vigilance in recipient animals of the same species (Thomas *et al.*, 1977; Zalaquett and Thiessen, 1991; Brown *et al.*, 2004). Similarly, perceptions of threat through other sensory channels increase cautiousness, latency for direct response, adaptability to environmental cues, and flexibility in recognizing relationship among variables in ambiguous situations in some animals but decrease these in others (Benus *et al.*, 1990; Blanchard *et al.*, 1991; also see review by Montgomery, 1955; Koolhaas *et al.*, 1999).

Perceptions of threat can also lead to threat-specific behavior. Chemicals released as warning signals can generate escape from intruders, attack of intruders (Blum, 1969; Thomas *et al.*, 1977; Zalaquett and Thiessen, 1991), and altered autonomic nervous system (Kikusui *et al.*, 2001) and immune responses (Moynihan *et al.*, 2000) in recipient animals of the same species. Perceptions of threat through other sensory channels increase flexibility in recognizing relationship in threatening situations and increased parasympathetic reactivity in some animals but decrease these in others (Benus *et al.*, 1990, Blanchard *et al.*, 1991, also see review by Montgomery, 1955; Koolhaas *et al.*, 1999). In humans, the threat-specific scenario is commonly (though not exclusively) discussed in the context of visual stimuli. Richards and French (1992) found that anxious people responded to threat-related words faster than to threat-unrelated words, whereas normal individuals did not differentiate between the two. Fearful images (snakes and bugs) increased arousal (skin conductance) (e.g., Öhman *et al.*, 2001) and were recognized faster than nonfearful images (e.g., threat faces in D.B. Broadbent and M. Broadbent,

1988; Bradley *et al.*, 1998; Öhman *et al.*, 2001); the effect existed even when the images were presented at a speed that precluded conscious awareness (Öhman *et al.*, 2001). Studies also found threat-related information grabbed so much attention that it impaired and slowed down task performance (e.g., Cloitre *et al.*, 1992).

The purpose of this study is to examine the impact of human fear chemosignals on behavior. Little is known about this subject. Based on what we know about nonsocial smells, however, there is reason to believe that fear chemosignals likewise bias cognition and perception. As a trivial example, the smell of mercaptan and the interpretation of it as an indication of a natural gas leak have led to panic attacks. In the laboratory, ambient smells of rose and mustard seed differentially modulated attention to brightness (Michael *et al.*, 2003), the smells of peppermint and muguet enhanced attention to visual stimuli (Warm *et al.*, 1991), and that of rosemary increased memory recall accuracy, albeit at the cost of slower performance (Moss *et al.*, 2003). The mechanism of the effect of these smells on attention and cognition is not yet clear; while some of these effects (e.g., peppermint) may be attributable to changes in arousal brought forth by the smells, others (e.g., muguet) cannot.

We predict that the impact of fear chemosignals in humans will be more implicit than the smell of mercaptan is for someone in an office building or fear chemosignals for animals whose livelihood depends on a keen sense of smell. This is because there has not been any evidence that human chemosignals release immediate behavior. Available evidence involving reproductive cycles (McClintock, 1971; Stern and McClintock, 1998), brain activations (Sobel *et al.*, 1999; Jacob *et al.*, 2001; Savic *et al.*, 2001), and mood (Chen and Haviland-Jones, 1999; Jacob and McClintock, 2000; Lundstrom *et al.*, 2003; Preti *et al.*, 2003; Bensafi *et al.*, 2004) suggests instead, as described by McClintock (1999), that they tend to either generate long-term endocrinological changes or modulate ongoing behavior at a level that is perhaps below conscious awareness.

We selected a priming task to examine the implicit role of fear chemosignals on behavior. The task, adapted from a previous study in a different context (Richards and French, 1992), asked participants to decide whether pairs of words were associated while participants were being exposed to an olfactory stimulus. We chose the word task over an image task because we thought words would be more likely to be influenced by fear chemosignals; images are believed to bias attention automatically, whereas words require greater attention and conscious perception (Bargh, 1992). Some word pairs in our task were related, some not; some contained threat, some not. In some word pairs, threat content was direct (both words were threatening). In others, it was more ambiguous (either both words were neutral or one neutral and one threatening). We included both related versus unrelated and threat versus neutral word pairs to test the global versus threat-specific scenarios. If fear chemosignals affect global task performance, we predicted that the influence (either enhancement or impedance) would be strongest on related variables, biasing the ability to recognize relationships, including ambiguous ones, and affecting both threat and nonthreat words.

Research on olfactory priming suggests that olfactory stimuli facilitate the detection of pictures or generation of words when the odor and subsequent stimuli are semantically (e.g., Platek *et al.*, 2004) or hedonically congruent with one another (e.g., Ehrlichman and Halpern, 1988). If the impact is threat specific (i.e., chemicals perceived as semantically/hedonically congruent to those words), we predicted that fear chemosignals would bias performance on words related to threat. Given evidence pointing toward the implicit nature of social chemosignals in humans, we are hypothesizing that the effect of fear chemosignals on the word task would be more likely to be global than threat specific.

Herein, we report the first study of the effect of human fear chemosignals on cognitive performance. In Part I of the study, we generated three types of olfactory stimuli: fear, neutral affect, and control odor carrier. Part II of the study examined the impact of these chemosignals on task performance in recipients.

Materials and methods

Part I: generation of the three types of olfactory stimuli—fear, neutral affect, and control odor carrier

Subjects

Seven healthy undergraduate nonsmokers (four males, three females) between the ages of 18 and 22 participated as sweat odor donors. The entire study (both Part I and II) was approved by the Institutional Review Board at Rice University.

Procedures

Collection of Olfactory Stimuli. Sweat Sample. Each donor was instructed to use the scent-free products provided by the experimenter, not to use deodorant/antiperspirants for 2 days prior to the experiment until after the session was over, and to take a shower the morning of the experiment. A different "4 × 4" pad (rayon/polyester for maximum absorbance) was placed under the armpits during each video segment. Each video segment documented a different emotional state. Pads were collected and batched according to emotional state, cut into 1.33 × 2-inch–sized pieces, and stored at −80°C until testing. The amount of perspiration absorbed was measured on an analytical scale (Fisher Scientific ACCU-224, $d = 0.01$ mg) by taking the difference in the pad weight before and immediately after it was worn.

Control Sample. Clean pads with no sweat were cut and stored in the same manner as above until testing.

Emotion induction. Individual donors were tested during a single session in ventilation and temperature controlled olfactory testing rooms. Emotions of fear and neutrality were induced with video segments tailored to the donor. Prior to the experiment, each donor was given a questionnaire encompassing approximately 50 popular films/documentaries of varying emotional content and was told that the list may or may not be related to the actual experiment. Each subject then answered questions about how each video had made or would have made him/her feel. The scary and neutral videos came from an extended collection that previous research had found successful at producing the target emotions (Gross and Levenson, 1995). Unbeknown to the donors, videos rated high in target emotions and low in nontarget emotions were selected. Scary and neutral videos, 20 min in length, were then presented in a counterbalanced order. At the end of each segment, donors indicated on a visual analog scale how happy, sad, angry, anxious, afraid, disgusted, or neutral each segment made them feel (0 = not at all, 100 = extremely). Donors were videotaped with a hidden camera during the session.

Physiological recordings. We also collected physiological responses. Heart rate variability, skin conductance, and respiration were recorded using Biopac Acknowledge 3.7.3 (Goleta, CA). Electrocardiogram signals were recorded using disposable snap electrodes attached to the right collarbone and the left and right (ground) rib cage. Heart rate variability was measured in terms of mean heart rate per minute and respiratory sinus arrhythmia (RSA), a measure of parasympathetic activity. Skin conductance signals were recorded using 8-mm diameter Ag/AgCl electrodes filled with Biopac isotonic electrode paste and attached bipolarly to the palmar area of the nondominant hand. Conductance signals were measured in terms of mean skin conductance amplitude in microsiemens. Respiration was measured using an airflow transducer placed around the nostril and mouth area (Grass Telefactor, West Warwick, RI). Data were analyzed using Mindware (Columbus, OH). Physiological indices were averaged every 4 min starting from the third minute (to eliminate the period during which people settle into the emotion) until the 18th minute.

The purpose of measuring physiological responses is not to show an invariant emotion-specific physiological profile. Instead, physiological responses serve as a measure (in addition to the self-report) of emotional responses to video stimuli. More recent theory based on meta-analysis questions the existence of emotion-specific physiological responses (e.g., Berntson *et al.*, 1993). For example, the heart is innervated by both the sympathetic and parasympathetic branches of the autonomic nervous system. The theory argues that changes in the heart rate could reflect an increase in one and decrease in the other, increase in both, decrease in both, or uncoupled changes in the two. This theory leads us to expect that anxious people could show anywhere from an increase, a decrease, or no change in the physiological indicators. For one, increase in heart rate has been observed in studies where participants were directed to move facial muscles and posed specific emotions (for a meta-analysis, see Cacioppo *et al.*, 1998). It has been interpreted as a defensive behavior in fear/anxiety. Decreased heart rate has been observed in studies where participants viewed pictures of snakes and other unpleasant stimuli (Cuthbert *et al.*, 1996, also see Cacioppo *et al.*, 1998). An initial decrease in heart rate has also been observed in laboratory animals when they were about to experience an electric shock (Bernston *et al.*, 1993; Campbell *et al.*, 1997; Lang *et al.*, 1997). It has been interpreted as orienting response during passive avoidance in fear/anxiety. There have also been reports of no change in heart rate (e.g., imagined fear in Stemmler *et al.*, 2001). With regard to skin conductance and respiration, an increase has been interpreted as arousal. Sweat glands are predominantly innervated by sympathetic and some nearby parasympathetic branches (Dawson *et al.*, 2000). Skin conductance habituates quickly to continuous presentation of similar stimuli.

Coding of mood induction videos. Also as an additional measure of the effectiveness of the video stimuli, responses to the videos were coded independently in a double-blind fashion. Two coders noted the number of occurrences and the duration of facial expressions using a coding scheme modeled after Izard (1979). Expressions coded included happiness (corners of the mouth up accompanied by cheeks pushed up, laughter), sadness [corners of the mouth down accompanied by corners of the eye brows pushed up and inward (inversed V shape)], disgust (nose wrinkled up accompanied by upper lip curled up), fear (eyes wide open accompanied by large eye white area with or without open mouth, eyes averted or partially covered in an attempt to avoid the video), and neutrality (expressionless, dozing off). Sound was turned off during coding.

Statistical analyses. To measure donors' self-reporting of mood in response to the neutral and scary videos, an eight (emotions: happiness, sadness, anger, fear, anxiety, neutrality, disgust, and sadness) × three (time: baseline, neutral video, and scary video) repeated measures analysis of variance (ANOVA) was performed. To examine physiological responses in donors in response either to videos or during the word task, two (emotions: neutral vs. fear) × four (time of assessment: 3–6, 7–10, 11–14, and 15–18 min) repeated measures ANOVA was performed with mean respiration rate as the dependent measure. Separate analyses were conducted for the mean heart rate, skin conductance amplitude, and RSA. For all repeated measures analyses for Part I and Part II of this study, the Greenhouse-Geisser adjusted degrees of freedom was used when the sphericity assumption was violated. To control for multiple comparisons, Bonferroni-adjusted significance levels were used in all pairwise comparisons.

Effect sizes were calculated using partial Eta^2, where a small effect size is 0.01, medium 0.06, and large 0.14 or greater.

Results

As shown in Figure 1, the emotion induction method was successful at producing fear and neutral affective states in the donors. Donors reported greater neutrality than any other emotion in the neutral video ($P < 0.03$) and greater fear, anxiety, and disgust than any other emotion in the scary video ($P < 0.05$). Donors' respiration rate was higher during the scary than the neutral video segment (17.43 vs. 16.56, SE = 0.60 vs. 0.52, $P = 0.04$, $Eta^2 = 0.53$). The donors' heart rates initially were lower during the scary video as opposed to the neutral video segment, but this difference decreased over time. Mean heart rates were 67.86, 67.75, 66.15, and 67.29 for the neutral video for the four time segments, SE = 5.09, 5.14, 5.36, and 5.24 versus 63.76, 64.55, 65.12, and 65.21 for fear, SE = 4.22, 4.15, 4.39, and 4.26. The difference between neutral and fear in the first segment was significant, $F(1,6) = 6.45$, $P = 0.044$, $Eta^2 = 0.52$. The heart rate versus time interaction also was significant, $P = 0.039$. No significant difference in RSA or skin conductance was found ($P > 0.05$). The amount of sweat collected during the neutral and fearful states did not differ by weight (mean = 0.018 g, SE = 0.021 and 0.024 for neutral and fearful state, respectively, for both arms). Video recordings showed that five out of seven donors displayed avoidance responses (startle response, eyes wide open, covering or squinting eyes to avoid looking at the screen) during the scary videos and none of them did so during the neutral video. Overall, donors during the neutral video displayed little facial expression. Intercoder reliability was 100%.

Discussion

In Part I of the study, we successfully produced olfactory stimuli from fear, neutral affect, and control odor carrier. The donors' self-report of emotions, their physiological responses, and observations of their overt behavior all suggested greater attention and orienting response during the scary videos. In particular, the initial lowering of the heart rate during fear induction is analogous to the "fear bradycardia" that is found commonly in laboratory animals (Bernston *et al.*, 1993; Campbell *et al.*, 1997; Lang *et al.*, 1997). It is also consistent with human studies where participants were viewing unpleasant versus neutral pictures (Cuthbert *et al.*, 1996). Nevertheless, consistent with the view that discrete emotions need not correspond to differentiated autonomic nervous system responses (Cacioppo *et al.*, 2000), although donors reported different affective experiences in the fearful and neutral states, their physiological data (skin conductance response) and amount of perspiration (weight of pads) did not reveal any direct arousal differences in the fearful versus neutral states.

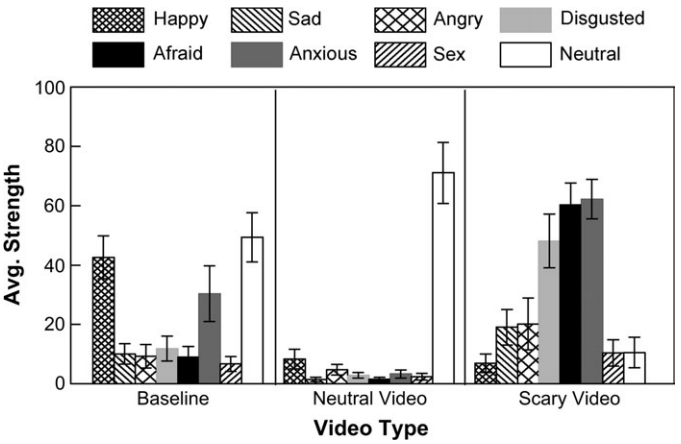

Figure 1 Average strength of self-report of emotion by video type.

Part II: examination of the effect of the emotional chemosignals on task performance in a group of recipients

Subjects

Sixty-eight female undergraduate nonsmokers who reported being healthy and having a normal or above normal sense of smell (4 or above olfactory sensitivity on a scale of 1 to 7, 1 being poor, 7 being superb) participated. None participated as donors. In order to study the modulation of fear chemosignals on cognitive performance, we focus on the participants (50 in total, age = 19.70 years, SE = 0.18) who were able to perform the task (at least 70% correct in each of the eight types of word combinations) and who also followed instructions. A third of the 50 participants used oral birth control pills over the course of the experiment. The distribution of those on versus not on the pill did not differ by chemosignal conditions ($P > 0.05$).

Procedures

Individual recipients were tested in the olfactory testing rooms described earlier and were not told about the nature of the olfactory stimuli. They were informed only that the purpose of the experiment was to assess the effect of natural compounds on mood, physiological responses, and task performance. They were instructed not to use any scented products on the day of testing. In this double-blind study, recipients were randomly assigned to one of the three olfactory conditions: sweat from donors experiencing fear, sweat from the same donors in a neutral state, or no sweat (blank pad control). Recipients evaluated their moods three times, once at the beginning of the experiment (before the olfactory stimulus was applied), once after the olfactory stimulus was applied, and once at the end of the experiment, after they had completed the word-association task.

Measures

Mood assessment. Mood was assessed using the Profile of Mood State (POMS) (McNair *et al.*, 1971), a widely used

clinical assessment. It consists of 72 items, each rated on a 0- to 4-point scale (0 = not at all, 4 = extremely), and assesses the confusion, depression–rejection, vigor, anxiety, and fatigue dimensions.

Anxiety. Recipients' anxiety was assessed with the Spielberger's state–trait anxiety scale (Spielberger *et al.*, 1983). Each state and trait scale consists of 20 items rated on a 1- to 4-point scale (1 = not at all, 4 = very much so). Anxiety state measures how anxious a person is at the time of testing, whereas anxiety trait measures how anxious the person is in general.

Verbal skills. Recipients' self-reports of verbal Scholastic Aptitude Test (SAT) scores were used as a measure of their verbal skills.

Physiological recordings

Same as in Part I of the Study.

Evaluations of olfactory stimuli

Olfactory stimuli were defrosted to room temperature at least 20 min before the session. The pads were taped between the nostril and mouth areas of the recipient. At the beginning of the session, recipients rated the intensity and pleasantness of the smell on a 7-point scale (1 = mild, 4 = average, 7 = strong) and described the smell.

Cognitive task

Developed and standardized by French and Richards (1992) and Nelson *et al.* (1980), the word-association task consisted of pairs of words that appeared successively on the screen. In this test, the pairs of words are either neutral or threat related. The first word primes the interpretation and processing of the second word depending on whether one or both words are threat related or neutral (unrelated). The first word (the prime) appears on the screen for 750 ms, and is immediately replaced by the second word (the target). The second word then remains on the screen until the subject makes a response. For this study, responses that occurred 3000 ms or more after the appearance of the target word were counted as misses. Half of the participants were asked to press the key "F" with their left index finger if the words went together and the key "J" with the right index finger if they did not. The other half of the participants were asked to press "J" for words that went together and "F" for words that did not. Each subject participated in a practice block of 16 trials with feedback followed by eight experimental blocks of 40 trials each without feedback. The entire work task lasted about 20 min. Participants viewed the display at a distance of about 64 cm from the monitor. The eight experimental blocks came from a four condition (two neutral prime–neutral target, threat prime–neutral target, and threat prime–threat target) × two relatedness (related vs. nonrelated) combination. Two neutral prime–neutral target conditions were used to ensure an equal frequency of the target word (Richards and French, 1992). An example of a neutral/neutral-related pair is "CAP" and "HAT," neutral/neutral unrelated is "CAP" and "WATER". An example of a threat/neutral-related pair is "ARMS" and "LEGS," threat/neutral-unrelated is "ARMS" and "WIND," threat/threat-related is "ARMS" and "WEAPONS," and threat/threat-unrelated is "ARMS" and "STRESS." Stimuli were presented randomly using Eprime (Psychology Software Tools, Inc., Pittsburg, PA). Reaction times and the number of correct responses were recorded.

Statistical analyses

The two neutral prime–neutral target conditions were combined into a neutral condition, separated by word relatedness, after we determined that they did not differ in reaction time or accuracy from one another.

Accuracy (assessed as proportion of correct identification) and reaction time (for the correct items) were separately measured with a relatedness (two: related vs. not) × word condition (three: neutral–neutral, threat–neutral, and threat–threat) repeated measures analyses with olfactory condition (3: neutrality, fear, and control) as a between-subjects factor. A similar analysis was performed on reaction times for the incorrect items. Information regarding accuracy and the reaction time for the correct items would tell us whether there is an accuracy by reaction time trade-off. The amount of time spent on incorrect items would allow us to compare those on correct items and determine whether there is faster or slower performance that is independent of accuracy.

To measure mood (POMS) changes in the recipients, a repeated measures ANOVA was performed on each mood dimension (e.g., vigor) with time of testing (baseline, post-odor, and post–word task) as a within-subjects factor and with olfactory condition as a between-subjects factor. Physiological responses were analyzed in the same way as in Part I of the study.

Results

Evaluations of olfactory stimuli. Fear was perceived to be of similar pleasantness to the neutral and control stimuli (4.63, 5.20, 5.18, SE = 0.25, 0.26, 0.24 for fear, neutral, and control, $P > 0.05$). Similarly, the olfactory stimuli did not differ in perceived intensity (1.38, 2.20, 1.47, SE = 0.27, 0.28, 0.26, for fear, neutral, and control, $P > 0.05$). Nor were the olfactory stimuli distinguished based on perceived olfactory qualities; four out of 16 in the fear condition and one out of 17 in the neutral condition described the smell as sweat, none did so in the control condition.

Accuracy. Overall, participants were less accurate at recognizing the relatedness of related words than the unrelatedness of unrelated words (0.82 vs. 0.95 proportion correct, SE = 0.007 vs. 0.005, $P = 0.0001$). When combined across word relatedness, olfactory condition was the biggest between-subjects factor for those who identified the word

pairs correctly, $F(2,47) = 3.47$, $\text{Eta}^2 = 0.13$, $P = 0.039$. Simple effect analysis showed that participants were slightly more accurate in the fear than the control condition (0.90 vs. 0.87 proportion correct, SE = 0.007 for both, $P = 0.054$) but did not differ from the neutral condition (0.90 vs. 0.88, SE = 0.007 for both, $P > 0.05$). When separated by word relatedness, in the related-word condition, participants were more accurate when they were exposed to the fear condition than to either the neutral (0.85 vs. 0.80 proportion correct, SE = 0.012 for both, $P = 0.012$) or the control condition (0.85 vs. 0.80 proportion correct, SE = 0.012 for both, $P = 0.042$) (Figure 2). Accuracy did not differ by olfactory conditions when the words were unrelated.

Reaction time. Participants responded faster to related words than to unrelated words (864.96 vs. 991.33, SE = 17.59 vs. 27.09, $P = 0.0001$) due to a response time/accuracy trade-off. When combined across word relatedness, olfactory condition was the biggest between-subjects factor for those who identified the word pairs correctly, $F(2,47) = 3.57$, $\text{Eta}^2 = 0.13$, $P = 0.036$. Simple effect analysis showed that participants in the fear condition were slower on the tasks they performed correctly than those in the neutral condition (1007.32 vs. 875.13, SE = 37.38 vs. 36.26, $P = 0.044$) but did not differ from the control condition (1007.32 vs. 901.98, SE = 37.38 vs. 36.26, $P > 0.05$). No significant difference in reaction times on incorrect items was found ($P > 0.05$). When separated by word relatedness, in the related-word condition, the response times did not differ by olfactory condition (925.69, 823.99, and 845.20 for fear, neutral, and control condition, respectively, SE = 31.08, 30.15, and 30.15, $P > 0.05$), in spite of greater accuracy in the fear condition. They also did not differ in the unrelated-word condition (1088.96, 926.29, and 958.77 for fear, neutral, and control, respectively, SE = 47.87, 46.44, and 46.44, $P > 0.05$).

Participants in the fear condition were slower at processing words that did not have a clear threatening content but performed similarly to others at processing words that did. This was shown in a word condition × olfactory condition interaction effect, $F(3.58,84.17) = 2.61$, $\text{Eta}^2 = 0.10$, $P = 0.047$. Specifically, participants in the fear condition were slower in response than those in the neutral condition when processing neutral targets primed by either threatening (1030.37 vs. 888.56, SE = 39.52 vs. 38.34, $P = 0.039$) or neutral words (1015.37 vs. 884.66, SE = 37.59 vs. 36.47, $P = 0.048$) but not when threatening targets were primed by threatening words (1009.87 vs. 892.50, SE = 38.04 vs. 36.90, $P > 0.05$) (Figure 3).

Other factors. Unlike some of the previous studies using androstadienone, a nonandrogenic steroid found in sweat (Jacob and McClintock, 2000), fear chemosignals did not alter self-report mood as measured by POMS [$F(2,47)$ ranges from 0.055 to 2.23, $P > 0.05$]; autonomic nervous system

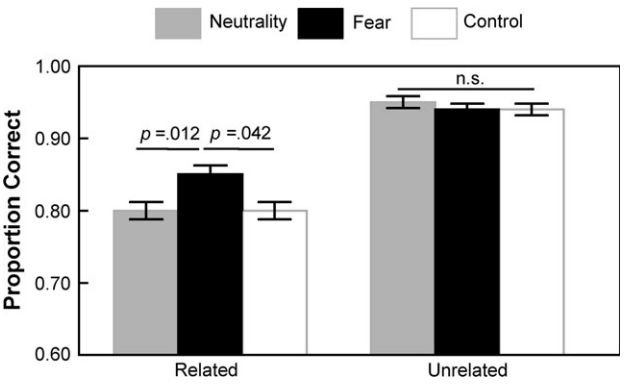

Figure 2 Proportion of accurate identifications by word relatedness and by smell.

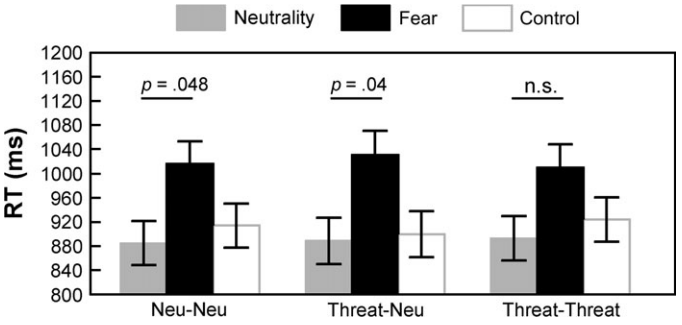

Figure 3 Reaction time (RT) by word condition by smell. RT was slower for fear than neutral in neutral–neutral and threat–neutral but not in threat–threat conditions.

responses were also not different during performance of the cognitive task [$F(2,45)$ ranges from 0.013 to 1.51, $P > 0.05$]. However, important differences in experiments and the nature of the olfactory stimuli may contribute to the differences in findings between the studies. The olfactory stimuli used in the present study contained a mixture of compounds and the timed word-association task cognitively is more demanding compared with the self-paced readings of neutral material in other studies. The cognitive demand of our task could have forced the participants to focus more on the task than on changes in their moods and at the same time created a ceiling effect in arousal. The state and trait anxiety levels were similar between olfactory conditions (36.41, 36.38, and 39.12, SE = 2.51, 2.59, and 2.52 for neutral, fear, and control in state anxiety, $P > 0.05$ and 38.00, 38.69, and 39.41, SE = 2.22, 2.29, and 2.22 for trait anxiety, respectively, $P > 0.05$). Furthermore, there were no differences in the verbal SAT scores between the groups (665.88, 697.50, and 696.47, SE = 28.54, 28.54, and 27.69 for neutral, fear, and control, respectively, $P > 0.05$).

Discussion

We showed that fear heightened caution and vigilance. Those in the fear condition behaved as if they were motivated

to avoid misses. In animals, cautiousness is especially exhibited in situations that contain ambiguous information about threat (Blanchard *et al.*, 1991). Likewise in the present study, cautiousness exhibited by participants in the fear condition was reflected in slower responses to word pairs that were ambiguous in threat content but not to word pairs that contained clear-cut threat content.

Interestingly, however, the greater cautiousness was not accompanied by an increase either in autonomic nervous system responses or in self-reported arousal. It is possible that the arousal/anxiety generated by the chemosignals was too mild to be detected by our instruments. It is also possible that the timed word task across all three olfactory conditions might have already generated sufficient arousal, making it difficult to detect any further arousal resulted from the chemosignals.

We found that human fear chemosignals do not produce immediate overt approach or avoidant behavior, as do fear chemosignals in many animals. Moreover, unlike findings in humans obtained with visual stimuli (e.g., picture of a menacing snake in Bradley *et al.*, 1998, or a human face in fury in D.B. Broadbent and M. Broadbent, 1988), we showed that the fear chemosignal did not selectively heighten attention to threat or predispose participants to threat-related information. This could have been due to the nature of the social chemosignals in humans; as was speculated earlier, they modulate ongoing but do not directly release new behavior in humans.

We found that the greater cautiousness exhibited by participants in the fear condition did not result from the perceived sensory qualities of the olfactory stimuli. As shown in the Results, participants rated the smells of fear, neutrality, and control to be of comparable pleasantness, intensity, and quality. Extended absence from deodorant (2 days in our case) cannot completely eliminate all the personal product–related volatiles, such as antimicrobial salts and fragrances, at a level detectable by the gas chromatography and mass spectrometry techniques (Labows *et al.*, 1979). Whether such residual volatiles have anything to do with the absence of smell difference among fear, neutral, and control is beyond the scope of the present work. In any case, the perceived quality of these volatile compounds cannot provide a mechanism for the effect we have reported in this work. We also ruled out verbal abilities, anxiety level at the time of testing, or personality differences in anxiety as explanations for this observation.

Recognizing signals from one's peers and quickly escaping from danger could be important for survival. The greater cautiousness and enhanced sensitivity in the cognitive task may have an evolutionary origin, reflecting a learned association between fear chemosignals and a heightened awareness of a potential threat in the environment. Learned responses to fear chemosignals have been reported in animals (Rottman and Snowdon, 1972; Carr *et al.*, 1980). In humans, olfactory learning has also been demonstrated in forming associations between specific odorants and significant emotional events (Kirk-Smith *et al.*, 1983; Epple and Herz, 1999) or enhancing absolute sensitivity due to repeated exposures (Dalton *et al.*, 2002). From a neuroanatomical perspective, a number of brain regions, including the amygdale (Irwin *et al.*, 1996; Zald and Padro, 1997; Anderson *et al.*, 2003; Neville and Haberly, 2004), are innervated by multiple sensory input. The amygdala plays an important role in forming fear associations (LeDoux *et al.*, 1990), and the strength of such learned association has been implicated in influencing enhanced sensitivity to the stimulus and overall vigilance and attentiveness (Goosens *et al.*, 2003). Such learned association in humans may prime people to be on the alert.

Experience of fear is accompanied by a series of neurochemical changes (Panksepp, 1998), some of which may be released in the sweat. These changes may then exert a pharmacological effect on cognition and behavior and in turn lead to more efficient strategies employed in cognitive tasks. In our experiments, the increased accuracy did not occur at the expense of increased response time; participants in the three olfactory conditions performed at comparable pace on related word tasks and also on unrelated word tasks. In fact, the hit reaction times showed much overlap in range (minimum = 764.28, 723.30, and 696.99 for fear, neutral, and control conditions, respectively; maximum = 1474.44, 1226.13, and 1264.25). This implies that participants in the different olfactory conditions were employing different strategies in the cognitive tasks. [That fear-induced cautiousness leads to more flexible problem-solving strategies is known to occur in animals (Benus *et al.*, 1987, 1990).]

Summary and conclusions

We have tested the effects of fear chemosignals on cognition and attention. Participants were assigned to one of the three olfactory conditions: sweat from people in fear, sweat from the same people in a neutral state, and no sweat (blank pad control). Overall, we found that participants in the fear chemosignal condition tended to be slower and more accurate. When processing meaningful (related) words, participants in the fear chemosignal condition, without sacrificing speed, were more accurate than participants in either the neutral or the control condition. Moreover, they behaved as if they were more aware of ambiguities than participants in the other olfactory conditions; they were slower in processing ambiguous words (words that begin with either a neutral or threat word and end with a neutral word) than straightforward threat words (words that begin and end with a threat).

To summarize, we have demonstrated that, in humans, fear chemosignals facilitated overall accuracy in identifying word relatedness independent of the perceived olfactory qualities of the smells. We have also suggested that the effect arises from a learned association including greater cautiousness and concomitant changes in cognitive strategies.

Acknowledgements

We thank Susan Barrows, Beth Leimbach, Stacey Meier, Sarah Park, and Jennifer Tsai for their assistance. We thank Jim Dannemiller and Jim Pomeranz for their comments and suggestions on an earlier draft. This study was supported by National Institutes of Health R03DC4956.

References

Abel, E.L. (1991) *Alarm substance emitted by rats in the forced-swim test is a low volatile pheromone*. Physiol. Behav., 50, 723–727.

Ackerl, K., Ztzmueller, M. and **Grammer, K**. (2002) *The scent of fear*. Neuro Endocrinol. Lett., 23, 79–84.

Agosta, W.C. (1992) Chemical Communication: The Language of Pheromone. Scientific American Library, New York.

Anderson, A.K., Christoff, K., Stappen, I., Panitz, D., Ghahremani, D.G., Glover, G., Gabrieli, J.D.E. and **Sobel, N.** (2003) *Dissociated neural representations of intensity and valence in human olfaction*. Nat. Neurosci., 6, 196–202.

Bargh, J.A. (1992) *Ecology of automaticity: toward establishing the conditions needed to produce automatic processing effects*. Am. J. Psychol., 105, 181–199.

Bensafi, M., Brown, W.M., Khan, R., Levenson, B. and **Sobel, N.** (2004) *Sniffing human sex-steroid derived compounds modulates mood, memory and autonomic nervous system function in specific behavioral contexts*. Behav. Brain Res., 152, 11–22.

Benus, R.F., den Daas, S., Koolhaas, J.M. and **van Oortmerssen, G.A.** (1990) *Routine formation and flexibility in social and non-social behaviour of aggressive and non-aggressive male mice*. Behaviour, 112, 176–193.

Benus, R.F., Koolhaas, J.M. and **van Oortmerssen, G.A.** (1987) *Individual differences in behavioural reaction to a changing environment in mice and rats*. Behaviour, 100, 105–122.

Bernston, G.G., Cacioppo, J.T. and **Quigley, K.S.** (1993) *Cardia psychophysiology and autonomic space in humans: empirical perspectives and conceptual implications*. Psychol. Bull., 114, 296–322.

Blanchard, D.C., Blanchard, R.J. and **Rodgers, R.J.** (1991) *Risk assessment and animal model of anxiety*. In Olivier, B., Mos, J. and Slangen, J.L. (eds), Animal Models in Psychopharmacology. Birkhauser Verlag, Basel, Switzerland, pp. 117–134.

Blum, M.S. (1969) *Alarm pheromones*. Annu. Rev. Entomol., 14, 57–80.

Bradley, B.P., Mogg, K., Falla, S.J. and **Hamilton, L.R.** (1998) *Attentional bias for threatening facial expressions in anxiety: manipulation of stimulus duration*. Cognit. Emot., 12, 737–753.

Broadbent, D.B. and **Broadbent, M.** (1988) *Anxiety and emotional bias: state and trait*. Cognit. Emot., 2, 165–183.

Brown, G.E., Poirier, J.-F. and **Adrian, J.C. Jr** (2004) *Assessment of local predation risk: the role of subthreshold concentrations of chemical alarm cues*. Behav. Ecol., 15, 810–815.

Cacioppo, J.T., Berntson, G.G., Klein, D.J. and **Poehlmann, K.M.** (1998) *Psychophysiology of emotion across the life span*. In Schaie, K.W. and Lawton, M.P. (eds), Annual review of gerontology and geriatrics, Vol. 17, Focus on emotion and adult development. Springer Publishing Co., New York, pp. 27–74.

Cacioppo, J.T., Bernston, G.G., Larsen, J.T., Poehlmann, K.M. and **Ito, T.A.** (2000) *The psychophysiology of emotion*. In Lewis, M. and Haviland-Jones, J.M. (eds), Handbook of emotions. Guilford Press, New York, pp. 173–191.

Campbell, B.A., Wood, G. and **McBride, T.** (1997) *Origins of orienting and defensive responses: an evolutionary perspective*. In Lang, P.J., Simons, R.F. and Balaban, M.T. (eds), Attention and Orienting: Sensory and Motivational Processes. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 41–67.

Carr, W.J., Zunino, P.A. and **Landauer, M.R.** (1980) *Responses by young house mice* (Mus musculus) *to odors from stressed vs. nonstressed adult conspecific*. Bull. Psychon. Soc., 15, 419–421.

Chen, D. and **Haviland-Jones, J.** (1999) *Rapid mood change and human odors*. Physiol. Behav., 68, 241–250.

Chen, D. and **Haviland-Jones, J.** (2000) *Human olfactory communication of emotion*. Percept. Mot. Skills, 91, 771–781.

Cloitre, M., Heimberg, R.G., Holt, C.S. and **Liebowitz, M.R.** (1992) *Reaction time to threat stimuli in panic disorder and social phobia*. Behav. Res. Ther., 30, 609–617.

Cuthbert, B.N., Bradley, M.M. and **Lang, P.J.** (1996) *Probing picture perception: activation and emotion*. Psychophysiology, 33, 103–111.

Dalton, P., Doolittle, N. and **Breslin, P.A.S.** (2002) *Gender-specific induction of enhanced sensitivity to odors*. Nat. Neurosci., 5, 199–200.

Dawson, M.E., Schell, A.M. and **Filion, D.L.** (2000) *The electrodermal system*. In Cacioppo, J.T., Tassinary, L.G. and Berntson, G.G. (eds), Handbook of psychophysiology, 2nd ed. Cambridge University Press, Cambridge, pp. 200–223.

Ehrlichman, H. and **Halpern, J.N.** (1988) *Affect and memory: Effects of pleasant and unpleasant odors on retrieval of happy and unhappy memories*. J. Pers. Soc. Psychol., 55, 769–779.

Epple, G. and **Herz, R.S.** (1999) *Ambient odors associated to failure influence cognitive performance in children*. Dev. Psychol., 35, 103–107.

French, C.C. and **Richards, A.** (1992) *Word association norms for a set of threat/neutral homographs*. Cognit. Emot., 6, 65–87.

Goosens, K.A., Hobin, J.A. and **Maren, S.** (2003) *Auditory-evoked spike firing in the lateral amygdala and Pavlovian fear conditioning: mnemonic code or fear bias?* Neuron, 40, 1013–1022.

Gross, J.J. and **Levenson, R.W.** (1995) *Emotion elicitation using films*. Cognit. Emot., 9, 87–108.

Howe, N.R. and **Sheik, Y.M.** (1975) *Anthopleurine: a sea anemone alarm pheromone*. Science, 189, 386–388.

Irwin, W., Davidson, R.J., Lowe, M.J., Mock, B.J., Sorenson, J.A. and **Turski, P.A.** (1996) *Human amygdala activation detected with echo-planar functional magnetic resonance imaging*. Neuroreport, 7, 1765–1769.

Izard, C.E. (1979) The Maximally Discriminative Facial Movement Coding System (Max). Office of Instructional Technology, University of Delaware, Newark, DE.

Jacob, S., Kinnunen, L.H., Metz, J., Cooper, M. and **McClintock, M.K.** (2001) *Sustained human chemosignal unconsciously alters brain function*. Neuroreport, 12, 2391–2394.

Jacob, S. and **McClintock, M.K.** (2000) *Psychological state and mood effects of steroidal chemosignals in women and men*. Horm. Behav., 37, 57–78.

Kikusui, T., Takigami, S., Takeuchi, Y. and **Mori, Y.** (2001) *Alarm pheromone enhances stress-induced hyperthermia in rats*. Physiol. Behav., 72, 45–50.

Kirk-Smith, M.D., Van Toller, C. and **Todd, G.H.** (1983) *Unconscious odor conditioning in human subjects*. Biol. Psychol., 17, 221–231.

Koolhaas, J.M., Korte, S.M., de Boer, S.F., van der Vegt, B.J., van Reenen, C.G., Hopster, H., de Jong, I.C., Ruis, M.A.W. and

Blokhuis, H.J. (1999) *Coping styles in animals: current status in behavior and stress-physiology.* Neurosci. Biobehav. Rev., 23, 925–935.

Labows, J., Preti, G., Hoelzle, E., Leyden, J. and **Kligman, A**. (1979) *Analysis of human axillary volatiles: compounds of exogenous origin*. J. Chromatogr., 163, 294–299.

Lang, P.J., Bradley, M.M. and **Cuthbert, B.N.** (1997) *Motivated attention: affect, activation, and action*. In Lang, P. J., Simons, R.F. and Balaban, M.T. (eds), Attention and Orienting: Sensory and Motivational Processes. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 97–135.

LeDoux, J.E., Cicchetti, P., Xagoraris, A. and **Romanski, L.M.** (1990) *The lateral amygdaloid nucleus: sensory interface of the amygdala in fear conditioning*. J. Neurosci., 10, 1062–1069.

Lundstrom, J.N., Goncalves, M., Esteves, F. and **Olsson, M.J.** (2003) *Psychological effects of subthreshold exposure to the putative human pheromone*. Horm. Behav., 44, 395–401.

McClintock, M.K. (1971) *Menstrual synchrony and suppression*. Nature, 291, 244–245.

McClintock, M.K. (1999) *Human pheromones: primers, releasers, signalers, or modulators?* In Wallen, K. and Schneider, J.E. (eds), Reproduction in Context. MIT Press, Cambridge, pp. 355–422.

McNair, D.M., Lorr, M. and **Droppleman, L.F.** (1971) Profile of Mood States (Manual). Educational and Industrial Testing Service, San Francisco, CA.

Michael, G.A., Jacquot, L., Millot, J.-L. and **Brand, G.** (2003) *Ambient odors modulate visual attentional capture*. Neurosci. Lett., 352, 221–225.

Montgomery, K.C. (1955) *The relation between fear induced by novel stimulation and exploratory behavior.* J. Comp. Physiol. Psychol., 48, 254–260.

Moss, M., Cook, J., Wesnes, K. and **Duckett, P.** (2003) *Aromas of rosemary and lavender essential oils differentially affect cognition and mood in healthy adults*. Int. J. Neurosci., 113, 15–38.

Moynihan, J.A., Karp, J.D., Cohen, N. and **Ader, R**. (2000) *Immune deviation following stress odor exposure: role of endogenous opioids*. J. Neuroimmunol., 102, 145–153.

Muller-Schwarze, D., Altieri, P. and **Porter, N.** (1984) *Alert odor from skin gland in deer.* J. Chem. Ecol., 10, 1707–1729.

Nelson, D.L., McEvoy, C.L., Walling, J.R. and **Wheeler, J.W.** (1980) *The University of South Florida homograph norms*. Behav. Res. Methods Instrum., 12, 16–37.

Neville, K.R. and **Haberly, L.B.** (2004) *Olfactory cortex.* In Sheperd, G.M. (ed.), The Synaptic Organization of the Brain. Oxford University Press, Oxford, pp. 415–454.

Öhman, A., Flykt, A. and **Esteves, F.** (2001) *Emotion drives attention: detecting the snake in the grass*. J. Exp. Psychol. Gen., 130, 466–478.

Panksepp, J. (1998) *Affective neuroscience: the foundations of human and animal emotions*. Oxford University Press, New York.

Platek, S.M., Thomson, J.W. and **Gallup, G.G. Jr** (2004) *Cross-modal self recognition: The role of visual, auditory, and olfactory primes*. Conscious. Cogn., 13, 197–210.

Preti, G., Wysocki, C.J., Barnhart, K.T., Sondheimer, S.J. and **Leyden, J.J.** (2003) *Male axillary extracts contain pheromones that affect pulsatile secretion of luteinizing hormone and mood in women recipients*. Biol. Reprod., 68, 2107–2113.

Regnier, F.E. and **Wilson, E.O.** (1969) *The alarm-defense system of the ant Lasius alienus*. J. Insect Physiol., 15, 893–898.

Ressler, R.H., Cialdini, R.B., Ghoca, M.L. and **Kleist, S.M.** (1968) *Alarm pheromone in the earthworm Lumbricus terrestris*. Science, 161, 597–599.

Richards, A. and **French, C.C.** (1992) *An anxiety-related bias in semantic activation when processing threat/neutral homographs*. Q. J. Exp. Psychol., 45A, 503–525.

Rottman, S.J. and **Snowdon, C.T.** (1972) *Demonstration and analysis of an alarm pheromone in mice*. J. Comp. Physiol. Psychol., 81, 483–490.

Savic, I., Berglund, H., Gulyas, B. and **Roland, P.** (2001) *Smelling of odorous sex hormone-like compounds causes sex-differentiated hypothalamic activations in humans*. Neuron, 31, 661–668.

Sobel, N., Prabhakaran, V., Hartley, C.A., Desmond, J.E., Glover, G.H., Sullivan, E.V. and **Gabrieli, J.D.E.** (1999) *Blind smell: brain activation induced by an undetected air-borne chemical*. Brain, 122, 209–217.

Spielberger, C.D., Gorsuch, R.L., Lushene, R., Vagg, P.R. and **Jacobs, G.A.** (1983) Manual for the State-Trait Anxiety Inventory (Form Y) ("Self-Evaluation Questionnaire"). Consulting Psychological Press, Palo Alto, CA.

Stemmler, G., Heldmann, M., Pauls, C.A. and **Scherer, T.** (2001) *Constraints for emotion specificity in fear and anger: the contexts counts*. Psychophysiology, 38, 275–291.

Stern, K. and **McClintock, M.K.** (1998) *Regulation of ovulation by human pheromones*. Nature, 392, 177–179.

Suh, G.S.B., **Wong, A.M.**, **Hergarden, A.C.**, **Wang, J.W.**, **Simon, A.F.**, **Benzer, S.**, **Axel, R.** and **Anderson, D.J.** (2004) *A single population of olfactory sensory neurons mediates an innate avoidance behavior in Drosophila*. Nature, 431, 854–859.

Thomas, D.A., Riccio, D.C. and **Myer, J.S.** (1977) *Age of stress-produced odorants and the Kamin effect*. Behav. Neural Biol., 20, 433–440.

von Frisch, K. (1941) *Uber einen Schreckstoff der Fischhaut und seine biologische Bedeutung*. Z. Vgl. Physiol., 29, 46–145.

Warm, J.S., Dember, W.N. and **Parasuraman, R.** (1991) *Effects of olfactory stimulation on performance and stress in a visual sustained attention task*. J. Soc. Cosmet. Chem., 42, 199–210.

Wyatt, T.D. (2003) Pheromones and Animal Behavior: Communication by Smell and Taste. Cambridge University Press, London.

Zalaquett, C. and **Thiessen, D.** (1991) *The effects of odors from stressed mice on conspecific behavior.* Physiol. Behav., 50, 221–227.

Zald, D.H. and **Padro, J.V.** (1997) *Emotion, olfaction and the human amygdala: amygdala activation during aversive olfactory stimulation*. Proc. Natl Acad. Sci. USA, 94, 4119–4124.

Accepted February 14, 2006