Brief Communications

# Smelling a Single Component of Male Sweat Alters Levels of Cortisol in Women

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**Rodents use chemosignals to alter endocrine balance in conspecifics. Although responses to human sweat suggest a similar mechanism in humans, no particular component of human sweat capable of altering endocrine balance in conspecifics has yet been isolated and identified. Here, we measured salivary levels of the hormone cortisol in women after smelling pure androstadienone (4,16-androstadien-3-one), a molecule present in the sweat of men that has been suggested as a chemosignal in humans. We found that merely smelling androstadienone maintained significantly higher levels of the hormone cortisol in women. These results suggest that, like rodents, humans can influence the hormonal balance of conspecifics through chemosignals. Critically, this study identified a single component of sweat, androstadienone, as capable of exerting such influence. This result points to a potential role for synthetic human chemosignals in clinical applications.**

*Key words:* **pheromones; hormones; chemosignals; human; olfaction; cortisol**

## Introduction

In most mammals, hormone levels are endogenously regulated in response to chemosignals, termed pheromones, that are released by conspecifics (for review, see Stowers and Marton, 2005; Brennan and Zufall, 2006). Although human behavioral phenomena such as menstrual synchrony resemble pheromonal effects in rodents (McClintock, 1971; Stern and McClintock, 1998), whether human pheromones exist remains a topic of vigorous debate (Wysocki and Preti, 2004). The steroidal compound androstadienone (4,16-androstadien-3-one) (AND), present in human male secretions such as sweat, saliva, and semen, has been implicated as a putative human pheromone (Grosser et al., 2000). AND influences context-dependent mood, physiological arousal, and brain activity, in both a sex-specific (Grosser et al., 2000; Jacob et al., 2001b, 2002; Savic et al., 2001; Lundstrom et al., 2003, 2006; Bensafi et al., 2004a; Lundstrom and Olsson, 2005; Villemure and Bushnell, 2007), and a sexual orientation-specific (Savic et al., 2005; Berglund et al., 2006) manner. However, whether AND satisfies the key criterion for pheromonal action, influencing endocrine balance, remains unknown.

To test this, we measured salivary levels of the hormone cortisol in 21 heterosexual women after a brief exposure (20 sniffs) to AND in one session, and to a control (CONT) substance with similar olfactory qualities but not present in sweat (baking yeast) in a second session. We chose to measure cortisol because AND influences arousal and mood, which are both linked to levels of this hormone (Brown and Heninger, 1975). We found that smelling AND maintained significantly higher levels of cortisol in comparison with smelling a control stimulus with similar olfactory qualities.

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## Materials and Methods

### *Subjects*

Twenty-one subjects (age, 22.5 ± 3.46 years) participated in the main study, and 27 (age, 20.1 ± 0.33 years) participated in a replication (reported in the supplemental material, available at www.jneurosci.org). These subjects also participated in a third unrelated session that was counterbalanced in order, and will be reported elsewhere. Subjects were heterosexual women who reported general good health, no chronic use of medication, no history of anosmia or nasal insult, and no use of oral contraceptives.

### *Compounds*

Thirty milligrams of AND, obtained from Steraloids (Newport, RI), were deposited in pure form into a 60 ml (4.5 cm in diameter at the opening; 9 cm high) opaque jar, to be smelled by participants. Of the various possible methods for delivery and compound concentrations, these were chosen so as to enable direct comparison with the results of Savic et al. (2001) and Bensafi et al. (2003, 2004a,b), because these were the methods used in those studies. Yeast served as the control substance, and its volume was individually adjusted (in a separate presession) so as to equate for pleasantness and intensity with AND (increasing the volume of yeast reduced the perceived pleasantness and increased the perceived intensity).

### *Experimental design*

All procedures were approved by the University of California Berkeley Committee for the Protection of Human Subjects. A within-subjects, double-blind, repeated-measures design was used such that each subject underwent testing with both compounds (AND and CONT), each pre-

sented on a different day. Thus, this study contains data from 42 recording sessions in the main study, and 54 sessions in the replication. Each session lasted ~120 min (from subject arrival at the laboratory to subject departure). Day-by-compound order was counterbalanced across subjects, but, critically, for each subject the separate sessions were conducted at exactly the same time of day so as to account for circadian fluctuations in cortisol (Angeli et al., 1978). For the 21 subjects in the main experiment, sessions were separated by 1 week, but for 27 subjects in the replication, sessions were separated by exactly 28 d, to address the possible influence of the menstrual cycle (Angeli et al., 1978; Russell et al., 1980; Hummel et al., 1991). All testing was performed in a temperature and humidity controlled, stainless-steel-coated, 5 × 8 foot room equipped with HEPA (high-efficiency particulate air) and carbon filtration. This room was designed specifically for olfactory experiments and prevents odor contamination across conditions. Subjects were left alone in the room during the experiment, and activity in the room was continuously monitored from the adjacent control room via a one-way mirror and video monitor. Presentation of the mood scale, video clips, compound sampling instructions, and recording of physiological data, were all time-locked through one central computer.

After completing a demographics questionnaire and providing written informed consent, subjects were taken into the testing room and seated in front of a computer monitor. A keypad was positioned in front of them and they were instructed to answer the questions that would appear on the monitor after the experimenter had left the room. At this point, the first baseline mood scale was administered via the monitor. On completion of the baseline scale, the experimenter reentered the room and fitted the physiological recording equipment to the subject. When physiological setup was complete (~15 min), ~5 min of habituation and remote blood pressure calibration measurements were performed. This period enabled subjects to relax and habituate to their new setting. Once physiological measures stabilized, recording was then initiated to obtain a 10 min physiological baseline. During this time, participants watched a nature video that is commonly used for its nonarousing contents (Piferi et al., 2000). This baseline recording was followed by the second administration of the mood scale, and a first collection of saliva for cortisol analysis. In other words, the first cortisol sample was collected after subjects had spent ~30 min in a well controlled and constant environment. Next, an opposite-sex experimenter (Jacob et al., 2001b) who was blind to the condition (AND or CONT) entered the room and held the appropriate experimental jar under the participant's nose for each of 20 sniffs that were timed and cued by computer-generated digitized voice instructions. The digitized voice prompted the subject to sniff at a tone after a countdown (e.g., "three, two, one, sniff"). After each sniff, subjects rated compound intensity and pleasantness on a 1–9 point scale presented on the monitor. There was no verbal interaction between experimenters and subjects during compound presentation. The experimenter then left the room and participants watched three consecutive counterbalanced epochs containing ~5 min video clips of either humorous, sad, or erotic content, each flanked by ~10 min videos of emotionally neutral content (Bensafi et al., 2004a,b). These mood induction stimuli were selected because the effects of AND are more pronounced in these emotional contexts (Jacob et al., 2001b; Bensafi et al., 2004a). Subjects answered the mood scale and provided a saliva sample again in between each segment. Finally, subjects provided a last saliva sample 15 min after completion of the entire study. Therefore, there were five saliva collections during the experiment: one at baseline (saliva 1), which was 30 min after subjects entered the room; one 15 min after the end of odor exposure (saliva 2); and one 15 min after each mood induction video (saliva 3–5). This experimental design accommodates the fact that there is a 15 min hysteresis between blood plasma cortisol and salivary cortisol (Aardal and Holm, 1995).

### *Physiological parameters*

The following eight autonomic nervous system parameters were simultaneously and continuously recorded and displayed during the experiment: skin conductance response (SCR), electrocardiogram (ECG), finger pulse (FP), ear pulse (EP), blood pressure (BP), skin temperature (ST), abdominal respiration (AR), and thoracic respiration (TR). In addition to these eight variables, subject body movement or fidgeting (MOV) was also recorded. All parameters were sampled and recorded at 1 kHz except BP, which was sampled at 250 Hz. Data were converted and amplified via a 16-channel amplifier (PowerLab 16SP; ADInstruments, Castle Hill, New South Wales, Australia), and displayed, stored, reduced, and analyzed with the Chart 5.2 software package (ADInstruments).

*SCR.* SCR was obtained through two bipolar finger Ag/AgCl electrodes (surface, 1 $cm^2$), placed on the second phalanx of the index and the third digit of the nondominant hand, attached with Velcro strap. SCR was measured by applying a 0.5 $\mu A/cm^2$ AC current. The SCR amplifier used was fully isolated with low voltage, 75 Hz (~40 mV) AC excitation. The variable reduced was the nonspecific skin conductance response (NS-SCR) expressed in number of events per minute. This has been described as the appropriate SCR measure for continuous non-event-dependent SCR (Dawson et al., 2000). The threshold for an event was a 0.5% deflection from the tracked mean.

*ECG.* ECG was obtained through three circular Ag/AgCl conductive adhesive electrodes (0.9 cm diameter). Skin surface was cleaned with alcohol before electrode placement. Electrodes were placed on both the left and the right sides of the abdomen (just under the thoracic cage), and a ground electrode was placed on the left leg. The data were reduced to ECG rate expressed in beats per minute (BPM).

*FP/EP.* Finger and ear pulses were recorded with infrared plethysmographs (size, 15 × 15 × 6.3 mm) placed on the fifth finger of the nondominant hand (finger pulse) and the ear on the side of the nondominant hand (ear pulse). These devices used an infrared photoelectric sensor to detect changes in tissue blood volume. They were attached with either a Velcro strap (for finger) or a clip (for ear). The data were reduced to pulse rate in beats per minute.

*BP.* An arterial tonometer (Colin 7000; Colin Electronics, San Antonio, TX) enabled continuous measurement of blood pressure waveforms (sampling rate, 250 Hz), as well as determining systolic and diastolic pressures noninvasively and continuously. The data were reduced to mean BP expressed in millimeters mercury.

*ST.* A small ceramic-encapsulated metal oxide semiconductor (9.5 mm in length, 2 mm in diameter) was used to measure skin surface temperature. The thermistor, designed to operate from 0 to 50°C was placed directly below the axilla. The data were reduced to temperature mean.

*AR and TR.* Two respiratory belt transducers (30 cm rest length, 10 cm maximum elongation, 4.5 cm in width) were used to measure changes in thoracic and abdominal circumference caused by respiration. They contained a piezoelectric device that responded linearly to changes in length (sensitivity, 4.5 ± 1 mV/mm). The data were reduced to abdominal and thoracic respiration rates.

*MOV.* Fidgeting, or movement, was measured by a high sensitivity (2500 mV/g) accelerometer (EGCS; Entran Devices, Fairfield, NJ) attached to the chair armrest. Recordings were used both as an analysis variable (motions reduced to movements per minute) and as a measure of detecting movement-related artifact in the physiological recordings.

### *Psychological rating*

A 17-item scale was used to measure compound effects on mood. Subjects rated how strongly they were experiencing each of 17 different emotions on a visual-analog scale ranging from "not at all" to "very strongly." This mood scale was devised to tap into mood rather than more transient emotional feelings (Ekman et al., 1980; Levenson et al., 1990). It is well validated and consists of the following variables: "afraid," "amused," "angry," "annoyed," "anxious," "bored," "calm," "confident," "content," "contemptuous," "disgusted," "embarrassed," "happy," "interested," "sad," and "stressed." The variable "sexually aroused" was added to the list as was done previously (Bensafi et al, 2003, 2004a,b).

### *Cortisol analysis*

Cortisol was collected in Salivette tubes without the cotton swab. Samples were stored at −20°C, and thawed and centrifuged before testing. Free cortisol from the supernatant was tested using the Extended Range High Sensitivity Salivary Cortisol Immunoassay kit (http://www.salimetrics.com/pdf/ER%20Cort%20Research%20Kit%20Insert.pdf). The saliva from each tube

was assayed in duplicated wells. Tubes from a given subject were all assayed on the same plate, and tubes from different visits obtained at a given time (for saliva 1–5) were assayed on the same column of the 96-well plate to avoid systematic errors between conditions. After completion of the immunoassay, the absorbance of the fluorescent cortisol conjugate–antibody complex in the wells were obtained at 450 nm and corrected at 490 nm with a Bio-Rad (Hercules, CA) multiplate reader (model 680). Standard dilutions of cortisol (0, 0.012, 0.037, 0.1, 0.333, 0.1, 0.3, 1, 3 $\mu$g/dl) were used along a nonspecific binding well in the first two columns of the kit for calibration. Defined high and low control concentrations were used to calibrate each column of the plate. The absolute salivary cortisol concentration was estimated from the fluorescence of the cortisol conjugate–antibody complex by computing the inverse value on the four parameters sigmoid fit obtained with the standard values. All data with >15% error between duplicates were retested. All analyses were conducted blind to the condition of collection. Finally, one subject was excluded from the cortisol analysis because of nonphysiological values (>1.5 $\mu$g/dl).

*Data reduction*

Physiological data were first expressed as a change score for each period of interest by subtracting the baseline value from that period. Results were then expressed as *z*-scores to combine them into a composite index and to compare them between subjects. To standardize the representation of our data, the psychological data were also expressed as change scores for each period of interest by subtracting the baseline value from that period. To reduce the number of comparisons, the psychological descriptors were grouped into three categories: positive mood descriptors, negative mood descriptors, and sexual arousal. This grouping was performed according to previously reported criteria (Bensafi et al., 2003, 2004a,b). In particular, the positive mood index was computed as the linear combination of *z*-scores from ratings of the six positive adjectives (amused, calm, confident, content, interested, and happy). Similarly, to reduce multiple comparisons, all physiological measures were equally weighted in a physiological arousal index such that an increase in physiological arousal was associated with an increase in NS-SCR, ECG, FP, EP, BP, AR, TR, and MOV, and with a decrease in ST. This weighting was chosen because it was the exact weighting used previously, based on independently (in time) obtained data (Bensafi et al., 2003). Corroborating this weighting, all measures were positively correlated in the current data as well (mean $r = 0.35$; all $p < 0.05$), except ST, which was negatively correlated with most measures.

Because absolute cortisol values have meaning (not only as relative change scores), both analysis and presentation were conducted on the raw values. The cortisol data were also expressed as a change score for each period of interest (by subtracting the baseline value from that period) and as a *z*-score to compare between subjects.

## Results

### Smelling AND maintained better mood, higher sexual arousal, and increased physiological arousal

AND and CONT were perceptually similar in terms of perceived pleasantness (pleasAND, 2.2084 ± 0.2482; pleasCONT, 2.04 ± 0.32; $t_{(20)} = 0.6899$; $p < 0.49$) and intensity (intAND, 2.86 ± 0.24; intCONT, 3.06 ± 0.24; $t_{(20)} = -0.6519$; $p < 0.52$) (supplemental Fig. 1, available at www.jneurosci.org as supplemental material). However, AND affected mood and physiological arousal in a manner that was significantly different from CONT and highly consistent with previous studies (Grosser et al., 2000; Jacob et al., 2001b; Bensafi et al., 2004a; Lundstrom and Olsson, 2005). Whereas mood and physiological arousal were not significantly different at baseline (before smelling either AND or CONT) (all $t < 0.68$; $p > 0.5$), separate ANOVAs on postexposure mood and physiology with main effects of compound (AND/CONT) and time (four postexposure experimental epochs) revealed no main effects of time (all $F < 0.9$; $p > 0.4$), no interactions (all $F < 1.89$; $p > 0.14$), but main effects of compound reflecting increased positive mood after AND compared with CONT ($F_{(1,167)} = 13.61$; $p < 0.0005$) (Fig. 1*A*), and increased composite physiological arousal score after AND compared with CONT ($F_{(1,248)} = 19.11$; $p < 1.9e\text{-}005$) (Fig. 1*C*). Subjective sexual arousal was also not significantly different at baseline ($t_{(20)} = -1.3068$; $p < 0.2061$), but a postexposure ANOVA revealed a significant main effect of compound, reflecting increased sexual arousal after AND compared with CONT ($F_{(1,167)} = 10.3857$; $p < 0.002$) (Fig. 1*B*), a significant main effect of time, reflecting increased sexual arousal as the study progressed ($F_{(3,167)} = 6.6713$; $p < 0.0006$), but no interaction ($F_{(3,167)} = 0.4148$; $p < 0.7430$). As noted, both the direction and magnitude of the above effects on mood, autonomic physiology, and subjective sexual arousal, were all highly consistent with previous reports (Grosser et al., 2000; Jacob et al., 2001b, 2002; Lundstrom et al., 2003; Bensafi et al., 2004a; Lundstrom and Olsson, 2005).

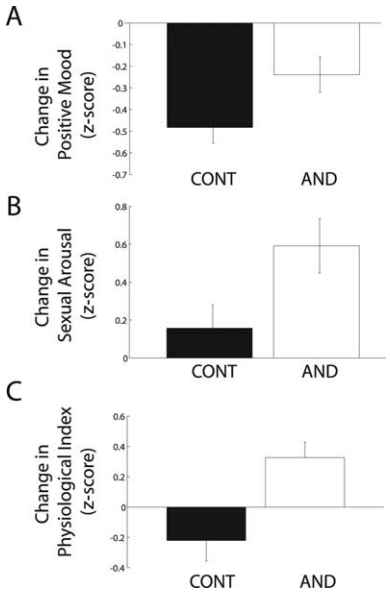


**Figure 1.** Smelling androstadienone altered mood and autonomic physiology. Androstadienone is shown in the white bars and control in the black bars. ***A–C***, All variables are shown as a change from baseline in *z*-score. Smelling AND maintained better mood (***A***), higher sexual arousal (***B***), and a higher physiological composite index (***C***).

### Smelling AND maintained elevated cortisol

Having validated that AND was acting in this study in a manner similar to previous reports in which it improved measures of mood (Jacob et al., 2001a, 2002; Bensafi et al., 2004a; Lundstrom and Olsson, 2005) and increased physiological measures of autonomic arousal (Grosser et al., 2000; Bensafi et al., 2003, 2004a), we now turn to the focus of this paper: the influence of AND on salivary cortisol. As in the case of mood and physiology, levels of cortisol were not significantly different at baseline (before smelling either AND or CONT) ([Cortisol], $AND_{baseline}$, 0.237 ± 0.048 $\mu$g/dl; $CONT_{baseline}$, 0.226 ± 0.036 $\mu$g/dl; $t_{(19)} = -0.7209$; $p < 0.4793$) (supplemental Fig. 2, available at www.jneurosci.org as supplemental material). However, an ANOVA on postexposure salivary cortisol with main effects of compound (AND/CONT) and time (four postexposure experimental epochs) revealed a significant main effect of time reflecting decreased levels of salivary cortisol as the study progressed ($F_{(3,152)} = 3.3794$; $p < 0.0253$), and critically, a significant main effect of compound, reflecting significantly higher levels of salivary cortisol after AND compared with CONT ($F_{(1,152)} = 11.88$; $p < 0.0011$) (Fig. 2*A*,*B*),

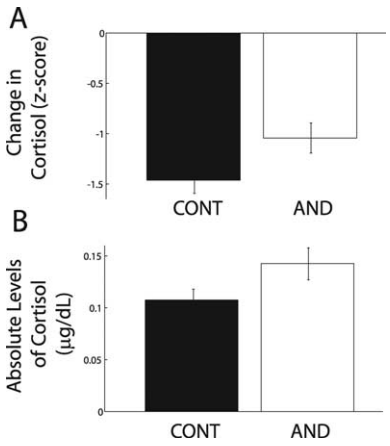


**Figure 2.** Smelling androstadienone maintained higher levels of salivary cortisol. Androstadienone is shown in the white bars, and control in the black bars. Smelling AND maintained higher levels of cortisol (***A***) as a change from baseline in *z*-score, and in absolute levels of cortisol (***B***).

but no interaction ($F_{(3,152)} = 0.2632$; $p < 0.8516$) (supplemental Fig. 2, available at www.jneurosci.org as supplemental material). Finally, we replicated the entire study a second time in 27 additional subjects, with minor methodological differences, and obtained nearly identical results. This replication is detailed in the supplemental material and supplemental Figure 3 (available at www.jneurosci.org as supplemental material).

## Discussion

### Androstadienone is a human chemosignal

Given the sex-specific and sexual orientation-specific effects of AND on brain mechanisms involved in hormonal regulation (Grosser et al., 2000; Jacob et al., 2001b; Savic et al., 2001; Bensafi et al., 2004a; Lundstrom and Olsson, 2005), we hypothesized that smelling AND, a chemosignal present in male sweat, may alter endocrine levels in women. Our results are consistent with this hypothesis. Smelling pure AND had a repeatable (supplemental Fig. 3, available at www.jneurosci.org as supplemental material) effect on levels of cortisol, apparent within 15 min, and maintained as long as 60 min after exposure. It is notable, however, that given the timescale of changes in mood and changes in cortisol, we cannot unequivocally determine whether AND influenced cortisol, which then influenced mood, or in turn, whether AND influenced mood through some nonhormonal mechanism, and the change in mood then led to a change in cortisol.

That humans have an endocrine response to human chemosignals is consistent with observed alterations in menstrual cycles after exposure to conspecific sweat alone (Stern and McClintock, 1998), and changes in pulsatile secretion of luteinizing hormone and mood in women resulting from exposure to male axillary extracts (Preti et al., 2003). However, sweat is a complex mixture, and in previous studies the identity of the molecules in female and male sweat responsible for the observed responses was unknown. The key contribution made here is the identification of a single molecule capable of triggering the endocrine response. That AND induces endocrine changes does not suggest that it is the only constituent of sweat that can do so. Indeed, it is possible that many more of the hundreds of molecules in sweat can induce a variety of endocrine changes. And the effect of AND on cortisol levels could be enhanced or reduced when mixed with other components of sweat. A second aspect is that, unlike previous studies in which sweat extracts were applied directly to the skin under the nose rather than smelled (Stern and McClintock, 1998; Preti et al., 2003), here we found that merely smelling (20 sniffs) AND without skin contact, a method of exposure resembling the natural setting, was sufficient to alter levels of cortisol. This finding complements previous reports regarding the psychological and physiological influences of smelling AND to suggest that AND may qualify as a human pheromone.

### Human chemosignals may have clinical applications

In addition to addressing one of the key criteria for pheromonal action, these results suggest a potential therapeutic mechanism whereby merely smelling synthesized or purified human chemosignals may be used to modify endocrine balance (Comfort, 1971). Diseases associated with altered hormonal state are usually treated with hormone therapy that often has negative side effects. For example, Addison's disease, characterized by low levels of the hormone cortisol, is treated with cortisol replacement therapy (Marzotti and Falorni, 2004). However, cortisol replacement therapy may cause peptic ulcers, osteoporosis, weight gain, mood disorders, and other pathologies (Marzotti and Falorni, 2004). Triggering endogenous mechanisms of hormone release may have several advantages over traditional hormone administration. For example, consistent with previous findings (Grosser et al., 2000; Jacob et al., 2001b; Bensafi et al., 2004a; Lundstrom and Olsson, 2005), AND had an anxiolytic-like influence on positive mood. However, in contrast to typical anxiolytics, AND increased rather than decreased sexual arousal. This dissociation highlights the potential advantage of triggering endogenous responses. Furthermore, we speculate that endogenous triggering of hormone release is likely to generate fewer negative side effects than exogenous hormone administration. Together, we suggest that human chemosignals present a novel and more natural mechanism of endocrine therapy.

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