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Odors Are More Sensitive to Evaluative Conditioning than Sounds

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Abstract

Introduction Stimuli of different modalities can acquire an affective value via *evaluative conditioning*. This process describes a shift in perceived affective quality of a neutral stimulus towards the hedonics of an associated affective stimulus. The olfactory system, as compared to other modalities, might be especially prone to attributing affective value to an odor due to its close neuroanatomical connectivity with brain regions processing emotion.

Methods In the present study, we investigated whether perceived affective quality of odors is more sensitive to evaluative conditioning than that of sounds. For this purpose, 48 healthy participants (50% male) rated unfamiliar and emotionally neutral odors and sounds before and after pairing with either aversive or neutral pictures.

Results Our results show a stronger decrease in odor valence and stronger increases in arousal and dominance ratings for odors paired with aversive compared to neutral pictures. For sounds, ratings of valence, arousal, and dominance were independent of picture emotionality.

Conclusion Odors appear to be more sensitive to evaluative conditioning than sounds. Our findings extend existing modality comparisons mainly focusing on characteristics of odor-associated memories by specifically looking at affective quality of the odor itself in associative learning.

Implications Perceived affective quality of a stimulus goes along with the tendency to approach or avoid this stimulus. For odors, it is especially prone to change into an aversive direction. This may have implications for food and fragrance choices but also for the understanding of clinical conditions in which odors become highly aversive, such as post-traumatic stress disorder.

Keywords Evaluative conditioning · Associative learning · Affective quality · Odor · Sound · Modality comparison

Introduction

How much we like or dislike a certain odor is in part determined by its physiochemical properties (Khan et al. 2007) and genetic variation in human odorant receptors (Keller et al. 2007) but also highly dependent on prior learning experience (Zellner et al. 1983; Herz 2005). Two people may perceive the same odor in a different way, depending on distinct prior experiences made with this odor. This was illustrated by a study of Robin et al. (1999), in which participants with dental fear rated eugenol, an odorant known for its use in dental care, as more unpleasant than non-fearful participants did. Furthermore, it was shown that hedonic perception of an unfamiliar odor can change from pleasant to unpleasant and vice versa, according to the emotional valence of the situation it was presented in (Herz et al. 2004a). Hedonic perceptions of the same odor may also converge over time due to shared experience with the odor, as it appears to be the case in couples in a long-term relationship (Groyecka et al. 2018).

To explain how we acquire liking and disliking of odors, a closer look at basic associative learning or conditioning principles can be of help. When pairing a neutral odor with another affective stimulus, a transfer of valence from the affective unconditioned stimulus (UCS) to the olfactory conditioned stimulus (CS) occurs. Thereby, perceived affective quality of the initially neutral odor shifts towards the hedonics of the affective stimulus. This process is called *evaluative conditioning* (Levey and Martin 1975). It applies to the acquisition of odor liking (Zellner et al. 1983; Baeyens et al. 1996; Yeomans et al. 2006; Djordjevic et al. 2007; van den Bosch et al. 2015) and has also been investigated using CS and UCS

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of different modalities (visual, haptic, auditory) with uni- and cross-modal designs (De Houwer et al. 2001).

One might assume that odors are especially sensitive to changes in perceived affective quality, because of a close coupling between olfaction and emotion. On a neuroanatomical level, the olfactory system and brain regions processing emotions are closely connected (Buck 2000; Soudry et al. 2011). Olfactory information entering the olfactory bulb is forwarded directly to brain regions, which are crucially involved in emotion processing. For instance, it takes only two synapses for an odor to get from the nasal mucosa to the amygdala (Buck 2000) and no more than three to the orbitofrontal cortex (OFC; Gottfried and Zald 2005). To this, a thalamic relay or further cortical processing of the information can occur but is not obligatory (Gottfried and Zald 2005). Moreover, behavioral studies have shown mutual interactions between olfaction and emotion. For instance, participants who judged a citrus odor as more pleasant showed less reduction in happiness when exposed to a helplessness paradigm while the odor was present (Hoenen et al. 2016). Pollatos et al. (2007) also showed that participants rated *n*-butanol odor as more pleasant after viewing positive pictures, and as more unpleasant after viewing aversive pictures, compared to a neutral picture condition.

Another example of the close connection between odors and emotion is the involuntary link between odors and emotional memories. It is known as the *Proust phenomenon*, referring to the power of odors to trigger vivid and emotionally charged autobiographical memories (Chu 2000). Descriptive autobiographical and experimental studies suggest odor-evoked autobiographical memories to be highly emotional, vivid, old, and detailed (Herz and Cupchik 1992) and even more so than those triggered by visual, verbal, or auditory cues (Herz and Cupchik 1995; Herz 1998, 2004; Herz and Schooler 2002; Chu and Downes 2002; Herz et al. 2004b; Willander and Larsson 2006, 2007; Toffolo et al. 2012; de Bruijn and Bender 2018).

These cross- and multimodal studies have proven extremely helpful for characterizing odor-evoked emotional memories. However, when it comes to perceived affective quality of the odor itself and how it is affected by associative learning processes, we face a lack of systematic comparisons between the olfactory and other modalities. This results in an inability to delineate modality-specific mechanisms that may make the olfactory system particularly sensitive for attributing affective value to an odor.

To find out whether affective quality of an odor is especially sensitive to associative learning processes, this study aims at a systematic comparison of odors and sounds in a cross-modal evaluative conditioning design. We paired unfamiliar and emotionally neutral odors and sounds with either aversive or neutral pictures in order to assess to what extent the perceived affective quality of the aversive visual stimuli is transferred to neutral olfactory and auditory stimuli. To measure affective stimulus quality, we assessed valence, arousal, and dominance of the odors and sounds. Thus, extending other studies on evaluative conditioning focusing on changes in valence of the CS, we consider a broader change in the affective response to the CS (Rozin et al. 1998). Due to the close link between olfaction and emotional processing, we expected a stronger change in affective stimulus quality in odors than in sounds after pairing with aversive pictures. Additionally, we expected the greater change in affective quality to go along with odors becoming more effective retrieval cues for the aversive pictures than sounds. For this purpose, recognition of the pictures was tested on the second day of the experiment.

Methods

Participants

We tested 48 non-smoking male ($n = 24$) and female ($n = 24$) participants aged between 18 and 35 years ($M = 25.35$, SD = 3.60). Female participants were not on hormonal birth control at the time of testing (Lundström et al. 2006; Renfro and Hoffmann 2013) and were not tested during their menses or during pregnancy (Doty and Cameron 2009). To control for circadian effects on odor perception (Herz et al. 2017), half of the male and half of the female participants were tested in the morning (8.00–12.30 h) and the other halves in the afternoon (12.30–17.00 h). Exclusion criteria were intake of drugs or medication, alcohol consumption exceeding the guidelines of the German Centre for Addiction Issues (DHS; Seitz and Bühringer 2010), allergies, asthma, common cold, any psychiatric disorders or chronic bodily diseases, and ongoing treatment by a physician or a psychotherapist. Participants reported neither deficits in hearing and smelling nor special musical or olfactory training. They were either paid an allowance of 25 € or received course credit.

Stimulus Material

Olfactory and Auditory Stimuli

To identify suitable olfactory and auditory stimuli, a pilot study was conducted. Please see the Online Resource for a detailed description of the pilot study. Stimuli were to be relatively unknown to the majority of participants, they were not supposed to have any emotional connotation, and should be similar with respect to familiarity and emotionality ratings. The odors that were eventually chosen were methyl benzoate (≥ 98%, Sigma-Aldrich Co., diluted 5 ml/l in paraffinum liquidum), linalool (≥ 97% Sigma-Aldrich Co., diluted 2 ml/l in paraffinum liquidum), and diethyl malonate (≥ 98%, Sigma-Aldrich Co., diluted 17 ml/l in paraffinum liquidum).

English horn a (110 Hz), ocarina fis′ (369 Hz), and electric piano es″ (622 Hz) were the auditory stimuli we selected. The selected stimuli did not differ in terms of valence, arousal, dominance, familiarity, and intensity (see Online Resource for the results of the pilot study).

Picture Stimuli

Aversive and neutral pictures from the Nencki Affective Picture System (NAPS; Marchewka et al. 2014) were selected according to valence and arousal ratings, obtained by Marchewka et al. (2014). Aversive stimuli had mean valence ratings of $M = 2.4$ (from 1 = negative to 9 = positive; SD = .38, range 1.33–2.96) and mean arousal ratings of $M = 7.0$ (from 1 = relaxing to 9 = arousing, SD = .37, range = 6.49–8.05). Neutral pictures had significantly higher valence ratings ($t(190) = -55.941$, $p < .001$) of $M = 5.5$ (SD = .40, range = 4.02–6) and lower arousal ratings ($t(164.108) = 57.672$, $p < .001$) of $M = 4.4$ (SD = .24, range = 3.16–4.65). More details about the selected pictures are provided in Table S4 of the Online Resource.

Procedure

Participants were tested on two separate days, with an interval of 48 h. On the first assessment day, they were shown aversive and neutral pictures, paired with either an olfactory or an auditory stimulus or without any stimulus. Recognition of these pictures was tested on the second assessment day. At two time points, participants provided affective ratings of the olfactory and auditory stimuli: directly before these were paired with the pictures for the first time (baseline, $t1$) and at the end of Day 2 ($t2$).

For presentation of the instructions, pictures, and tasks, and for recording participant's responses, MATLAB R2015a® was used. Odors were administered through the face mask of a six-channel constant-flow (40 ml/s) olfactometer, built in-house according to the instructions by Lorig et al. (1999). Sounds were presented via 80 Ω headphones (DT770M, beyerdynamic GmbH & Co. KG, Heilbronn, Germany) with a volume of 40 dB.

Day 1

After signing informed consent, participants underwent olfactory screening to check for smelling deficits. The *Screening 12 Test*® (Burghart Messtechnik, Wedel, Germany) was used (Hummel et al. 2001). Participants are presented 12 Sniffin' Sticks containing familiar odorants, each for 3 s. They are asked to identify the odorant by choosing one out of four possible answers. Only participants who correctly identified at least 10 out of 12 odors were included in the further testing procedure.

After the screening, participants rated the affective quality of the odors and sounds for the first time ($t1$) on a nine-point computer version of the Self-Assessment Manikin (SAM; Bradley and Lang 1994). The SAM was developed to directly assess valence, arousal, and dominance associated with a certain stimulus or event. Factorial analyses have repeatedly found these three dimensions to provide an adequate description of affective quality for a wide range of perceptual stimuli (Osgood et al. 1957; Mehrabian 1970; Russell and Mehrabian 1977; Bradley and Lang 1994; Dalton et al. 2008). For both, odors and sounds, a three-dimensional assessment of affective stimulus quality has been suggested. To capture the affective component of an olfactory experience, Dalton et al. (2008) found the factors evaluation, potency, and activity to explain 53% of the affective variance. These factors resemble the valence, dominance, and arousal dimension of the SAM (Mehrabian 1996). Of note, in this investigation, the oft-neglected dominance dimension explained the second largest percentage (15%) of variance. Likewise, the SAM has proven a useful tool to measure the affective quality of sounds that has, for instance, been used to characterize the International Affective Digitized Sounds (IADS; Bradley and Lang 2007). It consists of 3 nine-point pictorial rating scales, one for each of the three dimensions. The nine figures on the valence scale display gradations from an unhappy to a smiling face, with the verbal anchors "unpleasant" and "pleasant." For arousal, figures reach from "relaxed" to "aroused" and on the dominance scale, nine figures increasing in size depict the continuum of being "controlled" by or being "in control" of the rated stimulus. Of note, this means that a higher dominance of the odor is indicated by a lower rating score. Participants click on one of the figures to indicate their feelings towards the presented stimulus.

In the following conditioning phase, 54 aversive and 54 neutral pictures from the NAPS were presented on a screen for 1.5 s each. Participants were instructed to rate the valence and arousal of these pictures on the abovementioned scales of the SAM. Each picture was shown in the presence of an odor, a sound, or without any stimulus. A 3-s countdown at the beginning of each trial signaled the potential onset of an odor or sound. To minimize habituation effects, a 10-s fixation cross at the trial end guaranteed an interval of at least 17 s between two odors (Kassab et al. 2009). See Fig. 1 for an example of a typical trial sequence.

One odor and one sound each (CS) was always presented with aversive pictures (UCS) and another one always with emotionally neutral pictures. There were 18 CS-UCS pairings for each of the two odors and sounds on Day 1. The third odor and sound were only present on Day 2 and paired with both neutral and aversive pictures. They served as distractors in the recognition task. The assignment of the three selected odors and sounds to the three conditions (pairing with aversive (1), neutral (2), or both types (3) of pictures) was randomized for each participant individually. Presentation was split into six blocks of 18 pictures with nine emotional and neutral pictures each. Of the emotional pictures in each block, three were presented together with an odor, three with a sound and three without any stimulus. The same procedure was used for neutral pictures. The order of pictures within a block was randomized. Each block was followed by a 2-min break.

Day 2

Since we additionally intended to establish a recognition memory paradigm in this study, a second session took place 48 h after the first. The aim of the recognition test was to find out whether odors would become better retrieval cues than sounds for the aversive pictures.

Therefore, participants saw the same emotionally arousing and neutral pictures and a set of 108 new pictures that had not been presented on Day 1. Overall, 216 different pictures were presented on Day 2, again in blocks of 18 pictures. Participants were asked to rate each picture for how certain they were that they had seen it during encoding on a six-point scale (from 1 = very sure this is an image seen before to 6 = very sure this is a new image).

As on Day 1, pictures were presented in the presence of an odor, a sound, or without any stimulus. The assignment of the stimuli and the pictures was either congruent with the pairing on Day 1, meaning that a picture was paired with the same stimulus on both days or incongruent, meaning that a picture was paired with a third distractor stimulus of the same modality or no cue. Of note for the evaluative conditioning paradigm, the odor and sound that had been paired with aversive pictures on Day 1 were never presented along with neutral pictures on Day 2 and vice versa. In sum, there were 21 further CS-UCS pairings for each of the two odors and sounds on Day 2. The third odor/sound were presented 30 times, one half each with aversive and neutral pictures. After the recognition test, participants rated the odors and sounds again on the three scales of the SAM ($t2$).

Data Analysis

Affective Ratings of Odors and Sounds

The following analyses focus on the rating scores provided for the odors and sounds. For each participant, one odor/sound each had been paired consistently with aversive pictures. Another odor/sound had been paired consistently with neutral pictures and the third odor/sound with both, neutral and aversive pictures. Despite prior piloting, it turned out that the ratings measured before pairing with the pictures differed between modalities for valence ($t(47) = 5.96$, $p < .001$, $d = -1.2$), arousal ($t(47) = -3.468$, $p = .001$, $d = .5$), and dominance ($t(47) = 2.57$, $p = .01$, $d = -.4$). Odors were rated as more pleasant ($M = 6.74$, SD = 1.08) than sounds ($M = 5.11$; SD = 1.58), as less arousing ($M = 3.32$, SD = 1.48) than sounds ($M = 4.02$, SD = 1.51), and as less dominant ($M = 5.84$, SD = 1.66) than sounds ($M = 5.24$, SD = 1.73). For this reason, we generated three variables (Δ) representing these rating differences between odors and sounds, one each for valence (Δvalence), arousal (Δarousal), and dominance (Δdominance). The variables were obtained by subtracting the Day 1 average sound-rating (R_{sound}) of a participant from the Day 1 average odor-rating (R_{odor}) of this participant: $\Delta = R_{odor}(t1) - R_{sound}(t1)$.

The variables Δvalence, Δarousal, and Δdominance were inserted as covariates into $2 \times 2 \times 2$ ANCOVAs with the within-subjects factors Time, Emotionality, and Modality. The ANCOVAs were conducted to investigate how the ratings for odors and sounds varied depending on whether they were provided before ($t1$) or after ($t2$) pairing with the pictures and on emotionality of the pictures (aversive, neutral, both).

The directionality of a main effect was determined from pairwise comparisons. Simple contrasts were used to break down two-way interactions. Three-way Time × Emotionality × Modality interactions were followed up with 2(Time) × 2(Emotionality) ANOVAs conducted for the two modalities

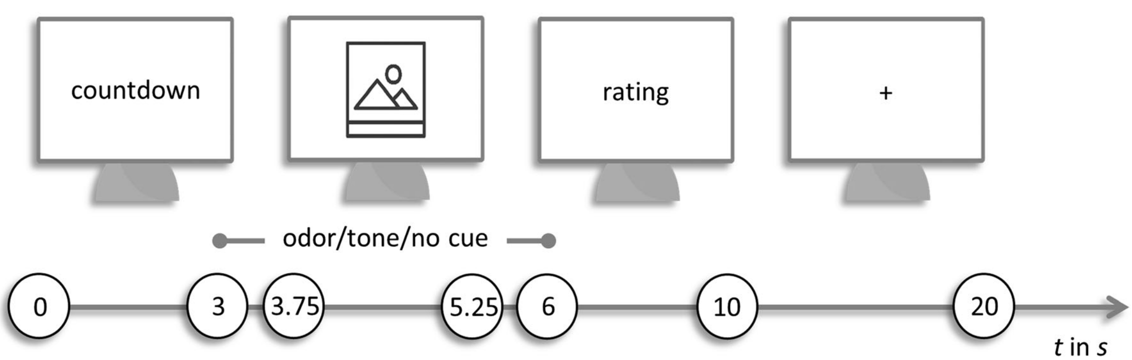

Fig. 1 Typical trial sequence. After a 3-s countdown, the cue (odor, sound, or no cue) was presented for 3 s. A neutral or an aversive picture from the Nencki Affective Picture System (Marchewka et al. 2014) was shown for 1.5 s with an onset of 75 ms after the cue. On Day 1, participants were then asked to rate valence and arousal of the picture, and on Day 2, they provided a recognition rating. The time for picture and recognition rating was limited to 4 s. At the end of each trial, a fixation cross was presented for 10 s

separately. In case of a violation of sphericity, Greenhouse-Geisser corrected values are reported.

Picture Recognition Performance

Hit rates, false alarm rates, the discrimination index d', as well as the bias index C were calculated according to Snodgrass and Corwin (1988) as measures of recognition memory performance. Moreover, we inspected the reaction times for the decision made in the recognition task. These indices were inserted into 2 × 3 ANOVAs with the within-subjects factors Emotionality (aversive, neutral) and Modality (odor, sound, no cue). The ANOVAs were conducted to investigate whether recognition performance varies depending on emotionality of the pictures, the stimulus they were paired with (odor, sound, or no cue), and the interaction of these two factors.

Results

Affective Ratings of Odors and Sounds

Descriptive Ratings

Mean valence, arousal, and dominance ratings of the odors and sounds as well as standard deviations are depicted in Table 1. As can be seen from descriptive inspection of the data, odors appeared to be rated as more pleasant, less arousing, and less dominant than tones. Moreover, changes of affective stimulus ratings seem especially pronounced for odors that were paired with aversive pictures.

Valence Ratings

The 2 × 2 × 2 ANCOVAs with the within-subjects factors Time, Emotionality, and Modality and Δvalence as a covariate revealed that valence ratings of the odors and sounds decreased after pairing with the pictures. This was indicated by a main effect of Time ($F(1, 46) = 22.50$, $p < .001$, $\eta_p^2 = .33$). A main effect of Modality ($F(1, 46) = 8.09$, $p < .01$, $\eta_p^2 = .15$) reflects higher valence ratings for odors than for sounds. Due to our controlling for valence differences at baseline ($t1$) via the covariate, these could be specifically attributed to the post-conditioning time point ($t2$). There was a Time × Emotionality interaction ($F(2, 92) = 3.19$, $p < .05$, $\eta_p^2 = .07$). Simple contrasts revealed that it was driven by a stronger decrease in valence ratings over time for stimuli paired with aversive rather than neutral pictures ($F(1, 47) = 6.17$, $p = .02$, $\eta_p^2 = .12$). Stimuli paired with both types of pictures did not differ from any of the other conditions. As illustrated by a Time × Modality interaction ($F(1, 46) = 8.09$, $p < .01$, $\eta_p^2 = .15$), valence ratings of the odors decreased more strongly than those of the sounds. An Emotionality × Modality interaction ($F(2, 92) = 8.13$, $p = .001$, $\eta_p^2 = .15$) reflects that for odors, valence ratings were highest if paired with neutral pictures, whereas sounds paired with neutral pictures had lowest valence ratings. For both modalities, valence of stimuli paired with aversive pictures did not differ from that of stimuli paired with both types of pictures.

Central to our hypotheses, data analysis showed a Time × Emotionality × Modality interaction ($F(2, 92) = 4.71$, $p = .01$, $\eta_p^2 = .09$) for valence ratings (see Fig. 2a). Post hoc 2 × 2 ANOVAS conducted for each modality separately revealed that valence ratings for odors decreased over time ($F(1, 47) = 19.75$, $p < .001$, $\eta_p^2 = .30$). Moreover, we found a Time × Emotionality interaction ($F(2, 94) = 6.46$, $p < .01$ $\eta_p^2 = .12$) for odors. Simple contrasts showed that it was driven by a stronger decrease in valence ratings for odors paired with aversive rather than neutral pictures ($F(1, 47) = 13.18$, $p = .001$, $\eta_p^2 = .22$). Odors paired with both types of pictures did not differ from any of the other conditions. Valence ratings for sounds also decreased over time ($F(1, 47) = 9.44$, $p < .01$, $\eta_p^2 = .17$, but there was no Time × Emotionality interaction for sounds ($F(2, 94) = .22$, $p = .80$, $\eta_p^2 = .01$). Thus, we can conclude that the decrease in sound valence ratings was not dependent on emotionality of the pictures.

Arousal Ratings

Arousal ratings were higher for sounds than for odors. This was illustrated by a main effect of Modality ($F(1, 46) = 5.21$, $p = .03$, $\eta_p^2 = .10$). Due to our controlling for arousal differences at $t1$, these could be specifically attributed to $t2$. As indicated by a Time × Modality interaction ($F(1, 46) = 5.21$, $p = .03$, $\eta_p^2 = .10$), there was a stronger increase in arousal for odors than for sounds.

Central to our hypotheses, there was a three-way Time × Emotionality × Modality interaction ($F(2, 92) = 4.63$, $p = .03$, $\eta_p^2 = .09$; see Fig. 2b). Post hoc 2 × 2 ANOVAs resulted in a Time × Emotionality interaction for odors ($F(1.7, 82.7) = 4.15$, $p = .023$, $\eta_p^2 = .08$). As revealed by simple comparisons, the increase of arousal ratings was stronger for odors paired with aversive rather than both types of pictures ($F(1, 47) = 8.90$, $p < .01$, $\eta_p^2 = .16$) and on a trend level than odors paired with neutral pictures ($F(1, 47) = 3.51$, $p = .067$, $\eta_p^2 = .07$). For sounds, there was only a main effect of Emotionality ($F(2, 94) = 3.63$, $p = .03$, $\eta_p^2 = .07$), driven by higher arousal ratings for sounds paired with aversive than neutral pictures. Most importantly, however, the absence of a Time × Emotionality interaction shows that there was no change of sound arousal

Table 1 Descriptive ratings of the odors and sounds before (pre) and after (post) pairing with aversive, neutral, or both types of pictures

	Valence				Arousal				Dominance			
	Pre		Post		Pre		Post		Pre		Post	
	M	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD
Odor aversive	6.88	1.89	5.06	2.57	2.83	1.83	3.77	2.17	6.02	2.19	4.79	2.41
Odor both	6.71	2.07	5.77	2.35	3.75	2.13	3.60	2.20	6.02	2.27	5.58	2.49
Odor neutral	6.65	2.29	6.29	2.17	3.38	1.94	3.43	1.79	5.48	2.32	5.83	2.46
Sound aversive	5.25	2.32	4.58	1.75	3.79	1.93	3.73	1.87	4.98	2.40	4.85	2.31
Sound both	5.42	2.40	4.52	2.26	4.08	2.14	4.29	2.23	5.38	2.25	4.79	2.38
Sound neutral	4.67	1.84	3.83	1.96	4.19	2.01	4.81	2.08	5.38	2.06	5.08	2.05

Valence (from 1 = negative to 9 = positive), arousal (from 1 = relaxed to 9 = aroused), and dominance (from 1 = controlled to 9 = in control) were rated on the Self-Assessment Manikin (Bradley and Lang 1994). Please note that lower dominance ratings indicate a higher perceived dominance of the stimulus

ratings over time depending on the emotionality of the pictures they were paired with.

Dominance Ratings

The 2 × 2 × 2 ANCOVA for dominance ratings resulted in a Time × Emotionality × Modality interaction ($F(1.71, 78.43) = 3.42$, $p < .05$, $\eta^2_p = .07$). Post hoc 2 × 2 ANOVAS for both modalities separately showed a Time × Emotionality interaction for odors. As revealed by simple contrasts, it was driven by a stronger decrease in dominance ratings for odors paired with aversive than neutral pictures ($F(1, 47) = 8.63$, $p < .01$, $\eta^2_p = .16$). Due to the dominance scale reaching from 1 = controlled to 9 = in control, this decrease signifies an increase in perceived dominance of the odors. Odors paired with both types of pictures did not differ from any of the other conditions. For sounds, there were no changes in dominance ratings depending on time or emotionality of the pictures observed.

Picture Recognition Performance

Measures of picture recognition performance (hit rates, false alarm rates, discrimination index d', bias c), as well as reaction times were neither modulated by the presence of a retrieval cue nor by an interaction of picture emotionality and retrieval cue (see Table 2). There was a significant main effect of Emotionality for the hit rates and the bias index C. It shows that participants more often correctly identified pictures that they had already seen on Day 1 for aversive rather than neutral pictures and responded more conservatively to neutral than to aversive pictures. A conservative response pattern reflects the tendency to rate a picture as new by stating that it was not presented on Day 1.

Discussion

In the present study, we investigated changes in perceived affective stimulus quality via evaluative conditioning in the olfactory and auditory modality. For this purpose, participants rated unfamiliar and emotionally neutral odors and sounds before and after pairing with aversive or neutral pictures. Additionally, recognition of the pictures was tested in order to test for retrieval cue effects of odors and sounds. In line with our hypotheses, affective quality of odors turned out to be more sensitive to evaluative conditioning than that of sounds. After pairing with the pictures, valence ratings decreased for all stimuli. For odors, this decrease was stronger, if they had been paired with aversive rather than neutral pictures. For sounds, the decrease in stimulus valence was independent of picture emotionality. Perceived arousal and dominance of odors increased strongest after pairing with aversive pictures. In contrast, changes in arousal and dominance of sounds did not substantially differ due to picture emotionality. Recognition memory performance was slightly enhanced for aversive pictures but not modulated by the presence of a retrieval cue.

To begin with, the general decline in stimulus valence is most likely to be attributed to the unpleasant character of the task itself. Participants were presented with 108 pictures on Day 1 and 216 on Day 2, half of which were extremely aversive. We assume that a decreased liking of the task from the beginning of Day 1 to the end of Day 2 has transferred to the valence ratings of the stimuli. Since this applies to all odors and sounds that were presented, we do not consider it to mask any effects driven by emotionality of the picture stimuli.

Our results showing successful evaluative conditioning in the olfactory modality are in accordance with reports of changes in odor valence observed in laboratory studies after pairing with emotionally charged UCS, such as tastants (Zellner et al. 1983; Yeomans et al. 2006; van den Bosch

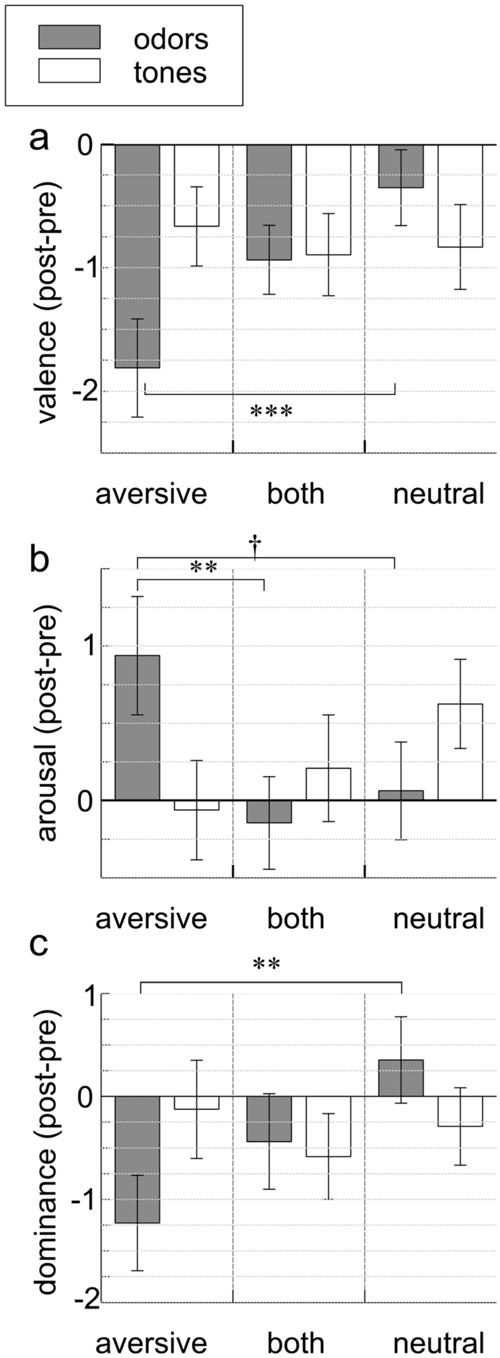

Fig. 2 Changes in ratings of odors (gray) and sounds (white) from before (pre) to after (post) pairing with emotional, neutral or both types of pictures. Valence (**a**; 1 = unpleasant to 9 = pleasant), arousal (**b**; 1 = relaxed to 9 = aroused), and dominance (**c**; 1 = controlled to 9 = in control) ratings were measured with the Self-Assessment Manikin (Bradley and Lang 1994). ***=p<.001. ** = $p < .01$. † = $p < .06$. Error bars display the SEM

et al. 2015), verbal labels (Djordjevic et al. 2007), or emotionally valenced situations (Herz et al. 2004a). Similarly, in real-world settings, it was shown that odor preferences vary according to hedonics of the context they are presented in (Baeyens et al. 1996; Rozin et al. 1998). To compare the change in valence observed in our study to the mean effect size reported in a meta-analysis on the evaluative conditioning literature (Hofmann et al. 2010), we calculated a pre-post contrast of valence ratings for odors paired with aversive pictures ($t(47) = 4.56$, $p < .001$, $d = .80$). This contrast indicates a strong effect that exceeds the mean medium effect ($d = .52$, 95% CI = .47–.58) reported in the meta-analysis. Moreover, extending previous investigations, we show that evaluative conditioning did not only evoke a decline in odor pleasantness but also increased arousal and a feeling of lower control over the odor. This represents a broad change of affective quality that is not limited to a single dimension of affective experience. Such clear evidence of successful evaluative conditioning with the odor-picture paradigm is remarkable against the background of two experiments using similar stimulus material (Rozin et al. 1998). In these experiments, eight neutral olfactory CS were each paired with a positive, neutral, or negative picture. Unlike the present study, Rozin et al. did not observe changes in odor valence for most of the pictorial UCS after eight CS-UCS pairings. Besides methodological differences between the studies, the choice of olfactory stimulus material might serve as an explanation for the diverging results. Conceivably, the odors used by Rozin et al. (lavender, sweet birch, jasmine, cajuput, sassafrass, sandalwood, coconut, and walnut) were more familiar and already emotionally connoted relative to those used in our study. Based on further experiments, Rozin et al. suggested that affective interpretation of odors is in general highly unstable, which is consistent with the strong changes in affective odor quality observed in the present study.

Unlike olfactory evaluative conditioning, we found variation in affective sound ratings to be unrelated to picture emotionality in the same experimental paradigm. No difference in stimulus valence, arousal, and dominance emerged between sounds paired with aversive and neutral pictures. In contrast to our findings, previous studies applying evaluative conditioning paradigms using sounds as CS have shown evaluative conditioning effects (Bliss-Moreau et al. 2010; Kattner and Ellermeier 2011; Bolders et al. 2012; Kattner et al. 2012). For instance, valence of neutral environmental sounds changed after pairing with positive or negative words (Bolders et al. 2012) or after pairing with unpleasant pictures (Kattner and Ellermeier 2011; Kattner et al. 2012). Of relevance for explaining the diverging findings might be a different complexity of the auditory CS. Although a vastly similar network of brain regions seems to be involved in affective processing of complex and simple sounds, it has been suggested that the extent to which certain brain regions are activated differs depending on stimulus complexity (Frühholz et al. 2016). For instance, learned affective valence of simple sounds as used in our study is mainly encoded in the amygdala (LeDoux et al. 1990; Frühholz et al. 2016), just as acoustic features of the sound (Kumar et al. 2012). For more complex sounds, such as the environmental sounds used in previous

Table 2 Results of 2 × 2 ANOVAs for indices of recognition memory performance

	F	*p*	η_p^2
Discrimination index *d*′			
Emotionality	.06	.82	.00
Modality	.84	.44	.02
Emotionality × Modality	.05	.96	.00
Bias index *C*			
Emotionality	4.07	.05	.08
Modality	2.96	.06	.06
Emotionality × Modality	.58	.56	.01
Hit rates[a]			
Emotionality	4.59	.04	.09
Modality	2.34	.10	.05
Emotionality × Modality	.36	.70	.01
False alarm rates			
Emotionality	3.31	.08	.07
Modality	1.33	.27	.03
Emotionality × Modality	.71	.49	.02
Reaction times			
Emotionality	.17	.68	.00
Modality	2.36	.10	.05
Emotionality × Modality	.51	.60	.01

studies, the auditory cortex and the OFC play a more important role (Frühholz et al. 2016). Although little is known about neuronal processes underlying evaluative conditioning, the role of the amygdala seems to be less critical as in fear conditioning (Coppens et al. 2006). Instead, the OFC was found to be involved in evaluative conditioning (Gottfried et al. 2002, Cox et al. 2005). The neuronal activation pattern might thus be more similar to that of affective processing of complex rather than simple sounds and become manifest in a more effective evaluative conditioning for complex rather than simple sounds.

To explain the diverging outcomes for odors and sounds, differential embedding of emotion processing in the olfactory and auditory sensory systems could be of relevance. Affective acoustic information can bypass the auditory cortex on a fast pathway from the thalamus' medial geniculate nucleus to the amygdala, as first demonstrated in the context of auditory fear conditioning (LeDoux et al. 1984). However, as outlined in the introduction, affective olfactory information can reach limbic brain regions even faster and at an earlier stage of cortical processing (McDonald 1998). The emotional significance of an odor might thus be encoded in a more direct way than that of sounds. Another factor modulating the success of evaluative conditioning in the olfactory and auditory modality might be cross-modal interactions. Identifying the emotional content of a situation often needs integration of sensory information from multiple modalities. In this regard, it is known that sensory cues perceived in one modality may alter the way information is processed in another modality. For instance, an odor is better identified, if presented together with a semantically congruent picture (Gottfried and Dolan 2003) or a corresponding color (Zellner 2013). An fMRI study by Schulze et al. (2017) revealed that emotional visual information is preprocessed in the piriform cortex, a central structure of the primary olfactory cortex. Hedonic quality of subsequently presented odors was shifted towards the valence of the visual input, even though it was not related to the odors. This suggests a direct integration of emotional visual information into the representation of an olfactory stimulus. Audiovisual interactions of emotional pictorial and neutral auditory stimuli (for a review, see Gerdes et al. 2014) appear to be more cognitive and become manifest in enhanced auditory novelty processing (Domínguez-Borràs et al. 2008), suppressed auditory sensory gating (Yamashita et al. 2005), and enhanced attention towards neutral auditory stimuli (Tartar et al. 2012).

Important to discuss in this context is selective associability in evaluative conditioning of odors and sounds. As first postulated by Garcia and Koelling (1966), certain stimuli appear to be better associable to specific emotional states than others. In their experiments, an electric shock (UCS) was better associable with an audiovisual CS than with a gustatory CS. In our case, aversive pictures (UCS) appear to be easier to associate with odors (CS) than with sounds (CS). This transfer of visual affective information to previously neutral and unfamiliar odors might be of a special adaptive significance: One of the main functions of odors is to constitute warning cues for various environmental or food-related hazards (Stevenson 2009). These warning cues have an important protective function for the organism, as they signal whether to approach a certain stimulus/environment or whether it should be avoided. They are therefore connoted with an affective value. To guarantee an adaptation to the specific needs of an individual, regular updates of odor affective quality via learning processes take place (Gottfried 2008). These are likely to be facilitated by a direct integration of cross-modal information such as visual cues into the affective value encoded for an odor.

In addition to changes in affective quality, we expected odors to become better retrieval cues for the aversive information they have been associated with than sounds would be. However, our results did not support this assumption. Picture recognition performance appeared to be slightly improved for aversive rather than neutral pictures, as indicated by higher hit rates and a lower bias index for aversive pictures. These findings are in accordance with the well-established emotional enhancement effect of memory (see McGaugh 2018 for a review). However, neither the presence of odors nor sounds revealed any facilitation of picture recognition performance. In contrast, previous research pioneered by Cann and Ross

(1989) has repeatedly shown a facilitation of picture recognition memory for participants exposed to the same odor during encoding and recognition test. For sounds, similar effects could be shown (Balch et al. 1992). An explanation of our failure to replicate effects of retrieval cues on recognition memory could be the cue-overload effect (Watkins and Watkins 1975). This details how recalling an item is more unlikely, the more items are associated with its retrieval cue. In our paradigm, subsuming 18 pictures under each retrieval cue may have prevented participants from associating a cue to the individual pictures. Thus, due to the absence of any retrieval cue effect, we cannot draw any conclusions about differential effectiveness of odors and sounds in facilitating recognition memory of aversive or neutral pictures.

The present study provided a direct comparison of evaluative conditioning between the olfactory and auditory modalities. A limitation of the study is the extent to which these two modalities can be compared with one another. Since odors cannot be classified by simple parameters such as pitch, frequency, or amplitude, we decided to aim for comparability of our monomolecular odors and simple sounds in terms of affective quality and familiarity characteristics. In the pilot study, odors and sounds were indeed rated as comparable to each other. However, on Day 1 of our study, the odors were rated as more pleasant, less arousing, and less dominant than the sounds, which necessitated statistically controlling for differences in stimulus ratings. Moreover, discrepancies regarding other stimulus properties that were not assessed here are conceivable, for instance, perceived stimulus complexity (Sulmont-Rossé et al. 2002), habituation to odors (Pellegrino et al. 2017) and sounds (Mutschler et al. 2010), or contingency awareness for the CS-UCS pairing (Hofmann et al. 2010).

Beyond the associability of odors and sounds to pictures in general, basic emotions elicited by the pictures might be an interesting aspect to assess in future studies. For instance, disgust and anger were shown to be the two negative basic emotions most frequently evoked by odors (Alaoui-Ismaïli et al. 1997). Perceived affective quality of an odor might therefore be especially sensitive to evaluative conditioning when using disgust- or anger-evoking pictures as UCS. In the present study, we did not systematically vary basic emotions elicited by the UCS. Instead, we paired our CS with several pictures classified a as being aversive or neutral based on its valence and arousal ratings (see "Picture Stimuli") and irrespective of the basic emotions elicited by an individual picture. To shed further light on mechanisms underlying differential evaluative conditioning in the olfactory and auditory modality, studies tracing the neural pathways as well as a selective targeting of cross-modal interactions in evaluative conditioning are required. Furthermore, it could be of interest whether these effects persist if measured implicitly, for instance by eye blink startle response or affective priming. First investigations indicate that at least for aversive evaluative conditioning, heart rate appears to be responsive to changes in odor valence (Royet et al. 2000; Djordjevic et al. 2007; van den Bosch et al. 2015) and sounds appear to be sensitive to affective priming (Bolders et al. 2012).

Despite the considerations mentioned above, our findings support the notion that the olfactory system, as compared to the auditory modality, is especially prone to attributing affective value to an odor. This was shown specifically for a transfer of visual affective information to previously neutral and unfamiliar odors which might be of a special adaptive significance, since a direct integration of visual cues into the affective value encoded for an odor might serve successful adaptation to the individual's specific environment. With regard to clinical conditions in which odors become highly aversive, such as post-traumatic stress disorder, it would be of special interest to investigate whether reversing a negative affective perception of an odor is as simple as the initial evaluative conditioning shown here, and whether this process is intact and accessible in patients. In accordance with research on odor-evoked emotional memories referred to in the introduction, our findings underline the special relationship between odors and the emotions they are associated with. We conclude that not only the memories evoked by an odor but also perceived affective quality of the odor itself is of a special emotional nature.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the local ethics committee of the Faculty of Psychology.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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