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Information processing during sleep: the effect of olfactory stimuli on dream content and dream emotions

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SUMMARY Research has shown that external stimuli presented during sleep can affect dream content, thus reflecting information processing of the sleeping brain. Olfactory stimuli should have a stronger effect on dream emotions because their processing is linked directly to the limbic system. Because selective olfactory stimulation does not increase arousal activity, intense olfactory stimulation is therefore a prime paradigm for studying information processing during sleep. Fifteen healthy, normosmic volunteers were studied by intranasal chemosensory stimulation during rapid eye movement sleep based on air-dilution olfactometry. For olfactory stimulation, hydrogen sulphide (smell of rotten eggs) and phenyl ethyl alcohol (smell of roses) was used and compared with a control condition without stimulation. The olfactory stimuli affected significantly the emotional content of dreams: the positively toned stimulus yielded more positively toned dreams, whereas the negative stimulus was followed by more negatively toned dreams. Direct incorporations, i.e. the dreamer is smelling something, were not found. The findings indicate that information processing of olfactory stimuli is present in sleep and that the emotional tone of dreams can be influenced significantly depending upon the hedonic characteristic of the stimulus used. It would be interesting to conduct learning experiments (associating specific odours with declarative material) to study whether this declarative material is incorporated into subsequent dreams if the corresponding odour cue is presented during sleep. It would also be interesting to study the effect of positively toned olfactory stimuli on nightmares.

KEYWORDS dream content, dream emotions, information processing, olfaction

INTRODUCTION

Whether and how external stimuli are processed during sleep has been studied mainly by two different paradigms: event-related potentials (Bastuji and Garcia-Larrea, 1999) and incorporation into dream content (Schredl, 2008). Whereas the first approach demonstrated that simple mechanisms such as detecting salient stimuli or deviance detection persist during sleep (for an overview, see Bastuji and Garcia-Larrea, 1999), the second approach is necessary to study whether conscious processes are also involved. The standard procedure is to present a stimulus during rapid eye movement (REM) sleep and wake the sleeper after a brief period of time to elicit dream content. The effect of various stimulus modalities on dream content have been studied and showed different incorporation rates: 9% (sinus tone; Dement and Wolpert, 1958), 11% (neutral words; Hoelscher *et al.*, 1981), 25% (rocking of the bed; Leslie and Ogilvie, 1996), 31% (mild pain stimuli; Nielsen *et al.*, 1993), 56% (electrical stimuli; Koulack, 1969) and 87% (pressure cuff on one leg; Nielsen, 1993). Overall, the dream studies indicate that some kind of information processing of external stimuli is present during sleep. Two issues have to be considered in this research. First, the stimuli must have an effect on the

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organism but not wake the sleeper (Koulack, 1969). For efficient stimuli such as cold water spray on the skin (incorporation rate: 42%), more than 30% of the trials resulted in awakenings (Dement and Wolpert, 1958). The second issue is to clarify how to score incorporation, i.e. whether only direct incorporations (see dream example below) or indirect incorporations (stimulus-related themes) were also coded. In order to take the variability of dream content into account, dreams stemming from control conditions without stimulation are necessary to compare the stimulated dreams. In the study by Nielsen (1993), for example, 25% of the control dreams included references to leg movement (compared to 82% of the stimulated dreams).

Using olfactory stimuli in this design is of interest because of two reasons. First, Carskadon and Herz (2004) have demonstrated that olfactory stimuli rarely woke the sleeper, and Stuck *et al.* (2007) showed that olfactory stimuli without trigeminal component such as hydrogen sulphide (H_2S) do not cause arousals even at high concentrations. However, Stuck *et al.* (2006a) found that olfactory event-related potentials can be measured during sleep, indicating that chemosensory stimuli are processed by the sleeping brain. Secondly, olfactory stimuli were processed differently within the brain compared with auditory stimuli: this includes the predominantly ipsilateral processing of the olfactory stimuli, and the almost direct projection from the olfactory bulb to the amygdala (areas for the processing of memories and emotions) and the association to the hippocampus via the transitional entorhinal cortex (cf. Smith and Shepherd, 2003), Thirdly, the fact that olfactory information processing largely bypasses the spinal cord, the brain stem and the thalamus – in contrast to all other sensory systems (Gottfried, 2006) – might explain the small number of arousals after stimulation which was comparable with non-stimulated sleep episodes (Stuck *et al.*, 2007) because thalamic reticular nuclei are involved in arousal generation (McCormick and Bal, 1997).

Trotter *et al.* (1988) carried out a small pilot study with five participants to study the effect of olfactory stimuli on dream content. The incorporation rate was 19% (79 successful trials in 22 nights). The following example was reported by a participant after presentation of a freshly cut lemon:

> I dreamed I was in Golden Gate Park. I was walking by some gardenias. They were just opening. All of a sudden, I could smell the gardenias, but they smelled like lemons instead of gardenias. (Trotter *et al.*, 1988, p. 95)

No effect of the pleasantness of the stimuli (pleasant stimuli: coffee, peanut butter, roses, cinnamon, chocolate, lemon; unpleasant stimuli: wood alcohol, dirty ashtray, match smoke, mould, dog faeces, onion) on dream emotions was reported (Trotter *et al.*, 1988). For interpreting the results of this study, several methodological issues need to be taken into account. First, there was no control condition without stimulation. Secondly, the authors did not describe how the olfactory stimuli were presented without disturbing the dreamer, e.g. entering the room and hold a freshly cut lemon in front of the dreamer's nose. It is also not clear whether they were able to guarantee that the smell was not still present at the time of awakening. Lastly, the olfactory stimuli included a trigeminal component, which is processed differently by the brain compared with pure olfactory stimuli (Rombaux *et al.*, 2006). Because of this methodological issue, increased measurement error variance might have had a possible effect on the hedonistic tone of the olfactory stimuli on dream emotions.

The aim of the present study was to investigate whether specific olfactory stimuli affect dream content by using sophisticated stimulation methodology (stimulation without disturbing the sleeper, no odour present at the moment of awakening, control condition). Regarding specific dream content, it was expected that pure olfactory stimuli are processed in higher cortical areas such as stimuli of other sensory modalities (see Stuck *et al.*, 2006b regarding event-related potentials as response to olfactory stimuli) and, thus, incorporated at least partly into dreams. The only study in the area of olfactory stimulation (Trotter *et al.*, 1988) is inconclusive caused by severe methodological limitations (see above) and needs to be validated. Because of the direct connectivity of the olfactory bulb to the amygdala, we hypothesized – despite the negative findings of Trotter *et al.* (1988) in this respect – that the strongest effect will be found for dream emotions, i.e. a positively toned stimulus should result in more positively toned dreams compared with a negative stimulus or control condition. Similarly, negatively toned stimuli should result in more negatively toned dreams.

METHODS

The study was conducted at the Sleep Disorders Center at the Department of Otorhinolaryngology, Head and Neck Surgery Mannheim. The study protocol was approved by the local ethics board of the Faculty of Clinical Medicine Mannheim of the University of Heidelberg; written informed consent was obtained from all participants.

Participants

Given that young females have demonstrated the best olfactory performance among human subjects (Covington *et al.*, 1999; Stuck *et al.*, 2006b), 15 young healthy female volunteers were included in this prospective study (mean age 23.0 ± 2.1 years, range: 20–28 years). Exclusion criteria were actual/previous history of smell or taste disorders, use of any medication known to affect chemosensory function and a history of sleep disorders. At the screening visit, relevant nasal pathology, such as mucosal inflammation, significant septal deviation and nasal polyposis were ruled out via a detailed clinical examination, including nasal endoscopy. Patency of the nasal airways was ascertained additionally using active anterior rhinomanometry (Rhinomanometer 300; ATMOS Medizintechnik GmbH & Co. KG, Lenzkirch, Germany).

Psychophysical testing of olfactory function

All participants underwent olfactory testing using the 'Sniffin' Sticks' test kit to establish normal olfactory function (Hummel *et al*., 1997; Kobal *et al*., 2000). Odorants were presented in odour dispensers similar to felt-tip pens. Testing involved assessment of n-butanol odour thresholds, odour discrimination and odour identification. In order to categorize olfactory function in terms of functional anosmia, hyposmia and normosmia, the sum of the three scores for odour thresholds, odour discrimination and odour identification was used [threshold–discrimination–identification (TDI) score; Wolfensberger *et al*., 2000].

Sleep recordings

The participants were admitted to the Sleep Disorders Center. Analogous to routine sleep studies, an overnight polysomnography was performed to assess nocturnal sleep. Monitoring included two electroencephalographic recordings (C3-A2, C4-A1), two electro-oculograms (left, right), two submental and two leg electromyograms (left, right). Sleep stages were scored according to Rechtschaffen and Kales (1968).

Chemosensory stimulation

For stimulation, a dynamic olfactometer based on air-dilution olfactometry was used (OM6b; Burghart Instruments, Wedel, Germany). This allows the presentation of odorous stimuli within a continuous airstream of 8 L min^{-1}, which does not alter the mechanical or thermal conditions at the nasal mucosa (Kobal, 1981). Moreover, this constant airstream ensures that the influence of breathing patterns on stimulus presentation to the olfactory epithelium is minimized. For specific olfactory stimulation the unpleasant H_2S, described typically as smelling like rotten eggs, was presented at 4 parts per million. The positive olfactory stimulus was phenyl ethyl alcohol (PEA), described typically as smelling like roses, administered at 20% v/v (both stimuli are clearly above threshold). Stimulus duration was 10 s. Odourless stimuli were presented additionally as a control.

To allow sufficient mobility during sleep, a tube of approximately 60 cm length was used to connect the subjects' nostril with the olfactometer outlet. This ensured that changes in body position had little influence on stimulus presentation. The tube was secured with tape to the nostril. A curtain separated the subjects' bed from the olfactometer and the investigator. Earplugs were administered to dampen external sounds.

REM awakenings

The participants were awakened by the experimenter who asked: 'What was on your mind before I woke you up?'. After pauses in reporting, the experimenter prompted up to three times: 'Was there anything else?'. Lastly, the participant was asked to estimate positive and negative dream emotions on 4-point scales (0 = none, 1 = mild, 2 = moderate, 3 = strong feelings). For determining the emotional tone, the negative score was subtracted from the positive score. The interview was recorded and transcribed later. All words not related to the dream experience and repetitions were excluded. Mean word count was used as a measure for dream length.

Dream content analysis

The following scales were adapted from Schredl *et al*. (1998): realism/bizarreness (1 = realistic, 2 = realistic but extraordinary, 3 = one or two bizarre elements, 4 = several bizarre elements) and positive and negative dream emotions (0 = none, 1 = mild, 2 = moderate, 3 = strong feelings). These scales showed good inter-rater reliability ranged $r = 0.642$–0.825 (Schredl *et al*., 2004). For the purpose of the study, two additional scales were developed: explicit mention of perception of smelling something (present versus not present) and dream elements which are associated normally with strong odour (present versus not present). Lastly, for each dream report the judges should make a guess as to what kind of stimulus (positive, negative, neutral) was applied.

PROCEDURE

The participant slept for 2 consecutive nights in the laboratory. The first night served as adaptation to the setting including polysomnography and taped tube of the olfactometer. Stimuli (pleasant, unpleasant, neutral) were presented in a balanced order during the second night during each REM period. Stimulation (duration 10 s) was started after 5 min into the first REM period, 10 min into the second REM period and 15 min of all following REM periods. One minute after presentation, the investigator awakened the participant and elicited dream content and self-rated dream emotions. Dream reports were taped, transcribed, randomized in order and rated by two independent judges along the rating scales described above. The judges were, therefore, blind to the condition and also not involved in the collection of the reports. Emotional tone (positive emotions – negative emotions) was used as variable for statistical analyses.

Statistical analyses were carried out with SAS version 9.1 (SAS Institute Inc., Cary, NC, USA). Data were submitted to analyses of variance for repeated measures with 'stimulus type' as within-subject factor. Contrasts were computed by dependent *t*-tests. Degrees of freedom are presented in brackets following the *F*-values and *t*-values. The alpha level was set at 0.05.

RESULTS

All subjects were normosmic (mean TDI score 38.4 ± 5.1; range 33.5–45.0). No abnormalities were detected during the overnight sleep recordings of the first night. Because of the

limited number of REM periods in several participants, 12 awakenings in the neutral condition and 13 awakenings in the positive condition could be carried out, whereas for the negative stimulus all 15 awakenings were performed. The time of night (measured as hours from midnight) was comparable across conditions and means were not statistically different (neutral condition: 4.37 ± 2.47 h, negative stimulation: 4.46 ± 1.39 h and positive stimulation: 4.02 ± 2.02 h). Dream recall was almost 100%; only one of 40 awakenings yielded no dream report, but for this participant the stimulation was repeated in the forth REM period.

In Table 1 and Fig. 1, the findings of the dream content analysis and the self-ratings of dream emotions are depicted. Because of missing values, ANOVAS were computed for 10 participants supplying dream reports in all three conditions. In order to maximize statistical power, all non-missing values were included in the pairwise comparisons. Note that because of differences in the number of included cases, ANOVA and pairwise comparisons might produce divergent results. Dream length did not differ significantly between the three conditions [$F_{(2,18)} = 0.1$, not significant (NS)]. Similarly, realism/bizarreness scores were comparable ($F_{(2,18)} = 0.0$, NS).

Regarding externally rated dream emotions the statistical analysis yielded a marginally significant difference between the three conditions ($F_{(2,18)} = 3.6$, $P < 0.07$), but two contrasts were significant (neutral versus negative: $t_{(11)} = 3.1$, $P < 0.01$; negative versus positive: $t_{(12)} = 2.5$, $P < 0.02$). Analysing the self-rated dream emotions, the differences are more pronounced: $F_{(2,18)} = 6.2$, $P < 0.01$, neutral versus negative: $t_{(11)} = 2.0$, $P < 0.04$, neutral versus positive: $t_{(9)} = 2.7$, $P < 0.02$, positive versus negative: $t_{(12)} = 2.9$, $P < 0.01$).

Explicit olfactory perception in the dream reports was scarce; i.e. in only one dream did the dreamer explicitly mention smelling something. Being part of a longer dream, the participant discussed with the experimenter why she did not wake her up more often because she had the impression of having dreamed more often. One of these dreams included a grinning Chinese woman who also looked disgusted because they (dreamer and Chinese woman) smelled something rotten. However, this dream was reported in the neutral condition. The statistical analysis (Fisher's exact test) was non-significant ($P = 1.0$). Four dreams included activities that are likely to be associated with olfactory perception in waking life: cleaning a toilet that was full of yellow liquid, eating a Kiwi fruit, eating potatoes with parsley and preparing a salad that included tuna, rice, corn and onions and being in a stuffy room. Again, the comparison between olfactory stimulation and control condition was not significant (Fisher's exact test: $P < 0.25$). The matching task where the raters should guess what stimulus was present prior to awakening was not successful: rater 1 matched 13 dreams correctly and rater 2 matched 15. Given that guessing randomly would yield on average 14 correct guesses (33.3% of 40 reports), this is a chance finding.

Table 1 Dream content and dream emotions across the three conditions (mean ± SD)

Variable	*Negative stimulus (n = 15)*	*Neutral Condition (n = 12)*	*Positive stimulus (n = 13)*
Word count	111.9 ± 66.1	123.9 ± 99.4	92.5 ± 59.4
Dream content analysis			
Realism/bizarreness	1.87 ± 0.83	1.75 ± 0.87	1.85 ± 0.90
Emotional tone	−1.00 ± 1.20	−0.08 ± 1.08	0.31 ± 1.38
Explicit olfactory perception (present versus not present)	0%	8.3%	0%
Activities that are likely to be associated with olfactory perception (present versus not present)	13.3%	0%	15.4%

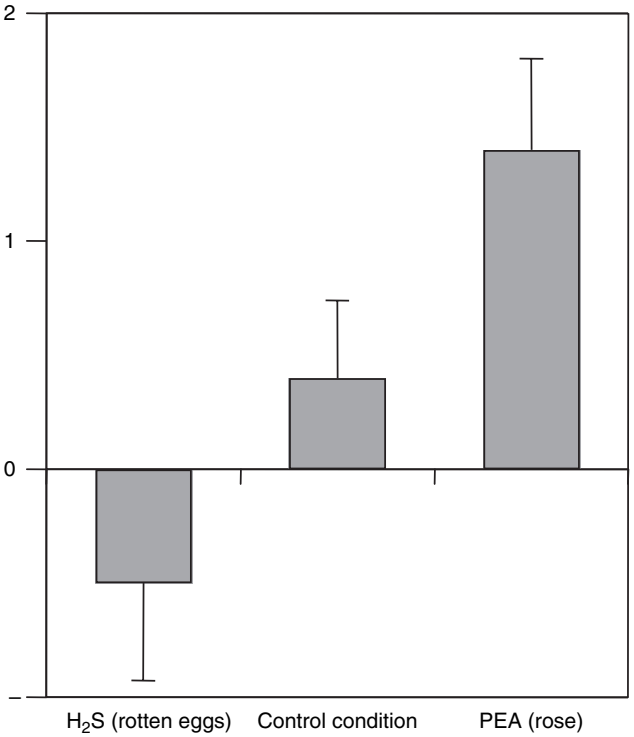

Figure 1. Emotional tone of the dreams of three different types of olfactory stimuli (self-ratings, means and standard deviations). H_2S, hydrogen sulphide; PEA, phenyl ethyl alcohol.

DISCUSSION

Overall, the findings indicate that olfactory stimuli were processed by the sleeping brain and affect the emotions but were not incorporated explicitly into dreams. This is compatible with the model of specific processing of olfactory stimuli within the brain, i.e. the direct anatomical connectivity to the amygdala (Gottfried, 2006). Direct incorporations as reported by Trotter *et al.* (1988) or for other stimulus types (see Introduction) were not found, thus indicating that olfactory stimuli are processed differently to other sensory modalities on higher brain levels. Maquet and Franck (1997), based on the

high activation of the amygdala during REM sleep (Maquet *et al*., 1996), proposed that the role of the amygdala is the processing of emotional memory. Given the direct connectivity of the olfactory bulb to this brain region, one might hypothesize that the emotional quality of the olfactory stimulus facilitates the processing of emotional memories with the same quality, i.e. the dream tone reflects the emotional tone of the stimulus but not the stimulus itself. Within this context, it would be interesting to pursue the idea studied by Saint-Denys (1982), who reported that olfactory stimulation yielded dream reports including memories which were associated with this specific odour in a more systematic way and tested the link between emotional tone of odour stimuli and declarative memory. In a presleep learning session, positively toned and negatively toned odour stimuli could be paired with words or other declarative material. One would expect that after olfactory stimulation dreams would include this associated material more often. This follow-up study would shed light on the psychological mechanisms underlying the present findings, i.e. whether the emotional tone of the olfactory stimuli might activate different sets of memories, including corresponding affects. Rasch *et al*. (2007) found that presenting a specific odour during slow-wave sleep probably reactivates mental content which was learned during the day while the same odour was presented. It would also be interesting to study the effect of the emotional tone of other stimuli, e.g. acoustic stimuli such as words, on the emotional tone of dreams. We would expect that the effect would be much less pronounced than for odour stimuli because of the specific processing within the brain, but a sufficiently large number of trials should also result in a significant effect.

The differences of our findings in comparison to the earlier study by Trotter *et al*. (1988) indicated clearly that sophisticated technology in presenting olfactory stimuli is necessary, i.e. a technique without affecting the mechanical and thermal condition of the nasal mucosa, and that ensures that the odour is not detectable at the time of the awakening. With regard to these shortcomings, the results of the Trotter *et al*. (1988) study have limited generalizability.

That the lack of incorporated olfactory stimuli is explained by methodological issues (e.g. forgetting this part of the dream because it happened 1 min prior to awakening) is unlikely, because the procedure of the present study was comparable with the designs of similar studies in the field that demonstrated an incorporation of stimuli of other sensory modalities (cf. Schredl, 2008). On the other hand, it was necessary to test whether manipulation of presentation length or repetition frequency could increase the possibility of incorporation of the pure olfactory stimuli. However, the Stuck *et al*. (2007) study indicates clearly that it is unlikely that an increase of stimulus intensity will produce stronger effects. In addition, the concentrations applied in the present study have been intense and clearly above threshold.

From a methodological viewpoint, it is interesting that the findings regarding dream emotions are more pronounced for the self-rating scales compared to the dream content analytical findings. Schredl and Doll (1998) have shown that external judges underestimate emotional intensity, particularly positive emotions, because of the fact that dreamers, even trained participants in dream studies, did not report all emotions experienced in the dream explicitly. This shift to more negative emotions in the externally rated emotions compared with self-ratings was also found in the present data. Schredl and Doll (1998) concluded that self-ratings are more valid measures of dream emotions than analysing dream reports, because of the selective underestimation of positive emotions by external judges.

Other methodological issues, such as the setting (olfactometer and experimenter in the same room with the sleeping participants), are unlikely to have affected the present findings, as these parameters did not change between the conditions (positive and negative stimulation as well as control condition) in this within-subject design. The subjects were not informed about the order of the different stimulus conditions, i.e. they were blind to the condition. Unfortunately, we did not ask them whether they were guessing regarding the stimulus. Previous studies with the same methodology showed clearly that the odour is not present at the time of waking the participant (1-min delay). The experimenter was not blind to the condition; by keeping the interaction between experimenter and participant to a minimum in an exact standardized manner, experimenter effects should be minimal.

We did not analyse the electroencephalogram (EEG) after presentation within this study because the previous study by Stuck *et al*. (2007), with a large number of stimulations, showed clearly that EEG measures are not affected by this type of olfactory stimulation (without trigeminal component). On the other hand, the number of stimulations in the present study is far too small to detect an effect on scalp EEG parameters (event-related potentials). Modern technology functional magnetic resonance imaging) might allow measuring the relationship between olfactory stimuli presentation and amygdala activation during REM sleep (cf. Wehrle *et al*., 2005).

The present study – as almost every other study in this field – was limited to stimulation during REM sleep. It would be interesting to study whether stimulation during non-REM (NREM) sleep is equally effective, even though the cost of these studies would be higher because of lower dream recall rates after NREM awakenings (cf. Nielsen, 2000).

To summarize, it was shown that the hedonic tone of olfactory stimuli are processed during REM sleep and affect dream content. In extension to previous work in the field, we showed the special status of pure olfactory stimuli in this context in contrast to other sensory modalities, i.e. a minimal effect on dream content and a strong effect on dream emotions. The minimal effect on dream content might be explained by the lack of arousals in poststimulation EEG, indicating clearly that pure olfactory stimuli are processed differently to stimuli of other sensory modalities. We hypothesized that the strong effect on dream emotions is due to the direct connectivity of the olfactory bulb (and not for other sensory modalities) to the

amygdala processing emotional memory during REM sleep. Whether olfactory stimuli are presented directly in dreams is a question which has not yet been answered; it might be speculated that declarative material which is associated with the specific odour might be found more often. Studies with presleep learning sessions in which odour cues are associated with specific cues might shed light on memory processing and consolidation during sleep. In addition, it would be interesting to study nightmare sufferers, i.e. whether positively toned olfactory stimuli yield a significant shift in the emotional tone of nightmares.

DISCLOSURE

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