

Can an Unconscious Behavior Be Modified During Sleep? Evidence from Closed-Loop Olfactory Biofeedback

Tomer Yaari ¹, Michal Ramot ¹

¹ Brain Sciences, Weizmann Institute of Science, Rehovot, Israel

Introduction

The potential of learning during sleep has long intrigued researchers, particularly as a window into the mechanisms underlying implicit acquisition of information. Biofeedback offers a promising approach for investigating these processes by transforming physiological activity into a real-time training signal that can promote behavioral change without requiring conscious awareness (Ramot et al., 2016). Sleep provides a unique framework for studying these mechanisms because learning can occur in the absence of attention, intention, and explicit awareness (Ruch & Henke, 2020). Among the available sensory modalities, olfaction is particularly well-suited for sleep-based learning due to its unique neural pathway and its ability to influence behavior while producing minimal sleep disturbance (Arzi et al., 2014). Sleep bruxism (SB), a repetitive jaw-muscle activity (Lobbezoo et al., 2013) expressed exclusively during sleep, offers a rare opportunity to examine these questions because both the behavior itself and any associated learning process occur entirely outside conscious awareness. Here, we tested whether aversive olfactory biofeedback delivered immediately following detected sleep bruxism events can induce lasting behavioral change, providing a model to investigate whether an unconscious behavior can be modified through learning driven by feedback that is itself processed outside conscious awareness.

Methods

Adults aged 18–60 years diagnosed with sleep bruxism (Bruxism Index, BI > 4 events/hour, (Lavigne et al., 1996)) and without known sleep or neurological disorders completed a nine-night home-based protocol consisting of one adaptation night, three baseline nights, two feedback nights, and three post-feedback nights across two consecutive weeks. Physiological signals (EMG, ECG, EEG, and EOG) were recorded using a wearable acquisition system (8-Channel biosignalsplux Kit). SB events were detected automatically in real time using a convolutional neural network trained on physiological signals. Following detection, participants in the experimental group received an 8-second pulse of aversive olfactory feedback (rotten-fish odor) delivered approximately 1 s after event onset through a portable olfactometer positioned above the bed, whereas control participants received clean air. Bruxism severity was quantified using the Bruxism Index (BI; events/hour). Bruxism change was quantified by subtracting each participant's average baseline BI (BL2–BL4) from the BI measured on each post-feedback night (POST1–POST3), thereby capturing increases or decreases in bruxism frequency relative to baseline. The final analysis included 50 participants (RF: n = 31; Control: n = 19).

Results

Participants receiving aversive olfactory feedback exhibited a progressive reduction in bruxism frequency across the three post-feedback nights, with the magnitude of the reduction increasing with temporal distance from the feedback sessions (Figure 1). In contrast, control participants showed stable or increasing bruxism levels across the same period. Consistent with this trend, the largest between-group difference was observed on the third post-feedback night (POST3), where BI change differed significantly between groups (permutation test, $p = 0.0349$; Figure 2). Interestingly, participants in the feedback group who reported consciously perceiving the odor during the night showed an increase rather than a decrease in bruxism frequency, suggesting that the observed behavioral effect may depend on feedback processing occurring outside conscious awareness. Together, these findings support the possibility that sleep bruxism can be modified through implicit learning driven by unconsciously perceived olfactory feedback.

Conclusions

Our findings demonstrate that closed-loop olfactory biofeedback delivered during sleep can induce lasting changes in sleep bruxism beyond the period of active stimulation. The progressive reduction observed across post-feedback nights, together with the absence of improvement among participants who consciously perceived the feedback, suggests that the effect may be mediated by implicit learning mechanisms operating outside conscious awareness. Nevertheless, substantial

intersubject variability remains, suggesting that factors influencing odor delivery, such as room airflow and environmental conditions, may modulate the intervention's effectiveness. Future work will focus on better controlling and quantifying these factors to improve intervention reliability and to further elucidate the mechanisms underlying sleep-based olfactory learning. These results support the notion that unconscious behavior can be modified through feedback processed during sleep and establish home-based olfactory biofeedback as a promising framework for investigating learning mechanisms in naturalistic environments.

Figures

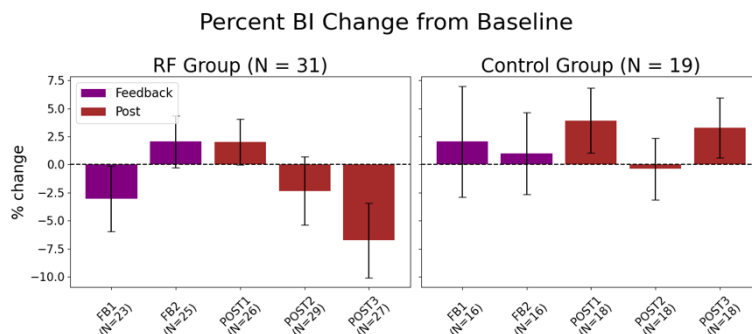


Figure 1. Average BI Change in percentage from the baseline per night type across two groups

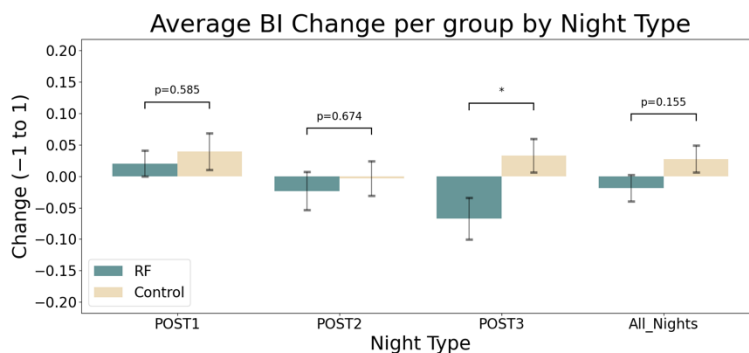


Figure 2. Average BI change per group, calculated by comparing each follow-up night to the averaged baseline. All_Nights is the average of all follow-up nights (POST1, POST2, and POST3).

References

- Arzi, A., Holtzman, Y., Samnón, P., Eshel, N., Harel, E., & Sobel, N. (2014). Olfactory Aversive Conditioning during Sleep Reduces Cigarette-Smoking Behavior. *The Journal of Neuroscience*, 34(46), 15382–15393. <https://doi.org/10.1523/JNEUROSCI.2291-14.2014>
- Lavigne, G. J., Rompre, P. H., & Montplaisir, J. Y. (1996). Sleep Bruxism: Validity of Clinical Research Diagnostic Criteria in a Controlled Polysomnographic Study. *Journal of Dental Research*, 75(1), 546–552. <https://doi.org/10.1177/00220345960750010601>
- Lobbezoo, F., Ahlberg, J., Glaros, A. G., Kato, T., Koyano, K., Lavigne, G. J., De Leeuw, R., Manfredini, D., Svensson, P., & Winocur, E. (2013). Bruxism defined and graded: An international consensus. *Journal of Oral Rehabilitation*, 40(1), 2–4. <https://doi.org/10.1111/joor.12011>
- Ramot, M., Grossman, S., Friedman, D., & Malach, R. (2016). Covert neurofeedback without awareness shapes cortical network spontaneous connectivity. *Proceedings of the National Academy of Sciences*, 113(17). <https://doi.org/10.1073/pnas.1516857113>
- Ruch, S., & Henke, K. (2020). Learning During Sleep: A Dream Comes True? *Trends in Cognitive Sciences*, 24(3), 170–172. <https://doi.org/10.1016/j.tics.2019.12.007>