



The Power of Odor Persuasion: The Incorporation of Olfactory Cues in Virtual Environments for Personalized Relaxation

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Abstract

Olfaction is the most ancient sense and is directly connected with emotional areas in the brain. It gives rise to perception linked to emotion both in everyday life and in memory-recall activities. Despite its emotional primacy in perception and its role in sampling the real physical world, olfaction is rarely used in clinical psychological settings because it relies on stimuli that are difficult to deliver. However, recent developments in virtual-reality tools are creating novel possibilities for the engagement of the sense of smell in this field. In this article, we present the relevant features of olfaction for relaxation purposes and then discuss possible future applications of involving olfaction in virtual-reality interventions for relaxation. We also discuss clinical applications, the potential of new tools, and current obstacles and limitations.

Keywords

sense of smell, virtual reality, relaxation, autobiographical memory

Odors have a power of persuasion stronger than that of words, appearances, emotions, or will. The persuasive power of an odor cannot be fended off, it enters into us like breath into our lungs, it fills us up, imbues us totally. There is no remedy for it.

—Patrick Süskind, *Perfume: The Story of a Murderer*

Smell is phylogenetically the most ancient sense. Given its relevant features, the sense of smell can enhance relaxation and emotion regulation. It has a unique relationship with emotions and homeostasis that is closer than that of other sensory modalities (Delplanque et al., 2017). It is related to energy balance, reward, disgust, and aversive signals (Morris, 2017; Riera et al., 2017). Indeed, the olfactory system is also wired to automatic learned responses (aversive or appetitive; Choi et al., 2011). It can directly

stimulate the amygdala, sidestepping a thalamic relay, rendering the perception of smells powerfully linked with emotions (Van Hartevelt & Kringelbach, 2012; Warrenburg, 2005). One of the most prominent characteristics of olfactory perception is its triggering effect on emotional and affective experience (Krusemark et al., 2013; Yeshurun & Sobel, 2010). For instance, consider the positive emotions that arise when smelling the scents of one's childhood, such as freshly baked cookies or the laundry detergent used by loved ones. Fragrances can also influence cognition, social behavior (for a review, see Sowndhararajan & Kim, 2016), mood, and quality of life (Cramer et al., 2010; Hong et al., 2015). Aromas have a modulating effect on psychophysiological activity and arousal (Moss et al., 2003). The potential mechanisms

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through which odor yields these effects include modulated attentional processes (Maggioni et al., 2018; Rinaldi et al., 2018), memory processes (Shanahan et al., 2018), judgment, and decision-making (Bonini et al., 2015).

The odor perception can also prompt the recollection of remote autobiographical memories (Herz & Schooler, 2002; Willander & Larsson, 2007) more vividly than other sensorial modalities. This effect is referred to as the “Proust phenomenon” from an often-quoted episode of Proust’s life in which the author described a vivid unintended reevocation of a childhood experience triggered by the taste of tea and madeleines. The flooding back described by Proust displays some essential features of the odor’s effect, involving old memories, affective experiences, and involuntary and automatic recall. Common examples may be the perfume of a beloved one immediately activating past affective memories or an unpleasant smell of foods that had made us feel sick, automatically triggering an aversive sensation (Boesveldt et al., 2010). Compared with other reevoking cues (e.g., words and pictures), olfactory stimuli can evoke autobiographical memories with more emotional and vivid experiences (Herz et al., 2004; Willander & Larsson, 2006). Furthermore, the higher the familiarity of an odor, the higher its perceived pleasantness (Bensafi et al., 2003; Engen & Ross, 1973).

Olfaction in the Field of Relaxation and Emotion Regulation

Given its emotional valence, the use of smell in clinical practice might give rise to new possibilities to enhance patient involvement and foster the efficacy of clinical techniques. This might be especially true with regard to relaxation exercises, one of the most common tools in clinical psychological settings. Relaxation procedures traditionally require that patients leverage imagery of calming scenes or past pleasant experiences to modulate psychophysiological arousal. Mindful attention to breath and progressive muscle relaxation are also often incorporated into clinical practice (Smith, 1999). Overall, these techniques encompass both top-down and bottom-up processes. Whereas the former involves cognitive control, attention-shifting, sustained attention, and memory recall, the latter requires sense awareness and psychophysiological modulation, lowering arousal, and muscle contraction.

Given the emotion- and memory-related features of olfaction, its use in relaxation might offer several benefits, both in the case of imaginary relaxing scenes and in the case of autobiographical memories. Olfaction stimulation might also stress bottom-up processes, one of the main targets of several relaxation strategies. Indeed, olfactory stimuli can evoke automatic rather

than conscious reactions (Atsumi & Tonosaki, 2007; Mark et al., 2018). Some chemicals can induce autonomic activations that are related to mating, eating, aversive reactions, and disgust (Boesveldt et al., 2010; Sarafoleanu et al., 2009).

However, unlike other sensorial modalities, it is hard to manipulate, stimulate, or evoke olfactory sensations with the imagination (Auffarth, 2013). For this reason, despite its promising results for relaxation, olfaction is rarely used in clinical settings (for a review, see Martin, 1996). One of the main examples of its use in clinical practices comes from King (1983), who reported a reduction of anxiety symptoms in subjects exposed to pleasant smells combined with a relaxation technique. Likewise, pleasant scents induced a perceived state of relaxation and perceived reduction of depressive symptoms (Schiffman, 1992; Schiffman & Siebert, 1991). Exposure to natural pleasant scents is also associated with a reduction of heart-rate frequencies, blood pressure, and negative affect (Dong & Jacob, 2016). Furthermore, Abramowitz and Lichtenberg (2009, 2010) developed what they called “hypnotherapeutic olfactory conditioning,” a procedure in which patients undergoing hypnosis learn to associate pleasant scents with a sense of security and personal control. The authors found preliminary positive results for the application of this technique to the treatment of patients with posttraumatic stress disorder (PTSD).

Emerging technologies in the field of virtual reality (VR) might allow olfaction stimulation to be applied in VR-relaxing interventions, giving rise to new clinical perspectives.

VR and Olfaction: Smelling Relaxation

VR for relaxation can bring the benefits of classic relaxation techniques derived from yoga, meditation, and muscle relaxation into virtual environments (VEs). VR may also solve difficulties that arise in applying classic relaxation techniques. For example, VR might help people with low mental imagery to perform imagery-relaxation tasks. VR can also decrease the cognitive load of relaxation techniques that require simultaneously following instructions and using mental imagery. VR interventions typically take advantage of two to three sensorial modalities (Freeman et al., 2017), focusing on the involvement of visual and auditory stimuli and, less frequently, tactile elements. VR for relaxation usually uses natural landscapes or other natural stimuli that are considered to possess intrinsic relaxing properties and narratives that directly derive or combine instructions from the aforementioned classic practices.

However, recent developments in VR interventions have tended toward content personalization based on

Table 1. Psychological and Physiological Processes Targeted by the Three Proposed Interventions

Process	Intervention		
	Relaxation	Personalized relaxation	Personalized exposure therapy
Perceptual involvement	✓	✓	✓
Arousal modulation	✓	✓	✓
Emotional link	✓	✓	✓
Personalization based on autobiographical experiences		✓	✓
Personalization based on users' preferences		✓	✓
Desensitization/extinction			✓

relevant personal and autobiographical content (Pizzoli et al., 2019). We propose that involving the sense of smell with olfactory stimuli within VEs might enhance both the effectiveness of relaxing interventions and the implementation of more personalized VEs.

Indeed, the higher emotional impact provided by scents throughout the reactivation of autobiographical memories might offer some valuable advantages in VR settings. First, smells can enhance a higher sense of presence (Baus & Bouchard, 2017; Jones & Dawkins, 2018; Munyan et al., 2016), although the results are still inconclusive. For instance, whereas Dinh et al. (1999) found a significant effect of smells on memory for but not on the sense of presence, Baus and Bouchard (2017) found an increased sense of presence when unpleasant scents were used in VR. However, this effect was not reported for pleasant scents, which, on the contrary, can enhance the sense of perceived reality (Baus et al., 2019). Furthermore, scents can augment affective activation and be another sensory stimulation in addition to classic VR modalities (e.g., visual, audio, tactile). In this way, the sensorial experience might become more similar to that of the real world, in which we use all of our senses. The second advantage of using scents in VR is the leveraging of the emotional engagement that can make relaxation more effective. Scents can provide sensorial experiences and perceptions that are not entirely mediated by cortical elaboration and that can activate emotion-related contents or experiences almost automatically. Last, because olfactory cues are strongly associated with autobiographical memories, scents may support the personalization of VR settings to patients' past experiences.

Olfaction Relaxation Meets VR: Possible Applications

Although olfactory inputs have received less attention than other sensorial features in VR interventions, the

idea of using scents in VR is not novel (Aiken & Berry, 2015; Baus & Bouchard, 2014; Chen, 2006; Matsukura et al., 2013; Obrist et al., 2014, 2017). Baus and Bouchard (2010) provided a comprehensive overview of scents' features and possible applications within VR settings. Since the first VR prototype by Morton Heilig, the Sensorama, which made use of all of the senses, smells have been proposed as valuable perceptual elements in treating PTSD through presence enhancement (Aiken & Berry, 2015; Rizzo et al., 2010). Other studies deepened the possibility of delivering smells in interaction with multimedia content and improving cognitive performances in different activities, such as attention while driving a car or notification perception (Amores & Maes, 2017; Dobbstein et al., 2017; Maggioni et al., 2018).

Here, we propose three nonmutually exclusive applications of olfactory stimuli within VR aimed at relaxation with a reduction of arousal stress. We divide the proposed applications into three different interventions: classic relaxation, personalized relaxation, and personalized exposure therapy. All the interventions involve the olfactory sensorial channel to modulate and lower arousal. The interventions differ from each other in terms of the link with personal contents, the specific relaxation aim, and how scents should be delivered within the relaxation sessions.

For each intervention, we trace some common features that can be used to describe, characterize, distinguish, and compare the three interventions. Regarding the processes involved in the interventions (Table 1), we consider six different dimensions that can be used to describe and compare the three types of interventions: perceptual involvement, arousal modulation, emotional link, personalization based on autobiographical experiences, personalization based on user preferences, and desensitization/extinction. Perceptual involvement refers to the fact that the interventions aim to achieve user relaxation through sensorial engagement, whereas

Table 2. Technical Features of the Three Proposed Interventions

Feature	Intervention		
	Relaxation	Personalized relaxation	Personalized exposure therapy
Users	General and clinical population	General and clinical population	Clinical population
Scents	Intrinsic relaxing properties	Intrinsic relaxing properties; user-centered or autobiographical relaxing scents	Intrinsic relaxing properties; user centered or autobiographical relaxing scents
Scent-delivery parameters	Gradual or stable	Gradual or stable	Gradual
Scenario	Relaxing scenarios	Tailored relaxing scenarios	Tailored exposure scenarios
Consciousness of sensorial perception	Above perceptual threshold	Above and under perceptual threshold	Above perceptual threshold

arousal modulation and emotional link refer to the modality by which the state would be achieved (i.e., by lowering physiological activity or activating positive emotions, respectively). The two dimensions related to the personalization of content point out the fact that the building of the three interventions can benefit from user-centered approaches. Whereas the former focuses on personal preferences, the latter aims at using or recreating relevant autobiographical cues. Finally, desensitization/extinction refers to the therapeutically psychophysiological process implying the reduction of the association between perceived threatening stimuli and anxiety response.

We also describe differences and commonalities between the interventions regarding the target population (general vs. clinical), the choice of olfactory stimuli (scents with intrinsic relaxing properties vs. user-centered or autobiographical relaxing scents) and their modulation (scent-delivery parameters: gradual vs. stable), the scenario type (relaxing, tailored relaxing, tailored exposure), and the perceptual threshold of the olfactory perception (consciousness of sensorial perception: above vs. under perceptual threshold; Table 2).

Classic relaxation

The first intervention deals with the use of scents with intrinsic relaxation properties, such as linalool scents (Atsumi & Tonosaki, 2007; Harada et al., 2018). From this perspective, scents could be used as relaxing stimuli per se, similar to the natural visual scenarios that are usually used in relaxation interventions. Advantages in using scents in this kind of relaxation may be represented by an enhanced emotional experience as well as an augmented immersion. To the best of our knowledge, only one study involving both touch and smell has used lavender scents to improve relaxation

in a general population sample (Serrano et al., 2016). The authors did not find significant results on relaxation. Because they used a simple delivery procedure (i.e., a ceramic diffuser), they advanced that other (simpler or more complicated) delivery methods might yield different results. We hypothesize that a more controllable procedure, for example, delivering scents synchronized with the instructions of the relaxation technique, might increase the effectiveness of the relaxation procedure.

Personalized relaxation

The second intervention personalizes the VR content. It is an attempt to collect and use autobiographical-relevant scents to give users personalized experiences and emotionally charged perceptions inside the VE. Such intervention is congruent with the personalized VR approach (Pizzoli et al., 2019) in that it aims to build user-centered VEs filled with multimodal stimuli derived from users' autobiographical elements. To collect scent categories, a qualitative approach such as the one used by Obrist and colleagues (2014) should be used. A qualitative approach consists of gathering personal autobiographical smells (i.e., "smell stories") and extracting personalized scent libraries. Such an approach would be the clinical operationalization of the Proust phenomenon: In a personalized smell-evoking setting it would be possible to activate autobiographical memories, even when the user does not deliberately intend to reexperience them. Thus, the use of autobiographical scents may trigger remote memories while lowering the cognitive load required to reevoke memories and experiences (Seigneuric et al., 2010). Thus, this would permit the allocation of more cognitive resources to follow narratives and instructions and perform relaxation exercises. Furthermore, because

the familiarity of an odor is positively related to its perceived pleasantness (Bensafi et al., 2003; Engen & Ross, 1973), using scents that have been rated as familiar and preferred would increase the pleasantness of users' experiences and would enhance positive sensations. Subjective user preferences toward specific features of the scents (e.g., intensity, crossmodality, or emotional associations) should be assessed and reported before the session (Maggioni et al., 2020). This would allow a personalized stimulation to maximize the therapeutic effectiveness.

Personalized exposure therapy

The third intervention is the most prominently focused on the therapeutic application because it is conceptualized to target clinical symptoms. Whereas the first two interventions take inspiration from relaxing practices and can be used to help both laypeople and individuals struggling with clinical symptoms to reach a state of relaxation, this intervention uses techniques specifically applied in specific psychiatric conditions, such as phobias and PTSD. Indeed, this last intervention takes advantage of exposure procedures, classical-conditioning extinction, and desensitization by combining user exposure to stressful visual-auditory stimuli with exposure to pleasant and presumably safe smells. It would be an attempt to gradually manipulate scents through the variation of delivery parameters such as time, intensity, and pressure and thus achieve emotional desensitization during VR-exposure therapies. This could also avoid possible habituation effects. As an ancient way to perceive the world and send messages associated with evolutionary responses (Boesveldt et al., 2010; Keverne, 2004; Lübke & Pause, 2015), olfaction might provide the possibility of sending relaxing or safe signals to the brain while the subject is exposed to a virtual scene associated with trauma or high stress. From this perspective, scents could be used to extinguish the association between traumatic triggers and arousal. Remarkable, pleasant scents can decrease arousal levels (Alaoui-Ismaili et al., 1997), an effect strongly targeted by desensitization practices.

Desensitization procedures can be useful when a traumatic trigger induces excessive arousal reactions associated with a traumatic trigger. In the field of VR, some examples of the application of scents combined with the treatment of fear and anxiety associated with a perceived threat are mainly present for PTSD. However, our proposed application differs from the procedure already used for patients with PTSD (Aiken & Berry, 2015; Gerardi et al., 2008; Rizzo & Shilling, 2018) or in exposure therapy (Munyan et al., 2016). Specifically, although in these procedures scents are used to

reevoke traumatic sensations in a realistic way or to enhance the sense of presence of the patients, here we propose using smell as a therapeutic means. Because relaxing and positive scents are emotionally charged stimuli with an evolutionary function, they may support patients' desensitization to a traumatic scene. Morrison et al. (2015) studied such an olfaction-extinction phenomenon in adult mice and showed neuroanatomical changes and a reverse in freezing behaviors after extinction training with odors. This study is of note given that olfactory cues may be associated with traumatic experiences in both humans and mice. Moreover, olfactory-receptive fields among humans maintain plasticity and the consequent capacity for adaptation in response to environmental stimuli across the life span (Morrison et al., 2015). For such interventions, both intrinsic relaxing scents and personalized odors would be useful. Notably, in the already cited studies by Abramowitz and Lichtenberg (2009, 2010), who found promising results on pairing hypnosis and scents to treat patients with PTSD and to overcome phobias and prevent panic attacks, scents were chosen according to patient's prior experiences. Indeed, patients were asked to choose scents that were already associated with calming memories and imagery.

Although exploiting olfaction to reach extinction between arousal and traumatic triggers would be extremely difficult in clinical settings, new VR tools may render this possibility feasible in the coming years within VR-exposure therapy, expanding possible therapeutic applications of the VR. Indeed, the extinction of the association between a perceived threat and excessive arousal can be beneficial for psychiatric conditions (Kong et al., 2014) in which the difficulty of extinguishing learned fear might occur (i.e., phobias, generalized anxiety disorders, panic disorder).

Current Obstacles and Developing Tools

Despite their promise, olfaction stimuli and devices devoted to scent administration present several difficulties, both technical (Kaye, 2004) and in relation to the nature of the stimulus (Auffarth, 2013). First, prolonged exposure to odorants may provoke both peripheral and central adaptation, leading to a decrease of sensorial sensitivity (Dalton, 2000; Poellinger et al., 2001). Olfaction can also adapt itself according to arousal levels and emotions (Krusemark et al., 2013; Pollatos et al., 2007); thus, there is a problem linked to the sensorial level of stimulations and real-time receptor adaptation. Adaptation would be a problem specifically for known odors because the sensitivity to new smells is largely intact (Köster & de Wijk, 1991). Furthermore, one olfactory percept embraces multiple odorants. This could

represent an issue when trying to reproduce autobiographical scents because the remembered percept can be composed of a multitude of different odorants. Second, individual differences in scent perception are also linked to biological (age, sex; Good et al., 2006; Pause et al., 1996) and cultural (Ghinea & Ademoye, 2011) factors. Individuals with poorer scent perception may benefit less than others from the addition of olfaction to VR techniques. Third, even if emotional valence and autobiographical relevance can be valuable advantages, they can also constitute limits because it may be difficult to establish a priori affective reactions to scents from a qualitative and quantitative point of view. Unconscious and automatic reactions should be explicitly explored to avoid negative or aversive associations. Stimulations should be provided above the perceptual threshold. This is especially true in the case of personalized exposure, in which patients should be able to consciously associate the scent and the sensations of safeness with the exposure to stressful elements. To avoid stimulations below the perceptual threshold, participants might be directly asked to report their perception.

User-specific responses to scents (e.g., perceived valence) need to be considered in clinical settings to ensure aversive scents are not used inadvertently with clients because this could reinforce the association that the procedure is aiming to extinct. To overcome these limits, Birkhead et al. (2019) proposed specific guidelines for developing the VR intervention as a meaningful therapeutic tool. They suggested starting from accurate pilot studies to assess the specific needs of the population of interest and its specific symptoms or disorders. The olfaction threshold should also be assessed because it might depend on biological and temperamental factors (age, trait or state anxiety, sex) as well as the condition to target (relaxation or specific desensitization). Psychophysiological correlates should also be continuously monitored, both before and during the intervention, to allow for the adjustment of the stimulation depending on the moment-by-moment psychophysiological state.

To realize the applications proposed in the current work, two main practical solutions can be traced. One approach has been to diffuse scents inside the whole room that the users are in by using a kit with smelling palettes. Another approach has been to use small devices connected to the VR headset. The former solution, however, has some limitations because it does not account for the habituation phenomena and the room scent saturation, whereas the latter more advanced scent-delivery device with a highly controllable scent delivery can avoid these limitations and provide personalization through the selection of scent preferences. Specifically, this second option can deliver scents

directly close to the user's nose or in the real environment with a highly reliable scent-delivery device synchronized with the VR settings and user actions. Notably, to date, some private companies are already trying to develop such tools, offering new possibilities both to conduct preliminary studies on user-preferred autobiographical scents and to perform precise pilot experiments assessing odors and their combination and quantity. Scent palettes actually make it possible to combine several olfactory stimuli, ranging from organic smells to artificial ones, and to make a refined combination of different olfactory elements, embracing specific users' needs.

In addition to stimuli features, methods to deliver olfactory stimuli have dramatically improved in the past few decades, starting from the first rather basic odor-delivery methods (i.e., squeezing bottles containing scents or the first olfactometers; Walla, 2008) to ad hoc and self-made computerized tools (Johnson & Sobel, 2007; Lorig et al., 1999; Lundström et al., 2010). An overview of the state of the art on scent-delivery devices as well as an evaluation of a scent-delivery portable device can be found in Risso et al. (2018). Other technology, such as OWidgets (Maggioni et al., 2019), allows for the integration of scents with the VEs and can direct the user attention using delivery outcomes with predefined spatial location or triggered by the scene in the VE or movement/action of the users. Technologies such as this can facilitate user-tailored and dynamic experiences inside VE with the application of olfactory stimuli.

To date, all of these methodologies have been scarcely used in clinical practice because of objective difficulties in delivering them to the general customer. Up to now, technological applications dealing with the properties of scents have been used in the field of human-machine interaction, aiming at improving user efficiency (Dmitrenko et al., 2017). The clinical application of these methodologies has been limited to date to treat addiction and related disorders (Bordnick et al., 2008; Marissen et al., 2007).

Conclusion

The sense of smell can be a powerful means to be present and to interact within VEs and to access the inner emotional world in an immediate and nonmediated way. Current obstacles linked to the sensorial-stimulation threshold and odor delivery are starting to be addressed by new technological applications, bringing newer opportunities for VR experiences and opening possibilities not only for the entertainment and video-games industry but also for clinical interventions tailored to patients' features.

Transparency

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Declaration of Conflicting Interests

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References

- Abramowitz, E. G., & Lichtenberg, P. (2009). Hypnotherapeutic olfactory conditioning (HOC): Case studies of needle phobia, panic disorder, and combat-induced PTSD. *International Journal of Clinical and Experimental Hypnosis, 57*(2), 184–197. <https://doi.org/10.1080/00207140802665450>
- Abramowitz, E. G., & Lichtenberg, P. (2010). A new hypnotic technique for treating combat-related posttraumatic stress disorder: A prospective open study. *International Journal of Clinical and Experimental Hypnosis, 58*(3), 316–328. <https://doi.org/10.1080/00207141003760926>
- Aiken, M. P., & Berry, M. J. (2015). Posttraumatic stress disorder: Possibilities for olfaction and virtual reality exposure therapy. *Virtual Reality, 19*(2), 95–109. <https://doi.org/10.1007/s10055-015-0260-x>
- Alaoui-Ismaïli, O., Robin, O., Rada, H., Dittmar, A., & Vernet-Maury, E. (1997). Basic emotions evoked by odorants: Comparison between autonomic responses and self-evaluation. *Physiology and Behavior, 62*(4), 713–720. [https://doi.org/10.1016/S0031-9384\(97\)90016-0](https://doi.org/10.1016/S0031-9384(97)90016-0)
- Amores, J., & Maes, P. (2017). Essence: Olfactory interfaces for unconscious influence of mood and cognitive performance. In *CHI '17: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 28–34). Association for Computing Machinery. <https://doi.org/10.1145/3025453.3026004>
- Atsumi, T., & Tonosaki, K. (2007). Smelling lavender and rosemary increases free radical scavenging activity and decreases cortisol level in saliva. *Psychiatry Research, 150*(1), 89–96. <https://doi.org/10.1016/j.psychres.2005.12.012>
- Auffarth, B. (2013). Understanding smell—The olfactory stimulus problem. *Neuroscience & Biobehavioral Reviews, 37*(8), 1667–1679. <https://doi.org/10.1016/J.NEUBIOREV.2013.06.009>
- Baus, O., & Bouchard, S. (2010). The sense of olfaction: Its characteristics and its possible applications in virtual environments. *Journal of Cybertherapy & Rehabilitation, 3*(1), 31–50.
- Baus, O., & Bouchard, S. (2014). Moving from virtual reality exposure-based therapy to augmented reality exposure-based therapy: A review. *Frontiers in Human Neuroscience, 8*, Article 112. <https://doi.org/10.3389/fnhum.2014.00112>
- Baus, O., & Bouchard, S. (2017). Exposure to an unpleasant odour increases the sense of presence in virtual reality. *Virtual Reality, 21*(2), 59–74. <https://doi.org/10.1007/s10055-016-0299-3>
- Baus, O., Bouchard, S., & Nolet, K. (2019). Exposure to a pleasant odour may increase the sense of reality, but not the sense of presence or realism. *Behaviour and Information Technology, 38*(12), 1369–1378. <https://doi.org/10.1080/0144929X.2019.1590458>
- Bensafi, M., Rouby, C., Farget, V., Bertrand, B., Vigouroux, M., & Holley, A. (2003). Perceptual, affective, and cognitive judgments of odors: Pleasantness and handedness effects. *Brain and Cognition, 51*(3), 270–275. [https://doi.org/10.1016/S0278-2626\(03\)00019-8](https://doi.org/10.1016/S0278-2626(03)00019-8)
- Birkhead, B., Khalil, C., Liu, X., Conovitz, S., Rizzo, A., Danovitch, I., Bullock, K., & Spiegel, B. (2019). Recommendations for methodology of virtual reality clinical trials in health care by an international working group: Iterative study. *JMIR Mental Health, 6*(1), Article 11973. <https://doi.org/10.2196/11973>
- Boesveldt, S., Frasnelli, J., Gordon, A. R., & Lundström, J. N. (2010). The fish is bad: Negative food odors elicit faster and more accurate reactions than other odors. *Biological Psychology, 84*(2), 313–317. <https://doi.org/10.1016/j.biopsycho.2010.03.006>
- Bonini, N., Graffeo, M., Hadjichristidis, C., & Perrotta, V. (2015). The effects of incidental scents in the evaluation of environmental goods: The role of congruity. *PsyCh Journal, 4*(2), 66–73. <https://doi.org/10.1002/pchj.76>
- Bordnick, P. S., Traylor, A., Copp, H. L., Graap, K. M., Carter, B., Ferrer, M., & Walton, A. P. (2008). Assessing reactivity to virtual reality alcohol based cues. *Addictive Behaviors, 33*(6), 743–756. <https://doi.org/10.1016/j.addbeh.2007.12.010>
- Chen, Y. (2006). Olfactory display: Development and application in virtual reality therapy. In *16th International Conference on Artificial Reality and Telexistence—Workshops ICAT'06* (pp. 580–584). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/ICAT.2006.95>
- Choi, G. B., Stettler, D. D., Kallman, B. R., Bhaskar, S. T., Fleischmann, A., & Axel, R. (2011). Driving opposing behaviors with ensembles of piriform neurons. *Cell, 146*(6), 1004–1015. <https://doi.org/10.1016/j.cell.2011.07.041>
- Cramer, C. K., Friedman, J. H., & Amick, M. M. (2010). Olfaction and apathy in Parkinson's disease. *Parkinsonism & Related Disorders, 16*(2), 124–126. <https://doi.org/10.1016/j.parkreldis.2009.09.004>
- Dalton, P. (2000). Psychophysical and behavioral characteristics of olfactory adaptation. *Chemical Senses, 25*(4), 487–492. <https://doi.org/10.1093/chemse/25.4.487>
- Delplanque, S., Coppin, G., & Sander, D. (2017). Odor and emotion. In A. Buettner (Ed.), *Springer handbook of odor* (pp. 787–794). Springer.
- Dinh, H. Q., Walker, N., Hodges, L. F., Song, C., & Kobayashi, A. (1999). Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In L. Rosenblum, P. Astheimer, & D. Teichmann (Eds.), *Proceedings IEEE Virtual Reality* (pp. 222–228). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/VR.1999.756955>

- Dmitrenko, D., Maggioni, E., Vi, C. T., & Obrist, M. (2017). What did I sniff? In *Automotive UI '17: Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 154–163). Association for Computing Machinery. <https://doi.org/10.1145/3122986.3122998>
- Dobbelstein, D., Herrdum, S., & Rukzio, E. (2017). inScent: A wearable olfactory display as an amplification for mobile notifications. In *ISWC '17: Proceedings of the 2017 ACM International Symposium on Wearable Computers* (pp. 130–137). Association for Computing Machinery. <https://doi.org/10.1145/3123021.3123035>
- Dong, S., & Jacob, T. J. C. (2016). Combined non-adaptive light and smell stimuli lowered blood pressure, reduced heart rate and reduced negative affect. *Physiology & Behavior*, *156*, 94–105. <https://doi.org/10.1016/j.physbeh.2016.01.013>
- Engen, T., & Ross, B. M. (1973). Long-term memory of odors with and without verbal descriptions. *Journal of Experimental Psychology*, *100*(2), 221–227. <https://doi.org/10.1037/h0035492>
- Freeman, D., Reeve, S., Robinson, A., Ehlers, A., Clark, D., Spanlang, B., & Slater, M. (2017). Virtual reality in the assessment, understanding, and treatment of mental health disorders. *Psychological Medicine*, *47*(14), 2393–2400. <https://doi.org/10.1017/S003329171700040X>
- Gerardi, M., Rothbaum, B. O., Ressler, K., Heekin, M., & Rizzo, A. (2008). Virtual reality exposure therapy using a virtual Iraq: Case report. *Journal of Traumatic Stress*, *21*(2), 209–213. <https://doi.org/10.1002/jts.20331>
- Ghinea, G., & Ademoye, O. A. (2011). Olfaction-enhanced multimedia: Perspectives and challenges. *Multimedia Tools and Applications*, *55*(3), 601–626. <https://doi.org/10.1007/s11042-010-0581-4>
- Good, K. P., Kopala, L., & Doherty, P. (2006). Sex differences and olfactory function. In W. J. Brewer, D. Castle, & C. Pantelis (Eds.), *Olfaction and the brain* (pp. 183–202). <https://doi.org/10.1017/CBO9780511543623.012>
- Harada, H., Kashiwadani, H., Kanmura, Y., & Kuwaki, T. (2018). Linalool odor-induced anxiolytic effects in mice. *Frontiers in Behavioral Neuroscience*, *12*, Article 241. <https://doi.org/10.3389/fnbeh.2018.00241>
- Herz, R. S., Eliassen, J., Beland, S., & Souza, T. (2004). Neuroimaging evidence for the emotional potency of odor-evoked memory. *Neuropsychologia*, *42*(3), 371–378. <https://doi.org/10.1016/j.neuropsychologia.2003.08.009>
- Herz, R. S., & Schooler, J. W. (2002). A naturalistic study of autobiographical memories evoked by olfactory and visual cues: Testing the Proustian hypothesis. *American Journal of Psychology*, *115*(1), 21–32. <https://doi.org/10.2307/1423672>
- Hong, J. Y., Sunwoo, M. K., Ham, J. H., Lee, J. J., Lee, P. H., & Sohn, Y. H. (2015). Apathy and olfactory dysfunction in early Parkinson's disease. *Journal of Movement Disorders*, *8*(1), 21–25. <https://doi.org/10.14802/jmd.14029>
- Johnson, B. N., & Sobel, N. (2007). Methods for building an olfactometer with known concentration outcomes. *Journal of Neuroscience Methods*, *160*(2), 231–245. <https://doi.org/10.1016/j.jneumeth.2006.09.008>
- Jones, S., & Dawkins, S. (2018). The sensorama revisited: Evaluating the application of multi-sensory input on the sense of presence in 360-degree immersive film in virtual reality. In T. Jung, T. Dieck, & M. Claudia (Eds.), *Augmented reality and virtual reality* (pp. 183–197). Springer.
- Kaye, J. (2004). Making scents: Aromatic output for HCI. *Interactions*, *1*(11), 48–61.
- Keverne, E. B. (2004). Importance of olfactory and vomeronasal systems for male sexual function. *Physiology and Behavior*, *83*(2), 177–187. <https://doi.org/10.1016/j.physbeh.2004.08.013>
- King, J. R. (1983). Have the scents to relax? *World Medicine*, *19*, 29–31.
- Kong, E., Monje, F. J., Hirsch, J., & Pollak, D. D. (2014). Learning not to fear: Neural correlates of learned safety. *Neuropsychopharmacology*, *39*, 515–527. <https://doi.org/10.1038/npp.2013.191>
- Köster, E. P., & de Wijk, R. A. (1991). Olfactory adaptation. In D. G. Laing, R. L. Doty, & W. Breipohl (Eds.), *The human sense of smell* (pp. 199–215). Springer. https://doi.org/10.1007/978-3-642-76223-9_10
- Krusemark, E. A., Novak, L. R., Gitelman, D. R., & Li, W. (2013). When the sense of smell meets emotion: Anxiety-state-dependent olfactory processing and neural circuitry adaptation. *Journal of Neuroscience*, *33*(39), 15324–15332. <https://doi.org/10.1523/jneurosci.1835-13.2013>
- Lorig, T. S., Elmes, D. G., Zald, D. H., & Pardo, J. V. (1999). A computer-controlled olfactometer for fMRI and electrophysiological studies of olfaction. *Behavior Research Methods, Instruments, and Computers*, *31*(2), 370–375. <https://doi.org/10.3758/BF03207734>
- Lübke, K. T., & Pause, B. M. (2015, February 1). Always follow your nose: The functional significance of social chemosignals in human reproduction and survival. *Hormones and Behavior*, *68*, 134–144. <https://doi.org/10.1016/j.yhbeh.2014.10.001>
- Lundström, J. N., Gordon, A. R., Alden, E. C., Boesveldt, S., & Albrecht, J. (2010). Methods for building an inexpensive computer-controlled olfactometer for temporally-precise experiments. *International Journal of Psychophysiology*, *78*(2), 179–189. <https://doi.org/10.1016/j.ijpsycho.2010.07.007>
- Maggioni, E., Cobden, R., Dmitrenko, D., Hornbæk, K., & Obrist, M. (2020). SMELL SPACE: Mapping out the olfactory design space for novel interactions. *ACM Transactions on Computer-Human Interaction*, *27*(5), 1–26. <https://doi.org/10.1145/3402449>
- Maggioni, E., Cobden, R., & Obrist, M. (2019). OWidgets: A toolkit to enable smell-based experience design. *International Journal of Human-Computer Studies*, *130*, 248–260.
- Maggioni, E., Cobden, R., Dmitrenko, D., & Obrist, M. (2018). Smell-O-Message: Integration of olfactory notifications into a messaging application to improve users' performance. In *ICMI '18: Proceedings of the 20th ACM International Conference on Multimodal Interaction* (pp. 45–54). Association for Computing Machinery. <https://doi.org/10.1145/3242969.3242975>

- Marissen, M. A. E., Franken, I. H. A., Blanken, P., van den Brink, W., & Hendriks, V. M. (2007). Cue exposure therapy for the treatment of opiate addiction: Results of a randomized controlled clinical trial. *Psychotherapy and Psychosomatics*, *76*(2), 97–105. <https://doi.org/10.1159/000097968>
- Mark, B.-L., Habel, U., Brehl, A.-K., Freiherr, J., Losleben, K., Schneider, F., Amunts, K., & Kohn, N. (2018). Implicit affective rivalry: A behavioral and fMRI study combining olfactory and auditory stimulation. *Frontiers in Behavioral Neuroscience*, *12*, Article 313. <https://doi.org/10.3389/fnbeh.2018.00313>
- Martin, G. N. (1996). Olfactory remediation: Current evidence and possible applications. *Social Science and Medicine*, *43*(1), 63–70. [https://doi.org/10.1016/0277-9536\(95\)00334-7](https://doi.org/10.1016/0277-9536(95)00334-7)
- Matsukura, H., Yoneda, T., & Ishida, H. (2013). Smelling screen: Development and evaluation of an olfactory display system for presenting a virtual odor source. *IEEE Transactions on Visualization and Computer Graphics*, *19*(4), 606–615. <https://doi.org/10.1109/TVCG.2013.40>
- Morris, A. (2017). Obesity: Olfactory senses linked to metabolism. *Nature Reviews Endocrinology*, *13*(9), Article 499. <https://doi.org/10.1038/nrendo.2017.94>
- Morrison, F. G., Dias, B. G., & Ressler, K. J. (2015). Extinction reverses olfactory fear-conditioned increases in neuron number and glomerular size. *Proceedings of the National Academy of Sciences, USA*, *112*(41), 12846–12851. <https://doi.org/10.1073/pnas.1505068112>
- Moss, M., Cook, J., Wesnes, K., & Duckett, P. (2003). Aromas of rosemary and lavender essential oils differentially affect cognition and mood in healthy adults. *International Journal of Neuroscience*, *113*(1), 15–38. <https://doi.org/10.1080/00207450390161903>
- Munyan, I., Neer, S. M., Beidel, D. C., & Jentsch, F. (2016). Olfactory stimuli increase presence in virtual environments. *PLOS ONE*, *11*(6), Article e0157568. <https://doi.org/10.1371/journal.pone.0157568>
- Obrist, M., Gatti, E., Maggioni, E., Vi, C. T., & Velasco, C. (2017). Multisensory experiences in HCI. *IEEE Multimedia*, *24*(2), 9–13. <https://doi.org/10.1109/MMUL.2017.33>
- Obrist, M., Tuch, A. N., & Hornbaek, K. (2014). Opportunities for odor: Experiences with smell and implications for technology. In *CHI '14: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2843–2852). Association for Computing Machinery. <https://doi.org/10.1145/2556288.2557008>
- Pause, B. M., Sojka, B., Krauel, K., Fehm-Wolfsdorf, G., & Ferstl, R. (1996). Olfactory information processing during the course of the menstrual cycle. *Biological Psychology*, *44*(1), 31–54. [https://doi.org/10.1016/S0301-0511\(96\)05207-6](https://doi.org/10.1016/S0301-0511(96)05207-6)
- Pizzoli, S. F. M., Mazzocco, K., Triberti, S., Monzani, D., Alcañiz Raya, M. L., & Pravettoni, G. (2019). User-centered virtual reality for promoting relaxation: An innovative approach. *Frontiers in Psychology*, *10*, Article 479. <https://doi.org/10.3389/fpsyg.2019.00479>
- Poellinger, A., Thomas, R., Lio, P., Lee, A., Makris, N., Rosen, B. R., & Kwong, K. K. (2001). Activation and habituation in olfaction—An fMRI study. *NeuroImage*, *13*(4), 547–560. <https://doi.org/10.1006/NIMG.2000.0713>
- Pollatos, O., Kopietz, R., Linn, J., Albrecht, J., Sakar, V., Anzinger, A., Schandry, R., & Wiesmann, M. (2007). Emotional stimulation alters olfactory sensitivity and odor judgment. *Chemical Senses*, *32*(6), 583–589. <https://doi.org/10.1093/chemse/bjm027>
- Riera, C. E., Tsaousidou, E., Halloran, J., Follett, P., Hahn, O., Pereira, M. M. A., Ruud, L. E., Alber, J., Tharp, K., Anderson, C. M., Brönneke, H., Hampel, B., de Magalhaes Filho, C. D., Stahl, A., Brüning, J. C., & Dillin, A. (2017). The sense of smell impacts metabolic health and obesity. *Cell Metabolism*, *26*(1), 198–211.e5. <https://doi.org/10.1016/j.cmet.2017.06.015>
- Rinaldi, L., Maggioni, E., Olivero, N., Maravita, A., & Girelli, L. (2018). Smelling the space around us: Odor pleasantness shifts visuospatial attention in humans. *Emotion*, *18*(7), 971–979. <https://doi.org/10.1037/emo0000335>
- Risso, P., Covarrubias Rodriguez, M., Bordegoni, M., & Gallace, A. (2018). Development and testing of a small-size olfactometer for the perception of food and beverages in humans. *Frontiers in Digital Humanities*, *5*, Article 7. <https://doi.org/10.3389/fdigh.2018.00007>
- Rizzo, A., “Skip” Difede, J., Rothbaum, B. O., Reger, G., Spitalnick, J., Cukor, J., & Mclay, R. (2010). Development and early evaluation of the Virtual Iraq/Afghanistan exposure therapy system for combat-related PTSD. *Annals of the New York Academy of Sciences*, *1208*(1), 114–125. <https://doi.org/10.1111/j.1749-6632.2010.05755.x>
- Rizzo, A., & Shilling, R. (2018). Clinical virtual reality tools to advance the prevention, assessment, and treatment of PTSD. *European Journal of Psychotraumatology*, *8*(Suppl. 5), Article 1414560. <https://doi.org/10.1080/20008198.2017.1414560>
- Sarafoleanu, C., Mella, C., Georgescu, M., & Perederco, C. (2009). The importance of the olfactory sense in the human behavior and evolution. *Journal of Medicine and Life*, *2*(2), 196–198. <http://www.ncbi.nlm.nih.gov/pubmed/20108540>
- Schiffman, S. (1992). Ageing and the sense of smell: Potential benefits of fragrance enhancement. In S. Van Toiler & G. Dodd (Eds.), *Fragrance: The psychology and biology of perfume* (pp. 51–62); Elsevier.
- Schiffman, S. S., & Siebert, J. M. (1991). New frontiers in fragrance use. *Cosmetics & Toiletries* *106*(6), 39–45.
- Seigneuric, A., Durand, K., Jiang, T., Baudouin, J.-Y., & Schaal, B. (2010). The nose tells it to the eyes: Crossmodal associations between olfaction and vision. *Perception*, *39*(11), 1541–1554. <https://doi.org/10.1068/p6740>
- Serrano, B., Baños, R. M., & Botella, C. (2016). Virtual reality and stimulation of touch and smell for inducing relaxation: A randomized controlled trial. *Computers in Human Behavior*, *55*, 1–8. <https://doi.org/10.1016/J.CHB.2015.08.007>
- Shanahan, L. K., Gjorgieva, E., Paller, K. A., Kahnt, T., & Gottfried, J. A. (2018). Odor-evoked category reactivation in human ventromedial prefrontal cortex during sleep promotes memory consolidation. *Elife*, *7*, Article e39681. <https://doi.org/10.7554/eLife.39681>

- Smith, J. C. (1999). *ABC relaxation training: An evidence-based approach*. Springer.
- Sowndhararajan, K., & Kim, S. (2016). Influence of fragrances on human psychophysiological activity: With special reference to human electroencephalographic response. *Scientia Pharmaceutica*, *84*(4), 724–751. <https://doi.org/10.3390/scipharm84040724>
- Van Hartevelt, T. J., & Kringelbach, M. L. (2012). The olfactory system. In J. K. Mai & G. Paxinos (Eds.), *The human nervous system* (3rd ed., pp. 1219–1238). Academic Press. <https://doi.org/10.1016/B978-0-12-374236-0.10034-3>
- Walla, P. (2008). Olfaction and its dynamic influence on word and face processing: Cross-modal integration. *Progress in Neurobiology*, *84*, 192–209. <https://doi.org/10.1016/j.pneurobio.2007.10.005>
- Warrenburg, S. (2005). Effects of fragrance on emotions: Moods and physiology. *Chemical Senses*, *30*(Suppl. 1), i248–i249. <https://doi.org/10.1093/chemse/bjh208>
- Willander, J., & Larsson, M. (2006). Smell your way back to childhood: Autobiographical odor memory. *Psychonomic Bulletin & Review*, *13*(2), 240–244.
- Willander, J., & Larsson, M. (2007). Olfaction and emotion: The case of autobiographical memory. *Memory & Cognition*, *35*(7), 1659–1663. <https://doi.org/10.3758/BF03193499>
- Yeshurun, Y., & Sobel, N. (2010). An odor is not worth a thousand words: From multidimensional odors to unidimensional odor objects. *Annual Review of Psychology*, *61*(1), 219–241. <https://doi.org/10.1146/annurev.psych.60.110707.163639>