Smells as Communication Pathways – why Emotions Pass through the Nose

Authors

Ilona Croy[1, 2], Antonie Bierling[1, 2, 3]

Affiliations

1 Institute for Clinical Psychology, Friedrich Schiller University of Jena, Germany

2 Department of Psychotherapy and Psychosomatics, University Hospital "Carl Gustav Carus" of Dresden, Germany

3 Institute for Material Science and Nanotechnology, Technical University of Dresden, Germany

Key words

Olfaction, emotion, communication, environment, human

Bibliography

Laryngo-Rhino-Otol 2023; 102: S93–S100

DOI 10.1055/a-1935-3214

ISSN 0935-8943

Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence

Prof. Dr. Ilona Croy
Professor for Clinical Psychology
Institute for Psychology
Friedrich Schiller University of Jena
Am Steiger 3/1
07743 Jena
Germany
ilona.croy@uni-jena.de

ABSTRACT

For many species, the sense of smell is the most important sensory system for interacting with the environment and conspecifics. In contrast, the role of perception and communication of chemosensory information in humans has long been underestimated. The human sense of smell was considered less reliable, so that it was given less importance compared to visual and auditory sensory impressions. For some time now, a growing branch of research has been dealing with the role of the sense of sell in emotion and social communication, which is often only perceived subconsciously. This connection will be examine in more detail in this article. First, the basics regarding the structure and function of our olfactory system will be described for better understanding and classification. Then, with this background knowledge, the significance of olfaction for interpersonal communication and emotions will be discussed. Finally, we conclude that people suffering from olfactory disorders have specific impairments in their quality of life.

Contents

1. Smelling is one of the oldest ways of communication

No creature exists on its own. To survive, all living beings must assess and process information from their environment. We, as human beings, for example, can receive sound waves and light stimuli and retrieve information from the sounds and images: Where is the food? Where is the enemy? Where is it cozy and homelike?

During evolution, the ability to perceive information has become more sophisticated. Especially vision and hearing are relatively new evolutionary performances of living beings. However, one of the oldest kinds of information is the perception of molecules from the environment. This performance is called chemosensation i. e., chemical binding of a molecule from the environment to an endogenous receptor. This ability is estimated to be a whopping 500 million years old [1]. In vertebrates, this ability of chemosensation is split into two chemical sensory systems of olfaction and gustation consisting of two different sensory organs with the tongue's taste buds and the olfactory epithelium of the nose.

The ability to retrieve information from the environment is only useful if this information leads to reasonable behavior. For example, the information about where the food is, is only beneficial if we move on to the food source and eat. The targeted moving toward a stimulus (or also away from the stimulus) is called motivation which is utmost pronounced when associated with strong emotions. So, emotions may be considered as the motor of our motivation. The anatomical base of our emotions is in the (evolutionarily) older structures of our brain, i. e. the subcortical areas, and the older areas of the cerebral cortex, the so-called allocortex. The brain of evolutionarily ancient reptiles and amphibians is dominated by structures serving for processing chemosensory stimuli and emotion and motivation (▶ **Fig. 1**). Of course, during evolution, new areas like the neocortex have developed. However, the same structures responsible for emotional processing of olfactory information in amphibians [2] are found in humans today. One of the more recent hypotheses states that the structures for chemosensation have further developed with those that are responsible for emotional perception [3]. This appears to make sense – the more pronounced the information intake from the environment, the higher the motivation to use this information. The same functions that that thus supervised the function of self and species-preservation in invertebrates still generate emotion and motivation in humans today (LeDeux 2021).

Interestingly, it is assumed that the evolution of olfactory function in the first central areas of olfaction, the olfactory bulb and the subordinate piriform gyrus, was one of the main reasons for the evolution of the entire brain in the Jurassic period, during the time of the dinosaurs [4].

In contrast to more recent types of information reception such as vision or hearing, the olfactory sense appears to be somehow "antiquated": It takes about 70 to 100 ms for an incoming molecule to trigger a potential at the olfactory mucosa [5] and about 600 ms before humans are able to react on an olfactory stimulus [6]. Thisis at least three times longer than the time it takes us to react upon a visual impression [7]. Additionally, olfactory information can only be recorded when new breath reaches our olfactory epithelium – typically every 2 seconds [8, 9]. Beside this rather poor temporal resolution, olfaction is also very poorly wired spatially. Without moving the head, humans cannot even tell whether an odor was inhaled through the right or left nostril. Thus, it is not surprising that people consider their sense of smell to be less reliable than their other sensory systems [10].

Despite the fact that so many more precise senses have evolved, smelling has an enormous impact on our orientation in the world, our well-being, and our interpersonal communication. The next chapters will describe why.

2. Olfactory function

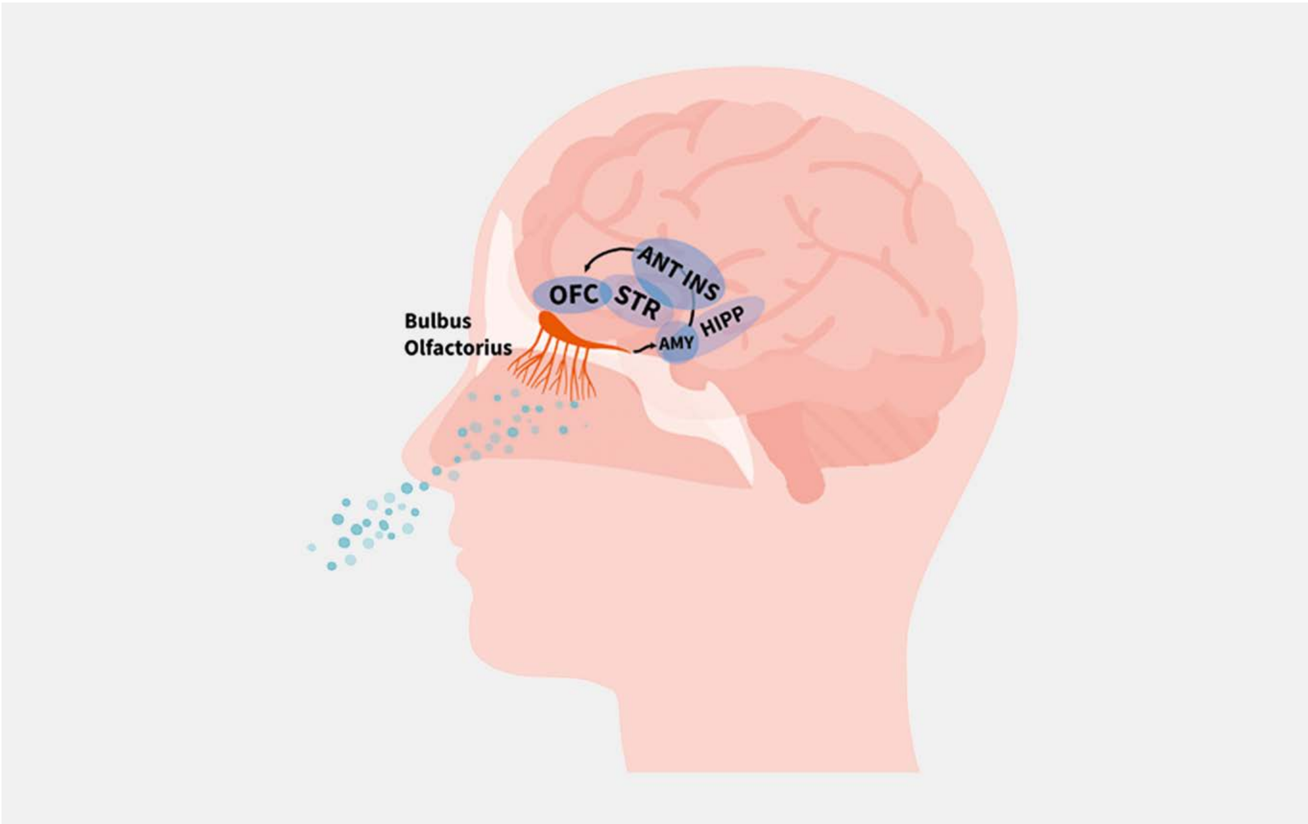
We can differentiate between the quality and the quantity of olfaction. The quality indicates whether what I smell also corresponds to the current environmental stimulus. For example, does the apple smell like an apple or something else entirely? A typical disorder of quality is parosmia. In this disorder, odors are perceived in an altered way. Unfortunately, this change is typically to the negative which means that the apple does not smell like an apple but foul, pungent, or even fecal. A special case of this kind of disorder is phantosmia, in which odors (also of typically negative quality) are perceived even through there is no source at all – the brain creates an olfactory hallucination. It is estimated that disorders of quality occur in about 1–5 % of the population [11]. For example, relatively typical is the development of parosmia after viral infectious diseases. In respiratory infections, cells of the olfactory epithelium are often also damaged. During the reformation of the destroyed nerve endings, the correct wiring to the olfactory bulb must first be relearned. In this process, the symptoms of parosmia may temporarily occur. This occurs frequently, for example, as a consequence of Covid-19 infection [12].

Disorders of the olfactory quantity are much more common and affect about 19–24 % of the population, with the main cause of decreasing olfactory sensitivity being age-related. Older people are less sensitive than younger ones. Among quantitative smell disorders, several types can be distinguished. Hyposmia describes a condition where scents can only be perceived in relatively high concentrations and fine nuances are not recognized. Anosmia, on the other hand, refers to the total inability to perceive an olfactory impression. A special case here is congenital anosmia. This disorder, in which people are unable to smell from birth, affects approximately one in five to ten thousand people according to our estimates [13], mostly due to a missing or underdeveloped olfactory bulb.

3. What is the importance of olfaction?

In a highly recommended review article, Richard Stevenson describes the functions of olfaction and divides them into three areas: Food intake, indication of hazard stimuli in the environment, and social communication [14] (▶ **Fig. 2**).While the first two areas serve primarily self-preservation, social communication serves primarily species preservation, i. e., reproduction and caring for our fellow humans.

That smelling is of fundamental importance for food intake is clear to anyone who has ever lost his sense of smell. In fact, what we commonly refer to as the "taste" of a food consists largely of olfactory information. Our sense of taste is only able to distinguish

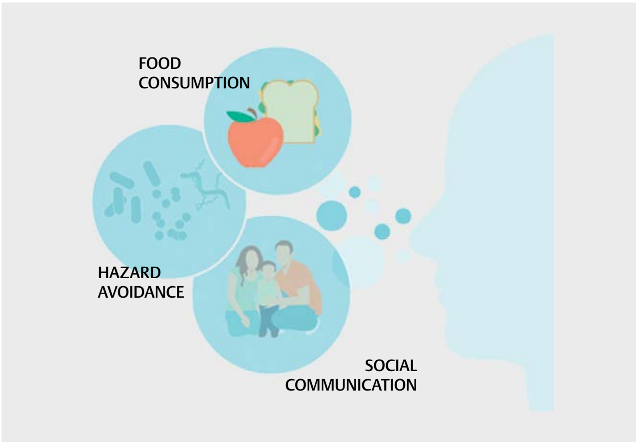


▶ **Fig. 1 Odor and emotion – shared structures:** The close connection between odor perception and emotions can probably also be traced back to shared structures in the respective information processing. After stimulus transmission of odor information from the olfactory epithelium to the olfactory bulb, the information is first transmitted to the primary olfactory cortex (piriform cortex, anterior olfactory nucleus, entorhinal cortex, amygdala [AMY]), then processed in secondary (orbitofrontal cortex [OFC], hippocampus [HIPP], anterior insula [ANT INS]) and tertiary (cingulate gyrus, superior temporal gyrus, striatum [STR]) structures. Thus, olfactory and emotion/salience processing share the interfaces of the amygdala, cingulate gyrus, and insula.

sweet, sour, bitter, umami and salty. The specific aroma of a strawberry or cherry, or the distinctive Christmas scent of cinnamon stars, is mediated by molecules that bind to our olfactory mucosa. Accordingly, people with hyposmia or anosmia typically complain that food tastes bland [15].

What most people are less aware of is that odors warn us about dangers in the environment. We typically associate the word "danger" with immediate threats that cause fear, such as a steep cliff, wild animals, or dark corners of houses and sounds of fighting. Our olfactory system does not warn us of any of these examples; it is also too slow and sluggish for that. Smelling warns us of the small invisible - but at least as deadly - threats: microorganisms. We smell when milk is spoiled, we smell when a tooth is rotten, we smell the feces in the subway underpass, and we smell the sweetly foul odor of festering wounds. The emotion that is triggered here is not one that prepares a quick fight and flight response, as fear does. The emotion we experience when odors indicate potential threats from microorganisms causes us to spit out the milk, wash our hands, and make it very clear to others with our facial expressions alone: you shouldn't touch this. We are disgusted. Our olfactory system has a particularly close connection to feelings of disgust. In contrast to visual impressions or sounds, no habituation takes place with disgusting smells, but we experience a strong reaction each time anew, which is accompanied by a drop in blood pressure [16]. When someone is disgusted, this also increases our attention to odors, allowing us to detect potential dangers more quickly and in lower concentrations [17]. The disgust we experience from smell is accompanied by a typical facial expression, which is characterized by a contraction of the nose, lowering of the eyebrows, and a tightened upper lip.

Our olfactory perception is so sensitive that we can even detect illness in other people. In a sensational experiment, Olsson and colleagues injected eight subjects with the substance endotoxin, which triggers an immune response in the body for a limited period of about 4 h, comparable to the nonspecific immune response to the common cold [18]. Meanwhile, subjects wore tight-fitting T-shirts to collect underarm sweat as a body odor sample. Subsequently, they had 40 other subjects smell the samples. This showed that the subjects rated samples with "disease odor" as disproportionately more unpleasant, intense and "unhealthy" than samples in which the body odor donors were injected with saline instead of endotoxin. The experiment is particularly interesting when viewed in the context of another finding: Unpleasant odors make us more attentive to touch and cause us to experience touch



▶ **Fig. 2 Functions of the sense of smell.** According to a review article published by Stevenson in 2010 [14], the human sense of smell primarily fulfils the function of food intake since scents contribute significantly to aroma perception. In addition, scents warn of potential microbial hazards and elicit disgust responses. Furthermore, they contribute to aspects of social communication by conveying familiarity, for example, but also rewarding interactions and providing important information about the other person, for example fitness or diseases.

as more unpleasant [19]. This occurs through a direct feedback loop in the brain between olfactory areas, insular cortex, and the hub for touch processing, the somatosensory cortex [20]. Thus, our brain is wired to avoid touch when we perceive unpleasant odors. This reduces the risk of contagion.

Stevenson states that three low-molecular weight compounds in particular – nitrogenous indoles, sulfurous thiols, and short-chain fatty acids – are considered as the prototypical characteristics of disgusting odors [21]. These three compounds reliably signal putrefaction, i. e., the microbial degradation of proteins, which is usually accompanied by the production of toxins and can be found in many bad odors [22]. Humans react to such odors by constricting nasal permeability, which is reflected in the typical disgust face (see above) [23]. According to Darwin, this has a self-regulating function to avoid the entry of harmful substances into the body [24] and at the same time thissignals “disgust” and “hazard” to observers, thus also warning others.

4. Social communication

That smelling is important for social communication in the animal kingdom is probably known to most people. A typical example is dogs, which sniff each other and their droppings extensively from all sides before they move on with their masters or mistresses. Humans typically do not do this, we have a very sophisticated means of communication in the form of language. Nevertheless, olfactory impressions of our fellow humans can provide interesting information and lead to very specific behavior. Take parents, for example, who can’t get enough of the sweet, soft smell of their babies and always want to smell their heads. Or the phenomenon that we would like to bury ourselves in the armpit or in the pleasant smell of the sweater worn by our partner. Body odors thus signal not only the presence of another person, but also a very clear rewarding message. Humans are relatively good at recognizing the smell of their partner [25] or of their own children [26]. Such smells are processed in the so-called reward centers of the brain [27, 28]. This fits well with the experience that we like to linger longer and “smell more” in such situations. The rewarding property, especially of children’s smells, is a genetic selection advantage, since the desire to smell the child can only be redeemed if the child is also nearby and thus experiences affectionate attention. Consequently, the parent-child bond is strengthened. Interestingly, mothers with diagnosed attachment problems to the child are less able to recognize the smell of their children and - in contrast to mothers with good attachment - they also do not prefer the smell of their children [29].

dors also signal sexual attraction to us. For example, derivatives of testosterone, the male sex hormone found in male sweat, influence the length of the female menstrual cycle [30] and also affect women’s mood [31]. Conversely, men are coincidentally able to correctly detect whether a woman is in the phase of ovulation by a woman’s body odor[32], and female body odor during ovulation increases testosterone concentration in men [33].

A review article recently demonstrated the importance of body odor in the formation, maintenance, and dissolution of intimate partnerships [34]. In particular, the compilation of the literature showed that familiarity conveyed via body odors may be involved in the maintenance, whereas feelings of disgust may be involved in the dissolution of a partnership. Finally, odors can promote the development of a partnership through olfactory mediated sexual attraction. Accordingly, people who have lost the sense of smell also often complain of decreased sexual interest [35].

A phenomenon that has received much attention in recent years is the human ability to recognize the phenotypic immune status of potential mates. The basic idea here is that humans have different encodings of the innate immune system. That is, not everyone is immune to the same pathogens, but there is quite a bit of variance in the population. The coding of the innate immune system is found in the so-called major histocompatibility complex (MHC for short). It is favorable for the individual to have as heterogeneous an expression of this complex as possible in order to be resistant to as many pathogens as possible. Since the MHC is inherited in a codominant manner [36], each individual receives a heterogeneous expression due to the fact that both parents possess a different MHC. Thus, in order to have the healthiest possible offspring, it is favorable if the mother and father differ in MHC. In the animal kingdom, fish [37] and mice [38], which have different MHC coding, therefore prefer to mate. For humans, it has also been shown that women find the odor of MHC-different men more attractive than that of MHC-similar men [39] and this is dependent on the use of the pill [40]. However, these studies could not always be replicated [41]. In Western cultures, there also appears to be no relevant impact of the so-called MHC effect on mate choice. In a study of over 3000 married couples, we were able to show that couples are not disproportionately likely to meet that are dissimilar to MHC. This is probably because MHC diversity is so high that it is very unlikely to encounter individuals who have a high match in MHC outside of laboratory studies [42]. Body odors can also convey some other information about our fellow humans. Interestingly, for example, vegetarian diets can be detected via the sense of smell [43]. In a review article, de Groot and colleagues [44] assume that humans are able to detect both more persistent (so-called “trait”) aspects of a person, such as the already discussed genetics, age [45] or even personality traits [46], as well as dynamic emotional states (so-called “state” aspects). The underlying assumption is that the different expression of traits in combination with dynamic states results in a characteristic chemical profile in body odor. That different emotions are indeed expressed in distinguishable chemical “fingerprints” was shown by Smeets et al. by comparing the chemical composition of underarm sweat taken while watching approximately 30-minute happy, scary, or neutral videos [47]. We learn these different “body odor profiles” in contact with our fellow human beings, so that over time certain body odors become associated (consciously or unconsciously) with these traits and states [44]. In various experiments, for example, it could be shown that people are able to distinguish fear or pleasure in the smell of armpit sweat from the smell of sweat in a control condition (often sporting activity) [48, 49]. As a result, the emotion communicated by the odor may even transfer to the other person [50–52], which may be reflected, for example, in a change in the recipient’s facial expression [50]. In addition to fear and pleasure, aggression [53], sexual arousal or disgust [50], for example, can also be transported and communicated via changes in body odor.

However, it is by no means the case that we as humans are able to determine precisely from body odor how other people are doing. Body odor is received as holistic information that gives us an impression, or a kind of “background”. Together with the sight of the other person, the voice and the type of touch, a holistic person perception is formed. An interesting study in this context was conducted with dental students. Here it was shown that they were influenced in their performance by the fearful odor of their patients - although they were not even aware of the odor [54].

Although odor information is much less precise than other sources of information, it can provide us with additional and, in everyday life, usually subtle assessments about other people. Accordingly, individuals who have a very well-developed sense of smell seem to have some advantage in evaluating other people: for example, they report that they get along better with others [55, 56]. This was shown by increased expression in the personality trait “agreeableness,” which is characterized by being empathetic, cooperative, and helpful. People who can smell well may be better able to use subtle olfactory cues from their environment to empathize with others or empathize with their feelings. In fact, a recent study shows that smells may even play a role in how we choose our friends, and our body odor may resemble that of our friends [57].

5. Olfaction and emotion processing

From the above functions of smelling, it follows that our ability to smell affects how we perceive the world. Smelling influences who we find attractive, how much we like to cuddle with our children, and which things we prefer to avoid. Accordingly, it is plausible that smelling has an impact on how we feel. Moreover, from the introductory remarks on the anatomy and evolution of the olfactory system, it is clear that our sense of smell has very close wiring to emotion centers. Accordingly, one may wonder whether people without a sense of smell experience the world differently. Indeed, higher vulnerability to depression is shown in individuals who have lost their sense of smell [15] and also in individuals who have never been able to smell in their lives [58]. Interestingly, individuals who are unaware of their (typically age-related) loss of smell do not appear to be at higher risk for depression [59]. This suggests that, at least in the case of acquired olfactory disorders, subjective suffering from the loss plays a more crucial role, i. e., some people do not seem to be “bothered” by their (objectively) reduced olfactory ability in their everyday life. The residual olfactory function - at least in the case of hyposmia - seems to be rather sufficient not to lead to increased depression vulnerability.

Viewed from the other side, major depression is often associated with decreased olfactory function in the areas of threshold, identification, and discrimination, as well as decreased central processing of odors [60]. A long duration of depression increases the susceptibility to decreased olfactory sensitivity [61].

It can be assumed that the connection between depression and impaired olfaction is not a coincidence but stems from the close connection between olfactory structures and central structures involved in emotion and salience processing. Thus, McLean already hypothesized an anatomically based involvement of the sense of smell in depressive states and originally described the sense of smell as an important part of the “visceral brain” [62], which he later called the “limbic system” [63]. The anatomical pathway of odor processing leads from the olfactory epithelium through the olfactory nerves to the olfactory bulb, which is the first central relay station of odor processing. From there, odor information is relayed to the primary olfactory cortex (piriform cortex, anterior olfactory nucleus, entorhinal cortex, amygdala) [64]. Secondary olfactory structures are formed by the orbitofrontal cortex (OFC), hippocampus, and anterior insula [65] and tertiary structures are the cingulate gyrus and superior temporal gyrus [66]. In this cascade, the amygdala, anterior cingulate cortex, and insula can be highlighted as common relevant brain regions for odor and salience processing [67]. This anatomical overlap is particularly pronounced in the anterior part of the insula, which is activated during both emotional tasks and olfactory stimulation [68]. These shared pathways are functionally relevant. In rat models, experimental removal of the olfactory bulb (so-called bulbectomy) leads to depression-like behavior and changes in neurotransmitter concentrations [69], as well as degeneration of nerve fibers in the amygdala [70]. In humans, reduced or absent olfactory input due to an aplastic or hypoplastic olfactory bulb is also associated with depressive symptoms [58, 71, 72]. Our own work also suggests that olfactory stimulation can alter the reactivity of central salience structures to emotional stimuli. For example, we have shown that patients with acquired hyposmia exhibit reduced processing of emotional images [73]. The hyposmia and healthy control groups were presented with images with emotional and non-emotional content while their brain activation was tracked in the fMRI scanner. Although the two groups did not differ in the rating and processing of non-emotional images, the hyposmia group rated the emotional images as significantly less arousing, and the patients showed decreased processing of emotional images in salience-relevant brain structures [73]. Based on this, there are currently efforts in our laboratory to harness the anatomical interface for depression treatment by attempting to send electrical signals to the brain via the olfactory mucosa to stimulate emotion processing. However, this research is still in its infancy.

6. Conclusions

With the above we have tried to clarify the functions of olfaction for humans, which are mainly focused on food intake, hazard avoidance and interpersonal communication. Individuals with an impairment of the olfactory system accordingly report problems in food preparation and consumption, worry more about potential dangers, and report specific limitations in the social domain, especially in partnered sexuality. In addition, the link between olfactory processing and emotion-processing structures suggests an interface between olfaction and depression that, on one hand, should be noted by otolaryngologists and explicitly addressed in the treatment of patients with olfactory disorders, and, on the other hand, may open an interesting window for the treatment of depressive disorders.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Stoddart DM. The ecology of vertebrate olfaction. Springer Science & Business Media; 2012

[2] Laberge F et al. Evolution of the amygdala: new insights from studies in amphibians. Brain, Behavior and Evolution 2006; 67: p 177–187

[3] Northcutt RG. Understanding vertebrate brain evolution. Integrative and comparative biology 2002; 42: p 743–756

[4] Rowe TB, Macrini TE, Luo Z-X. Fossil evidence on origin of the mammalian brain. science 2011; 332: p 955–957

[5] Kobal G. Elektrophysiologische untersuchungen des menschlichen geruchssinns. Thieme; 1981

[6] Cain W. Olfaction and the common chemical sense: some psychophysical contrasts. Sensory processes 1976; 1: p 57–67

[7] Spence C, Driver J. On measuring selective attention to an expected sensory modality. Perception & psychophysics 1997; 59: p 389–403

[8] Sela L, Sobel N. Human olfaction: a constant state of change-blindness. Experimental brain research 2010; 205: p 13–29

[9] Schriever V et al. Olfactory speed – Temporal odor processing of paired stimuli. Neuroscience 2015; 295: p 72–79

[10] Mainland JD. Olfaction. Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience 2018; 2: p 1–46

[11] Olofsson J, Ekesten F, Nordin S. Smell distortions: Prevalence, longevity and impact of parosmia in a population-based, longitudinal study spanning 10 years 2021

[12] Ohla K et al. Increasing incidence of parosmia and phantosmia in patients recovering from COVID-19 smell loss. medRxiv 2021

[13] Bojanowski V, Hummel T, Croy I. Isolierte congenitale Anosmie–Klinische und alltägliche Aspekte eines Lebens ohne Geruchssinn. Laryngo-Rhino-Otologie 2013; 92: p 30–33

[14] Stevenson RJ. An initial evaluation of the functions of human olfaction. Chemical senses 2010; 35: p 3–20

[15] Croy I, Nordin S, Hummel T. Olfactory disorders and quality of life – an updated review. Chemical senses 2014; 39: p 185–194

[16] Croy I et al. The sensory channel of presentation alters subjective ratings and autonomic responses toward disgusting stimuli – Blood pressure, heart rate and skin conductance in response to visual, auditory, haptic and olfactory presented disgusting stimuli. Frontiers in Human Neuroscience 2013; 7: p 510

[17] Chan KQ et al. Disgust lowers olfactory threshold: a test of the underlying mechanism. Cognition and Emotion 2020; 34: p 621–627

[18] Olsson MJ et al. The scent of disease: human body odor contains an early chemosensory cue of sickness. Psychol Sci 2014; 25: p 817–823

[19] Croy I, Angelo SD, Olausson H. Reduced pleasant touch appraisal in the presence of a disgusting odor. PloS one 2014; 9: p e92975

[20] Croy I et al. Olfactory modulation of affective touch processing – A neurophysiological investigation. Neuroimage 2016; 135: p 135–141

[21] Stevenson RJ et al. A proximal perspective on disgust. Emotion Review 2019; 11: p 209–225

[22] Laska M et al. Olfactory sensitivity for putrefaction-associated thiols and indols in three species of non-human primate. Journal of Experimental Biology 2007; 210: p 4169–4178

[23] Susskind JM et al. Expressing fear enhances sensory acquisition. Nature neuroscience 2008; 11: p 843–850

[24] Darwin C. (1965). The expression of the emotions in man and animals. London: John Murray 1872

[25] Mahmut MK, Stevenson RJ, Stephen I. Do women love their partner's smell? Exploring women's preferences for and identification of male partner and non-partner body odor. Physiology & behavior 2019; 210: p 112517

[26] Schäfer L et al. Body odours as a chemosignal in the mother-child relationship: new insights based on an human leucocyte antigen-genotyped family cohort. Philosophical Transactions of the Royal Society B 2020; 375: p 20190266

[27] Lundström JN et al. Maternal status regulates cortical responses to the body odor of newborns. Frontiers in psychology 2013; p 597

[28] Schäfer L, Hummel T, Croy I. The design matters: How to detect neural correlates of baby body odors. Frontiers in neurology 2019; 9: p 1182

[29] Croy I et al. Mother-child bonding is associated with the maternal perception of the child's body odor. Physiology & behavior 2019; 198: p 151–157

[30] Shinohara K et al. Axillary pheromones modulate pulsatile LH secretion in humans. Neuroreport 2001; 12: p 893–895

[31] Jacob S, McClintock MK. Psychological state and mood effects of steroidal chemosignals in women and men. Hormones and Behavior 2000; 37: p 57–78

[32] Haselton MG, Gildersleeve K. Human ovulation cues. Current Opinion in Psychology 2016; 7: p 120–125

[33] Miller SL, Maner JK. Scent of a woman: Men's testosterone responses to olfactory ovulation cues. Psychological science 2010; 21: p 276–283

[34] Mahmut MK, Croy I. The role of body odors and olfactory ability in the initiation, maintenance and breakdown of romantic relationships – A review. Physiology & behavior 2019; 207: p 179–184

[35] Schäfer L et al. Sexual desire after olfactory loss: Quantitative and qualitative reports of patients with smell disorders. Physiology & behavior 2019; 201: p 64–69

[36] Janeway CA Jr et al. The major histocompatibility complex and its functions, in Immunobiology: The Immune System in Health and Disease. 5th edition 2001 Garland Science

[37] Wegner KM et al. Parasite selection for immunogenetic optimality. Science 2003; 301: p 1343–1343

[38] Leinders-Zufall T et al. MHC class I peptides as chemosensory signals in the vomeronasal organ. Science 2004; 306: p 1033–1037

[39] Wedekind C et al. MHC-dependent mate preferences in humans. Proceedings of the Royal Society of London. Series B: Biological Sciences 1995; 260: p 245–249

[40] Wedekind C, Füri S. Body odour preferences in men and women: do they aim for specific MHC combinations or simply heterozygosity? Proceedings of the Royal Society of London. Series B: Biological Sciences 1997; 264: p 1471–1479

[41] Havlíček J, Winternitz J, Roberts SC. Major histocompatibility complex-associated odour preferences and human mate choice: near and far horizons. Philosophical Transactions of the Royal Society B 2020; 375: p 20190260

[42] Croy I et al. Marriage does not relate to major histocompatibility complex: a genetic analysis based on 3691 couples. Proceedings of the Royal Society B 2020; 287: p 20201800

[43] Havlicek J, Lenochova P. The effect of meat consumption on body odor attractiveness. Chem Senses 2006; 31: p 747–752

[44] de Groot JHB, Semin GR, Smeets MAM. On the Communicative Function of Body Odors:A Theoretical Integration and Review. Perspectives on Psychological Science 2017; 12: p 306–324

[45] Haze S et al. 2-Nonenal newly found in human body odor tends to increase with aging. Journal of investigative dermatology 2001; 116: p 520–524

[46] Sorokowska A, Sorokowski P, Szmajke A. Does personality smell? Accuracy of personality assessments based on body odour. European Journal of Personality 2012; 26: p 496–503

[47] Smeets MA et al. Chemical fingerprints of emotional body odor. Metabolites 2020; 10: p 84

[48] Chen D, Haviland-Jones J. Human olfactory communication of emotion. Perceptual and motor skills 2000; 91: p 771–781

[49] Ackerl K, Atzmueller M, Grammer K. The scent of fear. Neuroendocrinology Letters 2002; 23: p 79–84

[50] de Groot JH et al. Chemosignals communicate human emotions. Psychological science 2012; 23: p 1417–1424

[51] Prehn-Kristensen A et al. Induction of empathy by the smell of anxiety. PLoS One 2009; 4: p e5987

[52] Pause BM et al. Positive emotional priming of facial affect perception in females is diminished by chemosensory anxiety signals. Chemical senses 2004; 29: p 797–805

[53] Mutic S et al. You smell dangerous: communicating fight responses through human chemosignals of aggression. Chemical senses 2016; 41: p 35–43

[54] Singh PB et al. Smelling anxiety chemosignals impairs clinical performance of dental students. Chemical Senses 2018; 43: p 411–417

[55] Croy I et al. Agreeable smellers and sensitive neurotics – correlations among personality traits and sensory thresholds. PLoS One 2011; 6: p e18701

[56] Bendas J, Hummel T, Croy I. Olfactory function relates to sexual experience in adults. Archives of Sexual Behavior 2018; 47: p 1333–1339

[57] Ravreby I, Snitz K, Sobel N. There is chemistry in social chemistry. Science Advances 2022; 8: p eabn0154

[58] Croy I et al. Learning about the functions of the olfactory system from people without a sense of smell. PloS one 2012; 7: p e33365

[59] Oleszkiewicz A et al. Consequences of undetected olfactory loss for human chemosensory communication and well-being. Philosophical Transactions of the Royal Society B 2020; 375: p 20190265

[60] Kohli P et al. The association between olfaction and depression: a systematic review. Chemical senses 2016; 41: p 479–486

[61] Pabel LD et al. The impact of severity, course and duration of depression on olfactory function. Journal of Affective Disorders 2018; 238: p 194–203

[62] MacLean PD. Psychosomatic disease and the" visceral brain"; recent developments bearing on the Papez theory of emotion. Psychosomatic medicine 1949

[63] MacLean PD. The limbic system (visceral brain) and emotional behavior. AMA Archives of Neurology & Psychiatry 1955; 73: p 130–134

[64] Wilson DA et al. Cortical odor processing in health and disease. Progress in brain research 2014; 208: p 275–305

[65] Gottfried JA. Smell: central nervous processing. Taste and smell 2006; 63: p 44–69

[66] Sobel N et al. Time course of odorant-induced activation in the human primary olfactory cortex. Journal of Neurophysiology 2000; 83: p 537–551

[67] Soudry Y et al. Olfactory system and emotion: common substrates. European annals of otorhinolaryngology, head and neck diseases 2011; 128: p 18–23

[68] Kurth F et al. A link between the systems: functional differentiation and integration within the human insula revealed by meta-analysis. Brain Structure and Function 2010; 214: p 519–534

[69] Song C, Leonard BE. The olfactory bulbectomised rat as a model of depression. Neuroscience & Biobehavioral Reviews 2005; 29: p 627–647

[70] Carlson JM, Cha J, Mujica-Parodi LR. Functional and structural amygdala–anterior cingulate connectivity correlates with attentional bias to masked fearful faces. Cortex 2013; 49: p 2595–2600

[71] Negoias S et al. Reduced olfactory bulb volume and olfactory sensitivity in patients with acute major depression. Neuroscience 2010; 169: p 415–421

[72] Negoias S et al. Olfactory bulb volume predicts therapeutic outcome in major depression disorder. Brain imaging and behavior 2016; 10: p 367–372

[73] Han P et al. Olfactory loss is associated with reduced hippocampal activation in response to emotional pictures. Neuroimage 2019; 188: p 84–91