SMELL SPACE: Mapping out the Olfactory Design Space for Novel Interactions

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The human sense of smell is powerful. However, the way we use smell as interaction modality in HCI is limited. We lack a common reference point to guide designers' choices when using smell. Here, we map out an olfactory design space to provide designers with such guidance. We identified four key design features: (i) chemical, (ii) emotional, (iii) spatial, and (iv) temporal. Each feature defines a building block for smell-based interaction design and is grounded in a review of the relevant scientific literature. We then demonstrate the design opportunities in three application cases. Each application (i.e. one desktop, two virtual reality implementations) highlights the design choices alongside the implementation and evaluation possibilities in using smell. We conclude by discussing how identifying those design features facilitates a healthy growth of this research domain and contributes to an intermediate-level knowledge space. Finally, we discuss further challenges the HCI community needs to tackle.

CCS Concepts: • **Human-centered computing → Interaction techniques**; *Empirical studies in HCI*.

Additional Key Words and Phrases: Smell; Olfactory Design Space; Chemical Sense; Scent-based Interaction Design; Odour Interfaces; Smell-based Applications; Novel Interactions

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1 INTRODUCTION

Consider a future where your nose has become as important as your eyes in reading this sentence. Our sense of smell can help perceive information when our visual system is busy (e.g. visual overload) or unusable (e.g. in darkness). Similar to visual and also auditory stimuli [110], scents exist spatially. The presence of a scent source (i.e. a scent stimulus) and its diffusion can be located in space (i.e. scented air volume) even if out of sight [103]. Moreover, it has been shown that scents can convey meaning and complement visual information processing [101] and decision making

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(e.g. enabling cognitive shortcuts [20]). Above all, our sense of smell has a unique and robust link to emotions, and may make experiences more memorable [21, 109]. Despite the sense of smell being very powerful, its use within HCI is still very limited.

Within HCI, the use of scent for interaction and experience design is increasingly recognised (e.g. [68, 74, 97, 104]). Most efforts are however directed towards the development of novel scent-delivery devices (e.g. [1, 29, 32]) and the design of one-off application examples, such as the integration of scent-based interactions into virtual and augmented reality (e.g. [104] and [93]), gaming [90], and multimedia applications [43, 45, 89]. The most common motivation for designing with smell is to create more immersive experiences, mainly referring to concepts such as the sense of presence, immersion, and realism [3, 50, 64, 105]. In addition, we see attempts to study the effect of scent stimuli on emotions (e.g. to reduce stress [2, 127]) and behaviour (e.g. reduce distraction, help multi-tasking [52, 58, 82]). All those efforts demonstrate the desire of the HCI community to extend interaction design beyond the audio-visual domain. Moreover, it underlines the opportunities that our sense of smell provides application designers. However, to move the use of smell beyond one-off interaction examples, we need to establish a common reference point that enables designers to make informed decisions about the use of smell as interaction modality.

Based on a detailed literature review, drawing upon advances on our understanding of the olfactory system in psychology, neuroscience, sensory science, and biology, we identified four key design features for smell: chemical, emotional, spatial, and temporal. Those four features define the building blocks for the olfactory design space we introduce in this article. We then discuss how to navigate this design space by following a Design Space Analysis approach [81] that highlights Questions, Options, and Concerns (Q-O-C) as key anchor points. This rationale-based approach helped us to formulate specific questions linked to designing with smell and consider options based on specific concerns we highlight for three application cases. The application designs and evaluations include one desktop implementation (i.e. messaging system in a work context) and two virtual reality (VR) implementations (i.e. time management game in VR, localisation task in VR).

In summary, the main contributions of our work are threefold: First, we identify four key design features (i.e. chemical, emotional, spatial, temporal) that help map out the olfactory design space for HCI and thus provide designers with a common reference point when designing with smell. Second, we demonstrate the relevance of those features in the design process that includes the implementation and evaluation of three application cases (i.e. one desktop and two VR applications). Finally, we discuss how our theoretical and empirical exploration of smell as novel interaction modality enriches the audio-visual design space in HCI and adds new intermediate-level knowledge (i.e. bridging theory with practice) to the design of future smell-based interactive systems. We conclude by accounting for design trade-offs and the need for further research to move smell beyond its infancy state of today.

2 OLFACTORY DESIGN SPACE

Despite the complexity of the sense of smell (i.e. detection of chemicals in our environment), it is astonishing how well humans can react to and act on scent stimuli. We intuitively interact with the environment and the molecules in the air, making decisions beyond pure hedonic discrimination (i.e. pleasant/unpleasant scents). Scent can increase the saliency of an object and can facilitate its recognition and categorization [20]. For example, smelling coffee causes the mental representation of coffee to be activated. This can lead to a desire for coffee, or, with the implicit association between coffee and breaks, motivate us to have a break. At the same time, information delivered by scents can go beyond simple association and activate an instinctual behavioural reaction. For instance, recognising danger in the scent of gas (i.e. the smell of 'sulphur') triggers our survival instinct [67] and promotes actions to protect ourselves (e.g. open a window, leave the room).

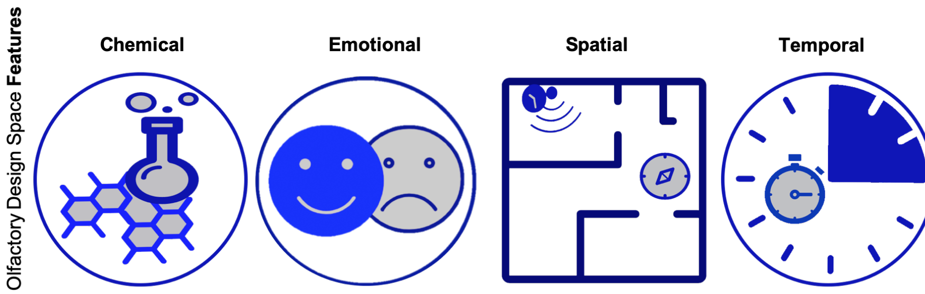


Fig. 1. Mapping out the Olfactory Design Space based on four key features (i.e. chemical, emotional, spatial, temporal) extracted from a systematic literature review on smell as future interaction modality in HCI.

The olfactory system has an eminent importance in classifying scents into the food or non-food category [7]. Apart from distinguishing edible sources, the availability of food (e.g. scent of freshly baked bread in western cultures), also triggers the human survival instinct and attracts us towards the source of the scent (e.g. salivation [7, 17, 73]). This instinctive behaviour does not necessary mean that we are at the edge of starvation, but it is a biological behaviour, automatic reaction to scents. It has been further shown that good and bad scents are associated with different reaction times (e.g. unpleasant food scents are detected faster and more accurately than scents of other categories, see [7]). Moreover, there is growing research into gaining a deeper understanding of the organisation of neural circuitry that mediate scent aversion and attraction [79].

It is increasingly acknowledged, based on scientific studies from various disciplines (e.g. psychology, neuroscience, sensory science, biology) that the sense of smell is more important in humans than generally accepted [70, 85, 111]. That in turn suggests that the sense of smell has played a large role in the evolution of human diet, habitat, and social behaviour. While the sense of smell gained lots of attention and resulted in groundbreaking new insights in other disciplines (mentioned above), within HCI we have only just started to explore its possibilities. In this article we promote a stronger emphasis on the sense of smell for interaction and experience design. To support that aim and explore this emerging design space, we first need to establish the necessary foundations to guide our design decisions. Hence, in the following sections, we present an overview on four key features of the sense of smell. We describe each feature and its relevance for HCI from a user-centred perspective. In other words, we explain the human sensory and perceptual capabilities underlying the four features: Chemical, Emotional, Spatial, Temporal (see Fig. 1). The four features are described individually, but it is worth noting that they are interlinked with each other, which is further illustrated in the design and evaluation of three application cases (see section 4).

2.1 Chemical Features

Scents are mixtures of chemical compounds in the air that have an effect on humans as a result of binding to olfactory receptors in the nose [13]. From a chemical point of view, we can characterize scents by their physical and chemical properties, including their molecular structure, functional groups, molecular weights, diffusion constants, vibration spectrum and molecular concentrations [6, 10, 12, 71]. These characteristics can be used to predict binding and hence sensing of scents by the olfactory receptors in the nose. Several models have been proposed to explain the chemical and physical properties of scent (e.g. 'lock and key models' [11], vibration theories [72]), however with no final agreed approach to date. Within this article and with respect to the relevance of those chemical features for HCI and design, we focus on the specific act of ‘smelling/sniffing’.

Our nose, the key organ for smelling, allows us to sense chemical molecules that exist in the environment. These molecules are called odorants [131] — for simplicity we refer to them as scents. Scents are a mixture of these volatile molecules [13, 131]. However, scent detection is only one part of an olfactory experience. The olfactory system completes the scent decoding process (i.e. sniffing action) by generating the appropriate internal representations in the brain, based on the associations related to the scent. In other words, scent-associated representations are based on a process of scent detection, decoding, and processing, which will ultimately define the users' experience [67]. This process can either be based on a conscious perception of scent stimuli (e.g. I know there is the scent of coffee) or happen sub-consciously (e.g. I feel the need for a break but not consciously perceive the coffee scent). Even if we are not conscious of a scent in the air, it can still have a profound influence on our behaviour [111] (e.g. body odors [42, 46]). Sub-conscious stimulation is also referred to as under-threshold stimulation [117]. Prior research has investigated the brain responses to sub-threshold stimulation and has shown that subjects presented with an odor at sub-threshold concentrations show lesser activation in the insula than subjects for which the odor – at the same concentration – is above detection threshold [55]. This leaves space for further investigations into the underlying neural mechanism, but at the same time inspires new design explorations (e.g. to influence a persons mood and cognitive performance, see [1]).

Overall, chemical sensing and processing are very complex processes and still hold a lot of unanswered questions, scientists in different disciplines tackle (from genetics to psychology [70, 72]). Here, we note the potential impact on design thinking in HCI moving beyond traditional modalities and the semantically rich interaction opportunities around scent stimuli.

2.1.1 How to select scents? When thinking about using scents, the selection of the appropriate scent stimuli is a critical first design decision to be taken. In contrast to other human senses (e.g. primary colours, basic tastes), we cannot rely on "primary scents". The lack of knowledge about the description and classification of scents for HCI has often resulted in arbitrary choices of scents, with no underlying formalisation of the scent-experience relationship [97].

There have been attempts to classify scents based on their chemical properties. Dravnieks [36] created the Atlas of Odor Character Profiles, a collection of 160 chemicals and mixtures that were rated based on input from trained panelists. While this dataset provides a valuable starting point to advance the research in the science of smell, it remains less accessible for design due to a lack of subjective descriptors of the olfactory experience. Another attempt, comes from Koulakov et al. [75] who analyzed and characterised mono-molecular scents into a set of 146 perceptual descriptors in a multidimensional sensory space. The results of this analysis showed how these mono-molecular scents can be classified into a two-dimensional space related to physio-chemical properties. It did so without eliminating the complexity related to human olfactory receptors. The first dimension represents the pleasantness or perceptual valence of the scents. The second dimension may be interpreted as a crossmodal correlation between scents and sound representations (e.g. lemon is high-pitch) [18]. This classification moves us closer to some of the recent explorations of scent stimuli in the context of crossmodal associations [9]. Other approaches include scent classifications via chemical receptors and neural structures, and also via cognitive association [15, 65, 91, 92, 106].

All these attempts are gradually advancing our language of smell from a chemical to a perceptual lens but require additional efforts to also reach the experiential dimension, that is so relevant in the context of HCI and interaction design [97]. It is worth noting, that we can see increased efforts especially within the multimedia community to investigate the users perceived experiences of olfaction-enhanced multimedia applications (e.g. [44] [89][88]). Those works help establish evaluation criteria and guidance on the integration of scent into applications and their effect on users quality of experience (QoE). Those efforts further discussions towards the standardisation of sensory effects (e.g. MPEG-V Sensory Information standards) [88].

Across all above described research efforts on classifying scents, the main aim is to guide a more systematic selection of scents in order to ultimately guide the design of reliable novel interactions and experiences. One of the biggest stumbling blocks, to date, is that there is a gap between the chemical, perceptual, and experiential classification of scents for design. We lack subjective descriptions of olfactory experiences that a designer could refer to, as they do when talking about colours and sounds. Therefore, designers are currently best supported through descriptors that capture the emotional "valence" and "arousal" dimensions [16] and the perceived intensity of a stimulus [68, 69], which can be further mapped towards users' experiences (see section 2.2 on Emotional Features). Moreover, we can draw upon a rich and growing literature on crossmodal correspondences [118] and apply those mappings between scents and shapes [48, 62], scents and colours [22], and scents and touch [23] in the design of interactive applications (e.g. to convey information [101]). While such correspondences have been shown to be valid across cultures, it is however, important to carefully consider any cultural differences for the specific context and interaction one is designing for (see Criteria, in the Q-O-C analysis framework).

2.1.2 How important is scent intensity? Closely linked to the choice of scents is also the perceived scent intensity. Recent studies have shown that it is possible to predict, with high accuracy, odor intensity and pleasantness from their chemical features [71]. Those predictions gain further momentum through advances in artificial intelligence (AI) (see [108, 121]), with the potential to benefit smell-based design, especially when integrated with emerging olfactory toolkits that account for scent intensity (e.g. [83]

The scent intensity can modify the user's experience and impact the perceived hedonic properties [14]. While some scents are known to have a different intensity (e.g. lavender is perceived much more intense than the scent of rose [31]), their perceived intensity can be further influenced through the chemical concentration (e.g. dilution and mixing of scents), the duration of the scent exposure and adaptation [131], and the chemical sensitivity [37]. The latter can be measured through olfactory self-assessment questionnaires [94] and standardized tests such as the Sniffin' Sticks test [41, 56]. In a recent effort to capture more perceptual data, including intensity ratings, odorant booklets were created using a scratch-and-sniff approach [116]. This approach allows to reach a large sample size (over 10.000 people in [116]). Such efforts are in line with recent work on the development of a new olfactory test (i.e. SMELL-S and SMELL-R - see [54]) to facilitate smell testing in different populations, without the need to adapt test stimuli to account for differences in familiarity with the test odors [54]. Those advances in measurement approaches in neuroscience and neurogenetics are very promising, and will in the long-term provide HCI with reliable frameworks to design personalised interactions. However, for the time being, until those new approaches are further validated and automated, a key measurement of scent intensity are self-assessment scales (e.g. 'olfactory assessment test' [94]). Moreover, prior work informs us about the differences in olfactory sensitivity based on gender (e.g. females are more sensitive than males [34]), age (e.g. decrease with increased age [35]), and cultural background (e.g. [33, 77]), which need to be taken into account for smell-based application design and evaluation.

In summary, apart from accounting for individual sensitivity differences, the scent intensity can be determined through changing the chemical concentration of a scent, controlling and adjusting the scent-delivery parameters of a delivery device (e.g. timing, duration of delivery). Moreover, a designer can select a different scent with a similar association, but with a different intensity to account for individual differences and preferences (e.g. both rose and vanilla are perceived as low intensity scents and both are associated with relaxing experiences, but vanilla has a stronger intensity [4, 28]). For further references on scent intensity and dilution approaches, see [63, 100, 102]. The scent intensity can also be modified through both the temporal and spatial properties (e.g. delivered from a greater distance, in pulses — see section 2.3), and can vary depending on the selected scent as discussed in the previous section. Beyond the choice of scent and the importance of scent intensity, there are further considerations relevant when designing with scent.

2.1.3 What can designers do with scent stimuli? Scents do not just exist in their chemical form described above, but also come with a specific meaning/semantics. Such a semantic link is either ‘learnt’ through natural associations, for instance linked to the source of a scent (e.g. banana scent is associated with a ‘banana’), or is a newly ‘trained’ association (e.g. specific perfume is associated with my ‘husband’). This definition is based on literature in psychology and grounded in the basic understanding of smell as chemical sense. For example, a banana smells like a banana because it contains the same chemical components across countries and cultures [131]. The first time a person is smelling a banana and someone defines it as a banana, a natural ’learnt’ association is established. This is true for any other object/item found in nature with a scent. In contrast to those ’learnt’ associations, ’trained’ associations do not naturally occur in nature, but are based on training. This is comparable to colours, lights, numbers, tastes, etc., that we can learn. We can even establish arbitrary associations to convey meaning or specific information. For example, at some point in the history of transportation, it was agreed that red is associated with stop, while green is associated with go. Similarly, one can think of scent-associations in the same way, as we will illustrate in our application case 2, where we trained participants to associate a specific scent with a particular person. The human ability to recognise and recall naturally learnt and trained scent-associations provides HCI with a rich design explorations [67].

Being able to design for those scent-associations enables cognitive shortcuts, which are closely connected to the conscious and sub-conscious perception of scents [20]. This is particularly relevant as humans have limited computational and cognitive abilities [113, 114]. Rather than scrutinising all available information, users often induce information from contextual factors and/or their emotions. This information is then used for cognitive shortcuts in order to simplify a decision process. Kahneman [66] defined this process as ‘effortless intuition’. Hence, scent stimuli can help users in making decisions under multi-tasking (e.g. prioritising actions) and dealing with disruptions (e.g. phone calls, emails, social media feeds). In particular, trained scent associations can help users to formulate better hypotheses about the potential outcome of actions, and consequently make better decisions [52, 58, 70].

In summary, as highlighted by Shepherd [111], there is still lots to be understood about the sense of smell, from its basic chemical/molecular structure to the perceptual effects, and underlying neurological mechanism. But there has never been a better time to think of smell from a HCI perspective, as we can build on the vast richness of knowledge emerging over the last decade. All this newly gained insights further tie in with the relevance of smell in relation to human emotions.

2.2 Emotional Features

When the olfactory receptors in the nose are stimulated, they transmit impulses to the brain. This neural pathway is directly connected to the limbic system [21], the part of the brain that deals with emotions. That’s why reactions to scents are rarely neutral — we usually like or dislike a scent. While there can be cultural differences in the perceived valence (if it is perceived pleasant or unpleasant), hence a scents hedonic effect, there are cross-cultural commonalities especially linked to trigeminal scents, that are generally accepted as bad and painful across cultures [40, 61]. We believe this is an important addition to be considered based on scents chemical properties alongside the cultural consideration of hedonic discrimination of scents.

The sense of smell is often defined as an emotional system [21]. The emotion-eliciting effect of scents is typically linked to childhood memories (see [129, 130]), and is closely linked to specific events, places, people, and activities [7, 73]. Obrist et al. [97] showed, for instance, that personally memorable smell experiences are mainly linked to past events, people, locations, and specific times in their life (e.g. wedding, grandmothers' chocolate cookies). The emotional link to scent stimuli is important for HCI as it suggests the relevance for recall and recognition. Indeed, past research has shown that scent affects the recall of target objects with the same accuracy as verbal, visual, tactile and auditory cues, but with a stronger connection to memories [51]. Thus, information recalled through scents can go further back in time (e.g. childhood memories).

Scents can also be used to increase the salience of an object (i.e. make something stand out and attract user's attention) and thus facilitate recognition and categorisation of an object due to the perceptual fluency [100, 115]. The salience can be increased through carefully selecting the scent based on their emotional (hedonic) effect. For example, the field of sensory marketing makes use of those hedonic effects in product design in order to reinforce the ties between users and products, brands, and services [17, 86, 87, 109, 120]. Within HCI, designing for the emotional dimension of scent gained attention in the context of gaming and multimedia experiences (e.g. [45, 89, 99]), enhanced-art experiences [123] and for the creation of more immersive and realistic VR experiences [104]. Those uses were however often based on researchers' best guesses. Here below we highlight some of the key questions (Criteria, in the Q-O-C analysis framework) to consider with regards to the emotional effects of scents.

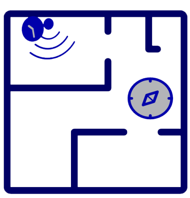
2.2.1 Which emotions are linked to which scents? Different scents can elicit different emotional reactions that can be simplified with respect to their perceived valence (i.e. pleasant-unpleasant) and arousal (i.e. calming-arousing). Emotional scent classification frameworks proposed in psychology and neuroscience studied this emotional effect further, for example by linking the arousing and relaxing effect with the neural system (e.g. [122, 127]), or by describing the effect of scents for inducing happy or sad emotions (e.g. [26, 122]).

Most relevant for HCI is the work of Chrea et al. [16] who investigated the link between scents and emotions, based on which they generated the 'Geneva Emotion and Odor Scale (GEOS)'. GEOS is a useful tool to measure users' emotional reactions to scent stimuli in the form of a standardised questionnaire. However, the scents are rated using semantic attributes representing an emotional response (e.g. sensual, revitalized, dirty), which can induce linguistic and cultural biases [78]. Non-verbal tools, such as the sensual evaluation tool (SEI) [59] could provide alternative approaches to explore the user's emotional reactions to sensory stimuli (e.g. as done for taste [95] or inspired work on scent-shape associations [62]).

2.2.2 What else can designers do with scent stimuli? In addition to building on crossmodal correspondences, a series of studies have investigated those associations through the lens of their emotional effect (pleasantness-unpleasantness). These studies have investigated how the emotional reaction to a scent is modulated through the scent's integration with, for instance, specific musical notes, geometrical shapes, colours, or tactile stimuli (e.g. [18, 23, 25, 48]). Exploring crossmodal factors designs will allow designers to consider scent through another sensory feature (e.g. high pitch sounds coupled with a lemon scent will create an arousing experience) and thus explore novel interactive experiences that go beyond arbitrary mappings and uses (i.e. 'best guesses') of scent in application designs (e.g. scent-visual associations for driving-relevant notifications [82], body image perception influenced by scent-sound associations [9]).

As stated at the beginning, each of the four key factors are interrelated. Moreover, both the chemical and emotional features, discussed so far, are further modulated by the spatial and temporal features of scent stimuli, discussed below.

2.3 Spatial Features



Scent stimuli convey spatial information including place, orientation, and movement in physical and virtual spaces. Similar to visual and auditory stimuli [110], scents exist in space. The presence of a scent's source (i.e. scent stimulus) and its diffusion in space (i.e. scented air volume) can be located even if the source is out of sight [103]. Sensorial cues in general are naturally used to direct a person's attention in space [107]. Scent - in particular its emotional value - modulates spatial attention (e.g. being attracted towards a source linked to a pleasant scent) [107]. The spatial information carried by scent also works on conscious and sub-conscious levels. For example, a scent perceived consciously or not may trigger us to change the path we walk (as a navigational feature), or bring our attention to a specific source (e.g. motivate us to search for the source of a pleasant coffee or pizza scent) [107]. Porter et al. [103] showed that humans can navigate a space by scent tracking. Recently, Jacobs et al. [60] showed that humans can navigate a given space through scent by following an olfactory grid, that is, a map constructed from chemical stimuli.

The ability of scent to enable spatial and attentional interactions could be beneficial in the design of not only virtual but also real environments where other sensory information (e.g. auditory cues) are obstructed [27, 76]. The latter could be particularly relevant in the design of sensory substitution devices augmenting current navigation systems for people with visual impairments [47]). Sighted people can also benefit from scent as an alternative navigation medium that allows them to keep their eyes on the path and still hear their surrounding (e.g. honking car, other peoples' voices).

2.4 Temporal Features

The temporal features concern the scent delivery (e.g. timing, duration, frequency) and users' habituation to scent stimuli [10]. When controlling temporal features, we need to account for the effect of the spatial features (reachability) and chemical features (perceivability) of the scent stimuli, together with the capabilities of the scent-delivery device (see an overview of scent-delivery devices in [88], comparison in [32]). Moreover, the habituation effect (also referred to as scent adaptation) causes a decrease in the perception of a scent or scent intensity over time [14, 39]. It is worth noting that the magnitude of the habituation correlates with the scent's concentration and the emotional reaction to scent stimuli [19]. Scents can habituate differently depending on their perceived pleasantness or unpleasantness [37].

Independently of the scent-delivery device used, repeated presentations of unpleasant scent stimuli reduce the emotional saliency due to a habituation effect (i.e. reduces feeling of disgust) [19]. A recent study demonstrated that habituation, in particular the decrease in neural activity due to smell decoding, is not only related to repeated smelling of negative scents, but also to repeated smelling of positive scents [37]. These findings are in line with a pioneering work by Cain and Johnson in the late 70s [14] that suggested how repeated exposure can shift the pleasantness ratings of scents towards neutrality (also referred to as affective habituation). In other words, frequent repetition of a pleasant scent typically decreases perceived pleasantness; conversely, repetition of

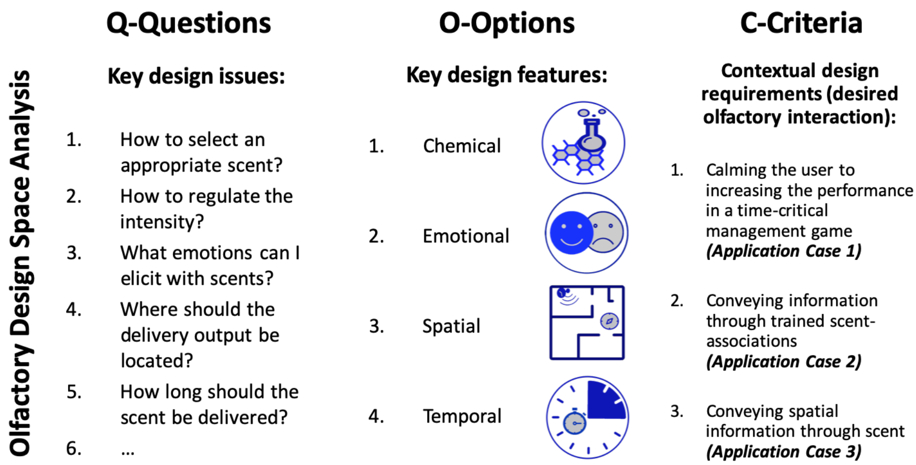


Fig. 2. Navigating the Olfactory Design Space based on the four key features applying the Design Space Analsysis - short Q-O-C framework composed of Q-Questions, O-Options, and C-Criteria. We demonstrate the use of the Q-O-C framework in the design, implementation, and evaluation of three application cases including one desktop and two VR applications.

unpleasant scents decreases perceived unpleasantness [37]. These particular aspects highlight the close interrelationship between the temporal and emotional features.

Apart from habituation, the user's experience is impacted by the lingering of a scent stimulus. Lingering is often referred to as the 'liveness of the scents' [37] in time (how long the scents stay in a space). The lingering effect of a scent can lead again to scent habituation and potentially to scent contamination (i.e. mixing of scents) when using multiple scents in an interaction scenario. While some of the lingering effects are caused by the scent-delivery device (see [8] [32]), lingering can also be accounted for and controlled through the scent's intensity (e.g. dilution of the chemical components, choice of different scents — see more in section 2.1 on Chemical Features). Most notably, less intense scents are less residual (e.g. lavender will linger longer than rose) [19].

In summary, within this section we provided an overview on the four key features that help define the design space for smell. The literature on this topic is continuously growing spanning various disciplines, lately also focused on linguistic descriptions of smell (e.g. [57, 84]), which provide additional input for the emotional features described in section 2.2. Next, we discuss how we can navigate this emerging design space from an HCI perspective.

3 NAVIGATING THE DESIGN SPACE FOR SMELL

In the previous sections, we described the state-of-the art knowledge around the human sense of smell and described four key features around scent stimuli (i.e. chemical, emotional, spatial, and temporal). We now focus on the question of how to use these features in the actual design of smell-based interaction. In other words, we will illustrate how to navigate this emerging smell space for novel interaction design. In Fig. 2 we show an overview on the four features which are considered in the design, implementation, and evaluation of three application cases (see section 4). For each application case the design choices are reflected back against the Q-O-C framework which is part of the Design Space Analysis approach [81]. All taken together, enables an illustration of how theoretical knowledge about smell (i.e. the Features) is used in specific design instances.

Depending on the specific design purpose of each application case, the Q-O-C framework emphasizes how designers can think about and navigate the smell design space and make informed design decisions. The framework provides a network of questions a designer needs to ask (Q-Questions), the possible solutions and alternatives to the questions (O-Options), and the underpinning reasons for a final design decision (C-Criteria). Following this design thinking process will, in the long-run, enable us as HCI community to move from single application cases to a rich ecosystem of smell-based applications and the creation of novel interactions. Using the Q-O-C framework aims to make design choices transparent, and thus allows other designers and researchers to reproduce designs as well as vary design choices according to their own explorations. Within this process, the four features are the key common building blocks.

Within the following sections we describe the design, implementation, and evaluation of three application cases. Each application case is cast in terms of the Q-O-C design framework. For each application case, we conducted a controlled experiment to investigate the specific effect of scent on the user's interaction, performance, and experience. It is worth keeping in mind that other factors, such as individual differences or crossmodal interactions, need to be taken into account when designing the specific application cases.

4 APPLICATION CASES FOR NOVEL INTERACTIONS BASED ON SMELL

In this section we present each of the three application cases with respect to the Q-O-C design framework, the specific test case implementation, the study design, set-up, and results.

Each of the three application cases was conducted in different moments across a six-months period. The participants' recruitment was based on a snowball sampling approach and the usage of the university' Sona recruitment system. Participants were asked if they took part in any previous experiment involving scent stimuli in the last year. Less than 15% of the overall sample had previously participated in studies involving smell. The probability of the same participant being involved in the same study across time is low and, in any case, irrelevant for the aims in each of the three application cases, as they are very distinct in the specific tasks. All the information about participants are stored anonymously with reference numbers using a participant's identity number according to the obtained ethics approval.

Across all three application cases, we used a custom-built scent-delivery device (see Fig. 3) that was adjusted for the different settings (see more details in each of the application case descriptions). The scent-delivery device is electrically controlled and composed of 6 electromechanical valves (Solenoids) that regulate the air passage (on-off) from a tank of compressed air. The clean pressurised air splits into individual channels, each passing through an electric valve and arriving to one of the small glass bottles (six in this set-up) that contain the scent stimuli (i.e. natural essential oils, off-shelf products from *Holland & Barrett Retail Limited*). The air supply pressure for the device can be set to a constant supply value between 0.5 and 3 Bar through an air regulator.

The output of scented air reaches the participant either through a 3D-printed merging nozzle (output diameter 1.5mm, in application case 2) and through a single tube (output diameter 2mm, in application cases 1 and 3). The output can be positioned at an adjustable distance from the participants' nose (e.g. positioned on a table for a Desktop application or mounted on a tripod in a VR set-up). A detailed description of the device can be found in [29].

Ethics approval for all three application case studies was obtained from the University's Ethics Committee. Each participant provided written consent to participate in the experiments. None of the participants reported any olfactory dysfunctions and had normal or corrected to normal vision. Details for each individual study design and procedure are provided in the following sections.

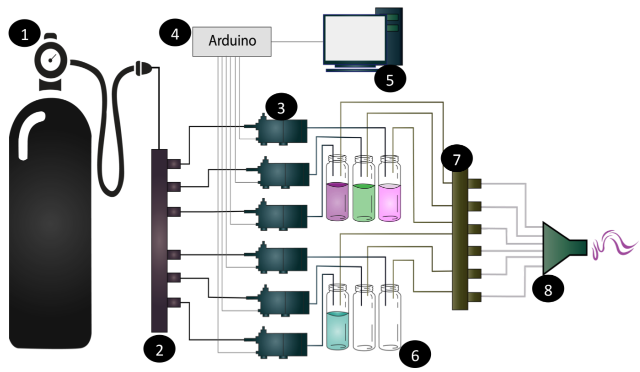


Fig. 3. Visualisation of the scent-delivery device used across all three application cases. (1) air-tank, (2) air-filters, (3) electric valves, (4) Arduino board, (5) PC, (6) glass bottles with the scents, (7) one-way valves, and (8) 3D printed output nozzle. More details on the technical details of the device can be found in [29].

4.1 Application Case 1

For our first application case, we developed a time management game (Birthday Box Factory - BBF). BBF is based on the existing Cooking Fever game, in which players complete food orders as quickly as possible. However, in our implementation we replaced food with gift items (see Fig. 4) in order to avoid any confusion with food smells. We chose to implement this game in VR to maximise the user's immersion in the task. The user was exposed to different stress levels (low and high).

Using smell in this interaction scenario aimed to modulate the stress induced through the game exploiting mainly its calming effect of scents (linked to the Emotional Features of smell). Moreover, from the chemical features described in the previous sections (see section 2.1.3, "What can I do with scent stimuli?"), we know that scent can help in the decision-making process when engaging in multiple actions. In summary, the aim of this design case was to test the effect of smell on the user's performance under stress.

4.1.1 Q-O-C design analysis. One of the first questions a designer needs to ask is which scent to use, depending on their design aim. Based on our analysis of the olfactory design space we know that scents can have different effects on the central neural system. In simple terms, scents can be either arousing or relaxing (see Section 2.2, Emotional Features). For this specific application case we wanted a relaxing scent that reduces the stress of the user and helps improve the user's performance. Rose, rosemary, and lavender are suggested in the literature as being relaxing [122, 127], and hence provide the designer with different options to consider in the implementation of a smell-based application.

We selected lavender due to its relaxing effect but also to ensure the perceivability of the scent in our VR implementation. Lavender is recognized to have a higher scent intensity compared to rose for instance [31]. In our research we build on this work. We further selected the air pressure (i.e. 1 Bar) of the scent-delivery device (Fig. 3) and the scent quantity (i.e. 2.5g of 100% pure lavender essential oils) with respect to the participants' distance from the delivery point (i.e. 1 meter), based on the previously established perceived intensity of lavender using the same scent delivery device [31]. The scent stimuli were delivered in pulses (i.e. duration of 5s, repeated 3 times with an interval of 10s between deliveries) in order to avoid habituation due to multiple exposures throughout the interaction.

Fig. 4. *Left*: The items, box, and an example of BBF game order to complete. *Right*: The BBF's virtual space. The player was standing in the centre of a 1×1m space with a 360°view of the gameplay items for each tray.

4.1.2 Study design. The study followed a within-subjects design with two scent conditions (i.e. lavender scent and no-scent), two levels of stress (i.e. low and high), and two repetitions. In total each participant played eight rounds of the BBF game with two rounds of the game without any time restrictions and without any scent, for a total duration of approximately 40min. The low-stress condition required ten orders to be completed in 2min, while the high-stress required 18 orders in 2min. The order of the conditions of induced-stress and scent were randomised across participants.

We measured the player's interaction performance through their accuracy in completing orders under a high-stress condition. Accuracy was measured with respect to the amount of irrelevant actions performed in relation to the ideal procedure in completing an order. Each order has a definable number of required actions and critical steps, which describes the optimal solution. For example, the user has to prepare three stars and one red balloon. If the user wrongly takes the blue balloon or the red ball then these actions are considered irrelevant actions. Thus, the number of irrelevant actions is the measure for accuracy. The low-stress condition was used as a control to test the effectiveness of the stress manipulation.

The scent-delivery output was mounted on a tripod at a height of 1.5m. The scent was delivered (5s, repeated 3 times with 10s of interval) when the first order instruction appeared (relevant for the Temporal Features, see details about the scent-delivery device in Fig. 3). The scent was perceived after 7s of receiving the order instruction. The main hypothesis was that the addition of a scent (lavender) based on its pre-defined emotional effect, would increase the player's performance (i.e. accuracy) in a stressful situation in the game.

4.1.3 Study results. Fourteen participants volunteered for this study (M_{age} = 26, SD= 4.36, 4 female). A repeated measures ANOVA showed a main effect of stress level on participants' accuracy (data normally distributed [112]), F(1, 25)= 15.72, p< 0.01, $\eta^2 = 0.70$, $M_{low-stress}$ = 1.80, SD= 1.4, $M_{high-stress}$ = 3.98, SD= 1.9, but no main effect of scent (p> 0.05), and an interaction between scent and stress level on participants' accuracy (F(1, 25)= 5.67, p< 0.05, $\eta^2 = 0.65$). Pairwise comparisons, Bonferroni adjusted, showed that the lavender scent significantly reduced the number of irrelevant errors compared to the no-scent condition in the high-level induced-stress condition (p< 0.05) (see Fig. 5).

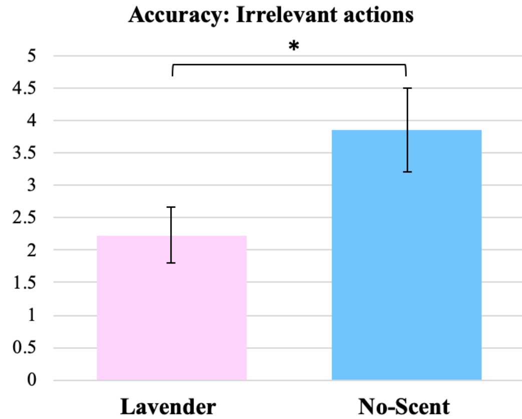


Fig. 5. The mean scores of participants' irrelevant actions in the game under high-level stress. Error bars, s.e.m., $*$ $p < .05$.

In this application case we showed that a carefully considered scent-interaction design can positively impact the user's performance in a time management game. This application case has a strong link to the emotional features of smell and the timing of the scent-delivery (Temporal Features). The key lesson from a design choice perspective was the careful selection of the appropriate scent in relation to the low- versus high-level stress activities. With the right choice of scent and appropriate delivery in the game, a positive impact on the user is achieved. What we didn't explore in this application case were any crossmodal effects, such as the combined effect of smell and auditory or visual stimuli that could improve the users accuracy and interaction along the game. Those are additional questions we will tackle in the following two application cases.

4.2 Application Case 2

In this second application case, we developed a smell-augmented version of the Slack messaging system to explore the effect of smell on users performance and perceived level of distraction (building on the basic Chemical and Emotional Features of smell).

Using smell in this interaction scenario aimed to modulate the distraction from a primary task through smell. Participants were first trained to associate specific scents (i.e. lemon and lavender) with a specific person in the messaging system (i.e. Slack team). After passing a scent-association test with an 85% success rate, they were asked to perform a memory card game as a primary task. The memory card game has been used in prior research [82, 124, 125] to compare different notification modalities. A total of 24 cards were presented face-down to the participants on a computer screen, with a maximum duration of 60s per game (see Fig. 6).

We designed a dedicated secondary task to notify the participant about a new message, measuring their reaction time and ability to recognise the senders' identify. We compared visual, olfactory, and visual-olfactory Slack notifications in this application case. In summary, the aim of this design case was to test the effect of trained scent-associations on users' performance.

4.2.1 Q-O-C design analysis. While a designer needs to think about which scent to use (as in application case 1) and account for its emotional effect, it is more important to build on the basic effects and abilities of our sense of smell (see section 2.1, Chemical Features) in this application case. We know that scents can convey information, naturally learnt and trained associations as specifically discussed in section 2.1.3. Such scent-associated information can be helpful in facilitating

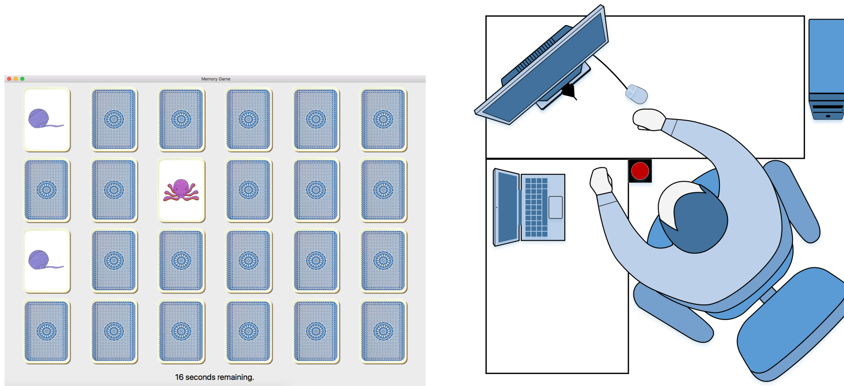


Fig. 6. Study setup, user sitting in front of a screen (right) completing a memory card game (left). Scent-output nozzle below the screen, red button to press when receiving any type of Slack notifications.

cognitive short-cuts and thus augment or change current interaction designs. For this specific application case we wanted to investigate the added value of smell in a work environment where users are often exposed to distractions (see more details in [82]). Next to smell, we also tested the integration of smell with visual notifications to account for multimodal interactions.

We explored the possibility to train new scent-associations and for this we wanted to select two scents that have the same perceivability in term of scent intensity (see section 2.1.2). To remove confounding effects on the scent-associations driven by the scents' hedonic/emotional values, we used scents with the same valence dimension (i.e. both pleasant) but opposite arousing effects (i.e. one arousing and one relaxing). The literature suggests that rose, rosemary, and lavender have a relaxing effect while lemon, peppermint, and black pepper have an arousing effect [120, 127]. We decided to use lavender and lemon, because both scents have similar intensity levels [31]. This ensures the perceivability and reachability of the scent stimuli. The pressure value of the scent delivery (we used the same device as in application case 1) and the scent quantity (a constant pressure of 1 Bar, 5g of 100% pure lavender and lemon essential oils) were selected to match the participants' distance from the delivery point (45cm) (see the Section 2.3, Spatial Features), and the perceived intensity for lavender and lemon established in prior work [4, 28].

4.2.2 Study design. The study followed a within-subjects design with 3 notification conditions (visual, olfactory, and visual-olfactory notifications), 2 sender identities (John-lemon scent and Cathy-lavender scent), and 2 repetitions. Each participant played a total of 12 memory card games, and 2 initial games to familiarize themselves with the game (without notifications). When receiving a notification, participants had to press a red button in front of them; this was used to measure their reaction times. The participant's accuracy in recognising the sender's identity was measured through a multiple-choice question at the end of each game. See Fig. 6 for an overview on the study set-up. Each notification was presented randomly every 25-30s after the memory card game had started. The visual notifications were presented for 5s, with 1s transitions on and off the screen, with the same timing for the visual-olfactory notifications.

Following prior work [124–126], we evaluated the primary task performance as an index of disruption level, using implicit measurements: the activity rate (card turns per second) and error rate (superfluous views per click). A superfluous view occurs when a participant repeatedly views a card without successfully matching it, suggesting that their mental mapping of card locations has been mismatched due to disruption. We additionally measured the perceived disruption level using a self-report question ("How much did the notification disrupt you from your task?") answered on a 7-point Likert scale (1= "Did not disrupt at all"; 7= "Disrupted very much"). The main hypothesis was that scent notifications based on trained scent-associations would be as efficient in conveying the senders' identity as visual notifications. Before running the main study, we tested whether both notification modalities were perceived at the same time to avoid any influence through synchronisation issues.

4.2.3 Study results. Fifteen participants volunteered (M_{Age}= 28.5 years, SD= 7.00, 2 female). We ran a repeated measures ANOVA to compare participants' reaction times in detecting the notifications (data normally-distributed [112]) in the three conditions (visual, olfactory, visual-olfactory). The results showed no statistically significant differences (p> 0.5) in the participants' reaction times in perceiving the notifications (M_{Visual} = 2.22s, SD= 0.83s; $M_{Olfactory}$ = 2.18, SD= 0.64, M_{V-O} = 2.39, SD= 1.5). Olfactory notifications were perceived as quickly as the visual and visual-olfactory combined notifications. To analyse the participant's accuracy in recognising the sender of the message, we used a Kruskal-Wallis H test (including Bonferroni corrected post-hoc tests). The results showed an overall statistically significant difference in accuracy across all the three notification modalities ($\chi^2(2)$= 20.5, p< .01). Participants were most accurate in the combined visual-olfactory modality (97%, SD= 4%) compared to olfactory (86%, SD= 10%, p< .05) and visual (84%,SD= 5%, p< .05). There was no significant difference between visual and olfactory notifications.

In this application case we demonstrated that designing interactions based on trained scent-associations leads to the same level of accuracy in identifying the notification's sender-identity as with the traditional visual notifications. Moreover, the user's performance increased when both modalities are presented synchronized in the application scenario. In contrast to the first application case we also gained insights on crossmodal interactions and how the combination of smell and visual stimuli can improve the users performance. A question that can be posed here is to what extend this is a one-time positive effect or if the use of smell has any long-term positive effects (i.e. do we remember the trained scent-associations beyond this one instance). Some initial and promising insights towards the positive effect of smell, beyond one-time exposure, can be found in [82], and are further explained in the opportunities linked to the chemical features (section 2.1).

4.3 Application Case 3

In this third application case, we created a VR interaction scenario (i.e. Find the Source - FS) that particularly focuses on the users' ability to locate the source of a spatial cue as quickly as possible. Users were presented with olfactory, auditory, and audio-olfactory cues. The main design purpose was to explore the spatial features of smell in a VR scenario. We began from the basic chemical features (see the section 2.1.3, "What can I do with scent stimuli?") to investigate the use of scent to convey spatial information in a virtual environment and to orient users' attention. We explored the fact that humans are good in localising a scent source (see section 2.3, Spatial Features).

We chose to implement FS in VR in order to hide the delivery point and to disorient the player by changing the position of various visual landmarks, which is difficult to do in a real environment [60]. Users stood in the centre of a circular space (see Fig. 8, 3m diameter), where they waited for the cue presentation (auditory, olfactory, and audio-olfactory). The audio stimulus was a 3s Chirp generated using the software Audacity (frequency 450-600Hz, sine wave form, amplitude 0.8, logarithmic interpolation). This sound was chosen because it is a dynamic sound (a parallelism with the scent's diffusion effect). To synchronise the olfactory and auditory cues, the scent stimuli were delivered for 3s, 1s after each FS trial started, and the auditory stimuli presented 6s after this, when the scent was in the optimally perceivable area. In summary, the aim was to test the effect of olfactory and novel multimodal cues on users' performance to find a source in a virtual space.

4.3.1 Q-O-C design analysis. As in the previous user studies, a designer needs to start with the question of how to select the appropriate scent. In this third application case, we wanted to select a scent with positive valence and high arousal. As before, we had different scent options for scents with these characteristics [122, 127]. Following this prior works, we selected peppermint as a pleasant and high intensity scent to ensure perceivability. We used 2.5g of 100% pure peppermint essential oil.

To accurately design the position of the delivery point in the VR environment (relevant for the Spatial Features), determine the timing (relevant for the Temporal Features, section 2.4), and pressure needed for the scent delivery, we performed several iterations of airflow simulations (see Fig. 7). Using the same scent-delivery device as in the previous two application cases, we simulated the scent delivery from different output heights, different duration, and with different pressure settings and determined the optimal delivery parameters as follows: a delivery of 5s using a constant pressure of 2.5 Bar, positioned 1.5m above the floor and with an output radius of 2mm. Using these scent-delivery parameters in Autodesk CFD, we determined that the scented air travels 1.5m after 6s. This volume is defined as the space in which the concentration of scented air is above 0.1%. We verified that this was perceivable by doing a pre-study (5 participants, $M_{age=}$ 32.5 years, SD= 2.5, 2 females) and recording reaction times (M= 6s, SD= 1.5). At the start of each trial, participants faced a white dot positioned 2m away from the centre, at a height of 1.72m. They had to select, as quickly as possible, the button corresponding to the source of the cue, once the cue was perceived. Between trials, participants returned to the centre of the circle and followed some orientation arrows to face in the direction of the next trial's white disc (see Fig. 8). The VR environment rotated, unnoticed by the participants, and thus changed the participants' reference points.

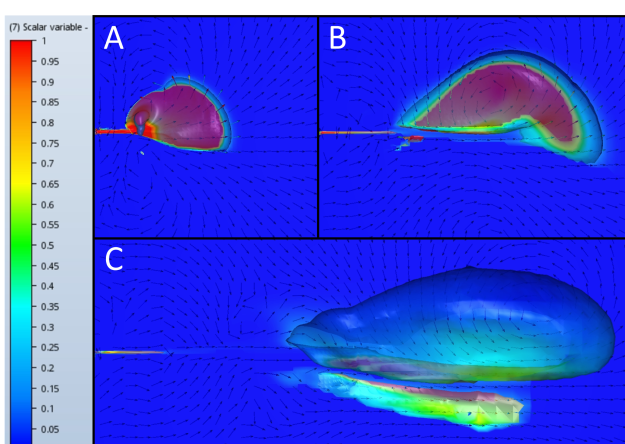


Fig. 7. A 3D simulation of airflow outputs images taken in three different times (A 2s, B 4s, and C 6s) with the relative travel distances (A 38 cm, B 79cm, C 145cm). The delivery had a duration of 5s, with a delivery output of 2mm, a diffusion speed of 0.35l/s of scented-air, calculated using a diffusion coefficient of $0.01 cm^2/s$.

4.3.2 Study design. The study followed a within-subjects design, with three sensory cues (auditory, olfactory, and audio-olfactory) and eight delivery positions (2 in each circle quadrant). Twenty-four trials were presented. For each trial, the physical delivery points were selected randomly and the virtual room rotated to align it with the desired delivery angle. In terms of resolution, the buttons are spaced 15 degrees apart for a total of 24 buttons positioned 360 degrees around the user. The

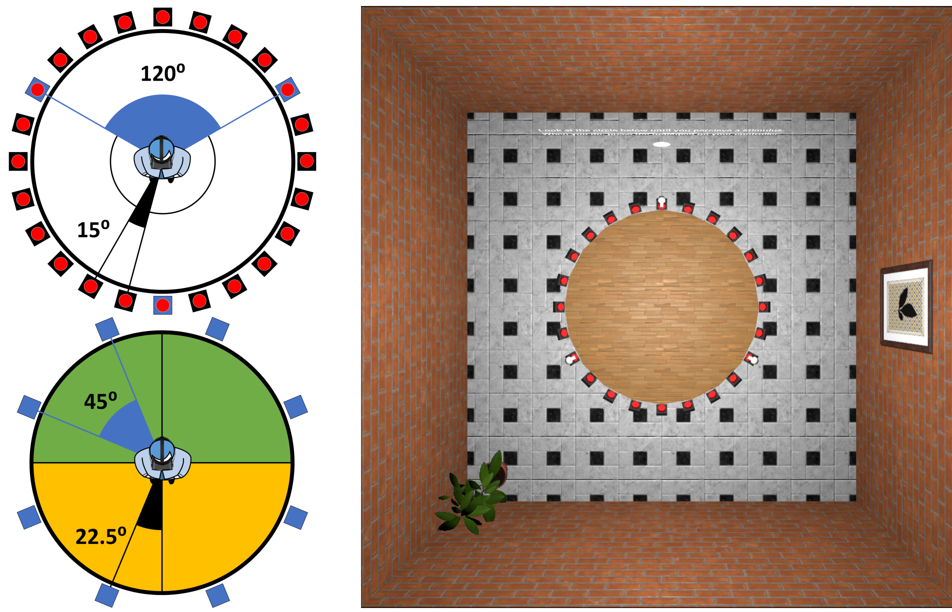


Fig. 8. *Left*: Outline of the VR environment where the buttons are the red circles, positioned with an angle of 15°between each other, while the blue squares represent the physical delivery output. *Right*: Top down view of the VR game environment.

total trials done were 24- 8 for each different cue conditions. The participants were presented with 2 initial trials to familiarize themselves with the task.

The main hypothesis was that olfactory cues would direct the user's attention in VR, just like auditory cues can do when the scent delivery (e.g. timing, output location) is accurately designed. We determined the accuracy with which users could locate the three source modalities (i.e. auditory, olfactory, audio-olfactory). We measured accuracy in terms of degrees in locating the source of the cues (i.e. select the desired button in the virtual environment), comparing the performance across various presentation angles around the user (e.g. front and back, see Fig. 8).

4.3.3 Study results. Twelve participants volunteered for this study ($M_{age=}$ 30.5 years, SD= 4.00, 4 female). All participants were familiar with VR (on a 7-point Likert scale, M= 5.55, SD= 2.55). The analysis of the recorded direction of the participants' heads allowed us to distinguish between front and back position (i.e. front position when the cue is presented within 180°centred on the head direction of the participants, and back position when outside 180°) (see Fig. 8, top left). To compare the accuracy in locating the correct cue's source between the cue modalities (i.e. auditory, olfactory, and audio-olfactory) in the two users' positions (i.e. front or back) we ran a repeated measures ANOVA (data normally-distributed [112]).

We found an interaction effect between the cue modality and user's position on the accuracy in locating the source ($F(2, 12)= 18.60$, $p< 0.01$, $\eta^2 = 0.75$). Post-hoc tests, Bonferroni corrected, showed that in the front position, the accuracy in locating the cue source was comparable between the cue modalities. However, in the back position, the accuracy was statistically different, between auditory and olfactory cues ($p< 0.01$), and between olfactory and audio-olfactory ($p< 0.01$) (see Fig. 9). These results provide information about users' performance in localizing auditory and olfactory cues. It is worth noting with respect to the performance of the modalities (especially Fig. 9 middle),

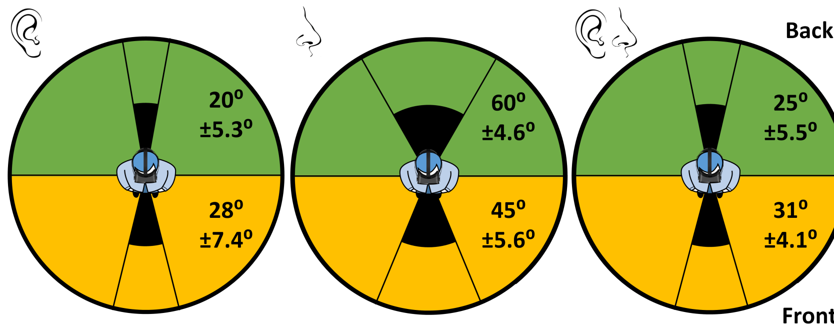


Fig. 9. Mean accuracy of participants in locating the source of the ambient cues in VR for the 3 conditions (back and front), s.e.m: 1. Auditory cue; 2. Olfactory cue; 3. Auditory and olfactory cues combined.

that the 45°range represents the mean accuracy when selecting the closest button to a olfactory or audio source (that is anywhere within the front 180°of the user's head orientation (see 8) bottom left for distribution of delivery locations). The 5.6°value refers to the calculated standard deviation (deviation from the mean) of that accuracy. In terms of resolution, the buttons are spaced 15°apart for a total of 24 buttons positioned 360°around the user (see 8). The total trials done were 24- 8 for each different cue conditions.

This application case demonstrated the importance of carefully choosing the scent-delivery parameters when exploiting the spatial features of smell. The design choices and options considered in this application case are important for designers to consider in order to ensure perceivability of an olfactory cue. Moreover, as in application case two, we also compared crossmodal interactions to demonstrate the possibilities around smell. As a result, we can see that participants achieve similar accuracy in locating the sources of olfactory, and audio-olfactory cues when presented frontally. This kind of insights opens up new design possibilities, exploiting olfactory stimuli to drive and capture user's attention in a VR environment, as part of new story-telling narrative. In a common VR experience, users are overstimulated by audio-visual information and considering the smell performance, in function of the scent-delivery parameters and locations, represents a new medium of information, which do not interfere with the other modalities.

5 DISCUSSION

With this article, we aimed to encourage design thinking and decision-making for smell-based interactions taking into account four key features. Those building blocks can help reduce the complexity of working with smell and also set the stage for reproducibility in olfactory interface design. If designers follow the interaction principles beyond single design instances (i.e. application cases), document their design choices along the four key features, it will become easier for others to replicate the interaction and thus help grow this design space.

In this section, we will discuss the relevance of the four features we identified as key building blocks for an emerging smell design space for HCI. We also reflect upon the relevance of those features to create and contribute to the intermediate-level knowledge space [53], bridging practice and theory around smell. Finally, we discuss remaining design trade-offs around smell and future research directions to move this emerging design space out of its embryonic state.

5.1 Relevance of the design features

The potential around smell for designing novel interactions in HCI was acknowledged over a decade ago [67, 68, 74]. Since then, the field has mostly explored one-off applications (e.g. [5, 67, 68, 93, 104]) but also contributed to some theoretical discussions with example implementations (e.g. [101]). To establish smell as design space for HCI, we identified four main features. The chemical, emotional, temporal, and spatial features. Each of those features is based on a rich knowledge established on the sense of smell, especially within experimental psychology, neuroscience, sensory science, and biology. We highlighted relevant characteristics for each feature to allow designers and HCI researchers in general to get a taste of the design potential around smell.

Each feature provides designers with a set of possible questions that will guide their design choices, allow reflection on possible options, and define criteria that are relevant for their particular design aim and intended interaction. The benefit of these features is their accessibility and openness. On the one hand, we aimed to represent them in such a way that the complexity of the sense of smell is reduced and thus hopefully encourages more researchers and practitioners to enter and explore this emerging design space. On the other hand, we made the feature descriptions evidence-based but open for future extensions, positioning the resulting design choices in-between theory and specific design instances (i.e. three design application cases).

Taken together, each feature provides designers with an anchor through a set of questions and possible options (solutions) for the specific design purpose. Having a clear purpose in mind also helps to define the implementation and evaluation steps and determine the specific measures. For example, in designing novel smell-based interactions, the conscious detection of scents is not always necessary. In our application case 1, the conscious detection of the scent was not required to have an effect on the users' performance. Participants were simply asked to indicate if they perceived a scent in the scent conditioning step, which was confirmed by all participants. In the other two application examples (2 and 3), the detection of the scent was an explicit part of the interaction we implemented and evaluated.

5.2 Contribution to intermediate-level knowledge

Compared to the other human senses, smell is still in an early development stage within HCI. It will take much more effort to establish it, compared to the audio-visual senses. Nevertheless, based on our work, we believe that we have the opportunity to bridge theory with practices by contributing intermediate-level knowledge [53, 80]. Intermediate-level knowledge is a form of knowledge that sits between theory and particular instances of design, encompassing such examples as guidelines, patterns, strong concepts, and heuristics [53, 80]. The idea is to allow for abstraction of key knowledge around a design challenge that can be applied to multiple application cases, but that does not aspire to the generality of the theory. Through our theoretical and empirical exploration of the olfactory design space, we are convinced that such new knowledge for the HCI and wider design community is emerging.

While we propose our four design features as 'guidelines', 'patterns' or 'strong concepts', we are aware that these features represent only an initial stepping stone between the theory and practice of scent-based interaction design. We only started to scratch the surface of this emerging design space and more application cases integrating scent as interaction modality are needed to establish our features more solidly as the design features for smell in the intermediate-knowledge space. However, what we achieved through this work – identifying four key features to guide design – is a reduction of the complexity around the sense of smell and demonstration of its successful integration in specific design application cases for smell.

5.3 Design considerations and trade-offs

In the effort to extend the audio-visual design space, we also need to acknowledge limitations and design trade-offs around smell.

First, scent-based experiences can be very subjective and can vary across individuals. Individual idiosyncrasies are based on preferences, scent liking, and perceptual sensitivities [38, 45, 45, 89]. As designers those individual differences need to be considered and can be addressed through allowing customisation (e.g. select your own scent from a pre-defined class of scents). For example, Maggioni et al. [83] categorised scents into valence, arousal, and perceived intensity dimensions as part of a smell design toolkit. Personalised design profiles can be created accounting for individual differences and preferences. Moreover, scent-association training provides a promising additional option, as applied in our application case study 2. Users are trained specific scent-association before engaging in an actual interaction. Although this results in a learning effort to begin with, its benefits can be seen over time [30, 82] and have been considered relevant in prior HCI implementations. For instance, Bodnar encouraged the use of scent-association training to increase the effect of scent-based interactions [5].

Second, smell is not yet a mainstream interaction modality. However, as scent-based interaction and applications steadily emerge and will grow over time, people will get used to it and become more comfortable and confident with it. Peoples' noses become more sophisticated as all our other senses get through use (e.g. graphic designers, musicians, chefs, perfumers). With the proliferation of smell-based applications, it is also key to find the right approach to evaluate the users' experience. Murray and colleagues [88] provide an extensive overview on relevant considerations for olfaction-based multimedia applications and provide a set of recommendations on how to conduct an evaluation focused on the quality of experience of such applications.

Third, the olfactory system is not always fully functional and can be compromised temporarily if someone has a cold or a hormonal fluctuation [24]. This can lead to limited olfactory capability, reducing the possibility of using scent in an interaction scenario. Hence, it is important to design for multi-modal/multisensory interactions where different sensory stimuli complement each other [96, 98]. As shown in our application case studies 2 and 3, scent-integration with visual or auditory stimuli leads to better performance in a given task.

Fourth and finally, scent reproducibility across devices and scent storage are practical challenges that can only be overcome through standardising the delivery mechanisms, enhancing current standards towards olfactory design (such as the MPEG-V Sensory Information standard). Conversion of chemical elements into binary digits for computer data communication and storage, is still a long way away. Spence and colleagues [119] provide a recent review on the possibilities and pitfalls around the chemical senses, accounting for chemical and also digital stimulation of the sense of smell. The potential substitution of chemicals for electrical stimulation of olfactory receptors in the nose is still an open research challenge, despite first efforts [49, 128]. Those challenges hence still limit the scalability of scent-based interactions.

6 CONCLUSION

Our nose provides a powerful sensory modality that we want to establish within the currently eyes-ears-hands dominated HCI design space. We summarised existing knowledge on the sense of smell to map out the olfactory design space composed of four key features: (i) chemical, (ii) emotional, (iii) spatial, and (iv) temporal. We demonstrated the relevance of those features in three application cases including VR and desktop implementations. The results from our three application cases highlight the design choices and the benefits of scent-based interaction on users' performance. We discuss how our olfactory design space helps the HCI community to navigate through the complexity of the sense of smell and open up new design opportunities. This paper makes a first necessary step towards a more coherent exploration of smell as an interaction modality.

ACKNOWLEDGMENTS

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