Opportunities for Olfactory Interaction in an Automotive Context

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

— PATRICK SÜSKIND

Declaration of Authorship

I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree. However, the thesis incorporates to the extent indicated below, material already submitted and published as part of the following scientific papers, written in collaboration with other researchers:

- Dmitrenko, D., Vi, C.T., and Obrist, M. A Comparison of Scent-Delivery Devices and Their Meaningful Use for In-Car Olfactory Interaction. In *AutomotiveUI '16* (New York, NY, USA, 2016), ACM. Authors' contributions: Dmitrenko, D. - 70%, Vi, C.T. - 15%, and Obrist, M. - 15% of the total work.

- Dmitrenko, D., Maggioni, E., and Obrist, M. OSpace: Towards a Systematic Exploration of Olfactory Interaction Spaces. In *ISS '17* (New York, NY, USA, 2017), ACM. Authors' contributions: Dmitrenko, D. - 70%, Maggioni, E. - 15%, and Obrist, M. - 15% of the total work.

- Dmitrenko, D., Vi, C.T., Maggioni, E., and Obrist, M. What Did I Sniff?: Mapping Scents Onto Driving-Related Messages. In *AutomotiveUI '17* (New York, NY, USA, 2017), ACM. Authors' contributions: Dmitrenko, D. - 70%, Vi, C.T. - 10%, Maggioni, E. - 10%, and Obrist, M. - 10% of the total work.

- Dmitrenko, D., Maggioni, E., and Obrist, M. Towards a Framework for Validating the Matching Between Notifications and Scents in Olfactory In-Car Interaction. In *CHI EA '19* (New York, NY, USA, 2019), ACM. Authors' contributions: Dmitrenko, D. - 80%, Vi, Maggioni, E. - 10%, and Obrist, M. - 10% of the total work.

- Dmitrenko, D., Maggioni, E., and Obrist, M. I Smell Trouble: Using Multiple Scents To Convey Driving-Relevant Information. In *ICMI '18* (New York, NY, USA, 2018), ACM. Authors' contributions: Dmitrenko, D. - 70%, Vi, Maggioni, E. - 20%, and Obrist, M. - 10% of the total work.

- Wintersberger, P., Dmitrenko, D., Schartmüller, C., Frison, A.K., Maggioni, E., Obrist, M., Riener, A. S(C)ENTINEL: Monitoring Automated Vehicles With Olfactory Reliability Displays. In *IUI '19* (New York, NY, USA, 2019), ACM. Authors' contributions: Wintersberger, P. - 30%, Dmitrenko, D. - 30%, Schartmüller, C. - 10%, Frison, A.K. - 10%, Maggioni, E. - 5%, Obrist, M. - 5%, Riener, A. - 10% of the total work.

- Dmitrenko, D., Maggioni, E., Brianza, G., Holthausen, B.E., Walker, B., Obrist, M. CARoma Therapy: Pleasant Scents Promote Safer Driving, Better Mood, and Improved Well-Being in Angry Drivers. In *CHI '20* (New York, NY, USA, 2020), ACM. Authors' contributions: Dmitrenko, D. - 70%, Maggioni, E. - 5%, Brianza, G. - 10%, Holthausen, B.E. - 5%, Walker, B. - 5%, Obrist, M. - 5% of the total work.

The seven papers mentioned above are presented in Part II of this paper-style thesis.

Signature: (Dmitrijs Dmitrenko)

Summary

Driving is a highly visual task. Nevertheless, it is a process that involves other senses as well. When we drive, we touch the steering wheel; we listen to what is happening around us, and, even if we are not paying attention to that, we smell what is happening with the car or around it. A scent of gasoline, the burning rubber, the plastic heated up by the sunlight - these are just a few examples. Smell is a very important sense for driving, though it has not been studied much in this context [85], despite being able to provide a much more vivid experience than any other human sense [80]. This thesis aims to fill this gap by investigating opportunities for olfactory interaction in an automotive context. The thesis is mainly focused on designing a scent-delivery device suitable for in-car interaction, on the topic of delivering driving-relevant notifications using scents, and on studying the effects scents have on the driving performance and behaviour, as well as the driver's mood and well-being.

This paper-style PhD thesis consists of two parts. Part II is a collection of seven published papers written in the scope of this thesis, and Part I describes how these papers build a coherent story. Part I starts with an introduction (see Chapter 1) that covers the research questions and contributions of the thesis. It continues with a summary of the background research (see Chapter 2). This overview part then moves on to the description of the approach (see Chapter 3) that covers the process of designing the scent delivery device, the olfactory interaction space, and the studies conducted throughout this PhD. Chapter 4 then summarises the core findings of each study, which are finally discussed in Chapter 5. Part I finishes with a conclusion (see Chapter 6).

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Contents

Part I

Overview

1 | Introduction

The majority of interaction techniques and user experiences in the field of Human-Computer Interaction (HCI) have been designed to stimulate vision and audition. Due to this reason, there is a limited number of devices that harness the olfactory system as a communication channel, even though olfaction provides much more vivid experience than any other human sense [80]. Already over a decade ago, Jofish Kaye has emphasised the fact that the sense of smell is underused in HCI [107]. Over the last 15 years, scents have been demonstrated to be useful in supporting such HCI-related tasks, as interaction with desktop applications [23, 129] and wearables [4, 3, 50], perceiving ambient notifications [19, 208], watching videos [196, 218, 140], playing games [134, 142, 98], and interacting with Augmented and Virtual Reality (AR and VR) applications [143, 34, 168].

Nevertheless, as pointed out by multiple researchers [107, 23, 19, 219], a scent is not easy to release in a controlled way and even harder to eliminate once it has been delivered to the user. These limitations did not allow as rapid evolving of the olfactory interaction as it happened in vision, audition, and touch-based approaches. However, with the knowledge about scent-delivery devices that we have now [153, 49, 45], we can overcome the above-mentioned challenges and focus on exploring the semantic potential of using scents as an interaction modality [48, 4, 50, 140, 168].

In an automotive context, tendencies have been similar, and the vast majority of in-car interfaces are based on visual and auditory stimulation. This makes sense because driving is a task that relies almost exclusively on visual and auditory cues. Such cues vary in their nature and the perception of each modality might differ. For example, Politis et al. [165] has investigated different visual (e.g. icons, texts) and different auditory (e.g. abstract sounds, spoken language) stimuli in a context of driving and demonstrated that the recognition time of such notifications varies also within one sensory modality. Moreover, visual information can be presented to the driver on different displays (e.g. head-up and head-down displays [190]). Nevertheless, drivers also perceive haptic (e.g. vibrations of the car because of the engine or the road condition) and olfactory (e.g. car interior scent) information while driving.

The decision behind investigating the sense of smell as an interaction modality in an automotive context is motivated by three major benefits mediated by the olfactory stimulation: (1) a strong link of the sense of smell to emotions and memories of the user [80], (2) efficiency of scents in activating the user's central neural system [10] and in enabling a direct link to the primary cortex [166], and (3) an ability of scents to improve the user's well-being [89, 3].

As our sense of smell has a strong influence on our emotions and memories [80], scents could be useful in calming the driver down [141], improving their mood [15, 130, 170], and reminding them on certain driving-relevant tasks (e.g. "Fill gas" [48]). Activation of the central neural system by means of scents [10] has been demonstrated beneficial, for example, in keeping drowsy drivers awake [220, 66]. For this reason, scents could help make drivers aware of driving-relevant events (e.g. lane departure without indicating [46]). Due to a direct link to the primary cortex [166], olfactory stimulation might potentially be able to help the driver process the perceived information faster.

Scents can improve our well-being too [89, 3]. This has been the motivating factor for the recent advancements in the automotive industry, where multiple manufacturers, including Mercedes-Benz [35], Audi [138], BMW [20], and Bentley [18] have created their own in-car scents to enhance hedonic driving experiences. The last study presented in this thesis looks into the effects that different classes of scents (e.g. positive valence and low arousal scents) have on the well-being of the driver during a driving phase. Here it is important to acknowledge that this thesis evaluates the effects of scents on the short-term well-being (i.e. while driving in the car). Long-term well-being (e.g. between car rides or over multiple driving sessions) is not assessed in the scope of the research activities summarised in this thesis.

Research has shown that scents have a positive impact on the alertness and mood of the driver [15, 170], drivers' braking performance [130], and on keeping drowsy drivers awake [220, 66, 157, 219]. However, all of the interfaces used in the examples mentioned above are delivering only ambient scents and without making use of the ability of scents to provide hints to the user. The potential of scents to convey information is evidenced by findings in psychology and neuroscience, mainly on crossmodal correspondences, object localisation and identification, and capturing attention [184], odour driven motor action [29], as well as the relationship between odour detection and semantically congruent cues [68]. Indirectly, drivers are already using their sense of smell for diagnosis purposes, e.g. the gasoline scent indicates a leak, but a smoky scent might mean there is a problem with the clutch. Adding scents to notify the driver about other events might help them become aware of the information that would have been missed otherwise. Olfactory cues could reduce visual demand and help keep the focal point on the road.

To convey information by using the olfactory channel, it is necessary to release scents in small portions, deliver them to the user's nose quickly, enable rapid switching between scents, and make scents disappear quickly after they have been delivered to the user [45]. Creating a device that is capable of enabling such features can be a challenging task. Several promising scent-delivery devices have been developed recently [153, 49], some of them have also been integrated into driving simulators [220, 66]. Some of the car manufacturers, like Ford [112], have already patented their in-car smell notification systems. Nevertheless, devices currently available on the market have their limitations (e.g. frequent cleaning requirements, scent cross-contamination), making them not suitable for scientifically rigorous explorations and motivating the creation of more precise delivery devices and olfactory interaction spaces (i.e. allowing control over several scent-delivery parameters). This is especially important in the context of confined spaces, like the interior of a car.

Talking about olfactory interaction in confined spaces, it is worth pointing out that this thesis could be extended towards application areas that share some of the interaction characteristics (e.g. cockpit interfaces [144], flight simulators [152]).

As scents take longer to get perceived by the user than visual and auditory stimuli, not every driving-relevant notification might be useful in olfactory interaction. Similarly, since not every scent is arousing enough to get noticed quickly, it is very important to choose the scents carefully. On this stage, we can learn a lot from the findings tackling the activation of the central neural system [110, 10]. To overcome scent unfamiliarity problem [107], we can learn from the findings on olfactory conditioning [115].

The **aim** of my research is to **establish an understanding of how scents can be applied in the context of driving, to not only improve hedonic experiences but also to convey driving-relevant information**. I achieve this aim by answering such **research questions** as **(1) How can we deliver scents in an in-car context? (2) How can we meaningfully integrate smell as an interaction modality in a context of driving?** and **(3) What new interactions and experiences can we design for by applying olfactory stimulation in a context of driving?**

This thesis answers the research questions highlighted above in two ways: by using scents as (1) an information delivery mechanism [46] and as (2) a potential tool for emotion regulation [44]. These two research directions create implications in the way the scent needs to be delivered. In the first case, the scent needs to be delivered to the driver's nose as quickly as possible. Also, in situations of rapid switches between the bits of information (i.e. below 10 seconds), the system might need to use an alternative communication channel (e.g. touch, sound). In the second case, when the scent is used to modulate the driver's emotional state, the speed of its delivery is not that crucial.

To enable this exploration, I propose recommendations for designing a scent-delivery device and an olfactory interaction space. To find out what scents could be useful in what driving scenarios, I propose an approach for establishing a mapping between scents and driving-related notifications. Finally, I suggest ways of validating this mapping by exploring the effect of scents on the driving performance and behaviour in contexts of manual and automated driving.

1.1 Main Definitions and Focus Area

This section introduces the main definitions used in this thesis (summarised in Table 1.1), along with the research focus shaped by the definitions. Every definition is explained with references to the related work.

1.1.1 Main Definitions

The main definitions used in this thesis explain the following terms:

(1) Scent-Delivery Device,

(2) Scent Mapping,

(3) Driving-Relevant Notification,

(4) Driving Performance,

(5) Driving Behaviour,

(6) Reliability Display,

(7) Trust in Automation,

(8) Self-Reported Scent Perception,

(9) Driver's Well-Being,

(10) Driver's Emotional State.

Explanation of each definition is provided in Table 1.1 (see next page) and, in more detail, in sub-sections following the table.

Term	Definition in this thesis	References
Scent-Delivery Device	*Device used for releasing a scent and delivering scent molecules to the user's nose.*	[126], [219], [142], [7]
Scent Mapping	*A term used to refer to the associations between specific scents (e.g. lavender, lemon) and driving-relevant notifications (e.g. "Slow down").*	[52], [71], [32]
Driving-Relevant Notification	*A message containing driving-related information, conveyed to the driver while performing a driving task.*	[163], [121], [185], [114], [135], [136]
Driving Performance	*Deviation from the centre of the lane (ideal path) measured in centimetres.*	[146], [135], [136], [185]
Driving Behaviour	*A measure of how a participant drives, quantified in two ways: (1) as a number of driving-related mistakes (e.g. events of exceeding the speed limit, changing the lane without indicating) and (2) as driving-dynamics-related data (e.g. mean speed or mean steering angle).*	[102], [101], [60] [173], [55]
Reliability Display	*A display communicating the reliability level of an automated vehicle (e.g. low/high) to its driver.*	[17], [149], [61], [78]
Trust in Automation	*A measure of the driver's trust in an automated vehicle, calibrated by means of reliability displays and assessed using the trust scale (TS) and the Technology Acceptance Model (TAM).*	[103], [38], [139], [122]
Self-Reported Scent Perception	*A measure of how a scent was perceived by a driver, assessed using a Self-Report Questionnaire (SRQ), based on psychometric standard guidelines (7-Point Likert scale), to evaluate scent liking, comfort, and intensity.*	[184], [15]
Driver's Well-being	*The driver's state of being comfortable, assessed by analysing comfort SRQ and interview responses.*	[86], [35], [18], [20]
Driver's Emotional State	*Emotions experienced by the driver in the process of driving, measured using the Self-Assessment Manikin (SAM).*	[102], [101], [60], [210], [173], [77]

Table 1.1: Summary of definitions used in this thesis.

1.1.1.1 Scent-Delivery Device

Scent-delivery device is a term used to refer to a device used for releasing a scent and delivering scent molecules to the user's nose [45]. In the research and laboratory context, it is often referred to as an olfactometer [126, 5, 109, 124]. Such terms as a scent/aroma diffuser [19, 88, 142, 66, 105] and an olfactory display [118, 157, 7, 107, 79, 219] are also common. This thesis describes how different scent-delivery devices can be compared, to identify their potential application scenarios (see Chapter 7), how a scent-delivery device can be built (see Chapter 8), and how it can be applied in olfactory interaction studies (see Chapters 9, 10, 11, 12, and 13), in particular to investigate different driving scenarios. Every experiment described in this thesis was conducted using a scent-delivery device designed, built, and improved throughout this PhD.

1.1.1.2 Scent Mapping

In this thesis, scent mapping is a term used to refer to the associations (links) between specific scents (e.g. lavender, lemon) and driving-relevant notifications (e.g. "Slow down", "Fill gas"). While scent mapping is a new term to HCI, it has been studied for decades in other domains (i.e. to assign labels to different scents [51, 52, 71, 32, 31]). This thesis describes both how a scent mapping can be established (see Chapter 9) and how such a mapping can be validated (see Chapters 10 and 11) for different scenarios.

1.1.1.3 Driving-Relevant Notification

A driving-relevant notification is a message containing driving-related information, conveyed to the driver while performing a driving task. The vast majority of notifications used in modern vehicles are visual; however, any distraction of the driver's visual attention on the road can have fatal consequences [163]. There are also proposals suggesting the application of tactile stimulation [121, 21, 185, 174], thermal feedback [42, 41], ambient lights [123], and auditory signals [114, 135, 136]. Only very few approaches are tackling the use of scents as a notification modality [46, 47, 215]. This thesis describes how olfactory notifications can be designed (see Chapter 9) and used in different driving scenarios (see Chapters 10, 11, and 12).

1.1.1.4 Driving Performance

The ways of quantifying driving performance are not consistent in the literature. There are suggestions of counting the number of driving mistakes (e.g. traffic rule violations, collisions [102, 101]) or measuring the lane deviation (i.e. distance from the centre of the lane [135, 136, 146, 185]). In this thesis, the driving performance is defined as the distance from the centre of the driving lane in centimetres, which demonstrates a deviation from the ideal driving path. In this thesis, the driving performance is calculated to measure how well participants drive when perceiving olfactory notifications in the process of driving (see Chapters 10 and 13).

1.1.1.5 Driving Behaviour

In this thesis, the driving behaviour is quantified in two ways: (1) as a number of driving-related mistakes (e.g. events of exceeding the speed limit, changing the lane without indicating) and (2) as driving-dynamics-related data retrieved from the driving log file (e.g. the mean driving speed or steering angle). Similar approaches have been used in the related work (e.g. in experiments investigating driver's emotions [102, 101, 60, 173, 55]). The driving behaviour was used to assess the change in the way participants drove after having received olfactory notifications (see Chapters 10, 11, and 13).

1.1.1.6 Reliability Display

This thesis also investigates the use of olfactory stimulation to enhance reliability displays (proposed by [17, 78]) used in automated vehicles. A reliability display communicates the reliability (or "uncertainty" [61]) level of an automated vehicle (e.g. low/high, in the form of a visual notification) to its driver. An investigation of how drivers can benefit from a vision-based reliability display, by adding olfactory feedback to its notifications, is presented in Chapter 12.

1.1.1.7 Trust in Automation

In conjunction with olfaction-enhanced reliability displays, this thesis looks into the topic of trust in automation [216, 87, 122, 139]. This is a measure of the driver's trust in an automated vehicle, assessed by using the trust scale (TS) [103] and the Technology Acceptance Model (TAM) [38]. This topic is covered in Chapter 12.

1.1.1.8 Self-Reported Scent Perception

This thesis discusses the application of a Self-Report Questionnaire (SRQ) used to assess how participants perceived different scents in every experiment (see Chapters 9, 11, and 12 for details). As there is no standardised questionnaire used for this purpose in the related work, the approach employed here relies on psychometric standard guidelines and utilises a self-report questionnaire based on a 7-Point Likert scale to report liking, comfort, and intensity of scents. Similar questionnaires can have been used in other olfactory studies (e.g. in [15, 184]).

1.1.1.9 Driver's Well-Being

Several user studies conducted throughout this PhD revealed findings on the effect of scents on the driver's well-being (see Chapters 9, 11, 12, and 13). In this thesis, the driver's well-being is discussed as a state of being comfortable, assessed by analysing participants' self-reported comfort ratings and interview responses. This is a very important topic in the scope of olfactory interaction, e.g. as demonstrated by current trends in well-being research [3, 4] and automotive industry [138, 20, 35, 86, 18].

1.1.1.10 Driver's Emotional State

Finally, due to a well-known fact of an olfactory function having a strong link with emotions [2], this thesis investigates ways of modulating drivers' emotions using olfactory stimulation. In this thesis, the driver's emotional state is explored as a set of emotions experienced by the driver in the process of driving. Emotions have been measured by using the Self-Assessment Manikin (SAM), as proposed by Bradley and Lang [22]. Driver's emotions have been widely investigated in the past (e.g. in [173, 77, 55, 102, 101, 60, 210]), but only very little work has been done about exploring the effect of scents on the emotional state of the driver [15, 170, 141]. This thesis presents a study, which investigated the effect of different scents on angry drivers (see Chapter 13).

1.1.2 Research Focus

The main focus of this thesis is the topic of conveying information in the process of driving, employing olfactory stimulation. Conveying information using scents is not a new topic in HCI. It has been used e.g. for photo-tagging [23] and ambient notification [19, 208] applications. In an automotive context, olfactory stimulation is common to increase the well-being of the driver [48], but not much has been done about applying it as an information transportation medium, e.g. to assist the driving task [49, 48]. To fill this gap, this thesis proposes a five-step procedure (see Figure 1.1): (1) finding a suitable scent-delivery device and identifying the scent-delivery parameters, (2) designing an olfactory interaction space, (3) establishing a mapping between scents and driving-relevant notifications, (4) validating the established mapping for different simulated driving scenarios, (5) testing the established mapping and identifying further applications scenarios for scents in the car.

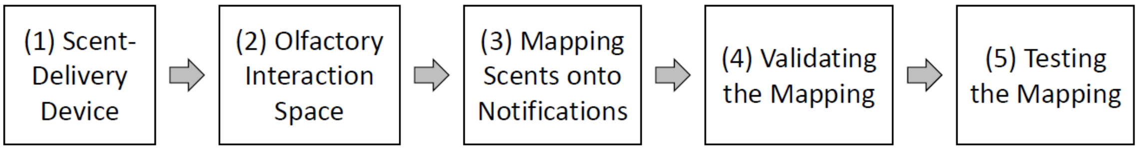


Figure 1.1: Five-step procedure defining the research focus of this thesis.

While this procedure summarises the main research focus of this thesis, it can be further extended to study olfactory interaction in an automotive context. One of the ways of doing that would be to explore multiple opportunities of testing the established mapping, e.g. by means of olfactory conditioning (i.e. to train the user based on the established scent-notification associations) or customisable user interfaces (i.e. give users a chance to select among multiple scents which are equally good for a certain notification). Another way would be to investigate how the established mapping is interlinked with the emotional effects since scents have strong links to emotions and memories [80] (partially explored in a study presented in Chapter 13). Finally, it would also be valuable to conduct further explorations of olfactory notifications in a context of autonomous driving (as in a study presented in Chapter 12).

1.2 Objective and Research Questions

This thesis investigates the problem of olfactory in-car interaction by employing a cross-disciplinary approach, merging engineering, olfaction, and automotive user interface design (see Figure 1.2). Engineering thinking is necessary to compare different scent-delivery devices currently available on the market (e.g. by quantifying their performance) and to identify their possible application scenarios. Furthermore, engineering comes into play in the process of designing an olfactory interaction space (e.g. controlling the airflow, designing the extraction system, constructing the body of the scent-delivery device). Knowledge of olfaction is necessary when establishing a mapping between scents and driving-relevant notifications (e.g. based on the arousal and valance levels of different scents), as well as in understanding the issues related to scent perception (e.g. scent lingering and habituation). Finally, it is an absolute must to consider this all in term of automotive user interface design best practices, since

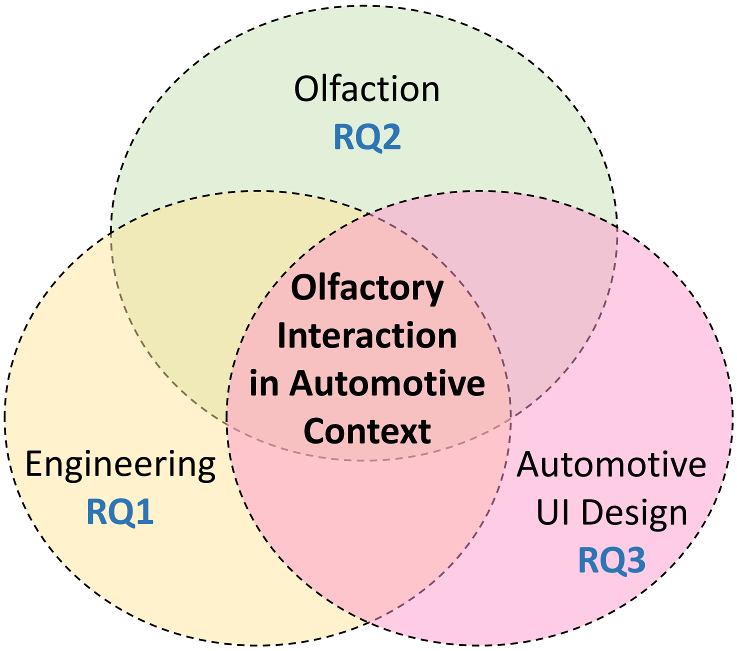


Figure 1.2: Contribution of the thesis lies on the intersection of three disciplines that define the overall objective and research questions.

every new proposal needs to be valid for in-car use (e.g. to make sure that olfactory interaction improves the driving behaviour).

The cross-disciplinary approach described above is based on the following three research questions:

RQ1: How can we deliver scents in an in-car interaction context?

The first research question explores the different delivery mechanisms for scents, how are they suitable for in-car use, and what potential application scenarios would they fit. Here, it is also important to investigate how an olfactory interaction space can be built, how to deal with scent-delivery (e.g. air supply, separate scent channels) and scent elimination (e.g. air extraction) related issues.

RQ2: How can we meaningfully integrate smell as an interaction modality in a context of driving?

The second research question investigates challenges related to human olfaction, to find out how to deal with scent perception, cross-contamination, lingering, and habituation issues on the way of using olfactory stimuli for in-car interaction. The focus here lies on the challenge of establishing a mapping between scents and driving-relevant notifications by building an understanding of what scents are useful in what scenarios.

RQ3: What new interactions and experiences can we design for by applying olfactory stimulation in a context of driving?

The third research question seeks suitable applications for scents in a context of driving. Here, it is important to explore what effect olfactory notifications have on the driving performance and behaviour in different application scenarios. It is also essential to investigate ways of helping the driver build associations between scents and driving-relevant notifications (e.g. by using olfactory conditioning). In terms of experiences, this research question aims to build an understanding of the effect of scents on the drivers' emotions and well-being when scents are used as a notification modality.

1.3 Thesis Context

The work on this thesis has been conducted over three years and three months. The research took place in the Sussex Computer-Human Interaction (SCHI) Lab at the University of Sussex. SCHI Lab was established only a few months before the start of this PhD. As the Lab was new, and no other researchers were working on Olfactory HCI in the Lab before the projects described in this thesis, I had the opportunity to contribute to the growth of this emerging research area, which required an active design of the experimental space and the setup for testing novel olfactory interaction concepts in an automotive context.

The first challenge was to find a scent-delivery device suitable for conducting scientific experiments described in this thesis. After an extensive background research, to find out which devices are available on the market and in academic research labs, four different devices (*DaleAir Vortex Activ USB*, *Scentee*, *oPhone*, and *Aroma Shooter*) were ordered for further exploration in the Lab. After conducting initial tests, a framework was established proposing a way to compare such devices and to identify their possible application scenarios (see details in Chapter 7). The initial explorations also showed that these devices are not precise enough for scientific experiments. I have encountered such issues as the scent cross-contamination and inability to deliver a scent to the user's nose quickly (in less than 10 seconds) and from a distant point in space (at least 50cm away from the nose), to allow fast interaction and to avoid interference with hand movements (see interaction recommendations described in Chapter 8). Based on these observations, it was decided to design and build Lab's own scent-delivery device, with isolated scent channels, controllable air pressure and scent-delivery duration (see Chapter 8). As the process of designing such a device, ordering the necessary parts, and assembling it took several months, it was also decided to conduct an experiment with manual scent-delivery (similar to [200, 109]), in order not to interrupt the research process. Such an experiment was conducted to establish an initial mapping between different scents and driving-relevant notifications, which were presented to participants in the form of storyboards (see details in Chapter 9). This step took 1.5 years to accomplish.

The second challenge was to make sure that there is an experimental space suitable for running olfactory interaction studies in a context of driving. After reviewing the literature and trying to find out how such a space needs to look like, it was decided to adopt a clean room setup (from *Connect 2 Cleanrooms Ltd.*, with the following size: *H= 2.1m, W= 1.3m, L= 2m*), by replacing its plastic curtains (because of a very intense scent) with an odourless water repellent fabric. This space was also equipped with two powerful air extractors and one clean air blower (see details in Chapter 8). In automotive user interface studies, it is common to mount a steering wheel on a simple office desk (e.g. like in [185, 146]), however, to enable high fidelity simulated driving studies, I decided to equip the olfactory interaction space with a proper driving simulator seat (from *FK Automotive*) with a *Logitech G27* steering wheel and pedals mounted on it. For the display of the driving scene (the view outside the car from the driver's perspective), the interaction space also featured a 55" curved screen with 60Hz refresh rate. This design and assembling process took six months in total.

The construction of the olfactory interaction space mentioned above had a high impact on my PhD and the work of the entire Lab. It has been used in multiple olfactory interaction studies (see Chapters 8, 9, 10, 11, and 13). It took me around ten months in total to conduct these studies.

To prepare each simulated driving study, it was also necessary to solve the third challenge, which was to find and adopt a driving simulator software suitable for each use case investigated throughout the PhD. In this process, I have explored such software packages as *CityCarDriving 1.5*, *Drive Megapolis*, *Racer*, *ETS2*, *OpenDS*, and *IPG CarMaker*, which took around four months in total. An overview of these packages, their advantages, disadvantages, and suitability for each use case, is available in Section 3.3.3.

1.4 Thesis Contributions

This section describes the contributions of this thesis, achieved in line with the research questions (see Table 1.2 for an overview). Each contribution is explained below.

Research Question	**Objective**	**Paper**
RQ1: How can we deliver scents in an in-car context?	• Design a framework for comparing different scent-delivery devices and identifying their application scenarios in the car.	Paper 1 (Chapter 7)
	• Summarise recommendations for the design of a fully controllable scent-delivery device and an olfactory interaction space suitable for running simulated driving experiments.	Paper 2 (Chapter 8)
RQ2: How can we meaningfully integrate smell as an interaction modality in a context of driving?	• Investigate how quickly users perceive different scents and evaluate how liking, comfort, and intensity ratings change depending on scents used for interaction.	Paper 2 (Chapter 8)
	• Establish a mapping between scents and driving-relevant notifications.	Paper 3 (Chapter 9)
RQ3: What new interactions and experiences can we design for by applying olfactory stimulation in a context of driving?	• Validate the scent-notification mapping in combination with a driving task by exploring the effect of olfactory notifications on the driving performance and behaviour.	Paper 4 (Chapter 10)
	• Explore olfactory conditioning as a way of familiarising the driver with associations between scents and driving-relevant notifications, and analyse its effect on the perceived comfort ratings.	Paper 5 (Chapter 11)
	• Investigate effects of scents on the driver's behaviour and their attitude towards olfactory notifications in the context of autonomous vehicles equipped with reliability displays.	Paper 6 (Chapter 12)
	• Investigate effects of scents on driver's emotions and well-being.	Paper 7 (Chapter 13)

Table 1.2: Overview of the research questions of this thesis highlighting the key objectives and associated papers/chapters.

RQ1: How can we deliver scents in an in-car context?

- Based on the initial comparison of four commercially available scent-delivery devices, a novel framework for comparing different delivery devices was established. This framework created a tool for identifying the application use cases for each scent-delivery device in automotive contexts, based on the properties of the scent-delivery, i.e. volume, distance, and speed (see Chapter 7).

- Considering the insights gained from the initial exploration of commercially available scent-delivery devices, it was possible to extract the drawbacks of existing solutions and use them to design a new device, which would overcome the current limitations. This device, along with a dedicated interaction space, built to test it, emerged the second contribution - the creation of a novel set of recommendations for the design of a scent-delivery device and an olfactory interaction space suitable for running simulated driving experiments (see Chapter 8).

RQ2: How can we meaningfully integrate smell as an interaction modality in a context of driving?

- After having built a scent-delivery device and an olfactory-interaction space, it was necessary to validate this setup in a user study, which evolved the third contribution. This study measured the scent detection and lingering times while setting the scent-delivery device to three different air pressure levels, for three different scents, with two dilutions. Such a design of the study provided a new approach for exploring an olfactory interaction space. Moreover, it produced knowledge on how quickly users perceive a scent delivered by such a device and of how quickly a scent disappears after the delivery, depending on the scent used for interaction (see Chapter 8). With this knowledge, it became clearer what automotive scenarios would such a setup fit.

- Based on the related work on arousing and calming effects of different scents, it was possible to set up a study to investigate a mapping between scents and driving-relevant notifications. The set of notifications, used in this study, was defined taking into account the findings on scent-detection time (see the previous contribution). This study established an initial mapping between different scents and driving-relevant notifications, making a new step towards solving a problem of conveying information in an in-car context (see Chapter 9).

RQ3: What new interactions and experiences can we design for by applying olfactory stimulation in a context of driving?

- After it became clear how to design a scent-delivery device and an olfactory interaction space, how quick the scent detection and lingering is, and how scents can be mapped onto driving-relevant notifications, it became possible to design the first application scenarios for scents as an in-car notification modality. The total of three studies was conducted to test such scenarios and to demonstrate how olfactory notifications can improve driving performance and behaviour (see Chapters 10, 11, and 12).
- While studying the effects of olfactory notifications on the driving performance and behaviour, it was also possible to observe the influence of such olfactory stimulation on the driving experience (i.e. emotions and well-being of the driver). Findings on this are presented in Chapters 11, 12, and 13.

1.5 Thesis Overview

This thesis has been written as a paper-style PhD thesis, as approved by the guidelines for research students at the University of Sussex. It is based on a collection of seven papers (six published and one to be submitted for publication shortly after submitting this PhD thesis) and consists of two main parts. Part I is the introductory part, which explains how the seven papers are related to each other, describing different steps of the research process. This part covers the main definitions of the thesis, research questions, related work, research method, and contributions while referring to each paper from Part II. Part II includes the collection of the papers, in the order that creates a logical sequence of contributions to the thesis topic.

The Overview part is organised into the following chapters:

- Chapter 1: Introduction provides an overview of this thesis, presents the main definitions, research questions, thesis context, and the contributions of this thesis.
- Chapter 2: Background provides insights from the related work demonstrating how different senses are harnessed as interaction modalities in automotive user interfaces, underlying the benefits and challenges of the sense of smell.
- Chapter 3: Approach presents the contexts and the detailed methods of each user study conducted throughout the PhD.

- Chapter 4: Findings summarise the main results of each user study, conducted to answer the research questions.
- Chapter 5: Discussion covers the main contributions of the thesis, along with the key limitations.
- Chapter 6: Conclusion describes the concluding remarks of the thesis, including the implications for future work.

The Scientific Papers part consists of the following chapters:

- Chapter 7: A published paper on a framework that can be used to compare different scent-delivery devices. This paper also suggests a way of identifying a meaningful application for each of such devices, based on the distance, speed, and volume of scent delivery.
- Chapter 8: A published paper that provides a set of recommendations for designing and building a scent-delivery device and an olfactory interaction space.
- Chapter 9: A published paper that describes a way of mapping driving-relevant notifications on different scents.
- Chapter 10: A published paper proposing a framework for validating a mapping between driving-relevant notifications and scents.
- Chapter 11: A published paper presenting how a mapping between driving-relevant notifications and scents can be used to assist a task of driving.
- Chapter 12: A published paper demonstrating how scents can be used to assist a task of interacting with an autonomous vehicle.
- Chapter 13: A paper on investigating a link between the driver's emotions and scents, as well as how scents influence the driving behaviour of drivers in an induced angry state.

The current chapter of the thesis has provided a detailed description of the main definitions used in this thesis, explanation of every research question, and the core contributions of this thesis. To provide background information on how the thesis was written and what the research environment was like, this chapter also described the context of the conducted research. The next chapter will cover the most relevant findings from the related work that motivated the research activities in the scope of this thesis. The core emphasis will be made on the advantages and the limitations of the olfactory interaction compared to stimulating other human senses in a vehicle.

2 | Background

After having explained the main definitions, research questions, and the contributions of this thesis, it is now important to go through the most relevant references from the related work. Automotive User Interface (AUI) Design is a sub-field of HCI, yet it has its distinct features. As outlined by Kern and Schmidt [108], devices in AUI are fix-mounted in a car, and the driver is constrained in their mobility. This imposes quite a few constraints onto the way they inetract with the user interface. At the same time, drivers can act with their left or the right hand, as well as with the left or right foot, which is not always the case in non-automotive user interfaces. Users deal with similar opportunities and limitations in cockpit interfaces [144] and flight simulators [152], however, these interface types are designed for highly trained professionals, who go through a more extensive training than drivers. While many widely used user interfaces (such as smartphone apps) often require only visual attention, driving involves integration of multiple sensory cues [85]. This chapter will explain how automotive user interfaces have been designed to stimulate such human senses as vision, audition, and touch most efficiently, and what are the advantages and challenges of using olfaction as an interaction modality in a context of driving.

2.1 Different Interaction Modalities in Automotive User Interfaces

Visual notifications dominate in modern vehicles. However, any distraction of the driver's visual attention on the road can have fatal consequences [163]. Sound can reduce the visual load and help the driver perceive the urgency of the warnings [54], but it can also be annoying [14] or even distracting [54]. This has stimulated the exploration of other modalities [153]. Tactile interfaces have been widely studied and have indicated, e.g. a positive effect on users' attention in safety-critical environments [189], faster braking reaction times [127] in simulated driving, while also being less annoying [121]. Olfactory stimulation is, still largely unexplored in automotive contexts, even though it could help drivers process information [184]. The benefits and drawbacks of each modality are discussed in more detail below.

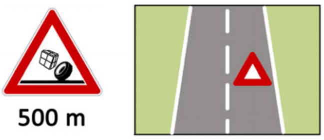
Variants	example
text only	Lost cargo 500 m right lane
icon only	
mixed 1	
mixed 2	
speech	"Lost cargo in 500 m on the right lane"

Figure 2.1: Visual notification modalities used in the experiment of Cao et al. [28].

2.1.1 Vision

Vision is a dominating sense in the process of driving. This is the reason for the wast majority of in-car interfaces to be visual, even though using visual stimulation for secondary tasks or assisting the task of driving may cause distraction [181].

Cao et al. [28] demonstrated that text-only notifications require the most time while icon only resulted in the shortest recognition time. These notifications are visualised in Figure 2.1. The finding mentioned above was true for visual notifications appearing in the bottom right corner of a screen (a desktop-based simulated driving setup).

Politis et al. [165] investigated visual head-up notifications and discovered that recognition times of warning urgency during a non-critical driving situation were shorter for abstract warnings, highly urgent warnings, and warnings that included visual feedback. The complete set of visual feedback notifications is presented in Figure 2.2. The driving task employed in this study was limited to one lane and one car in front of the ego car (i.e. the car driven by the participant).

Rajan et al. [167] used a Google Glass to project visual (textual) notifications and showed that such notifications are distracting. Such results were observed in a user study where participants had to perform a ConTRe (Continuous Tracking and Reaction) driving task that involves pressing the pedals (gas and brake) when requested and

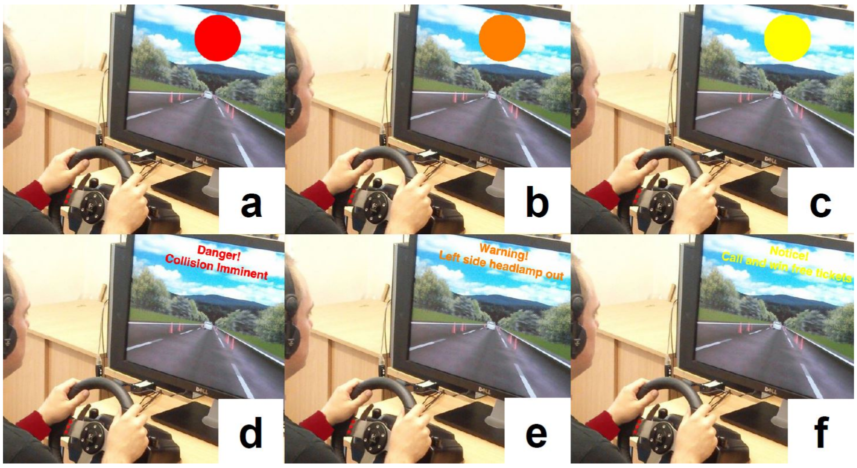


Figure 2.2: Visual notifications (icons (a-c) and textual messages (d-f)) used in the study of different notification modalities conducted by Politis et al. [165].

matching two cylinders (yellow and blue) on the screen of the driving simulator (as shown in Figure 2.3), by using the steering wheel. This task is used to introduce a certain degree of complexity to the process of driving.

Häuslschmid et al. [73] discovered that geometric shapes (i.e. squares, triangles, and circles) could be recognised in considerably smaller sizes than text when presented on the car's windshield (see Figure 2.4). These visual stimuli appeared on the windshield in the process of driving, and participants had to respond by pressing a button on the steering wheel.

Helldin et al. [78] has investigated the use of visual notifications in a context of autonomous driving, where a set of horizontal bars (see Figure 2.5) was used to represent the system's reliability level (displayed in the instrument cluster of the car). Their results indicated that such a display helped participants be better prepared to switch to manual

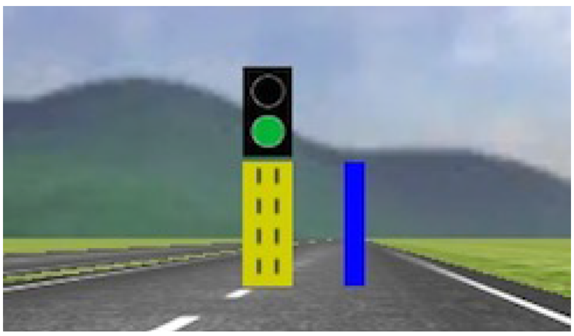


Figure 2.3: Screenshot of the ConTRe (Continuous Tracking and Reaction) Task displaying the yellow reference cylinder with the traffic light (top), and the blue tracking cylinder (right) [167].

Figure 2.4: Geometric shapes displayed as notifications on the windshield in the simulator study conducted by Häuslschmid et al. [73].

control when required, compared to a control condition (where no information on the car's automation reliability was provided). In this study, participants had to drive through a narrow road, in bad weather conditions. 20/33 participants of this study, who stayed on the road after a take-over request (i.e. a request to (re)start driving the vehicle manually), were from a condition in which a reliability notification was displayed. These participants also spent significantly more time taking their focal point away from the road. Nevertheless, here it is important to bear in mind that the virtual car carrying the participant was driving most of the time autonomously (requiring smaller visual demand from the driver than in manual driving scenarios) and that no other display modalities were investigated in this study.

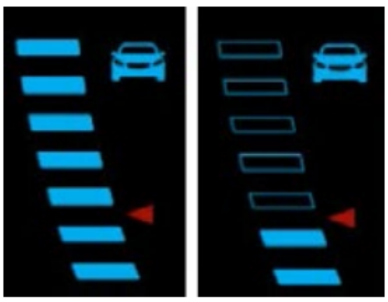


Figure 2.5: Horizontal bars displayed on the dashboard to represent the ability of the car to drive autonomously, ranging from 7 (very high ability, left figure) to 1 (no ability, right figure). The red triangle indicates the threshold for when the performance of the automation no longer can be guaranteed. [78].

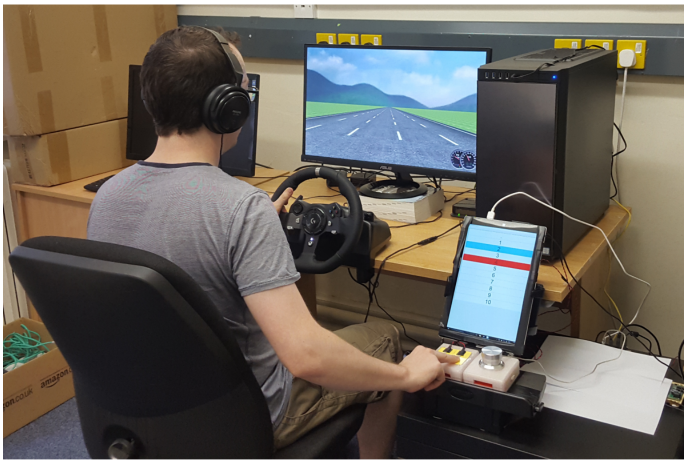


Figure 2.6: The experimental setup of the touchscreen interface used in lab-based study conducted by Ng et al. [146]. Participants had to keep the virtual vehicle in lane as accurately as possible while interacting with the touchscreen.

Visual displays have also been explored for capturing driver's input (i.e. through visual menus displayed on touchscreens). For example, Ng et al. [146] found that such input displays are nearly as efficient as traditional dials. This result was confirmed both in a lab-based (see Figure 2.6) and an on-road study.

As we can see from the related work, visual notifications can have a positive effect on the driving behaviour and get perceived by the driver quicker (e.g. when conveyed using icons or geometric shapes) than some other modalities (e.g. text). However, this depends greatly on the task the driver needs to accomplish, the driving scenario, and where the information is displayed. As demonstrated by Ng et al. [146], visual information can be conveyed more efficiently by combining it with tactile stimulation (e.g. through vibrating touchscreens). Also, as shown by Politis et al. [165], visual notifications combined with audio can reduce the response time. Such effects will be discussed in more detail in the next two subsections.

2.1.2 Audition

Auditory displays (i.e. speakers) are probably the next most common type of interfaces for in-car use, after the vision-based displays (i.e. screens). The same applies to auditory notifications. Both are often combined (e.g. a "Fill gas" sign normally appears accompanied by a corresponding high-pitch sound). Some of the recent findings on the efficiency of auditory notifications for communicating information to the driver are summarised below.

Politis et al. [165] demonstrated that auditory and combined audio-visual notifications could result in significantly shorter response times than in the case of visual-only notifications. This was measured by a press of the brake pedal when the corresponding notification (i.e. warning) was displayed, and the car in front of the participant was breaking. Chan and Singhal [30] showed that negatively charged auditory stimuli (i.e. English words of negative valence spoken by a male voice) led to reduced lateral control and slowed driving speed. This was true when participants drove on a two-lane, bidirectional highway, in a rural setting, with oncoming traffic, and periodically received the corresponding auditory stimuli.

A positive effect of auditory stimulation could, on the contrary, be observed when it was presented in the form of music. For example, Fakhrhosseini et al. [60] proved that participants who listened to either happy or sad music had significantly fewer driving errors than those who did not listen to music. In this study, participants drove through a route that included a tunnel-driving portion with low visibility and one hazardous event (lane obstruction), followed by an easier but frustrating portion filled with frequent red lights and stop signs. Furthermore, Burnett et al. [27] showed that participants drove significantly slower after the music had faded from the front to rear speakers. Here, participants drove on a three-lane motorway with traffic in the opposing lanes.

Koo et al. [114] investigated the use of auditory feedforward (coming before an event) notifications to assist an automated braking feature of a vehicle. They found that notifications conveying "how" (i.e. description of action) information led to poor driving performance, whereas "why" notifications (i.e. the reason for action) resulted in better preferences from the drivers' side and better driving performance. Notifications containing both "how and why" information promoted the safest driving performance but increased negative feelings in drivers. Here, participants drove through a course incorporating urban, suburban, and highway sections, which featured stop signs and traffic signals. The course included several hazards that triggered automated breaking. The driving performance was quantified through the number of road edge excursions.

Mok et al. [135] used auditory notifications to alert the driver about an "automation off" event, which was delivered to the driver 2s, 5s, or 8s before the critical event (construction site on the road). Participants drove through a rural setting, with some traffic. It was found that the optimal time for delivering such an auditory warning is somewhere between 5s and 8s before the critical event, as no participants crashed in the 8s condition and 6/10 participants in the 5s condition managed to surpass the hazard safely. No other modalities were explored in this study.

As we can see from this related work, auditory notifications can be very useful and in some cases even more efficient than visual (e.g. as in [165]). Auditory stimulation can also prevent accidents (e.g. as in [135]) and help us slow down (e.g. as in [27]). However, it can, on the contrary, become annoying (as suggested by Baldwin [14]) and elicit negative feelings in drivers (as suggested by [114]). Some of these limitations might be solved by introducing tactile interfaces, which will be covered in more detail in the next subsection.

2.1.3 Touch

Touch-based interfaces are very common in modern vehicles. Drivers interact with knobs, buttons, and touchscreens. However, using tactile feedback (e.g. a vibrating steering wheel) to notify the driver about a driving-relevant event is less popular. This subsection will cover some of the latest findings on how tactile interfaces can be used as a notification modality.

Shakeri et al. [185] proposed projecting haptic feedback patterns using an actuated surface (made of solenoids) on a steering wheel. Haptic patterns were delivered to participants while they were asked to keep the car in the middle lane of a five-lane motorway. Their findings suggested that displaying haptic patterns on the steering wheel could be useful for delivering non-critical messages to the driver (e.g. incoming text messages), as these do not decrease the driving performance (i.e. result in a higher lane deviation) or increase perceived mental workload (based on the NASA-TLX questionnaire [75]).

Sadeghian Borojeni et al. [21] implemented a shape-changing steering wheel that notified the driver about a take-over request and the best steering direction, in a context of an automation failure, by using inclining rods integrated inside the rim. Participants were seated in an autonomous vehicle that drove in the middle lane of a three-lane motorway and were asked to steer to a free lane when notified about an upcoming danger (e.g. road works) by a haptic take-over notification described above. Authors found that haptic cues on steering wheel at take-over requests act as a reassuring stimulus for drivers.

Di Campli San Vito et al. [43] used solenoid pins and thermal actuators (Peltier devices) on the rim of the steering wheel to convey navigation notifications to the driver. Participants were driving through a city environment and received a notification 200m before and immediately at a turn. They were asked to turn left or right, depending on the origin of the stimulus on the wheel. It was found, for example, that the turn-notification recognition rate was significantly lower when the temperature returned to neutral immediately.

Rümelin et al. [174] investigated the use of mid-air haptic feedback (delivered by ultrasound) to notify drivers about an event of successfully pressing a mid-air button inside a car. They demonstrated that the feedback is perceived by participants as most suitable when a modulation frequency of about 150-200Hz is used. This study was conducted in an in-car environment. However, participants were not performing any driving task.

Lee et al. [121] delivered graded haptic feedback through the driver's seat and found that such notifications were perceived as less annoying and more appropriate by the participants. In the experiment, participants had to follow a vehicle which was braking multiple times. They were alerted about these events using the vibration notifications.

Politis et al. [165] demonstrated that tactile and combined tactile-visual notifications led to significantly shorter response times than in the case of visual-only notifications. At the same time, tactile and combined tactile-visual notifications require significantly longer response times than, for example, auditory and audio-visual notifications. This was measured by a press of the brake pedal when the corresponding notification (i.e. warning) was displayed, and the car in front of the participant was breaking. It is, however, important to mention that tactile stimulation was delivered through a wristband, which might not be the best tool for this purpose in a context of driving.

The related work shows that tactile stimulation can be useful to convey driving-relevant information (even though not always suitable for urgent notifications). As the self-report and qualitative data suggest, participants also find such stimulation less annoying and more appropriate (e.g. as in [121]), as well as reassuring (e.g. as in [21]). This is similar to olfactory stimulation, which has been demonstrated to be more comfortable than, e.g. visual modality (as per [46]). Furthermore, as shown by Politis et al. [165] and pointed out by Schmidt et al. [181], the most efficient notifications might be multimodal (due to the integration of multiple sensory channels). The next section will describe the benefits and challenges of the olfactory stimulation in an automotive context and how olfactory notifications can support alerts presented by other modalities.

2.2 Olfactory Interaction in an Automotive Context

Despite being less common, olfactory user interfaces are slowly making their way to an in-car use [49]. This is evidenced both by academic research activities (e.g. to fight drowsiness in drivers [220, 66, 157]) and by industry trends among car manufacturers (e.g. by Mercedes-Benz [35], BMW [20], and Bentley [18]). This section will cover the key benefits and challenges of employing such interfaces in contexts of driving.

2.2.1 Benefits

Several research activities have highlighted the features of olfactory stimulation that could be beneficial in HCI and more specifically for car-driver interaction. For example, scents have been demonstrated to be good at activating the neural system (as per [110, 203, 10]). This could help the driver perceive the important information better and become more aware of the relevant problem with the car or on the road. Olfactory stimulation can help enable crossmodal correspondences stronger than each sensory modality on its own [184, 29]. This could enhance the ability of the driver to comprehend notifications. Finally, due to a strong link to emotions and memories [80], olfactory stimulation could help the driver stay calm and potentially remind them about some important pieces of information.

In the automotive research, olfactory stimulation has been proven useful in three major areas: (1) modulating the driver's emotional state, (2) improving the driving performance, and (3) increasing the alertness of the driver. The findings related to each of these areas are summarised below:

1. **Emotions:** Mustafa et al. [141] conducted a study in a driving simulator, where participants were asked to drive the circuit, consisting of corners, straight roads, and roundabouts, while exposed to a scent of vanilla, lavender, or no scent at all. They found that the presence of scents (both vanilla and lavender) led to participants experiencing positive feelings, such as being relaxed and alert. Participants also felt more comfortable and fresh. In the no-scent condition, participants reported feeling uncomfortable and unable to concentrate on their driving. Moreover, Baron and Kalsher [15] proved that the scent of lemon can improve the mood of the driver. Finally, Raudenbush et al. [170] showed that both peppermint and cinnamon reduced participants' frustration and helped them focus on the driving task (i.e. driving along a particular route).

2. **Performance:** Martin and Cooper [130] showed that the scent of lemon can have a positive impact on driver's braking performance during a simulated driving task. Furthermore, in the study of Raudenbush et al. [170], the scent of peppermint was associated with faster reaction times.

3. **Alertness:** Baron and Kalsher [15] proved that the scent of lemon can increase the alertness of the driver. The alertness was measured by the ability of participants to maintain a visual stimulus (displayed on the screen of a desktop computer) within predefined horizontal or vertical boundaries, by using a joystick. Furthermore, Yoshida et al. [220] developed a scent-delivery system to fight drowsiness while driving. In this study, participants were required to drive along the centre line of an expressway that had straight and curved sections. Authors showed that releasing specific scents (peppermint, rosemary, eucalyptus and lemon) could extend the wakefulness of drivers by nine minutes. These results are in line with the findings of Funato et al. [66], Hiroike et al. [83], and Oshima et al. [157]. Finally, Raudenbush et al. [170] also demonstrated an increase in the driver's alertness and attentiveness through the release of peppermint and cinnamon.

As we can see from the related work, scents can have a positive impact on our physiological state [220], driving performance [130], and emotions [141] in the process of driving. To make the full use of these advantages, it is necessary to carefully control as many scent-delivery parameters as possible, to avoid unwanted negative side effects. Challenges that need to be tackled on the way of enabling that are summarised below.

2.2.2 Challenges

Smell is a chemical sense and cannot be switched on and off. Also, scent molecules can intermix, linger, or cause differences in perception among a group of individuals. This subsection summarises some of the major challenges that require appropriate handling when designing for olfactory in-car interaction.

Based on the analysis of multiple commercially available scent-delivery devices [49] and the knowledge collected from the recent scent-delivery prototypes developed in the academia (e.g. [126, 219, 150, 142]), it is possible to extract the following challenges:

- The scent-delivery nozzle needs to be located at least 50cm away from the driver's face (to **allow enough space for hand movements**, like in [219, 1]).

- Channels (e.g. tubes) used to deliver different **scents need to be well isolated from each other** (as per [126, 142]).
- The scent-delivery device needs to enable **precise control of the blowing time and scent intensity** (as per [8, 7]).
- It needs to be possible to **deliver multiple scents to the driver in a single session** and an option of replacing the scents between the sessions needs to be available (as described in [126, 7]).
- A scent-delivery device needs to be capable of **rapidly switching between the presented scents** (e.g. a new scent every 19 seconds, as per [46]).
- To account for interpersonal differences, **a scent-delivery interface needs to be customisable**, so that a driver can select a scent based on their personal olfactory preferences. Nevertheless, a selection of specific scents could be offered, e.g. only scents with the valence and arousal levels that correspond to the intended notification (as suggested in [48]).
- Finally, in-car notification systems would need to **enable switching to an alternative delivery modality**. For example, if the driver's olfactory function is temporary impaired, they could switch to a tactile or auditory stimulation for a particular notification (as suggested in [47]).

As we can see, there are quite a few challenges to tackle. Nevertheless, it is possible to control each of them and turn them into opportunities, rather than limitations, if the scent-delivery parameters are controlled. The next section will describe opportunities that well-controlled olfactory interfaces can bring into the field of autonomous driving.

2.3 Potential for Olfactory Interaction in a Context of Autonomous Driving

As discussed in the previous section, olfactory stimulation has been proven to be able to assist drivers in several different ways and different driving scenarios. Such scenarios mainly involved manual driving. Nevertheless, some of the effects of olfactory stimulation (e.g. activation of the neural system [110, 203, 10]) might be useful also in a context of driving an autonomous vehicle (e.g. for take-over requests). This section will describe some of the ways where scents could become useful also in a self-driving car.

Beller et al. [17] conducted a simulated driving study in which they introduced uncertainty displays to convey the car's current reliability level to drivers, during an autonomous driving mode. In this study, participants were driving along a two-lane highway, with a slower driving lead car appearing several times. Participants could then either rely on the automation to brake or take over the control and push the brake pedal themselves. The reliability level was conveyed to them using visual notifications (a special symbol) displayed in the front console, behind the steering wheel. Their results showed that the presentation of uncertainty information increased the time to a collision in the case of automation failure. Moreover, participants reported a higher situation awareness and increased trust when driving with an uncertainty symbol. Nevertheless, such notifications still demanded a shift of participants' visual attention, which might not be ideal if they need to focus on the road or perform a secondary task. For this reason, it is interesting to investigate the use of olfactory stimulation to convey the current uncertainty level.

Mok et al. [135] have investigated the use of auditory messages to find the shortest notification time necessary for a driver to safely take back the control before a critical event. In this study, participants drove through a rural setting, with some traffic, before entering a critical event (a construction site on the road). It was found that the optimal time for notifying the driver about such an event by using auditory messages (i.e. *"Emergency! Automation off!"*) was 5-8s before the critical event. Authors of this paper have suggested the exploration of other modalities for this purpose. Scent perception is not instant, but still, it can be perceived in a matter of 10s (as per [45]). This motivates the exploration of olfactory notifications also for take-over requests. If the car's board computer can predict a critical event well in advance, an olfactory notification could be released on time for the driver to perceive it. Moreover, due to a link to emotions and memories [80], scents might be able to make a driver better prepared for an emergency situation on the road.

To explore tactile stimulation for take-over requests, Sadeghian Borojeni et al. [21] implemented a shape-changing steering wheel with haptic feedback elements. Such a steering wheel notified drivers about a take-over request and provided tactile cues suggesting the best steering direction. In this study, participants drove an autonomous vehicle along the middle lane of a three-lane motorway and were asked to steer to a free lane when notified about an upcoming danger (e.g. construction site). Authors found that haptic cues on steering wheel act as a reassuring stimulus for drivers. As olfactory stimulation is known to be able to convey directional information [115] and to calm drivers down [141], a similar effect might be achievable also by using scents as a notification modality in such a context.

To sum up, we can see that there are several ways in which olfactory stimulation could become useful in both manual and autonomous driving scenarios. As discussed in the summary of challenges implied by olfactory interaction (see Subsection 2.2.2), this is possible but only if the scent-delivery parameters are controlled (e.g. scent channels are isolated from each other, each scent is delivered in a small amount). It is also important that the interaction space is designed following all the recommendations (e.g. made of materials that do not absorb scents, with a good air extraction system). Following all these guidelines, it is possible to set up meaningful user studies that will reveal new knowledge on the effects of scents in different driving scenarios. The way user studies were designed and carried out in the scope of this PhD thesis, will be described in the next (i.e. "Approach") chapter.

3 | Approach

The review of the related work, provided in the previous chapter, shows how important it is to have a rigorous method to come up with findings that will enable a novel contribution to the field. This chapter describes the approach used in this thesis.

3.1 Research Context

This thesis was written in a context that combines three very different areas: **Engineering**, **Olfaction**, and **Automotive User Interface** Design. To be able to study Olfactory Interaction in an Automotive Context, it is necessary to not only collect knowledge on the human olfactory function, but also to design and build a scent-delivery device and an olfactory interaction space. Furthermore, there is a need for a driving simulator that would enable integration of an olfactory interface.

This chapter starts with a description of how a setup for running olfactory interaction studies was designed and built. This is an essential first step that requires **Engineering** thinking. Without this step it would be impossible to set up a lab space powerful enough to enable rigorous user studies of olfactory interaction in a context of driving. Section 3.2 of this chapter explains how such a space was created.

To explore olfaction enhanced **Automotive User Interfaces**, it is also important to choose software that would enable exploration of olfactory stimulation in combination with a driving task. Section 3.3 provides an overview of all driving simulators explored in the scope of this thesis, on the way of choosing the most suitable one for each of the conducted user studies.

Finally, the user studies conducted to provide the knowledge on human **Olfaction** in different driving contexts are presented in Section 3.4. This section summarises the design of each user study and their links to research questions.

With the help of such a structure, this chapter presents the research context of this thesis, detailing each individual step of the approach.

3.2 Designing an Olfactory Interaction Space

As summarised in the challenges of olfactory interaction (see Subsection 2.2.2), when working with scents, it is necessary to control as many scent-delivery parameters as possible. For this purpose, it is necessary to have a fully configurable scent-delivery device and a dedicated olfactory interaction space. Key recommendations for designing and building each of these are provided below, and more details are provided in the *OSpace* framework (see Chapter 8).

The following **scent-delivery device characteristics** have been extracted based on the problems encountered in scent-delivery devices available on the market [49] and in non-commercial prototypes (e.g. [126, 219, 150, 142]):

- Scent blowing distance of at least 50cm (to allow some space for the steering and other hand movements, like in [219, 1]).
- Strictly isolated channels for each scent used in the device (as per [126, 142]).
- Full control of the blowing time and scent intensity (e.g. as in [8, 7]).
- An option of delivering multiple scents to a user in a single session and an option to replace scents (e.g. scent containers) between sessions (e.g. as per [126, 7]).
- An opportunity to enable rapid switching between the presented scents (e.g. a new scent every 19s, as in [46]).

A new scent-delivery device has been built in the scope of this thesis (see Figure 3.1) by following the device characteristics listed above. Its structure is outlined in Figure 8.1 and a photo of the final prototype is available in Figure 3.1b.

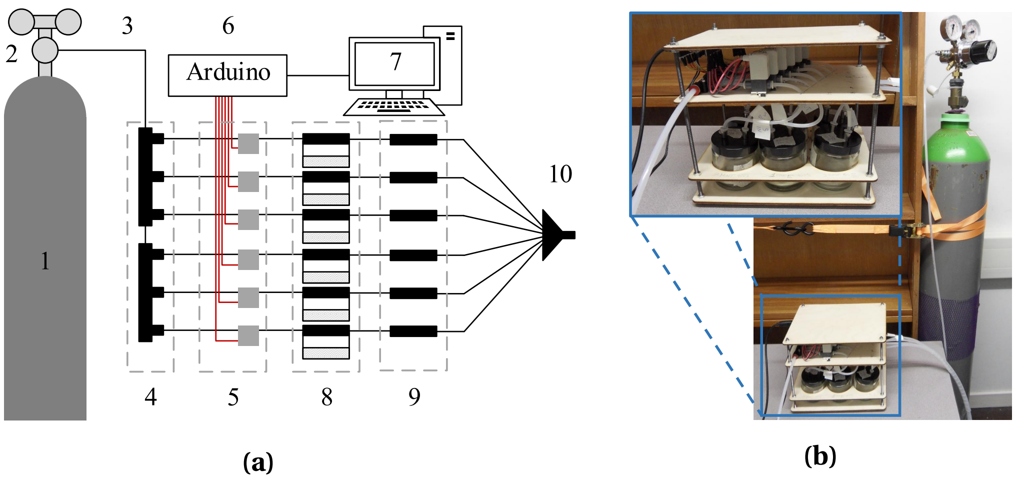
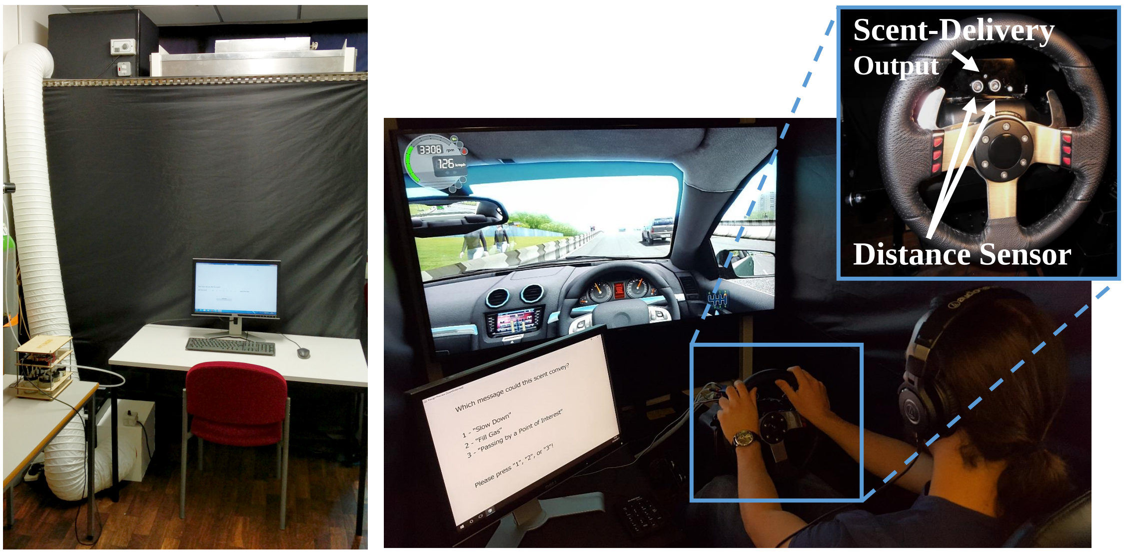


Figure 3.1: (a) Structure of the scent-delivery device: 1 - air tank, 2 - manometer, 3 - plastic tube, 4 - two manifolds, 5 - six electric valves, 6 - Arduino board, 7 - PC, 8 - six jars containing scents, 9 - six one-way valves, 10 - output nozzle; (b) Scent-delivery device (20.5×16.5×22.5cm) with an air tank (150.0×25.0×25.0cm).

Based on implications of using olfactory interfaces in physical spaces (such as scent lingering and contamination of the centralised ventilation system) addressed in [23, 19, 118], the following set of **requirement for building an olfactory interaction space** can be defined:

- An olfactory interaction space needs to be composed out of odour-repellent materials, to avoid absorption of scents.
- The air extraction system (to take the scented air away from the room) needs to be independent of the building's centralised ventilation system. This way, it is possible to enable direct control over the circulation (i.e. refreshing) of the air in the interaction space.

Based on these requirements, an olfactory interaction space was built in the scope of this thesis (see Figure 3.2a) to be able to start a rigorous exploration of opportunities for smell in HCI.



(a) **(b)**

Figure 3.2: (a) Olfactory interaction space: a clean room with walls made of black water repellent fabric, equipped with an air extractor and the clean air blower on the top, as well as a scent-delivery device and an air extractor in the bottom-left corner (outside the clean room); (b) Setup of the driving simulator inside the olfactory interaction space.

In the scope of this PhD thesis, such an olfactory interaction space has been equipped with a driving simulator (see Figure 3.2b). One of the main challenges of setting up a realistic driving simulator was to choose the right simulation software. This process is covered in the next section.

3.3 Choosing the Right Driving Simulator

To conduct the research outlined in this thesis, it was necessary to choose a driving simulator that provides a realistic driving experience (i.e. modulated by high-quality graphics and sound). Such a simulator would also need to enable an integration with a scent-delivery device (e.g. through an API), and supports the collection of driving performance and behaviour relevant metrics (e.g. position of the car on the road, vehicle's current speed, steering angle, etc.) that can be logged multiple times per second. This section provides an overview of different driving simulator software packages, discussing their suitability for different use cases. The following simulators have been investigated over the course of this PhD: *CityCarDriving 1.5*, *Drive Megapolis*, *Racer*, *ETS2*, *OpenDS*, *NERVteh Compact Motion Based Driving Simulator*, *Forum8 VR-Design Studio*, and *IPG CarMaker*. This exploration took around four months in total.

Driving simulators that would be most appropriate for the type of research carried out in the scope of this PhD thesis are *NERVteh Compact Motion Based Driving Simulator*, *Forum8 VR-Design Studio*, and *IPG CarMaker*. These three pieces of software offer a broad range of opportunities in terms of simulating different driving-relevant situations and achieving realistic driving experience. More details on each of these tools are provided below.

NERVteh Compact Motion Based Driving Simulator (see Figure 3.3) has been developed by a Slovenian research and development company NERVteh. This software is modular and customisable. It provides a variety of virtual scenes, can simulate different road and weather conditions, as well as involve AI-based traffic [201]. Thanks to its

Figure 3.3: Screenshot of the city road simulated using the NERVteh Compact Motion Based Driving Simulator [201].

Figure 3.4: Screenshot of the city environment simulated using the Forum8 VR-Design Studio driving simulator [64].

vehicle dynamics features, it can render real-life driving experience. With this software, it is possible to run simulations on screens or on a VR headset. It also enables integration with external devices, making it possible to connect a scent-delivery device to it.

Forum8 VR-Design Studio (also known as *UC-win/Road*) is a simulation software developed by Forum8, a company established in Japan. This tool can, for example, simulate 3D photo-realistic immersive driving scenes (see Figure 3.4), support multiple drivers in the same road network, produce potentially any possible driving scenarios, and simulate Advanced Driver Assistance Systems (ADAS). Thanks to its SDK, this software also enables integration with external devices (e.g. a scent-delivery device), making it well suited for olfactory in-car interaction studies.

IPG CarMaker (see Figure 3.5) is a great driving simulator, which offers not only realistic driving experience (mediated by high-quality graphics, game physics, and sound) and left-hand traffic support but also an API. *Carmaker's* API can be used to connect to a scent-delivery device and to retrieve almost any data about the vehicle's current state (e.g. position on the road, speed, engine rotations, torque) and driver's

Figure 3.5: Screenshot of the IPG CarMaker driving simulator, while driving on a freeway.

input (e.g. steering angle, gear stick position). In the scope of this thesis, *IPG CarMaker* was used in two user studies: (1) to investigate the support of reliability displays with the help of olfactory stimulation, in a context of autonomous driving (see Chapter 12) and (2) to study the effect of scents on the driver's emotions and behaviour on the road (see Chapter 13). In both studies, the *CarMaker's* scenario editor was used to create critical situations on the road (e.g. a vehicle cutting in suddenly). The API was used to connect to a scent-delivery device and to deliver a scent to a participant before each event or before each switch of the automation's reliability level.

As we can see from the summaries above, *NERVteh Compact Motion Based Driving Simulator*, *Forum8 VR-Design Studio*, and *IPG CarMaker* are simulators that are very well suited for the purposes of this PhD thesis. However, the major challenge associated with using them is the high cost (i.e. £5,000-20,000). Due to this reason, it was also decided to investigate cheaper options, i.e. such driving simulators as *CityCarDriving 1.5*, *Drive Megapolis*, *Racer*, *ETS2*, and *OpenDS*. These tools are presented below.

CityCarDriving 1.5 was the first driving simulator to be explored in the scope of this thesis. This software was initially chosen due to its high quality (i.e. realistic) graphics and sound and due to the support of left-hand driving and traffic rules (see Figure 3.6). This was important because four out of five simulated driving studies described in this thesis were conducted in the UK. Beyond the excellent presentation of the driving environment, this software also enables selection of pre-defined driving scenes (e.g. cities, rural roads, motorways) and displays visual notifications when the driver obeys the traffic rules (e.g. when the speed limit is exceeded or a lane is changed without indicating). What is also important, is that the price of the single-licence version of this software was very affordable (£25.26). The main drawback of

Figure 3.6: Screenshot of the CityCarDriving 1.5 driving simulator, while driving on a motorway.

this software is that it provides no API or SDK to enable smooth integration with other systems. This issue complicates the simulator's synchronisation with other components (e.g. a scent-delivery device). In the scope of this thesis, *CityCarDriving 1.5* was used in the scent-mapping study (see Chapter 9), where synchronisation was not that important because scents had to be delivered after a certain time past the start of the driving phase. Due to the availability of visual notifications, this simulator was also used to explore scents as feedback notifications, delivered to the driver after a corresponding driving mistake was made and the visual notification has been shown (see Chapter 11). In this case, the delivery of each scent was triggered manually by the experimenter when the corresponding visual notification was displayed by the simulator. This was possible due to the feedback nature of such notifications (i.e. to be delivered after a traffic rule violation event, to support the perception of an already displayed visual notification). This way, the experimenter was also able to log each driving-behaviour-relevant event.

Due to the challenges mentioned above, regarding the integration of *CityCarDriving 1.5* with a scent-delivery device and limited opportunities for collecting driving performance and behaviour data, it was necessary to find a new solution. The next software package explored in this process was *Drive Megapolis* (see Figure 3.7). This driving simulator also offers high definition graphics and sound, as well as multiple scenes, traffic settings, and weather conditions. Moreover, it was available for as little as £3.99. However, an API (to connect a scent-delivery device) was not provided. The software demonstrated good performance in terms of a feeling of driving a realistic vehicle, but had some compatibility issues with the driving simulator hardware (e.g. the gear stick) available in the lab and did not enable left-hand driving. Due to these reasons, it had to be disregarded from the use in experiments.

Figure 3.7: Screenshot of the Drive Megapolis driving simulator, while driving in a city environment, in good weather conditions [192].

Figure 3.8: Screenshot of the Racer driving simulator, while driving on a racing course.

The next simulator software explored on this way was the *Racer* (see Figure 3.8). This is a free car simulator project (for non-commercial use) that uses high-end car physics to achieve a realistic feeling and a render engine for graphical realism. Vehicles and tracks can be created and imported into the simulator. As the source code of the project is available, it could potentially enable the collection of any driving performance and behaviour data. However, due to some technical issues, it did not run on lab's machines (potentially due to lack of recent simulator's updates) and had to be disregarded as well.

Another driving simulator that was investigated, was the *ETS2* (i.e. *Euro Truck Simulator 2*, see Figure 3.9). It was available for £14.99. This software also enabled realistic driving (i.e. via high-quality graphics and sound, as well as good game physics). Despite this software package being sold as a commercial tool, it offered opportunities to import other cars and even provided its own tool for building custom tracks and environments. Nevertheless, no support for these features was provided, making their

Figure 3.9: Screenshot of the Euro Truck Simulator 2 driving simulator, while driving on a motorway [193].

usage quite inefficient and limited. Finally, as no option of linking this software to a scent-delivery device was found, it was decided not to consider it for user studies.

A driving simulator that has been chosen for one of the further user studies was *OpenDS* (see Figure 3.10). This simulator is free and open source. It allows the collection of such driving performance and behaviour data as the vehicle's current position, speed, and steering angle. As it is open source, connecting it to a scent-delivery device was also fairly straightforward. However, this platform has its limitations. For example, the game engine used in this simulator offered only very basic implementation of physics (e.g. driving with a speed of 70mph would not feel very different from 30mph and hitting a cone would feel like driving over a rock) and the usage of complex scenes would require building them in external tools (e.g. Blender) and then importing them to *OpenDS*. Also, the behaviour of traffic was limited (e.g. an AI car would hit the participant's car if their paths cross). Moreover, scenes, where the driver needs to perform many turns quickly led to motion sickness during initial pilot tests. For this reason, it was decided to utilise this driving simulator only for motorway driving tasks, e.g. to study the effect of scents on the speeding behaviour while driving along an empty motorway (see Chapter 10).

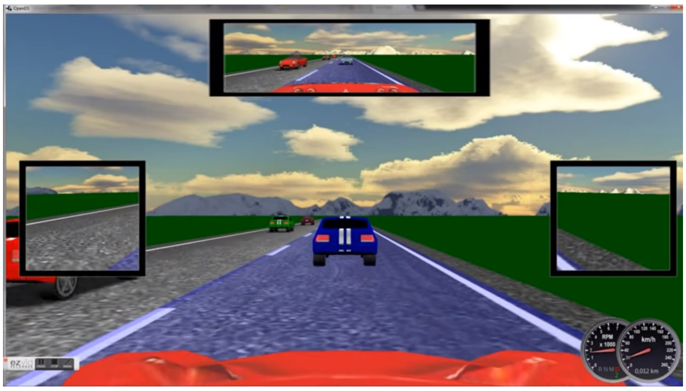


Figure 3.10: Screenshot of the OpenDS driving simulator, while driving on a motorway [205].

This section provided an overview of driving simulators that are most appropriate for the type of research carried out in the scope of this PhD thesis. As high-end driving simulators are expensive, this section also covered cheaper options, explaining their benefits and how they were used in this thesis. The section also demonstrated how important it is to have a flexible simulator for investigating olfactory in-car interfaces and experiences. The next section will describe how the user studies (i.e. the primary research method of this PhD thesis) were set up to make the full use of the opportunities offered by the chosen driving simulator.

3.4 Research Method

Research in Human-Computer Interaction, and the field of Automotive User Interfaces, in particular, is based on the Human-Centred Design, the fundamental part of which are user studies [172]. User studies allow the researchers to collect qualitative (e.g. like in [136, 153]) and quantitative (e.g. like in [121, 19]) data. In this thesis, user studies have been conducted to collect and analyse quantitative and qualitative data. This section describes what user studies were carried out to answer the research questions of the thesis (summarised in Table 3.1).

Research Question(s)	**Number of Studies**	**Study Design**	**Total Number of Participants**	**Relevant Paper**
RQ1, RQ2	1	between participants	21	Paper 2 (Chapter 8)
RQ2	2	within participants	47	Paper 3 (Chapter 9)
RQ3	1	within participants	21	Paper 4 (Chapter 10)
RQ3	1	within participants	22	Paper 5 (Chapter 11)
RQ3	1	within participants	25	Paper 6 (Chapter 12)
RQ3	1	between participants	40	Paper 7 (Chapter 13)

Table 3.1: Summary of user studies conducted over the course of this thesis.

A quantitative (between participants) user study with 21 participants (seven per condition) was conducted to answer the **second objective** of **RQ1** and the **first objective** of **RQ2**. This user study was designed to evaluate the scent-delivery device and the olfactory interaction space, built in the scope of this thesis, to enable further investigation of olfactory interaction in automotive context (see Paper 2, Chapter 8). The study measured the scent detection and lingering times while setting the scent-delivery device to three different air pressure levels, for three different scent types, with two dilution values. Based on the insights from this user study, it was possible to form a list of recommendations for designing and exploring a scent-delivery device and an olfactory interaction space.

Investigation of **RQ1** partially (i.e. in the case of its **first objective**) has also been carried out without a quantitative or a qualitative study, by comparing the performance (volume, distance, and speed of scent-delivery) of four commercially available scent-delivery devices. This exploration enabled the creation of a framework for comparing different scent-delivery devices and identifying their application use cases in automotive contexts (see Paper 1, Chapter 7).

Two quantitative (within participants) user studies with a total of 47 participants were conducted to answer the **second objective** of **RQ2**. The first user study (30 participants) employed the manual scent-delivery to establish the initial mapping between four scents and three driving-relevant notifications. The second study (17 participants) has confirmed the previously established mapping in the driving simulator. These two studies (see Paper 3, Chapter 9) allowed the creation of the first mapping between scents and driving-relevant notifications, which did not exist before.

A quantitative (within participants) user study with 21 participants has been carried out to validate the mapping of the scent of lavender on the "Slow down" notification. The lavender scent was delivered to the driver each time they exceeded the speed limit while driving on a motorway. The lane deviation, speed, number of speeding events, and the mean speeding time were collected to quantify the driving performance and behaviour. As the results had confirmed the previously established mapping, the approach mentioned above (i.e. testing the mapping in its context and analysing the relevant driving metrics) has been proposed as a framework of validating a mapping between notifications and scents in olfactory in-car interaction (see Paper 4, Chapter 10). This framework also suggests extending it towards other modalities (e.g. visual, auditory, or tactile notifications). The findings presented in this paper did the first step towards meeting the **first objective** of **RQ3**.

A quantitative (within participants) study with 22 participants was conducted to explore the effect of the trained associations, between scents and driving-relevant notifications, on the driving behaviour (see Paper 5, Chapter 11), quantified through the number of driving mistakes (speeding, lane departure, and short inter-vehicle distance). Moreover, this study provided insights on the perceived distraction, help, liking, and comfort of the olfactory notifications quantified through a self-report questionnaire. This study enabled carrying out the first-time exploration of olfactory conditioning in the context of driving, answering the **second objective** of the **RQ3** and provided the second confirmation for the mapping between the lavender scent and the "Slow down" notification, as per the **first objective** of the **RQ3**.

A within-participants study (N= 25) analysing both the quantitative and the qualitative data has been conducted in an autonomous driving context. This study aimed to investigate the effects of two scents (lavender and lemon) on the behaviour of drivers while interacting with an autonomous vehicle equipped with olfaction enhanced reliability displays. The study also assessed the attitude of participants towards such displays (Paper 6, see Chapter 12). The drivers' performance was quantified through the way they interacted with the braking pedal and a mobile device while performing a secondary task. Interviews were conducted to look into their attitude towards such displays (i.e. by asking to what extent they found olfactory notifications helpful). This study met the **third objective** of the **RQ3**.

Finally, a between participants study (N= 40, 10 per condition) analysing both the quantitative and the qualitative data has been conducted to investigate the effects of scents on driver's emotions and well-being (see Paper 7, see Chapter 13). This study involved three scents (rose, peppermint, and civet) and explored their effects on drivers in an induced anger state. Drivers' performance and behaviour were quantified by the driving metrics (lane deviation, steering angle, speed). Their emotions and well-being were assessed by using self-report questionnaires (on scent liking and perceived comfort) and by analysing interview responses (on how they could describe their feelings after being exposed to a scent). The findings of this study satisfied the **fourth objective** of the **RQ3**, completing the set of accomplishments defined for this thesis.

All the user studies described above define the research method of this thesis. They enabled the exploration of scent-delivery devices for creating novel user interfaces and opened a space for contributions on the knowledge regarding the effects of scents on user's behaviour. This chapter also covered the context in which the research of this thesis has been conducted, the design of an olfactory interaction space used in the above-mentioned studies, and the process of choosing a driving simulator suitable for investigating olfactory in-car interaction. The next chapter will elaborate on the findings delivered by the conducted user studies.

4 | Findings

The previous chapter has presented the process of designing a scent-delivery device and selecting a driving simulator suitable for in-car olfactory interaction experiments. Both of these achievements have enabled several user studies conducted to contribute to the knowledge on the perception and effects of scents in different driving scenarios. The design of these studies has been summarised, and the corresponding research questions have been addressed. The next step is to elaborate on the findings delivered by each of these studies. This will demonstrate how the findings shape the major contributions of the thesis. A summary of these findings is presented in Table 4.1 and further details are provided below.

4.1 Comparing Different Scent-Delivery Devices

The first step of working on this thesis was to find out how to deliver a scent to the user in an automated way. A framework for comparing different scent-delivery devices was proposed in Paper 1 (see Chapter 7). Commercially available scent-delivery devices and non-commercial prototypes are very distinct from each other, and all use different delivery mechanisms. This complicates the task of finding a device that is suitable for an intended use case. The framework mentioned above suggests comparing such devices based on the distance, volume, and speed of the scent delivery (see Figure 4.1).

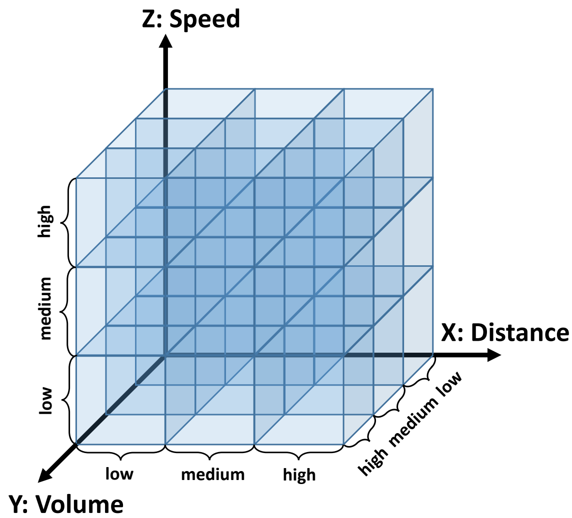


Figure 4.1: Three-dimensional comparison framework used to evaluate the X: Distance, Y: Volume, and Z: Speed of scent-delivery demonstrated by four commercially available devices.

The usefulness of this framework was demonstrated by mapping four commercial scent-delivery devices onto its three-dimensional space. The devices used for this purpose were: (i) DaleAir Vortex Activ USB [36], (ii) Scentee [178], (iii) oPhone DUO [156], and (iv) Aroma Shooter [9]. All of them were available on the market in 2016, when the framework was proposed. By mapping the devices mentioned above on the 3D space (see Figure 4.2), based on the scent-delivery characteristics, it was possible to identify their potential application scenarios.

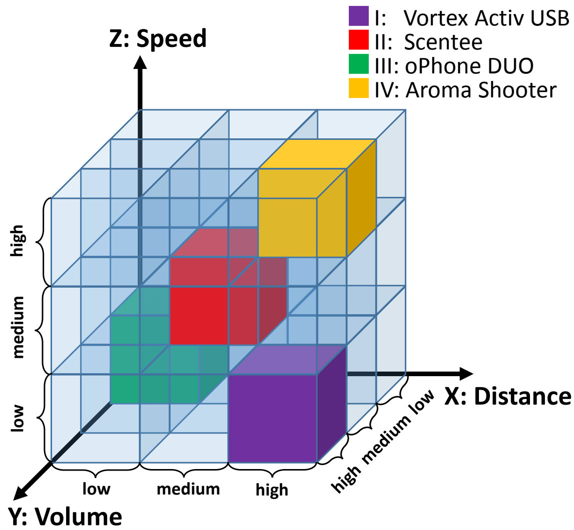


Figure 4.2: A three-dimensional evaluation framework (based on the distance, volume, and speed of scent delivery) with four commercially available devices mapped onto it.

For example, the DaleAir Vortex Activ USB might be suitable for ambient scent delivery, for applications like modulation of the driver's mood and emotions (e.g. similarly like in [141]). Its application for interaction tasks is limited by several constraints (e.g. slow delivery, long lingering time). The way the scent channels were separated from each other proved itself not suitable for quick changes between different scents. On the contrary, Aroma Shooter might be suitable for driving-relevant notifications, particularly in combination with other modalities, i.e. visual, auditory, and tactile (e.g. similarly like in [165]). As mentioned above, this framework was taking into account devices available on the market three years ago. Some of them are not being sold anymore (e.g. DaleAir Vortex Activ USB [36]) and some new ones have appeared (e.g. from OWidgets [158]). By using this framework, it is possible to constantly update the knowledge on the currently available devices and understand what can be achieved with their help.

Research Question(s)	Explored Scents	Findings	Relevant Paper
RQ1	Vanilla, Lemon, Coffee, Tangerine, Peppermint.	Scent-delivery devices can be compared based on the distance, volume, and speed of scent delivery. These characteristics can also reveal their potential application scenarios.	Paper 1 (Chapter 7)
RQ1, RQ2	Lemon, Rose, Peppermint.	Scents can be detected by the user within 10s, when a scent is delivered from a distance of 68cm by using compressed air. It takes 9s for a scent to disappear, both with extraction on and off.	Paper 2 (Chapter 8)
RQ2	Peppermint, Rose, Lavender, Lemon.	Rose was associated with a "Passing by a point of interest". notification. Lavender, Lemon, and Peppermint were found to be equally suitable for the "Fill gas" and "Slow down" in-car notifications.	Paper 3 (Chapter 9)
RQ3	Lavender	Using lavender as a "Slow down" notification, results in fewer events of speeding, helps reduce speed faster and drive slower. Assessing the relevant driving behaviour metrics enables the validation of the mapping between notifications and scents.	Paper 4 (Chapter 10)
RQ3	Lemon, Lavender, Peppermint.	Training the drivers on "Lemon - Lane departure", "Lavender - Slow down", and "Peppermint - Short inter-vehicle distance" notifications results in fewer occasions of making the corresponding driving mistakes.	Paper 5 (Chapter 11)
RQ3	Lemon, Lavender.	These scents can help perceive the current reliability level of an autonomous vehicle.	Paper 6 (Chapter 12)
RQ3	Civet, Rose, Peppermint.	Angry drivers crash more when receiving civet olfactory notifications. Peppermint and Rose can improve the valence of the driver’s emotional state.	Paper 7 (Chapter 13)

Table 4.1: Summary of findings of this thesis.

4.2 Exploring an Olfactory Interaction Space

When the scent-delivery devices available on the market were compared, it became clear what limitations they have (e.g. scent cross-contamination and lingering). This motivated the creation of the own delivery device and olfactory interaction space for more rigorous research. The design process of this interaction space has been described in Section 3.2. With its help, it was possible to investigate how quickly the different scents can get perceived by a user and how long it takes for the released scents to disappear. This exploration (presented in Paper 2, Chapter 8) allowed finding out how timing values change depending on the parameters of scent delivery (i.e. distance to the user's nose, air pressure, scent dilution level, and availability of air extraction).

The olfactory interaction space was tested in a user study (N= 21), by delivering the scents of lemon, rose, and peppermint (each as pure essential oil and a 50% dilution) from a distance of 68cm (i.e. the maximum distance from the delivery nozzle to the participant's nose in the driving simulator used in Paper 3, Chapter 9). The air pressure was set to the value of 0.5, 1, or 1.5 bars, depending on the between-participants condition. The results showed that any of the explored scents could be detected within 10 seconds (time recorded by a button press performed by participants upon detecting a scent), with no significant differences between scents (see Figure 4.3).

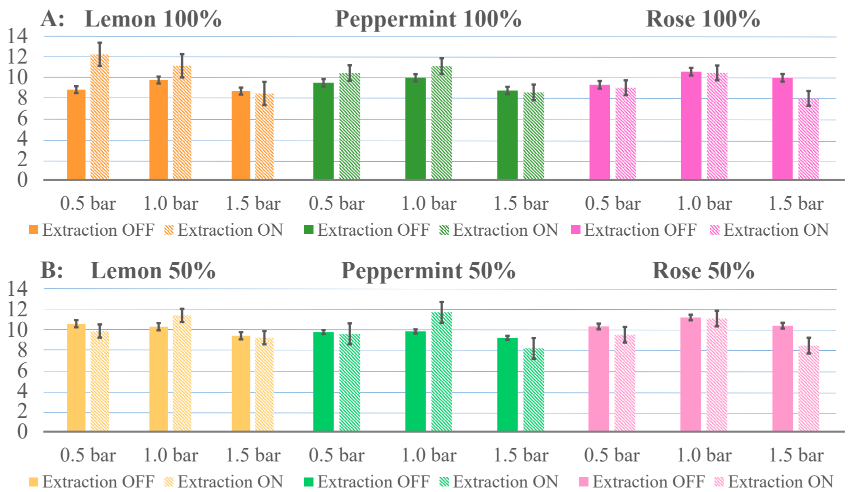


Figure 4.3: Mean Scent Detection times in seconds under the air pressure conditions of 0.5, 1.0, and 1.5 bars, for A: 100% pure essential oils of lemon, peppermint, and rose, and for B: 50% dilutions of lemon, peppermint, and rose essential oils with water. Error bars, ± s.e.m.

Participants were asked to press the button for the second time when the delivered scent was no longer perceivable. The time recorded by a button press was used as a measure of the scent lingering. The results demonstrated that all of the investigated scents stop lingering nine seconds after they have been released (see Figure 4.4).

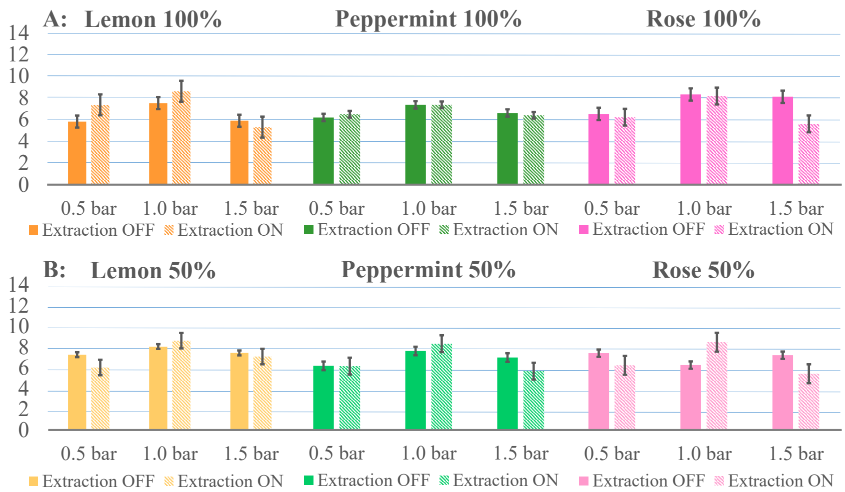


Figure 4.4: Mean Scent Lingering times in seconds under the air pressure conditions of 0.5, 1.0, and 1.5 bars, for A: 100% pure essential oils of lemon, peppermint, and rose, and for B: 50% dilutions of lemon, peppermint, and rose essential oils with water. Error bars, ± s.e.m.

As no statistically significant effects of scents, dilution levels, air pressures, or availability of air extraction were found, these results suggest that the amount of the delivered scent (blown for only five seconds) is so small that it disappears soon after the end of the delivery, without the need for a powerful (and potentially noisy) air extraction system. This enables a wide variety of different application scenarios, including gaming (e.g. like in [1, 142]), VR/AR (e.g. like in [134, 143]), multisensory cinema (e.g. like in [218, 140]), desktop applications (e.g. like in [23, 208]), and driving (e.g. like in [170, 15]).

4.3 Establishing a Mapping Between Driving-Relevant Notifications and Scents

Once the scent detection and lingering times were known, the next step was to establish an initial mapping between driving-relevant notifications and scents that could convey these notifications in a car. This was necessary to be able to start the initial tests in a context of specific driving scenarios. As this research activity started before a scent-delivery device and an olfactory interaction space were developed, its first study employed manual scent-delivery, by using glass bottles/jars filled with essential oils to deliver a scent to the participant's nose (see Paper 3, Chapter 9 for details).

This within-participants study (i.e. Study 1) had 30 participants and involved participants watching a slide show explaining a driving scenario to which they then had to assign a scent. There were three scenarios involving three driving-relevant notifications (i.e. "Slow down", "Fill gas", and "Passing by a point of interest") and four scents (i.e. lemon, lavender, rose, and peppermint). The mapping preferences were evaluated based on what notification participants ranked as the most suitable for each scent (i.e. by filling in a mapping questionnaire).

The results demonstrated statistically significant differences in the way the participants ranked the scents ($\chi^2(4)= 18.77,\ p< .001$). In particular, rose has been highly ranked in association with the "Passing by a point of interest" notification ($\chi^2(2)= 6.21,\ p< .05$). The other ranking preferences did not provide any clear mapping. However, from the graph (see Figure 4.5) it became clear that both peppermint and lemon could be a good choice for the "Slow down" or "Fill gas" notifications, whereas lavender would fit the "Slow down" notification. This motivated a follow-up study in a driving simulator (i.e. Study 2).

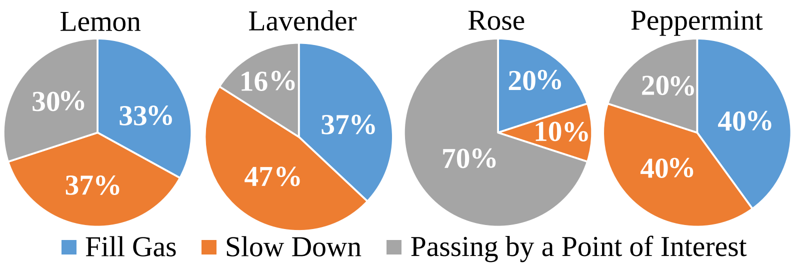


Figure 4.5: Percentage of participants having ranked the corresponding driving-relevant notification as first (best) for each scent.

In Study 2 (N= 17), it was chosen to use only three scents (i.e. lemon, rose, and peppermint), because investigating the scents of lemon and peppermint would go in line with simulated driving studies conducted in the past [130, 15, 170, 219, 157, 66] and investigating the effect of rose would make a novel contribution (no soothing scents have been used in a context of driving in the past).

Participants drove through a mixed setting, involving parts of a motorway and a city environment. They received one of the three scents mentioned above every five minutes of their driving time (three different scents over 15 minutes, for five seconds each). Participants had to define which of the three driving-relevant notifications (i.e. (1) "Slow down", (2) "Fill gas", or (3) "Passing by a point of interest") they associate with the delivered scent, by pressing a button with the corresponding sequence number.

A non-parametric analysis of the Study 2 data revealed statistically significant differences in the mapping preferences (see Figure 4.6). In particular, the scent of rose has been mapped onto the "Passing by a point of interest" notification (χ^2 *(2)= 7.88, p< .01*), which matches the findings of Study 1. The scent of peppermint has been equally associated with "Fill gas" and "Slow down" notifications (χ^2 *(2)= 5.77, p< .05*), while the scent of lemon has mainly been mapped onto the "Slow down" message (not a statistically significant difference).

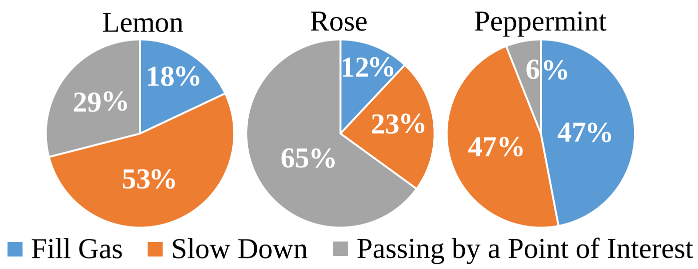


Figure 4.6: Percentage of participants having mapped the corresponding scent on one of the three driving-relevant notifications.

The findings of these two studies demonstrate that mapping scents onto driving-relevant notifications is not an arbitrary process and that there is a correlation between the urgency levels of notifications and the arousal levels of scents. For example, the "Slow down" notification conveys an urgent need to reduce the driving speed and the scent of lemon, associated with it, is an arousing stimulus [15]. Similarly, the "Passing by a point of interest" notification conveys a message that there is a point of interest nearby, but it is fine to miss it and turn around later or access it via a different road. So, the urgency of this notification is not high, just like the arousal level of the scent of rose that was associated with this notification.

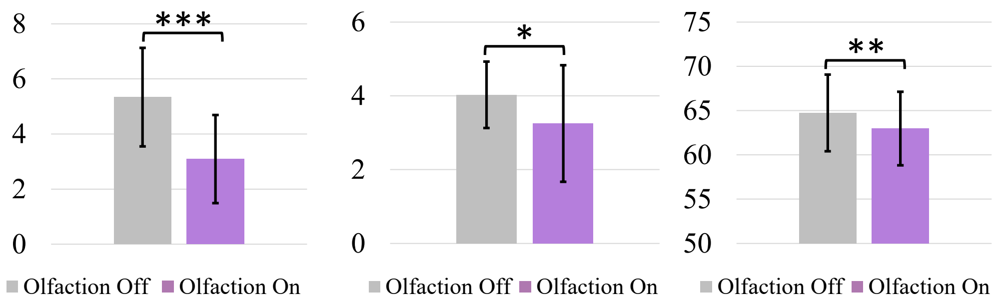
These finding established the basis for further studies in a driving simulator, to validate the usefulness of the mapping between notifications and scents in situations where participants need to perform realistic driving tasks. The findings of such studies will be described in the next four sections.

4.4 Validating a Matching Between Driving-Relevant Notifications and Scents

When the initial mapping between the driving-relevant notifications and scents is established, it is necessary to validate it in realistic driving scenarios. For this purpose, it was decided to choose the scent of lavender as an olfactory "Slow down" notification. A mapping of the scent of lavender to the "Slow down" notification has been demonstrated in Study 1 of the previous section. Moreover, lavender is known to have a calming effect on people [137]. This means that lavender notifications might serve both as an alert and as an implicit soothing stimulus, causing drivers to reduce the speed.

In a simulator study (see Paper 4, Chapter 10) 21 participants were asked to drive along a two-lane motorway while following a speed limit of 70mph (112.654km/h). In the "olfaction on" condition, they received a puff of lavender each time they happened to go over the speed limit. In the "olfaction off" condition, they had to rely on the speedometer data. Their driving performance and behaviour data (e.g. speed, position on the road) was logged while they performed the driving task.

A two-way repeated measures ANOVA test revealed a statistically significant effect of the lavender olfactory notifications on the participants' driving behaviour. These results are summarised in Figure 4.7.



(a) Mean speeding time (s) (b) Mean number of speeding events (c) Mean speed (mph)

Figure 4.7: Driving behaviour results of the "olfaction off" (no olfactory notifications presented) and the "olfaction on" (with olfactory notifications) conditions: (a) Mean speeding time in seconds, (b) Mean number of times the participants have exceeded the speed limit in each trial, (c) Mean driving speed in mph ("olfaction off": *M= 104.17km/h* (*SD= 6.97km/h*); "olfaction on": *M= 101.34km/h* (*SD= 6.70km/h*). Error bars, ± SD, $*p< .05$; $**p< .01$; $***p< .001$

When receiving olfactory notifications, participants reduced the speed significantly faster ($F(3, 18)= 10.519$, $p< .001$; Wilks' $\lambda= .363$) than without such notifications. Participants required *M= 5.34s* (*SD= 1.79*) to return the car's current speed back to the speed limit of 70mph (112.654km/h) in the "olfaction off" mode, but only *M= 3.09s* (*SD= 1.60*) in the "olfaction on" mode (see Figure 4.7a).

Participants also exceeded the speed limit less often in the "olfaction on" (*M= 3.25, SD= 1.58*) than in the "olfaction off" (*M= 4.03, SD= .90*) mode (see Figure 4.7b), which was a statistically significant difference ($F(3, 18)= 3.304$, $p< .05$; Wilks' $\lambda= .645$).

The results also showed that with the olfactory notifications, participants generally drove significantly slower (*F(3, 18)= 6.675, p< .01; Wilks' λ= .473*). The mean speed in the "olfaction off" mode was *M= 64.73mph/104.17km/h* (*SD= 4.33mph/6.97km/h*), whereas in the "olfaction on" *M= 62.97mph/101.34km/h* (*SD= 4.16mph/6.70km/h*), which can be seen on Figure 4.7c.

These results demonstrated a clear benefit of using lavender as a notification modality for events of speeding, as it makes the drivers slow down faster, exceed the speed limit less often, and drive with a slower average speed. Nevertheless, it needs to be considered that no other modalities were investigated in this study. For this reason, the Paper 4 (see Chapter 10) suggests extending this framework towards visual, auditory, and tactile modalities, to find out which notification type works best for the intended message that needs to be conveyed to the driver. The findings of the next paper (i.e. presented in the next section) show how olfactory notifications could be explored in combination with the visual modality.

4.5 Using Multiple Scents and Visual Notifications To Convey Driving-Relevant Information

Following the idea of comparing different notification modalities presented in the previous section, it was decided to conduct a user study, in which olfactory stimuli would be used as a feedback modality for visual notifications shown on a head-up display. The details of this investigation are presented in Paper 5 (see Chapter 11).

22 participants of this simulator study were trained to associate specific scents with specific visual notifications (following the proposal of Kuang and Zhang [115]). The following three associations have been used in the training phase: (1) lavender - "Slow down", (2) peppermint - "Short inter-vehicle distance", and (3) lemon - "Lane departure". Participants drove through a mixed setting, involving parts of a motorway and a city environment. Each time a participant made one of these three mistakes throughout the driving, the corresponding visual notification was shown on the screen of the driving simulator, and the corresponding scent was delivered for five seconds. Half of the driving time, there were only visual notifications, and for the other half of the driving time, both modalities were used. Each driving mistake was recorded.

A dependent t-test for paired samples was conducted to analyse the number of driving mistakes when receiving visual and combined visual-olfactory notifications (see

Figure 4.8). The results revealed that participants had significantly fewer instances of exceeding the speed limit (*t(20)= 4.552, P<.001*) when receiving visual "Slow down" notifications accompanied by the scent of lavender (*M*= 4.44, *SD*= .39), than in the case of visual-only notifications (*M*= 7.71, *SD*= .83). Participants also made significantly fewer mistakes of a short inter-vehicle distance (*t(20)= 4.027, P<.01*) when receiving the corresponding visual notifications accompanied by the scent of peppermint (*M*= 1.41, *SD*= .10), than in the case of visual notifications only (*M*= 2.53, *SD*= .26). Finally, the same effect was observed for the "Lane departure" notification, where participants made significantly fewer mistakes (*t(20)= 7.802, P<.001*) when receiving visual notifications combined with the scent of lemon (*M*= 1.27, *SD*= .07), than in the case of visual notifications only (*M*= 3.07, *SD*= .22).

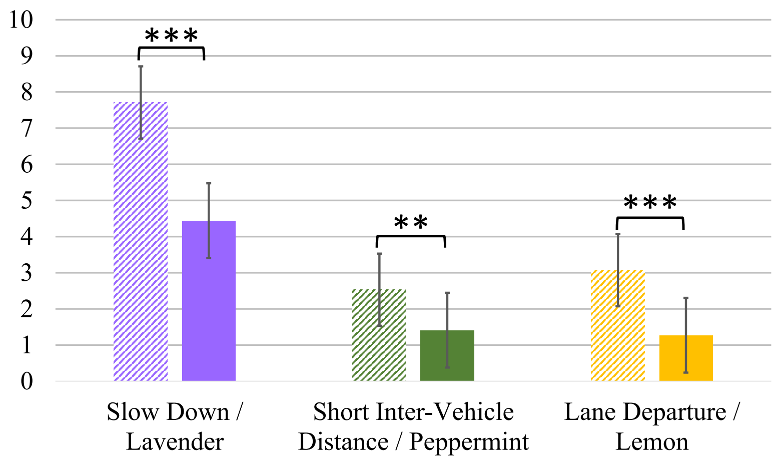


Figure 4.8: Mean number of mistakes made by participants in the process of driving through a mixed setting, involving parts of a motorway and a city environment. Striped bars represent the driving phase in which participants received visual notifications and solid bars - the driving phase with visual-olfactory notifications. Error bars, ± s.e.m., $**p < .01$; $***p < .001$

Self-report data were also collected to evaluate how much participants liked each interaction modality, as well as how distracting, helpful, and comfortable each modality appeared to them. A dependent t-test for paired samples demonstrated that the olfactory modality had been reported significantly less distracting than the visual modality (*t(20)= 5.510, P<.001*). Participants also found the olfactory modality more helpful in understanding the notifications than the visual (*t(20)= -5.477, P<.001*). Moreover, the olfactory modality was liked significantly more than the visual modality (*t(20)= -7.345, P<.001*). Finally, the olfactory modality was perceived significantly more comfortable than the visual (*t(20)= -4.298, P<.001*). These results are summarised in Figure 4.9.

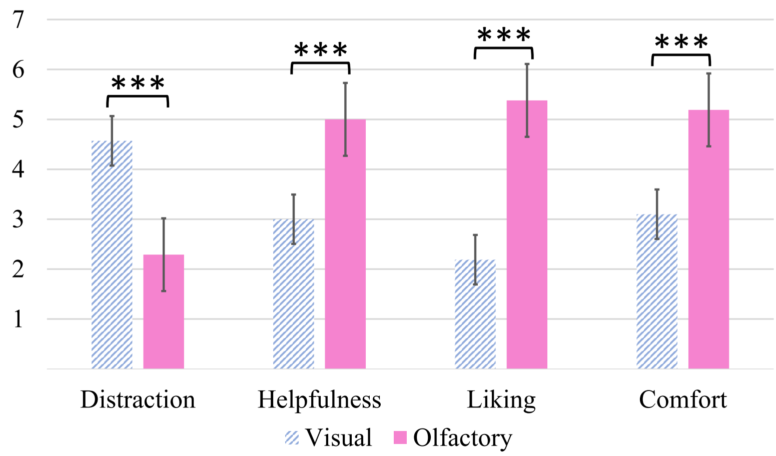


Figure 4.9: Mean ratings of distraction, helpfulness, liking, and comfort of the visual and olfactory modalities (1= "Not at all", 7= "Very much"). Error bars, ± s.e.m., $***p < .001$

The findings of this research activity showed how useful olfactory stimuli could be in supporting the perception of driving-relevant visual notifications. Moreover, they also contribute to the comfort and well-being of the driver. This has motivated the exploration of visual displays supported by olfactory feedback also in an autonomous driving context, where driver's visual attention could be occupied by a secondary task. Details on this investigation are provided in the next section.

4.6 Monitoring Autonomous Vehicles With the Help of Olfactory Displays

As olfactory notifications can help the user perceive visual information (see the previous section), it makes sense to use them in a context where visual displays convey essential information to the driver. One such application scenario takes place in a context of reliability displays (also known as uncertainty displays). Such displays convey the current automation reliability level in autonomous vehicles, and the driver can assess how much alertness and readiness to take over the control is expected in each particular time slot of an autonomous driving session. This section demonstrates the benefits of using olfactory notifications for conveying the switch between low and high automation reliability levels (see Paper 6, Chapter 12 for details).

A simulated driving study with 25 participants investigated how well such displays help drivers monitor the autonomous vehicle. In this study, participants were driven by an autonomous car through a two-lane motorway. Multiple times there was a slower

	Condition Mean (SD)			Statistics	
	Baseline	*Reliability*	*Olfactory*	F	Sig (η_p^2)
Braking Behaviour					
No of brakes	15.08 (12.89)	13.67 (5.92)	20.33 (26.89)	-	.808 (-)
Avg. duration (s)	2.91 (2.48)	2.46 (.92)	2.33 (1.01)	-	.882 (-)
Avg. intensity (%)	.52 (.19)	.49 (.18)	.46 (.20)	2.844	.068 (.11)
Secondary Task Performance					
Avg. resp. time (s)	.81 (.10)	.80 (.10)	.80 (.12)	-	.68 (-)
True positive rate	.62 (.09)	.63 (.09)	.65 (.09)	3.496	**.039 (.13)**
False positive rate	.0143 (.004)	.0125 (.005)	.0113 (.003)	4.823	**.013 (.17)**

Table 4.2: Descriptive and test statistics of objective data: braking behaviour (number of brakes, average brake duration, average intensity) and secondary task performance (average response time, true positive rate, false positive rate). In case of missing F-values, Friedman ANOVA was utilised. Significant differences are printed in boldface.

lead vehicle appearing in front of the participant's car. Depending on the reliability level, participant's car would either brake automatically (high-reliability level) or fail to brake half of the time (low-reliability level), providing an opportunity for the participant to brake manually. In the *olfactory* condition, a scent of lavender was delivered to the participant's nose each time the reliability level switched from high to low (to help the participants relax [125]) and a scent of lemon was delivered each time the reliability level switched from low to high (to arouse/alert the participants [15]). Condition *reliability* contained only the visual display and the condition *baseline* had no display support.

The number of brake pedal actuations, the average brake duration, as well as the average intensity of braking actions were recorded to analyse the braking behaviour. All parameters showed no significant differences between the conditions for these measurements (see Table 4.2 for descriptive statistics). However, there were statistically significant differences in the secondary task performance (i.e. performing the detection-response task on a mobile device, explained in Chapter 12). Friedman ANOVA showed no statistically significant differences in the average response time ($\chi^2(2) = .75, p = .687$). Nevertheless, a significant difference using repeated measures ANOVA was found in the true positive ($F(2,46) = 3.496, p = .039$) and the false positive ($F(2,46) = 4.823, p = .013$) rates. When olfactory notifications were in use, the true positive rate was the highest, and the false positive rate was the lowest.

Participants of this study were also asked to fill in a post-driving questionnaire containing questions on the Trust Scales, Technology Acceptance Model, as well as the Positive and Negative Affect Scale.

	Condition Mean (SD)			Statistics	
	Baseline	*Reliability*	*Olfactory*	F	Sig (η_p^2)
Trust Scale					
Trust	1.71 (1.08)	2.99 (1.06)	3.35 (1.26)	22.725	**<.001 (.486)**
Distrust	3.93 (1.40)	3.15 (1.08)	2.28 (0.91)	18.508	**<.001 (.435)**
Technology Acceptance Model					
Perceived ease of use	2.38 (1.28)	4.06 (1.02)	4.21 (0.92)	37.061	**<.001 (.607)**
Perceived usefulness	1.32 (1.22)	2.60 (1.41)	2.91 (1.65)	17.272	**<.001 (.418)**
Attitude towards use	1.92 (1.64)	3.11 (1.42)	3.84 (1.62)	15.232	**<.001 (.388)**
Intention to use	1.44 (1.66)	2.52 (1.61)	3.20 (2.00)	-	**<.001 (-)**
Positive and Negative Affect Scale					
Positive Affect	2.82 (1.10)	2.74 (1.08)	3.07 (1.20)	2.038	.141 (.078)
Negative Affect	2.49 (1.57)	2.24 (1.34)	1.67 (1.34)	6.729	**.003 (.219)**

Table 4.3: Descriptive and test statistics of subjective scales (Trust Scales, Technology Acceptance Model, Positive and Negative Affect Scale). In case of missing F-values, Friedman ANOVA was utilised. Significant differences are printed in boldface.

The trust scale from Jian et al. [103] delivered significant differences for both sub-scales of trust and distrust (see Table 4.3). In the *olfactory* condition, distrust was significantly higher than in the *reliability* and the *baseline* conditions ($F(1.606, 38.550) = 18.508, p < .001$). Distrust in the *olfactory* and the *reliability* conditions was significantly lower than in the *baseline* condition ($F(1.454, 34.891) = 22.725, p < .001$).

Significant differences were present in all sub-scales of the Technology Acceptance Model. The repeated measures ANOVA revealed that in the conditions *olfactory* and *reliability*, the system was perceived as significantly easier to use ($F(1.428, 34.273) = 37.061, p < .001$) and significantly more useful ($F(1.348, 32.349) = 17.272, p < .001$) than in the *baseline* condition. The attitude towards using the system was the highest in the *olfactory* condition, which was a significant difference ($F(1.484, 35.615) = 37.061, p < .001$). Participants also had a significantly higher intention to use the system in the *olfactory* condition than in the *baseline* condition (Friedman ANOVA, $\chi^2(2) = 19.3, p < .001$). However, there was no statistically significant difference between the conditions *baseline* and *reliability*.

No significant differences in the positive affect could be identified when looking at the results of the Positive/Negative Affect Scale (PANAS) questionnaire ($F(2, 48) = .280, p = .869$). The negative affect on the other hand resulted in significant differences ($F(2, 48) = .6.729, p = .003$). Participants felt significantly less negatively affected in the condition *olfactory* than in the conditions *reliability* ($p = .036$) and *baseline* ($p = .02$).

The findings of this study mainly suggested that there is an improvement in the secondary task performance (i.e. interacting with a mobile device) while monitoring an autonomous vehicle utilising an olfaction-enhanced reliability display. Moreover, such displays resulted in a better trust in the automated vehicle, while also contributing to its ease of use and perceived usefulness. This got further confirmed in the interviews, where 80% of participants claimed that they found olfactory cues helpful in perceiving a change of the vehicle's reliability level. As the self-reported negative affect also dropped in the olfactory condition, this might mean that drivers felt more relaxed about interacting with reliability displays that employ olfactory stimuli for conveying the switch between reliability levels. This is an important argument to consider in terms of how the driver feels about interacting with scents. For this reason, the next study conducted in the scope of this thesis was targeting the problem of understanding the effects of scent on the driver's emotions and well-being.

4.7 Effects of Scents on Driver's Emotions, Well-Being, and the Safety of Driving

As the study presented in the previous section suggested that scents have a positive effect on the perceived ease of use of autonomous vehicles and that scents also reduce the negative affect, the next step is to look in more detail into the question of modulating driver's emotions and well-being using olfactory stimulation. The sense of smell has a very strong link with emotions and memories [80], which is another motivation for investigating the use of scents for this purpose. As the research around driver's emotions is focused on the feeling of being angry [102, 101, 173, 60] and anger promotes dangerous driving behaviour [53], it makes sense to investigate whether influencing the driver's emotions by using scent correlates with changes in the safety of driving. Details of this research activity are provided in Paper 7 (see Chapter 13).

A between-participants study (N= 40, 10 per condition) was conducted to investigate the effects of the scents of rose (positive valence, low arousal), peppermint (positive valence, high arousal), and civet (negative valence, high arousal) on angry drivers. In this study, participants were shown anger-inducing pictures from an International Affective Pictures System (IAPS) database [120], before driving. They then drove through a rural road setting (one lane in each direction) and experienced randomly occurring anger-inducing on-road events (e.g. a car cutting in, a pedestrian suddenly crossing the road).

Ten seconds before each event, there was a scent delivered to their nose for five seconds. The scent type (i.e. rose, peppermint, civet, or clean air as a control stimulus) depended on their between-participants condition.

Participants were asked to rate their emotional state (by using Self-Assessment Manikin (SAM) [22]) at the start of the experiment, after the anger induction procedure, and after the driving phase.

A Shapiro-Wilk test showed a significant departure from normality for all the variables in this dataset. We ran a Wilcoxon-Signed-Ranks test to compare the means between two variables. We compared the valence of the emotions before the experiment with its value after the IAPS pictures were shown. The same comparison was done for the corresponding arousal ratings. Concerning the valence ratings, the test indicated that the valence before the experiment (*mean rank= 17.52*) was significantly higher than after viewing the IAPS pictures (*mean rank= 11.00, Z= -4.058, p<.001*). Concerning the arousal ratings, the test indicated that the arousal before the experiment (*mean rank= 10.33*) was statistically lower than after viewing the IAPS pictures (*mean rank = 13.22, Z= -2.611, p< .01*).

This means, at the start of the study, all participants were calm (as per [175]). After viewing the IAPS pictures, participants' self-reported emotional state shifted towards the negative valence and high arousal quadrant (see Figure 4.10), which also contains the anger emotion (as per [175]).

After having driven through an anger-inducing course, participants reported still being aroused (all mean arousal ratings were above three on a 5-Point Likert scale). There was a clear distribution of the emotions over the negative and positive valence

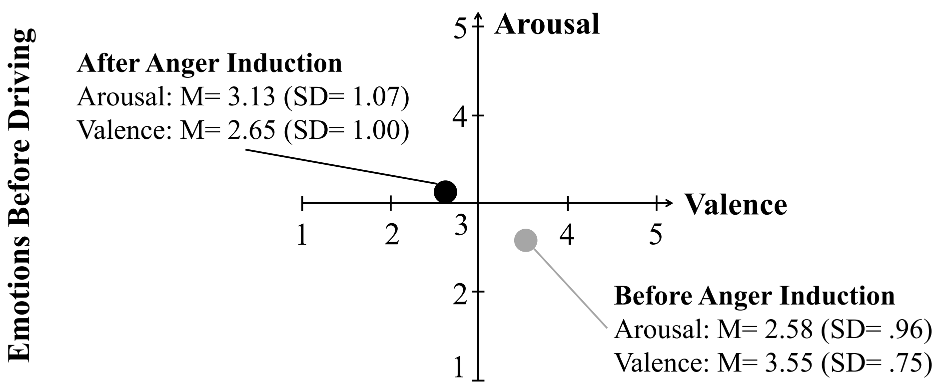


Figure 4.10: Mean Arousal (1= "Low", 5= "High") and Valance (1= "Negative", 5= "Positive") ratings of the participants' self-reported emotional state before and after the anger induction procedure (i.e. viewing the anger-inducing IAPS pictures).

quadrants (see Figure 4.11), however, this was not supported by the statistical tests. A Shapiro-Wilk test showed a significant departure from normality for all the variables in this dataset. The Kruskal Wallis test showed no statistically significant differences in the arousal (χ^2 *(3)= 5.39, p= .145, median= 3.0, 25th quartile= 2.0, 75th quartile= 4.0*) and valence (χ^2 *(3)= 2.87, p= .412, median= 3.5, 25th quartile= 3.0, 75th quartile= 4.0*) ratings. We also checked for the changes of the self-reported emotions between the three points of time: before the experiment, after viewing the IAPS pictures, and after driving. The Friedman test showed a statistically significant effect of timing on the arousal (χ^2 *(1)= 6.76, p< 0.01*) and valence (χ^2 *(1)= 5.76, p< 0.05*) ratings. There was no significant interaction between the time and the scent for the arousal (*p= .320*) and valence (*p= .104*).

While experiencing critical events (e.g. car cutting off), it was important for the participants to avoid collisions. However, only five participants out of 40 (three in rose and two in peppermint conditions) were able to complete their driving without colliding into another vehicle, a bicycle, or a pedestrian. A Shapiro-Wilk test showed a significant departure from normality for all the variables in this dataset. The Kruskal Wallis test showed statistically significant differences in the number of collisions between the scents (χ^2 *(3)= 26.27, p< .001, median= 1.0*) with the highest number of collisions in the civet condition (see Figure 4.12). However, no significant differences were found in the binary measures of catastrophic road excursions (χ^2 *(3)= 7.13, p= .068, median= .0*). No excursions were recorded in the rose condition. There were two such occurrences in the water (clean air, control) and peppermint conditions. Finally, half of all 10 participants in the civet condition had experienced an excursion.

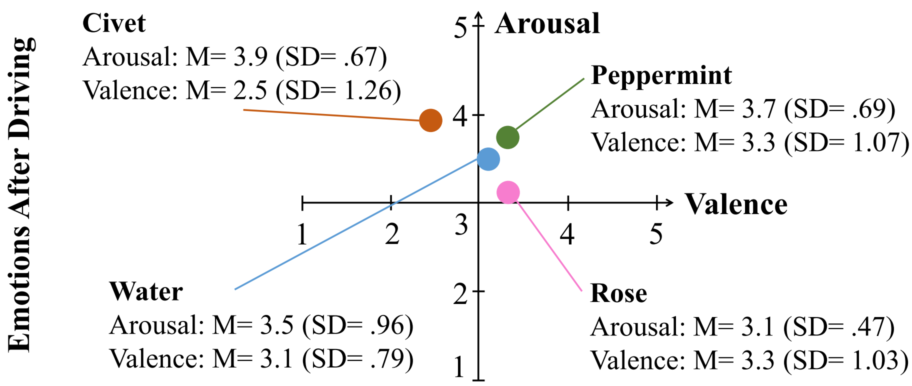


Figure 4.11: Mean Arousal (1= "Low", 5= "High") and Valance (1= "Negative", 5= "Positive") ratings of the participants' self-reported emotional state after the driving phase performed in the "water" (clean air), "rose", "peppermint", and "civet" conditions.

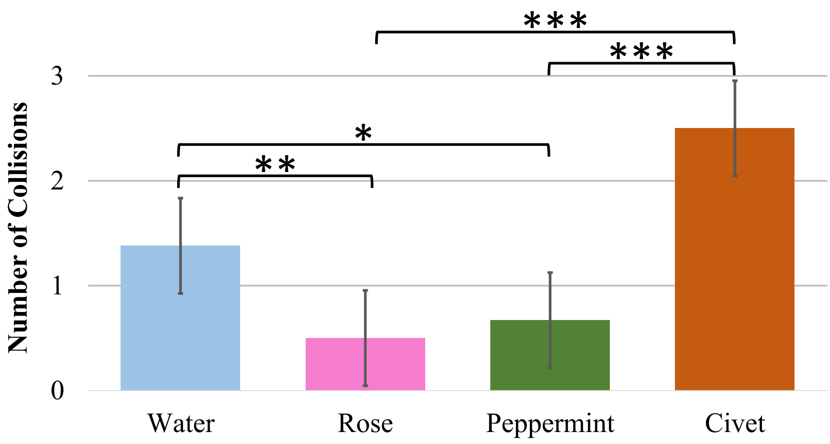


Figure 4.12: The mean number of collisions in the water (clean air, control), rose, peppermint, and civet conditions. Error bars, ± s.e.m., $*p < .05$; $**p < .01$; $***p < .001$

After the experiment, participants were asked to rate how much they liked interacting with the scent and how comfortable that was on a 5-Point Likert scale (*1= "Not at all", 5= "Very much"*). A Shapiro-Wilk test showed a significant departure from normality for all the variables in this dataset. The Kruskal Wallis test showed no statistically significant differences in the scent liking ratings ($\chi^2(3) = 6.32$, $p = .097$, *median= 4.0*) and a significant effect of scents on the comfort ratings ($\chi^2(3) = 7.81$, $p = .05$, *median= 4.0*) with rose rated significantly higher than civet (see Figure 4.13).

These findings were further confirmed by participants' responses in interviews conducted at the end of the experiment. All 10 participants who smelled rose said that this scent made them feel less nervous (1), more relaxed/peaceful/settled/soothed (5),

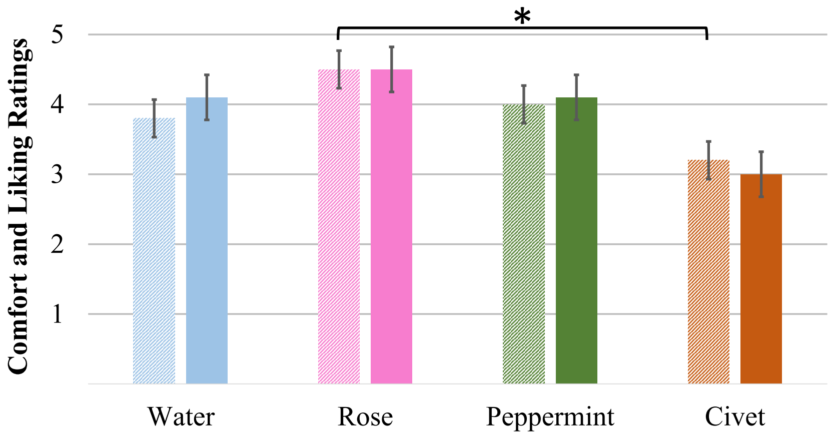


Figure 4.13: Mean Comfort (left) and Liking (right) ratings (1= "Not at all", 5= "Very much") of interacting with the scents of water (clean air, control), rose, peppermint, and civet. Error bars, ± s.e.m., $*p < .05$

positively affected (1), less emotional (1), more attentive (1) and more positive (1). For example, *P35* said: *"It made me feel more relaxed... It was nice to have it in the car."* and *P9* said: *"It did positively affect me, it slowed me down. I started appreciating the smell."*

To sum up, this study demonstrated that the scents of rose and peppermint are capable of improving the mood of angry drivers, whereas the scent of civet only makes it worse. Moreover, the civet scent promotes dangerous driving behaviour, resulting in participants crashing significantly more than in any other tested condition (i.e. rose, peppermint, or clean air). Finally, rose demonstrated itself as a significantly more comfortable scent to interact with than civet. This was further supported by interview responses, where participants in the rose condition confirmed that they found this scent relaxing, soothing, and settling. These findings suggest that car manufacturers might want to avoid unpleasant scents when designing for angry drivers. On the contrary, such scents as rose might help angry drivers be more careful and comfortable on the road.

This section concludes the Findings chapter. This chapter has highlighted several core benefits of using olfactory notifications to convey driving-relevant information. Such benefits mainly contain improved perception of the driving-relevant information (e.g. "Slow down"), better driving behaviour (e.g. fewer lane departures), safer driving style (e.g. fewer collisions), and better mood (e.g. shift of the valence towards positive in angry drivers). The next chapter will discuss what these findings mean on a broader scale, how can they inform better design of in-car user interfaces, and what application they might have outside an automotive context. Since modern in-car user interfaces are mainly based on visual and auditory stimuli, the next chapter will also present a discussion on which combination of modalities (e.g. visual-olfactory, visual-auditory, visual-haptic) might work best for what application scenario.

5 | Discussion

Within the previous chapter, the main findings of the thesis were presented, which are mainly focused on the improved perception of the driving-relevant information, better driving behaviour, and better mood. The current chapter discusses the implications of these findings on the topic of olfactory interaction in a driving context and beyond. Based on the findings of this thesis, the discussion needs to cover four major aspects: (1) how an olfactory interaction space designed for this thesis can be used, (2) how can we benefit from the knowledge on scent perception and the effects of different scents in the car, (3) how can we use this knowledge to design novel in-car user interfaces and experiences, and (4) how can we combine different sensory modalities for the car-driver interaction. Each of these points is discussed below.

5.1 Using Olfactory Interaction Spaces

The olfactory interaction space designed and built in the scope of this thesis (see Chapter 8) has been demonstrated to be very efficient for investigating olfactory interaction in different driving scenarios (see Chapters 9, 10, 11, and 13). It could also be used to study the effect of scents on drivers' drowsiness (e.g. like in [220, 66, 157]), alertness (e.g. like in [15, 170]), braking performance (e.g. like in [130]), and mood (e.g. like in [141]). However, the size and the specifications of this interaction space make it suitable for many more interactive applications. Some of such examples will be discussed below.

One of the most interesting applications for an olfactory interaction space outside an automotive context is Virtual Reality (VR). Smell-based interfaces have already been explored in VR, for such applications as playing a VR harvesting game [134] or VR-based rehabilitation with scents as reward stimuli [34].

Beyond these examples, an olfactory interaction space could be used to enhance the interaction with virtual environments used for educational purposes. For example, in a *VR Safari Park* [96], a user could receive a scent of different plants, animals, or even weather conditions to help understand the concept of the *World Tree* and simulate different scenes in a more efficient and fun way.

Another example could be a virtual block matching task (e.g. like in the *ViBlock* approach [99]). In such a task, scents could be used to give additional hints to the user for more efficient block matching (as per [184]) or as a reward stimulus (as per [34]).

In VR, scents are also good for immersion. This has been demonstrated by the team of *New Reality Co.*, the creators of the *TreeVR* experience [145], in which a user embodies a tree an gets to smell different stages of its life.

On the intersection of VR and Gaming, olfactory stimulation could, for example, be used to help the user distinguish the different scenes/worlds the virtual character is moving through. Such an idea might help enhance such VR games as *Light Tracing* [6], where the user controls a virtual character by pointing its direction with a virtual light beam. In this context, scents could help convey information on what location/obstacle the virtual character is approaching. A similar idea has been already used for desktop gaming. For example, Abid et al. [1] applied burning scents to enhance a 3D shooter and Nakamoto et al. [142] used a scent mixing device to help a player smell the ingredients of a meal in a cooking game.

In terms of collaborative work, the process of computer game creation in a small group has been demonstrated to be a powerful tool for exercising team-working skills and building self-esteem in young people [171]. Potentially, the prototyping stage of this process could become even more fun and engaging if young game creators were also able to assign scents to the virtual objects that they create and/or insert in the target game. This is motivated by the recent explorations of olfactory interaction to stimulate the creation of inclusive technologies for children [133].

In serious games, which, for example, are targeted to help young people learn new concepts (e.g. game scripting [91]), olfactory interaction spaces could potentially create more efficient teaching rooms or practice labs. Such spaces could facilitate more efficient learning, as scents are known to have strong links with memories [80] and to facilitate better learning [115].

Finally, **a very interesting use case for olfactory interaction spaces is Multisensory Cinemas** (e.g. like in [84]). **Olfactory stimulation is known to be able to enhance the perception of visual content when both modalities are synchronised** [140]. Some researchers have also tackled the challenge of making this technology available at home [196]. Moreover, as proposed by Wu et. al [218], with the help of machine learning, it could become possible to synchronise visual content with the congruent olfactory stimulation automatically (e.g. a scent of an apple would be delivered to the user when an apple is shown on the screen). Storing all the possible scents to match any possible shape captured on a video frame might not be feasible. To overcome this, it is possible to match the visual content with olfactory stimulation based on the emotional aspect of a video clip and the arousal/valence level of a scent. For example, an intense scene in a movie could be matched with a sharp scent (e.g. a scent of lemon to accompany a deadly flight of a space ship in *Interstellar* [26]).

Nevertheless, as the primary aim of this thesis is to investigate the opportunities for scents in different driving scenarios, the olfactory interaction space presented here was equipped with a driving simulator. Benefits and further options of such explorations are discussed in the next section.

5.2 MAKING USE OF SCENTS IN A CONTEXT OF DRIVING

An olfactory interaction space described in this thesis is capable of hosting different interactive prototypes. A driving simulator is not an exception. The findings chapter (see Chapter 4) of this thesis presented multiple interesting results that contributed to the knowledge on human olfaction in different driving contexts. This section discusses the implications of these findings, along with further opportunities.

It has been demonstrated that mapping olfactory stimuli onto driving-relevant notifications is not arbitrary (see Chapter 9) and can be performed based on the arousal levels of scents and urgency levels of notifications (e.g. lavender suits "Slow down"). This has been further validated in a study which confirmed that participants exceed the speed limit less often and decrease the speed faster when receiving a lavender notification after each speeding (see Chapter 10). Scents could potentially also help the driver perform the task better when olfactory stimuli are used for such alerts as "lead vehicle braking" [165] or "take over the control" [21].

Similar results have been found for olfactory feedback used to accompany visual notifications on a head-up display (e.g. lemon scent resulted in fewer lane departures, see Chapter 11). This suggests that olfactory stimuli can be useful in improving driving behaviour. Knowing that it takes 10 seconds for a scent to become perceived by the driver (as per Chapter 8), the initial mapping study was based on notifications that do not necessarily require an instant reaction from the driver (e.g. a "Fill gas" notification does not imply an immediate stop at a gas station). Nevertheless, a follow-up study (see Chapter 11) demonstrated that scents could also be employed for more urgent notifications (e.g. "Short inter-vehicle distance"), as long as an olfactory notification is not used alone, but in combination with a (faster) visual stimulus. Due to this, the validation study described in Chapter 10 also suggested exploring different sensory modalities in combination with olfactory stimuli to make the full use of crossmodal effects (e.g. as explained by [184]). This would also go in line with previous proposals of combining different modalities for car-driver interaction (e.g. as in [165, 164]). Knowing that, for example, tactile stimulation has demonstrated an increase in driver's attention in safety-critical environments [189] and faster braking reaction times [127], it would be interesting to find out how such results change when the smell is involved.

Such findings motivate making the full use of human olfactory function in a context of driving and going beyond current trends of hedonic in-car experiences (e.g. as per [35, 20, 18]). Olfactory notifications can be a powerful tool for conveying important driving-relevant information, as long as the scent delivery parameters are well controlled (see Chapter 8). This motivates exploration of olfactory notifications in further scenarios, especially in automotive context (as demonstrated in Chapter 12), where driver's eyes might be engaged in a secondary task. What makes olfactory notifications even more attractive, is that, due to a strong link with emotions and memories [80], scents are capable of not only alerting the driver, but also helping them calm down, feel more relaxed, and drive more safely as a consequence (see Chapter 13). This is in line with previous findings [141, 130] and could create new opportunities for car-driver interaction. Some ideas for this are presented in the next section.

5.3 Designing Novel In-Car Interfaces

As outlined above, olfactory stimulation enables new opportunities for the car-driver interaction, e.g. in terms of improved information perception, safer driving behaviour, and better mood. Some further ways of how designers could make use of smell-based interaction are summarised below.

Olfactory interaction is plausible in the context of autonomous driving. As explained above, olfactory stimuli have already been proven to be efficient for conveying the switching between automation reliability levels (see Chapter 12). Another useful application might be a take-over scenario, in a situation when an automated vehicle fails to drive autonomously (e.g. because of construction works on the road) and needs to pass the control over to the driver. Mok et al. [135, 136] has investigated the use of auditory notifications for this purpose, and Lee et al. [121] has demonstrated the usefulness of tactile stimuli. Olfactory notifications have not been explored for driving take-over alerts yet. Nevertheless, there are several arguments for doing so, including the activation of the central neural system [10] (to make the driver better prepared), a link to emotions and memories (to potentially help keep the driver calm), and a direct path to the primary cortex [166] (to directly reach the central parts of the brain).

Also in semi-autonomous driving scenarios (e.g. when using advanced driving assistance systems), scents could be used to alert the driver about a certain upcoming event. For example, Politis et al. [165] used visual, auditory, and tactile stimuli to convey a message of sudden braking of a lead vehicle. While an olfactory notification might not be quick enough to notify the driver about an event with such an immediate impact, with an advance of artificial intelligence, in the future, a car might be able to predict such an event and start delivering a scent to the user some seconds before a visual notification would be displayed. A scent could also be used as a feedback notification, e.g. to help the driver understand why a car braked itself in a dangerous situation (e.g. as in case of feedback notifications proposed in [114]).

In terms of designing novel experiences, it is important to consider the effects of olfactory stimulation on the well-being of the driver. The findings presented in this thesis have shown that angry drivers feel more relaxed and comfortable when receiving pleasant scents, like rose and peppermint (see Chapter 13); however, other emotions still need to be explored. For example, Jeon et al. [101] found that happy drivers become less happy after having experienced a difficult driving phase. Moreover, they made almost as many errors as angry drivers. So, it would be very interesting to find out if it is possible to help happy drivers stay happy longer and drive more carefully using olfactory stimulation.

The examples mentioned above explain how olfactory notifications could contribute to the creation of novel in-car interfaces and experiences. This could be mainly achieved thanks to the ability of olfactory stimuli to activate our neural system and due to strong links with emotions. Nevertheless, there could be situations when scents would not be the best sensory modality to use in the car. This topic is discussed in the next section.

5.4 Combining Different Sensory Modalities

This thesis has shown that olfactory stimulation can be useful in helping the driver become aware of driving-relevant events (see Chapters 9 and 10), perceive visual notifications better (see Chapters 11 and 12), and calm down (see Chapter 13). However, there are situations in which other sensory modalities and their combinations would work better. This section discusses such situations.

Smell could work well for driving-relevant notifications that do not require immediate attention (e.g. "Fill gas"). In such a case, initially, the information could be conveyed to the driver using a visual stimulus (e.g. a petrol pump sign on the dashboard) and the corresponding scent could come afterwards to remind the driver every now and than that the fuel level requires their attention. Scents could also be combined with auditory stimuli. For example, this thesis has shown that the scent of rose could be used to convey a "Passing by a point of interest" message (as per Chapter 9). This means, there is a potential for integrating olfactory stimulation into the car's navigation system, to notify the driver about location-based information. As auditory stimuli are common for conveying navigation alerts, a scent could, for example, be delivered before an auditory message needs to be played (e.g. 500m before the left turn, the driver would perceive a scent of lemon) and an auditory message would come immediately before the turn. A similar approach has been used for thermal stimulation on the steering wheel [43] in the past and could be adapted to olfactory interaction use cases.

If the car needs to notify its driver urgently, e.g. about a safety-relevant event (such as, "Take over the control" in autonomous vehicles), then olfactory stimulation might not be the best choice. The study described in Chapter 8 suggests that it might take as long as 10 seconds for a scent to be perceived by the driver. This means that in such a case, an alternative modality (or a combination of multiple modalities) should be used. A study conducted by Politis et al. [165] showed that audio-visual in-car notifications have the fastest recognition time. This suggests that audio-visual notifications might be the best for such (and similar) urgent events. Moreover, when using audio-visual notifications, it is important to choose the right delivery modality within the sensory channel (e.g. text or symbols for vision and voice or abstract sounds for audition).

There might also be situations in which auditory notifications might not work well even for urgent events, for example, if the driver is playing loud music or is in a very loud traffic. In such cases, it might be worth using tactile stimuli (e.g. on the steering wheel). These could be, for example, lane departure or speeding alerts. As a study of Shakeri et al. [185] suggests, haptic feedback on the steering wheel has no effect on the lane deviation, such notifications could potentially be applied without causing any distraction to the driver.

Combinations of auditory and tactile notifications could be used when driver's complete visual attention is required on the road (e.g. when navigating through an unknown dark environment). A paper of Baldwin et al. [14] suggests that drivers might get annoyed by auditory stimuli. A study conducted by NHTSA [148] claims that some drivers even mute certain auditory notifications. If tactile stimuli are used to support the auditory notifications, the chance of missing the important driving-relevant information (e.g. "low tyre pressure") could potentially decrease.

This section has discussed some of the combinations of visual, auditory, tactile, and olfactory stimuli to convey driving-relevant information. There could be many more combinations that in-car interaction designers might find useful for specific application scenarios. There is no straightforward answer to which combination is best for what use case. However, the discussion presented here should serve as a good starting point for approaching the in-car interaction as a multisensory challenge.

This chapter has discussed the implications of using olfactory stimulation as a notification modality in a driving context. The core advantages of such notifications include improved information perception, safer driving behaviour, and a better mood. After having discussed these details by reflecting on the related work, the research method, and the findings, it is now important to summarise the conclusion of this thesis, along with limitations and some directions for the work that can be done in this field in the future.

6 | Conclusion

This thesis has been presented through an overview of its main definitions, the focus area, the objectives, and the contributions. All that has been supported by a detailed description of the related work, the research method, the findings, and the discussion. The current chapter will summarise the conclusion of the thesis, elaborating on its contributions, limitations, and ideas for future work.

6.1 Contributions

This section summarises the contributions of this thesis by extracting the main achievement of each research paper written over the course of this publication-style work.

Scent-delivery devices can be compared concerning their scent-delivery potential based on distance, volume, and speed. Such a three-dimensional framework can also be used to identify the potential application scenarios of each delivery device. For example, a device with high speed and long distance of scent delivery could fit the task of displaying urgent notifications to the driver. On the contrary, a device that is capable of delivering a big volume of a scent over an extended time might be suitable for ambient notifications relevant to all people seated in a vehicle. It could also be used to modulate their emotional state using scents.

With the help of a scent-delivery device and an olfactory interaction space developed in the scope of this thesis, a scent can be perceived by the user in ten seconds, and it takes nine seconds for the scents to disappear. A user study confirms that such a performance is also maintained when the air in front of the user is not being extracted, proving that such a scent-delivery device can also be applied without additional air extraction solutions. This finding was confirmed for three different air pressure conditions (0.5, 1.0, and 1.5bar), three scent types (lemon, peppermint, rose), and two dilution levels (100% pure essential oil and 50% dilution with water). The framework proposed based on these finding presents a novel set of recommendations for olfactory interaction design. It suggests, for example, that a scent-delivery device should enable a scent blowing distance of at least 50cm (to allow space for user's hand movements), well-isolated scent channels, control of the scent delivery time and intensity, delivery of multiple scents in a single session, and an option of rapidly switching between scents. Based on this framework, an olfactory interaction space should be composed of materials that do not absorb scents and have an air extraction that is independent of the building's centralised ventilation system. Such a framework creates multiple opportunities for the exploration of olfactory applications in HCI (such as in gaming, multisensory cinema, VR, and simulated driving).

Using olfactory stimuli as an alternative interaction modality in the car is not arbitrary, and participants can establish a mapping between specific driving-relevant notifications and scents. Based on the induced alertness level of both the notification and the scent, it is possible to establish a new semantic layer of information delivery for the driver. For example, such arousing scents as lemon and peppermint can be associated with alerting notifications of "Fill gas" and "Slow down". On the contrary, a calming scent of rose can be linked to a less alerting notification "Passing by a point of interest", where it is fine to miss such a landmark and turn around or come back later. These insights open up new opportunities to further explore the topic of conveying information using smell in contexts of driving and beyond.

The work covered in this thesis presents the first proposal of an approach for validating a mapping between scents and driving-relevant notifications. There have been multiple proofs of concepts demonstrating the effectiveness of olfactory stimulation in an automotive context, but none of those indicates a clear procedure for making sure the initial mapping is valid considering such driving behaviour measures as lane deviation, mean speed, and the time required to recover from an error. The initial study demonstrated how such measurements could be taken into account for carrying out the validation task (i.e. by demonstrating how a match between a lavender scent and a "Slow down" notification can be validated). This study showed, for example, that the scent of lavender can help participants exceed the speed limit less often, decrease their mean speeding time, and drive with a lower mean speed overall. All that is possible when the scent of lavender is delivered as a short puff to the driver upon detection of an event of speeding. These findings motivate for an exploration of how well other scents match their intended notifications (e.g. the scent of peppermint and the "Fill gas" notification).

Olfactory notifications can improve our hedonic experience (i.e. the feeling of comfort). Moreover, such notifications can also act as a non-distracting, helpful, and comfortable interaction modality. When it comes to the driving behaviour, then olfactory feedback has the potential of giving the driver hints that could have been missed when relying on visual stimuli only, e.g. in cases of exceeding the speed limit, short inter-vehicle distance, and lane departure. The study that investigated these three example scenarios has shown that, when visual notifications are accompanied by the corresponding scents (i.e. lavender, peppermint, and lemon), participants make significantly fewer driving mistakes. Also, their comfort and liking ratings of interacting with the notification modality increase significantly when visual notifications are combined with the corresponding olfactory stimuli. These results could be achieved after a conditioning procedure that trained participants on the associations between scents and driving-relevant visual notifications.

In a context of autonomous vehicles, olfactory cues can improve performance in a dual-task setting. With the support of olfactory cues, participants showed smoother braking behaviour compared to the baseline (no reliability display, no scent) condition. Also, adding olfactory notifications to the visual stimuli resulted in significantly higher performance in the visual detection-response task (performed as a secondary task on a mobile device). In addition to that, the olfactory modality was subjectively preferred by study participants in both self-report questionnaires and semi-structured interviews. In interviews, 80% of the participants stated that olfactory cues help perceive a change in the vehicle's reliability levels. These results suggest that olfactory stimuli, combined with the corresponding visual notifications, can be useful in conveying the reliability level of an autonomous vehicle to its driver. This means that, with the help of scents, a driver is better aware of the current state of the automation and is better prepared to take over the control, if needed.

What it comes to emotions and well-being of the driver, then the scents of rose and peppermint have been demonstrated to be able to improve the mood of angry drivers (i.e. shift the valence of the emotion from negative to positive) and contribute to the feeling of comfort. On the contrary, the scent of civet led to an even worse mood (i.e. an even more negative valence and even higher arousal). Moreover, the civet scent decreased the perceived comfort of interacting with the vehicle and resulted in an unsafe driving behaviour (i.e. significantly more collisions than in rose, peppermint, or clean air conditions). These findings were further supported by interview responses. All ten participants in the rose condition confirmed that this scent made them feel more relaxed. Whereas, four out of ten participants in the civet condition claimed that this scent made them irritated and annoyed. Surprisingly, two participants in the civet condition liked the scent. Moreover, two participants in the peppermint condition mentioned that this scent made them more relaxed (despite its arousing properties). The two exceptions mentioned above suggest that future cars should provide customisable olfactory interfaces, where a driver can choose a scent for each purpose based on their personal preferences (provided that drivers can choose from a set of scents that research has proven to be useful for the intended application scenario).

To sum up, we see that olfactory in-car notifications can contribute to improved driving behaviour, better mood, and increased well-being. The design of such notifications is not arbitrary and can be carried out based on the arousal level of scents and alertness level of the driving-relevant information. When the scent-delivery parameters are well controlled (e.g. scent channels are well isolated, scent can be delivered for a short time and with the required air pressure), olfactory notifications could help us, for example, maintain a safe driving speed, keep a safer distance to a lead vehicle, and monitor our autonomous vehicle more efficiently. Moreover, by choosing pleasant scents for such notifications, it could be possible to shift the driver's emotional state towards the positive valence and improve the feeling of comfort. When the benefits of using olfactory notifications are summarised, it is also necessary to acknowledge the limitations of the approaches discussed in this thesis.

6.2 LIMITATIONS

We have made progress in our understanding of the role of smell for in-car interaction and have achieved technological advances to test the effects of scents, but there is still a long way to go. Despite the progress, I also need to appreciate the limitations of the research presented in this thesis. Even though olfactory interaction has become increasingly popular, we still know very little about it. This thesis (especially Chapter 8) has made a significant contribution to the understanding of how to mitigate the side effects of olfactory interaction (e.g. scent cross-contamination). However, every approach presented in this thesis has its own limitations. These limitations are summarised below.

Despite the fact that the total of seven user studies have been conducted in the scope of this PhD thesis, the number of participants in every study was relatively low, i.e. 17-30 in within-participants and 21-40 (7-10 per condition) in between-participants studies. This means that further studies with a larger sample size are required to confirm the effects identified in this thesis.

Moreover, it needs to be acknowledged that the olfactory functions of the participants involved in the studies of this PhD thesis (e.g. their sensitivity to different scent dilution levels) has not been tested. All participants have been carefully screened for olfactory dysfunctions and adverse reactions to strong scents, however, this has been done using a self-report questionnaire (i.e. not olfactory tests).

Furthermore, it is essential to acknowledge that all driving-relevant studies presented in this thesis are lab-based and have been conducted in a driving simulator of a relatively low fidelity. A higher degree of the simulator's fidelity (e.g. real car's interior, motion platform, etc.) might have an impact on the results found in this thesis. Conducting these experiments on real roads, with real-life traffic might influence the results too.

Talking about investigating olfactory interfaces in real cars on the real-life roads, it is also necessary to acknowledge that this thesis does not provide insights of how the distribution of scents and their perception would work in an interior of a real car (e.g. if scents would soak into the materials of the car's interior and how the car's ventilation system would cope with the task of getting the scented air out of the car). It is also not known how the scent delivery would work when the car's window is open or if it is being used in a convertible car.

Furthermore, this thesis has not investigated whether a scent delivered to the driver would also be perceived by their co-pilot or passengers. In relation to that, it is important to acknowledge that we do not know how efficient an olfactory interface would be if a driver or their passengers are wearing perfume or have brought other strong scents (e.g. smelly food) with them into the car.

In terms of advancements in the field as a whole, it is important to acknowledge that the scent-delivery technology presented in this thesis is currently not synchronised with the breathing patterns of a driver. Ohtsu et al. [155] have demonstrated the advantages of delivering a scent to the user exactly when the user is inhaling. This normally requires the use of a breath sensor that is quite invasive and needs to be worn as a strap around the user's chest, making it less feasible for driving scenarios. For this reason, it was chosen to always deliver a scent for five seconds, which is known to be a big enough time frame for a user to inhale and exhale at least once, i.e. to perceive a scent (as also shown by Ohtsu et al. [155]). In the future, it could be possible to overcome this by installing a flexible breath sensor in a seat belt (e.g. from *Flexpoint Systems* [63]).

As a scent needs to be delivered to the driver for at least five seconds, a certain time is also needed for this scent to disappear and become no longer perceivable. As per the findings presented in Chapter 8, it takes a user nine seconds to stop perceiving a scent. This means that a new olfactory notification cannot be delivered within nine seconds after a previous notification has been delivered. This is quite a long time frame, especially in such a fast pace process as driving. To overcome this limitation, a car could make use of alternative modalities (e.g. auditory or tactile) until the timeout of nine seconds has expired. The necessity of such a timeout could vanish if the breath sensing (introduced above) was implemented. This way, it would potentially be possible to release an even smaller amount of a scent, resulting in a shorter lingering time.

A substitute notification modality (e.g. tactile) could also be used when the driver's olfactory function is impaired (e.g. due to the flu), when a driver becomes very sensitive to scents (e.g. during pregnancy) or is not able to perceive scents at all (a significant proportion of drivers are anosmic, i.e. not able to smell). In such cases, it would be necessary to make use of other sensory channels. A framework of deciding which modality would fit a target driving scenario is proposed in Chapter 10.

Regarding the perception of scents, it is also important to mention the possibility that the driver might miss a jet of scented air if they turn or move their head at the moment the scent gets delivered. It could be possible to overcome this limitation by implementing a flexible nozzle (e.g. like in [191]) and using computer vision algorithms to detect where the driver's nose is located, to adjust the delivery direction according to the position of the driver's head.

Finally, it is important to consider that drivers are not all the same, meaning that they all have different sensitivity to olfactory stimuli and different scent preferences. To overcome this challenge, cars of the future would need to offer olfactory interfaces that can be calibrated (e.g. to adjust the scent intensity based on the current state of the driver's olfactory function). Such interfaces would need to be customisable based on the driver's preferences (e.g. a driver can choose whether lemon or peppermint would be a better fit for a "Fill gas" notification and what intensity would it have). Further research is necessary to identify the best strategies for dealing with interpersonal differences. Implications for the future work will be discussed in the next section.

6.3 FUTURE WORK

Based on the achievements outlined in the previous section, this section summarises the activities that should be performed as the next steps of the research process, to identify new opportunities for scents in the car and to better understand ways of mitigating challenges set out by olfactory stimulation. This section also reflects on the entire thesis and proposes a roadmap of moving towards the ultimate goal of using olfactory stimulation in a real world driving environment.

As mentioned in the Limitations section, future studies would need to be conducted with a larger sample size, in real-life driving environments, with external scents (i.e.

scents brought into the car) involved, and investigating the capabilities of ventilation systems to extract scents from the car's interior. All that needs to be done on the way of implementing the olfactory interfaces in real cars. A detailed discussion on this process is presented below.

One could think of different dimensions when defining the roadmap for the future investigation and development of in-car olfactory interfaces and experiences. For example, to decide what scents work best for each driving scenario, it would be necessary to use the two-dimensional space of scent valence and arousal. On the other hand, to understand the distribution of scents in the car's interior, one would need a three-dimensional space of the time, distance, and speed of scent delivery. However, for the definition of the roadmap for all the steps that need to be performed on the way to using olfactory stimulation in a real world driving environment, I propose using a two-dimensional space of the research/development time and the fidelity of the developed olfactory interface (see Figure 6.1).

The steps that need to be done within this 2D space can be divided into three groups: (1) lab-based studies (i.e. as conducted in the scope of this PhD thesis), (2) on-road tests and integration of the prototype into a real vehicle, (3) use of the olfactory interface in the real life. These steps and an example of how they could be used to transform a

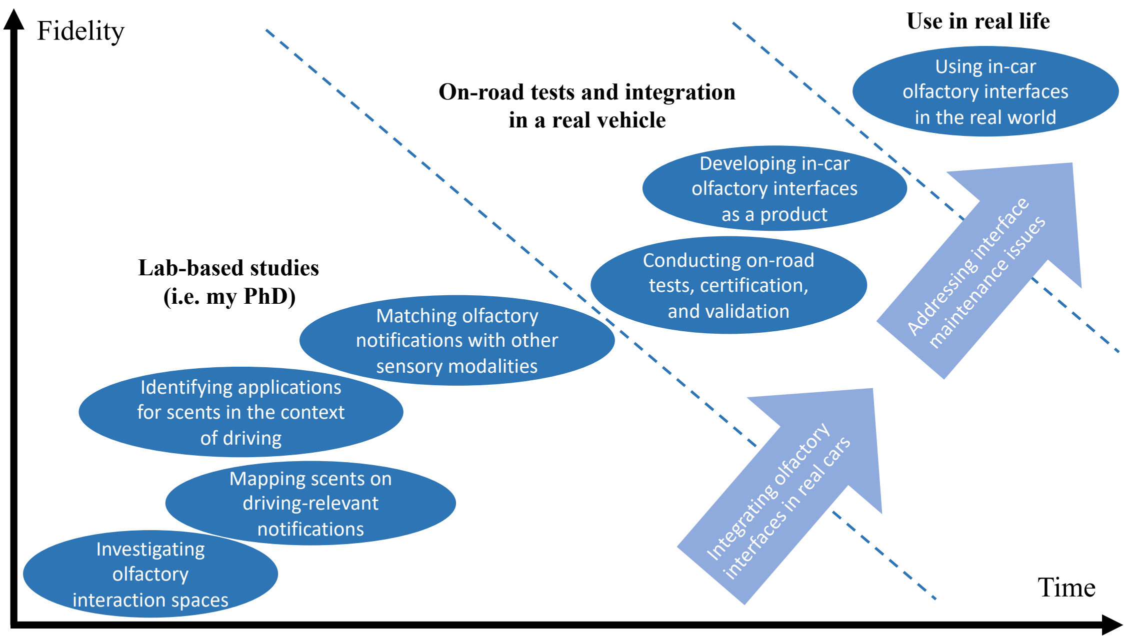


Figure 6.1: The 2D roadmap defining the fidelity of in-car olfactory interfaces and interactions over time that shows how this research could continue beyond my PhD, eventually leading to a product that can be used in real cars and on regular roads.

research finding into a real-life product (including the transitions to on-road tests and the use in real life) are presented below.

This PhD thesis has presented the total of seven lab-based studies tackling different aspects of the in-car olfactory interaction design (e.g. scent-delivery, perception, mapping onto driving-relevant notifications, etc.). Further studies could be conducted to identify new links between driving-relevant notifications and scents and to investigate effects of scents on the driving behaviour and the driver's emotions. Also, as mentioned above, these would need to be conducted with a larger sample size. What this PhD thesis did not make use of is the analysis of physiological measures. In the future, it would be valuable to collect such data as the heartbeat changes, galvanic skin response, breathing patterns, and EEG. Considering that it is possible to overcome the problem of the noise in the signal due to driver's movements, this data might reveal insights that cannot be extracted from the self-report data (especially what it comes to the emotions experienced by the driver). Such measurements might be interesting for both lab-based and on-road studies.

Despite modern driving simulators being quite close to the real driving, the results of this thesis should be validated in the real traffic conditions (i.e. in a real vehicle). This way, it would be possible to understand both how a driver behaves when receiving olfactory notifications in real traffic conditions (i.e. when every situation needs to be treated with great care) and if scents get absorbed by a real vehicle's interior (e.g. whether they soak into the car's interior materials). At this stage, olfactory interfaces would also need to go through extensive testing and certification stages before they can become a part of mass-production vehicles.

Once an olfactory interface has made it to real-road environments as a completed product, it would be very valuable to collect field data. An industry standard for that would be to use marketing research (e.g. conducted by *J.D. Power* [100]), however, the driving log data might be also good in terms of understanding the overall picture (e.g. how often the interface is used, what scents are delivered, how the driving behaviour changes when the interface is in use, etc.).

As an example of an in-car olfactory interaction technique that could be implemented in a real vehicle, I propose the "Passing by a point of interest" notification that has been investigated in Chapter 9. Details of each implementation step of this notification are outlined below.

The lab-based studies conducted in the scope of this PhD thesis suggest that the "Passing by a point of interest" notification can be perceived within 10 seconds and that it is associated with the scent of rose. It might be that a different floral scent (e.g. jasmine) proves itself suitable for this purpose too, or that this scent can be perceived by the driver faster in a setup of a higher fidelity. However, the lab-based findings stated above provide a good starting point of on-road investigations.

To test this notification in real-road environments, it would be first necessary to decide how a scent-delivery system can be installed in a real vehicle. Cars have air compressors, extractors, and fans. However, it is still necessary to decide where to place the scent-delivery nozzle and the jars containing the scents. One could try installing the nozzle on top of an air conditioning vent and the jars inside the glove compartment. While testing such a setup with the "Passing by a point of interest" notification (mediated by the rose scent) in a real car, it would be necessary to investigate the scent perception (i.e. how quickly does the driver perceive it) and lingering (i.e. how long does the scent stay in the car) times. Furthermore, it would be necessary to find out whether this scent gets absorbed by the car's interior materials and how quickly after its use can the new scents be delivered. Finally, there are further practical implications to explore (e.g. driving with an open window, in a convertible, or with a different strong scent present in the vehicle).

Once it is known how to tackle all the above-mentioned challenges, it is necessary to carry out all the required software and hardware tests (including safety checks) and to take care of the certification. In a real-life car, this notification might become useful for navigation systems, i.e. to notify the driver about approaching a particular place they might be interested in (e.g. a sightseeing place during a holiday roadtrip).

Before in-car olfactory interfaces make it to the consumer market, the industry needs to address the relevant maintenance issues. This is important, since consumers are likely to purchase cars with olfactory interfaces if they know that things like refill scent cartridges and device cleaning liquids (if applicable) are widely available for purchase.

Once the "Passing by the point of interest" notification is available in the vehicles' navigation systems, it would be worth collecting data about how people use it in real-life situations. This might involve drivers agreeing to share their driving log data with the manufacturer or participating in marketing research surveys. Such information might become valuable for improving the system further (e.g. assigning a different scent or adjusting the delivery parameters) and developing new features (e.g. using scents to deliver other notifications).

As in-car scent is a very important topic for car manufacturers and new car buyers, it would also be interesting to conduct studies that would provide an understanding of how scents contribute to the creation of luxury experiences and the feeling of premiumness, or perhaps simply to the association with the brand. Considering that currently, olfactory interfaces (i.e. used to modulate the driver's hedonic experiences) are available only in high-end vehicles (e.g. BMW 7-Series, Mercedes-Benz S-Class, and Bentley Mulliner Edition), such a research activity would match the tendencies of the automotive industry and potentially attract more HCI practitioners to this topic.

Only liquid scents (i.e. essential oils) have been explored in the user studies conducted in the scope of this thesis. In the future, it is necessary to explore the use of solid odourants, to see how they contribute to such factors as the stability of the scent intensity and the durability of a scent stimulus (i.e. how long can a scent container be used without a need for a refill). This step is motivated by the fact that solid odourants are already being used in commercially available scent-delivery devices (e.g. *AromaShooter* from the *Aromajoin* company [9], whose scent cartridges can last several months).

It would also be necessary to continue investigating the ways of improving the scent-delivery technology. Breath sensors (e.g. such as *Flexpoint* [63]) could be integrated into the seat belt to synchronise the delivery of the scent with the driver's breathing patterns. Mechanisms for modifying the position of the scent-delivery nozzle (e.g. such as in [191]) could be used to enable automatically adjustable scent-delivery direction (e.g. to account for the driver's head movements). Finally, an exploration of compressors and valves that allow automatic control of air pressure could help enable frequent air pressure changes depending on the distance of the driver's nose to the delivery nozzle.

To conclude, it is important to acknowledge that we still know very little about how people perceive scents in the process of driving and what effects scents have in different driving scenarios. In this scope, it would be especially important to explore ways of dealing with interpersonal and inter-cultural scent perception differences, as well as differences in scent preferences. This step would require further cross-cultural studies and explorations of customisable olfactory interfaces. Furthermore, it would be essential to investigate various scenarios in the scope of autonomous driving, as the technology of autonomous vehicles is expected to become available for unrestricted on-road use within the near future.

This chapter concludes Part I that has provided an overview of this publication-style PhD thesis. Part II of this thesis presents a collection of scientific papers that have been referred to from every chapter of the Overview part.

Part II

Scientific Papers

7 | A Comparison of Scent-Delivery Devices and Their Meaningful Use for In-Car Olfactory Interaction

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Abstract

In the field of Human Computer Interaction (HCI), vision and audition have been the dominating modalities for interacting with users. This is despite the fact that humans are equipped with five basic senses. Because of this, there is a limited number of tools that harness the olfactory system as a communication channel. Recently, several promising scent-delivery devices have been developed, however, there is a lack of guidance on how to use them in a meaningful way for different interactive tasks. In this paper, we propose a three-dimensional framework to compare different scent-delivery devices based on the distance, volume, and speed of the scent-delivery. We discuss how this initial exploration can guide the design of in-car olfactory interfaces beyond previous work on drivers' physical and emotional state.

7.1 Introduction and Background

In recent years, there has been an increased interest in smell-based interaction design and advancements in scent-delivery devices for the end user market [153]. Consequently, the use of olfactory stimulation has gained attention in the automotive context. For example, Yoshida et al. [220] developed a system to fight drowsiness while driving and has demonstrated in a study that releasing specific smells (peppermint, rosemary, eucalyptus and lemon) could extend the wakefulness of the driver. Baron and Kalsher

Characteristics	Scent-Delivery Devices: Manufacturer Specifications *Vortex Activ USB*	*Scentee*	*oPhone DUO*	*Aroma Shooter*
Scent cartridges	4	1	8	6
Scent combinations	16	0	>300000	64
Platforms	Windows	iOS	iOS	Windows/Linux/iOS
Interfaces	USB	Audio Output	Bluetooth	USB

Table 7.1: Comparison of four scent-delivery devices based on their key features.

[15] proved that the scent of lemon increases both alertness and the mood of the driver, while Martin and Cooper [130] showed it to have a positive impact on people's braking performance during a simulated driving task. Moreover, Raudenbush et al. [170] demonstrated an increase in driver's alertness and attentiveness through the release of peppermint and cinnamon. While it was shown that both peppermint and cinnamon reduced frustration and helped participants to focus on the driving task, peppermint was also associated with faster reaction times.

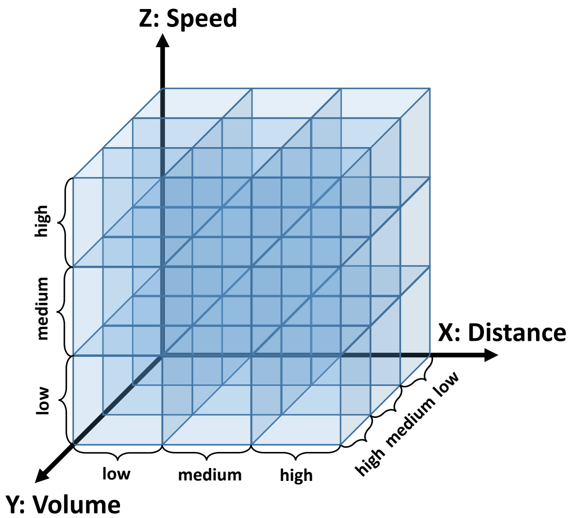

Figure 7.1: Three-dimensional comparison framework used to evaluate the X: Distance, Y: Volume, and Z: Speed of scent-delivery demonstrated by four commercially available devices.

All these previous studies demonstrate the potential to enhance the in-car interaction. However, these findings are mainly focused on the driver and the primary task of driving, but do not go beyond the modulation of their physical (e.g. fighting drowsiness, increasing alertness) and emotional state (e.g. better mood when driving). We aim to extend this emerging field of research and are interested in understanding to what extent smell stimulation can be used to convey specific information in the automotive context. Smell could be used to convey information both to the driver and to the passengers (co-driver and rear seat passengers). Some examples for this could be as follows: (i) the driver receives a scented notification of approaching a point of interest (e.g. gas station), (ii) the co-driver receives a smell for an interesting landmark recommended by Google Maps, (iii) rear-seat passengers receive different scents to enhance the interactive experience when watching movies or playing computer games. Previous work outside the automotive context has shown that smell can enhance specific activities and create new experiences. Brewster et al. [23] demonstrated the use of a smell-based photo tagging tool in their Olfoto prototype, while Bodnar et. al. [19] studied the use of smell as an ambient notification modality. Their results indicate that smell is less disruptive than visual and auditory stimuli. In addition, Herz and Engen [80] pointed out that smell provides more vivid experiences than any other sense, proving itself as a very powerful interaction medium.

Despite all the advancements in this field, we are still left with the question of which parameters of a scent-delivery device we should pay attention to when tackling the challenge of conveying specific information using smell. As all devices are unique, we established a framework for the comparison of all scent-delivery devices, using three dimensions: distance, volume, and speed of scent-delivery (see Figure 7.1). These three dimensions are relevant comparison criteria across devices and provide a starting point for a meaningful design exploration of in-car olfactory interaction. We will first present the comparison framework and then apply it to compare four commercially available scent-delivery devices. We will conclude with the discussion of how to apply these devices to in-car interaction scenarios based on smell.

7.2 Comparison Framework

We compared four commercially available scent-delivery devices: (i) Vortex Activ USB [36], (ii) Scentee [178], (iii) oPhone DUO [156], and (iv) Aroma Shooter [9]. Each device has specific characteristics with respect to the number of scent cartridges, scent combinations, interaction possibilities (interfaces and control software), and platform compatibility issues (Table 7.1).

It is worth noting that this was not a quantitative experimental study (which is planned for future work), but a first qualitative exploration to capture the core characteristics and abilities of the four devices enabling us to map them into the 3D space offered by our framework. The first author of this paper has tested each of the four devices individually in a lab environment and recorded the particular delivery pathways and experiences. These were then discussed with the co-authors. A stopwatch and a ruler were used to record time (used to calculate the speed) and distance. The volume of scent-delivery was estimated based on the perceivability of the delivered scent in different locations around the device. Different scents were used in the testing process. Based on this comparison, we wanted to understand the potential of the explored devices in the context of smell-based in-car interaction scenarios. Our comparison framework is based on 3 dimensions (Figure 7.1):

1. Distance: measured between the device and the furthest point at which the smell is still clearly perceived by the user. Example units to measure are centimetres, metres, etc.

2. Volume: the size of space that a smell can expand in and still be clearly distinguished by the user. Example units to measure are cubic centimetres, cubic metres, etc.

3. Speed: the average speed across the distance dimension. Example units are cm/s, m/s, etc.

As a first step, we mapped each of the four devices onto a two-dimensional space, where two of the three proposed dimensions form the two axes. As we aim to present the framework, rather than precise measurements in this paper, we categorised the devices into three levels of each dimension: low, medium, and high (see Figure 7.2). We made a decision on which level to map each device to, based on our observations, comparing the devices with each other. The nature of such comparison suggests no strict baseline, which still needs to be established in the future.

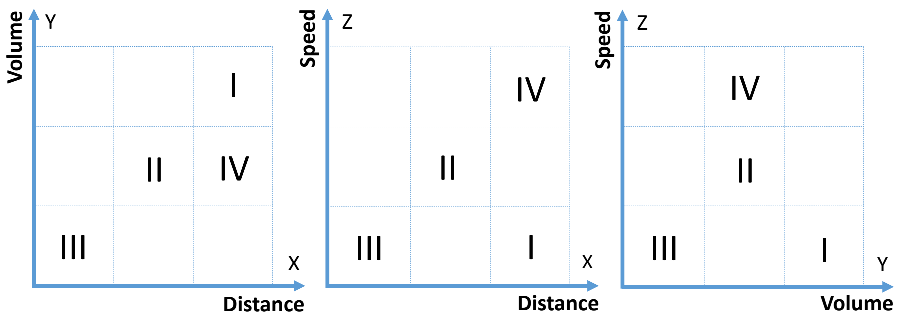

Figure 7.2: Mapping of the devices on the 2D spaces derived from the 3D comparison framework, by comparing the corresponding dimensions of the following four devices to each other: (I) Vortex Activ USB, (II) Scentee, (III) oPhone DUO, (IV) Aroma Shooter.

Figure 7.3: Scent-delivery devices (from left to right): Vortex Activ USB, Scentee on an iPad, oPhone DUO, Aroma Shooter.

The benefit of mapping the devices on a 2D space before projecting them onto our 3D framework are two-fold. First, two dimensions allow an easy evaluation of a new scent-delivery device, which can then be further projected into a 3D space. Second, the 2D spaces are useful to explore different interaction scenarios, where one of the dimensions might be irrelevant, and hence, an HCI designer only needs to work on an ad-hoc and simplified version for the comparison. For example, speed might not be relevant, when the scent-delivery device is needed for non-urgent notifications (e.g. approaching the destination, when the journey is very long).

7.2.1 Device I: Vortex Activ USB

Vortex Activ USB (Figure 7.3) is a scent dispensing system developed by DaleAir that allows the delivery of four individual scents by exposing their cartridges to four individually controlled fans. Over 300 different scent cartridges are available for purchase. Each scent cartridge is located in a separate tube inside the device. Once the driver is installed (automatically under MS Windows), this device can be considered a plug-and-play USB controller. Four scents can be released either individually or in combination, by turning the fans on or off in the graphical user interface (no further features are available to control the intensity or duration). The smell released by this device was perceived 5m away from the output in any direction after one minute, and we assigned the following dimensions: distance - high, volume - high, speed - low.

7.2.2 Device II: Scentee

Scentee is a scent-based extension for iOS devices. It comes in the form of a scent cartridge that needs to be charged and then plugged into the audio output of an iPhone/iPad. A variety of scent cartridges can be purchased, but only one at a time can be used. The scent extension is controlled by the Scentee app, allowing the user to manipulate the duration and the interval of the scent delivery (Figure 7.3). Scentee pushes the odorized air out of the device in the shape of a 10-15cm long misted cloud. This increases the detectability of the released scent which is further indicated by a blinking LED light. However, the user needs to hold their nose close to the release point in order to perceive the scent. Using Scentee, the odorized air reaches the user's nose approximately 2 seconds after the release. We assigned the following dimensions: distance - medium, volume - medium, speed - medium.

7.2.3 Device III: oPhone DUO

oPhone DUO by Vapor Communications comes with eight scent cartridges, and is controlled by the oNotes iOS app. The interface of the oPhone requires the user to move the nose closer to the scent releasing unit through the design of two tubes (see Figure 7.3), each containing four different scents, which can be further mixed. The scent can be perceived at a distance of not more than 10cm, in approximately 5 seconds. We assigned it the following dimensions: distance - low, volume - low, speed - low.

7.2.4 Device IV: Aroma Shooter

The Aroma Shooter (Figure 7.3) was developed by Aromajoin and gives space for 6 scent cartridges. The device works across platforms and is connected through USB. This device delivers a directional airflow, allowing precise transmission of scent at a distance of up to 30cm after 3 seconds. The delivered scent can be easily detected by a person at that distance, however if the nose is displaced or a person is moving their head, the scent-delivery could be missed. This can be compensated for by a longer delivery time, which can be set in milliseconds using the API. The developer can also choose which of the 6 scents to deliver, to what extent the air blower is activated, and the desired intensity of the scent. We assigned the following dimensions: distance - high, volume - medium, speed - high.

7.3 Discussion for the Automotive Context

In this paper, we propose a comparison framework based on the exploration of four devices. We compared the devices with respect to distance, volume, and speed of the scent-delivery in the first step. We are aware that there are many more features that could have been considered and included in the comparison (e.g. size of the device, type of the actuators and created airflow, physical and chemical properties of the odorants). However, from an interaction design perspective, distance, volume, and speed form a good starting point, as they can be linked to specific tasks, scenarios, and interaction goals. Below we discuss all the investigated devices in relation to various in-car interaction scenarios based on smell.

Due to its directional stimulation, the Aroma Shooter is very suitable for precise scent delivery and quick reaction times. Such a mechanism could become very beneficial for the interaction of the driver with the car, extending existing audio-visual modalities by smell, through a crossmodal design approach, such as described by Pfleging et al. [164]. Alternatively it could be applied to deliver a feedforward stimulus for driving-take-over tasks in (semi)autonomous driving, currently limited to audio input such as investigated by Koo et al. [114].

The user can easily interact with Scentee while on the move. This device is suitable for mobile applications, where it is desirable to keep the scent-delivery within a personal space and not to disturb surrounding people. Hence, it makes it suitable for the co-driver, who can take the eyes away from the road and interact with a mobile device. Scentee could be used to receive notifications from social media or to indicate interesting landmarks in the environment (e.g. retrieved from Tripadvisor). This device could also be used for the stimulation of the co-driver to modulate positive judgment of driver's performance when using a parking assistant, extending previous work in this field carried out by Trösterer et al. [197].

Similarly to Scentee, oPhone DUO is suitable for the delivery of less urgent information, but is less portable and currently only useful for desktop applications. It could potentially be integrated into the rear seat of the car. We see its application in the delivery of scents as rewards for children playing games in the back of a car, extending the scenarios proposed by Sundström et al. [195]. The benefit of the oPhone DUO is its high number of scent combinations, which opens opportunities for a broader design spectrum and more interactive use cases. It is also important to mention that a new smaller version of the oPhone, for the car context, has been announced [199]. This device may have applications beyond the rear seat scenarios.

Finally, the Vortex Activ USB device is suitable for ambient uses, such as influencing the mood and emotions. Its application for interaction tasks relies on several constraints. The separation of scent cartridges proved itself not suitable for quick changes between different smells. Compared to other devices, Vortex Activ USB also offers a less sophisticated control over the delivery parameters, but it is useful for ambient notification, such as suggested by Warnock et al. [208]. This device could be applied to give ambient warnings ahead of time (e.g. for upcoming traffic jams), or to send notifications relevant to all the people seated inside the car (e.g. to inform about the remaining traveling time retrieved from the navigation system).

7.4 Conclusions and Directions for Future Work

We presented four different scent-delivery devices currently available on the market, with respect to their scent-delivery potential based on distance, volume, and speed. In Figure 7.4 we mapped the explored devices based on the chosen parameters, but a further investigation to grasp the differences between olfactory stimulation opportunities is still needed.

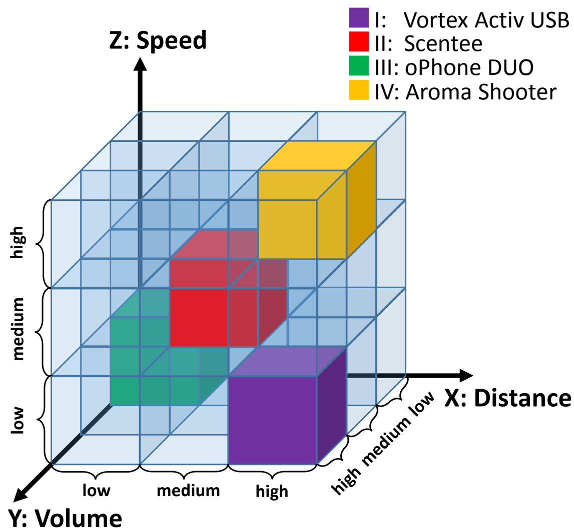

Figure 7.4: A 3D evaluation framework with four scent-delivery devices mapped onto it.

In the scope of the in-car interface design, scents could be released as alarming or rewarding stimuli, enhance the quality of driving experience and the pleasure of driving, or provide added value for the in-car infotainment. Here it will be crucial to explore controllability and extendibility of the sensations, as well as types of aromas (liquid or solid). These parameters will offer new dimensions for the comparison of such devices. For the future work, it is essential to systematically explore the various devices and how they can be useful and meaningful for in-car interactions based on smell. In particular, we plan to investigate the use of the Aroma Shooter for car-driver interaction, Scentee for the infotainment of the co-driver, and oPhone for rear seat applications. Vortex Activ USB could be applied for non-urgent notifications of the driver and/or passengers. Moreover, another big challenge is to not just deliver, but also to control the scent-delivery, as well as remove the smell from an enclosed space, such as the interior of a car. Weiss et al. [211] proposed "olfactory white", which might provide a way towards increasing the meaningful use and application of smell in the automotive context.

8 | OSpace: Towards a Systematic Exploration of Olfactory Interaction Spaces

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Abstract

When designing olfactory interfaces, HCI researchers and practitioners have to carefully consider a number of issues related to the scent delivery, detection, and lingering. These are just a few of the problems to deal with. We present OSpace - an approach for designing, building, and exploring an olfactory interaction space. Our paper is the first to explore in detail not only the scent-delivery parameters but also the air extraction issues. We conducted a user study to demonstrate how the scent detection/lingering times can be acquired under different air extraction conditions, and how the impact of scent type, dilution, and intensity can be investigated. Results show that with our setup, the scents can be perceived by the user within ten seconds and it takes less than nine seconds for the scents to disappear, both when the extraction is on and off. We discuss the practical application of these results for HCI.

8.1 Introduction

The field of olfactory interaction has fascinated researchers and engineers for over a century, however, only recently it gained new momentum through advances in our understanding of the human olfactory system [62, 39], insights into olfactory experiences [153], approaches to digital smell interfaces [169], and the design of scent-delivery devices [49]. While guidelines for audio-visual, and increasingly for haptic [59, 182] interaction design have been established, olfaction often leaves designers clueless about what scent-delivery approach to use, how to build a delivery device, how to equip an interaction space and to configure the equipment. Without guidance on those questions, we don't know if the olfactory interface is designed appropriately for the intended use.

Recent proposals on the design of an olfactory interaction space include a vortex based scent-delivery setup [219], an exhibition booth enhanced by smell [8], an artwork with an interactive olfactory interface [118], and a room with "dynamic olfactory zones" [74]. Moreover, there is a variety of scent-delivery devices that have been built as one-off applications for gaming [142, 98, 1], ambient notifications [19, 208], simulated driving [66, 220], and virtual reality [134, 34]. Nevertheless, all of these research activities are linked to specific applications, the scent-delivery parameters (e.g. distance, intensity, delivery time) are ad hoc, and the scent cross-contamination and lingering issues are often addressed as limitations without rigorous solutions.

We synthesised insights from prior research and determined specific design parameters for a scent-delivery device and an olfactory interaction space. In summary, the contributions of our paper are:

i. A novel setup enabling scent detection time of 10s and scent lingering time of <9s for the distance of 68cm from the device output to the user's nose.

ii. A scent-delivery device allowing the control of the type and dilution of scents, as well as the air pressure these scents can be delivered with, and also the delivery time.

iii. A detailed exploration of scent-delivery and air extraction parameters in the scope of olfactory interaction spaces supported by a user study.

iv. A non-invasive air extraction method for desktop olfactory interaction applications.

v. A novel set of recommendations (i.e. OSpace) to design and build a scent-delivery device and an olfactory interaction room.

vi. Practical application suggestions of OSpace in HCI.

Based on the research presented in this paper, we now know that OSpace can help to define all the parameters addressed above (in relation to the intended setup) and to create a well-controlled environment for studies on olfactory interaction.

8.2 RELATED WORK

Here we review prior related work on olfactory interaction, covering scent-delivery device proposals and their applications, explorations of scent-delivery parameters, and the design of olfactory spaces.

8.2.1 Scent-Delivery Devices

There are a number of commercially available scent-delivery devices that HCI researchers have access to today [49]. Multiple examples of their successful integration into interactive olfactory systems have been presented. For example, Brewster et al. [23] demonstrated the use of a smell-based photo tagging tool in their Olfoto prototype, while Bodnar et. al. [19] and Warnock et al. [208] studied the use of smell as an ambient notification modality. Nevertheless, the capabilities of such devices (e.g. choice of scents, delivery distance, and resistance against cross-contamination) are rather limited, which also restricts the range of their applications. Moreover, those devices are often expensive [107, 79], which motivated many researchers to design and build their own prototypes.

Lundström et al. [126] proposed a very good "do-it-yourself" approach of building an inexpensive scent-delivery device, which is excellent for temporally-precise olfactory studies, but has little applicability in HCI due to the requirement of wearing a nosepiece (a very invasive interface). Moreover, Herrera and McMahan [79] proposed a method to build a simple and inexpensive scent-delivery device that could be easily applied for VR studies and other immersive applications. However, this prototype only contains one scent. McGookin and Escobar [131] pushed this idea further and came up with an approach for creating an open-source scent-delivery device that contains multiple scent cartridges. The benefit of their solution is not only a proposal of a reliable, cheap, easy-to-build mechanism but also a suggestion of using this device in a broad range of use cases, including both static (e.g. desktop) and mobile applications. However, no user studies have supported these claims and hence only provide limited guidance beyond this one-off implementation.

There is a number of prototypes capable of delivering multiple scents, the efficiency of which has been demonstrated in practice. Ando [8, 7] presented a device allowing to rapidly switch between multiple scents. By containing six different scent cartridges very close to each other, he was able to instantly redirect the flow of the compressed air from one cartridge to another. However, he did not explain how to eliminate the cross-contamination problem inside the device. Nakamoto et al. [142] proposed a mechanism with clearly separated scent channels. The advantage of their setup was the option of choosing which scents the user wants to mix. This function was demonstrated through a cooking game. Due to individual scent channels, the mixing process could be easily controlled and was going on without unwanted contamination. Although this prior work tackles one challenge in olfactory interaction, it does not provide insights into how far the scent can travel and what the constraints are in terms of scent lingering artefacts.

Another example of smell enhanced gaming was proposed by Abid et al. [1], who built a heat based scent-delivery device and presented it in an immersive 3D shooter game, where the users could smell several kinds of smoke. This is a very original approach, but due to the application of the laser, which is burning solid odorants, the extendibility of this use case to further scenarios is limited.

When it comes to wearable devices, their applications can be found in the fields of augmented and virtual reality. Narumi et al. [143] created a MetaCookie prototype for gustatory applications enhanced by smell, which gave the users an opportunity to taste different flavours from a regular sugar cookie by just changing the scents emitted during the interaction process. Covarrubias et al. [34] have proposed a system to apply scents as a reward stimulus in rehabilitation exercises. Both Narumi et al. and Covarrubias et al. have suggested attaching the output of the scent-delivery device to the VR/AR headset, while Mochizuki et al. [134] came up with an idea of placing it on the users' hand to help them explore the scents of the virtual objects they are grasping. Despite many technical details related to the functionality of the entire system presented in these papers, we still know very little about how to decide what scent dilution level shall we use for wearable devices, how far from user's nose do we need to place the output, what air pressure shall we choose, etc.

Taken together, the olfactory design space gained lots of attention but is diverse and scattered in its approaches. Below we review in more detail specific scent-delivery parameters.

8.2.2 Parameters for Scent-Delivery

Yanagida et al. [219], for instance, explored different interaction distances using an "air cannon" approach. While this underlines the relevance of the delivery distance as a design parameter in olfactory stimulation, the authors did not provide any justification for setting it to 120cm. Abid et al. [1] proposed placing the output 70cm away from the participant for their heat-based scent-delivery prototype, but also did not explain the pretests conducted to identify it.

As well as the distance, the scent dilution is a relevant design parameter and can influence choices with respect to the intensity and frequency of olfactory stimulation. Seigneuric et al. [184] studied crossmodal associations between olfaction and vision using twelve different scents (apricot, bacon, banana, coffee, strawberry, melon, orange, fish, lavender, rose, soap, and vanilla) with different dilutions. While the variety of explored scents is impressive, the rationale behind the choice of the dilution levels is not transparent.

Another parameter to consider is the timing of the scent-delivery. Noguchi et al. [150] proposed pulse ejection of a scent in six timings (0s, 0.2s, 0.4s, 0.6s, 0.9s, and 1.3s) after the beginning of the moment of breathing in. This approach requires precise detection of the moment when the user inhales. Moreover, the scent-delivery distance studied here (10cm) is rather short compared to the majority of mid-air applications. Also, it is not clear, how the timings change depending on the scent. In another proposal, Yoshida et al. [220] discovered the alerting and awakening effect of scent when presented at 30s intervals, but the specifics of the interval design in relation to the scent dilution (e.g. can the interval be reduced with higher scent dilution) remain unclear.

Various prior studies have investigated the use of pressurised air with limited insights on the pressure values or their selection [8, 126, 220]. For example, Lundström et al. [126] used a compressor capable of maintaining the pressure of 2 bars, while Yoshida et al. [220] applied a compressor without mentioning what pressure it was set to. Ando et al. [8] have used an air-blower which was creating a pressure inside a cube located on top of it. A small opening on top of the cube helped to create an airflow, which would transmit the scent to the user’s nose. No pressure levels are known from this approach either. Nevertheless, the pressure values are very important as they affect scent intensity.

Finally, there also seems to be no standard of how to approach the problem of scent lingering in a room after the delivery. Brewster et al. [23] reported having conducted an experiment in a "well-ventilated room", but Bodnar et al. [19] said they "limited the amount of scent", without mentioning the details. Lai [118] made use of the building’s centralised ventilation system, acknowledging that an individual ventilation system would have been a better solution.

Today, researchers seem to be using their best guess for the ventilation problem, but we remain uninformed about their actual effect on the olfactory stimulation and perception, which is particularly relevant when exploring olfactory interfaces in enclosed spaces (e.g. virtual environments, desktop gaming, multimedia, in-car interaction).

8.2.3 Olfactory Interaction Spaces

Multiple researchers have tackled the problem of designing for olfactory interaction in physical spaces, areas such as museum rooms and exhibition halls, or for an automotive (i.e. in-car) context.

An olfactory interaction setup without a strict application context was proposed by Yanagida et al. [219], whose device allowed multiple users seated only 50cm away from each other to receive their own stimuli from the same "air cannon". This was possible due to the vortex ring technology and a very small amount of scent being injected into the vortex.

In the context of exhibition and museum rooms, Ando et al. [8] have proposed a setup in which visitors were interacting with virtual representations of antique objects being able to not only touch but also smell them by means of a scent-delivery device equipped with a piezoelectric blower. Moreover, Lai [118] presented a museum room in which scent-delivery devices motivated the users to explore a piece of modern art. Finally, Haque [74] described an olfactory interaction space based on "dynamic olfactory zones and boundaries" floating through the room and engaging visitors to interact with different scents.

In the automotive context, Funato et al. [66], and Yoshida et al. [220] presented complete solutions of an olfactory interaction space in the context of simulated driving. Funato et al. used the "air cannon" to deliver the scent to the driver, while Yoshida et al. applied scent chambers connected to an air compressor. Both of these research activities have targeted the problem of keeping drowsy drivers awake.

Even though these are some good examples of how to build an olfactory interaction space, multiple issues (e.g. scent-delivery time, room ventilation) are not very well discussed. This lack of a standardised framework of olfactory interaction is slowing down the advancements in this field, not allowing researchers to verify the methods applied in all the different techniques. We are making a first step towards filling this gap and propose a step-by-step approach to designing, building, and exploring an interactive olfactory environment.

8.3 DESIGNING AN OSPACE

We demonstrate how the parameters of this setup can be carefully investigated to understand the ways of the meaningful application of the OSpace in HCI.

8.3.1 Scent-Delivery Device

Based on the problems encountered in the commercially available scent-delivery devices [49] and the knowledge collected from multiple existing scent-delivery prototypes (e.g. [126, 219, 150, 142]), we extracted the following device characteristics:

i. scent blowing distance of ≥50cm (to allow some space for hand movements, like in [219, 1]).

ii. well isolated channels for each scent (as per [126, 142]).

iii. control of the blowing time and scent intensity [8, 7].

iv. delivery of multiple scents to the user in a single session and replacement of the scents between the sessions [126, 7].

v. option of rapidly switching between the presented scents (the timing of which we decided to explore in our experiment since insufficient information on this topic is available).

To comply with the distance requirement, we decided to adapt the approaches of Yoshida et al. [220] and Ando et al. [8, 7]. Both of them used pressurised air to deliver a scent to the user. To ensure a satisfactory level of air pressure (up to 1.5 bars [126]), and to comply with health and safety regulations, we discarded the idea of an air compressor, and installed an air tank (see Figure 8.1.1), which can be manually controlled by means of a manometer connected to it (see Figure 8.1.2).

To make sure we have separated and well-isolated channels for each scent, the clean and the saturated air are delivered through individual plastic tubes (4mm in diameter for the scents and 6mm for the compressed air source). The clean air tube is connected to the air tank (see Figure 8.1.3). To split the clean air channel into six separate scent channels (one tube per scent), we used two Norgren Pneufit C C00D30604 manifold unions with two 6mm outlets and three 4mm branches each. Connecting them in the way depicted in Figure 8.1.4, we could create six well-isolated scent channels. Such a

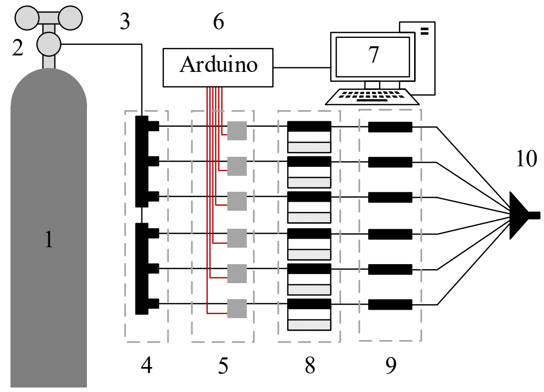

Figure 8.1: Structure of the scent-delivery device: 1 - air tank, 2 - manometer, 3 - plastic tube, 4 - two manifolds, 5 - six electric valves, 6 - Arduino board, 7 - PC, 8 - six jars containing the scents, 9 - six one-way valves, 10 - output nozzle.

setup is scalable and can be easily extended towards further scent channels (e.g. adding just one more manifold would give another three channels).

To be able to control the blowing time, we let each scent channel go through an electric valve (see Figure 8.1.5). Each valve (SMC Compact Direct Operated 2 Port Solenoid Valve) was connected to an Arduino board (see Figure 8.1.6), which we controlled through our software (written in Java) running on a Windows PC (see Figure 8.1.7). Using Arduino and electric valves, we were able to rapidly (valve response time of ~30ms) trigger the scents delivery, and to adjust its duration. By manually operating the manometer, we could control the air pressure (used to vary the scent intensity).

To enable the delivery of multiple scents to the user in a single session, we connected each of the six air channels to one of the six glass jars (see Figure 8.1.8), which are suitable for both liquid and solid scents. In our setup, we decided to explore liquid scents, because they are easy to obtain (in the form of essential oils) and straightforward to use for the first prototype. The glass jars (see Figure 8.2) do not absorb scents and can be closed tightly (using ethylene-vinyl acetate sealing) to avoid leakage. Jars (including their metal covers) can be easily washed (in hot water mixed with sodium bicarbonate) and filled with a new scent, when necessary. This ensures the requirement of replacing the scents between the sessions is met. Extensibility can be achieved by installing an additional layer of jars into the scent-delivery device (see Figure 8.2).

To eliminate uncontrolled flow of scents from the jars to the output of the device (see Figure 8.1.10), we directed each scent channel into a one-way valve (six Norgren T51P0004 4mm Inline Non-Return Valves, see Figure 8.1.9), which would let the air go through only above a certain pressure.

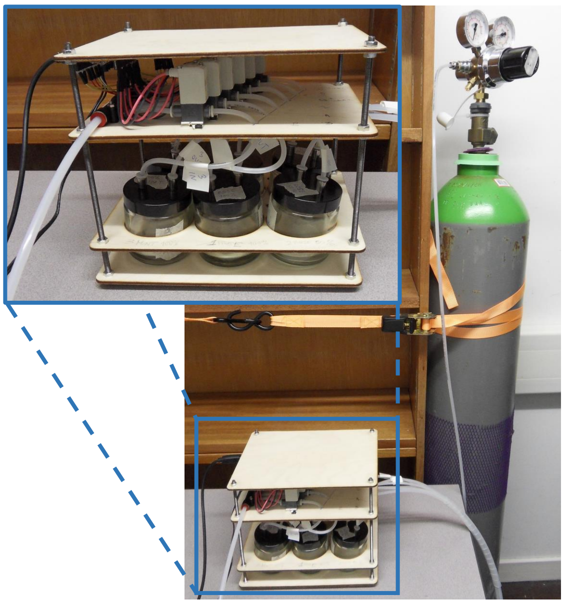

Figure 8.2: Scent-delivery device (20.5×16.5×22.5cm) with the air tank (150.0×25.0×25.0cm).

Finally, all six scent channels are connected to the 3D printed output nozzle (see Figure 8.1.10). The nozzle collects six scent tubes together and has an extended end (20mm in length, see Figure 8.3), which helps to stabilise the airflow and direct it towards the user's nose.

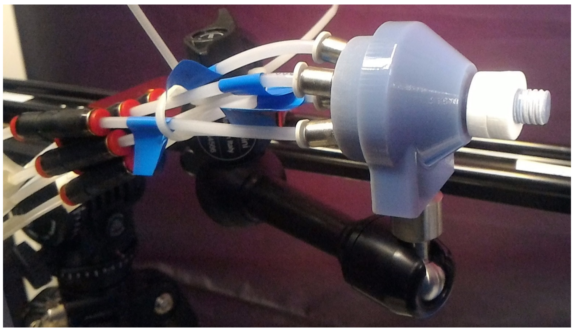

Figure 8.3: The 3D printed output nozzle of the scent-delivery device connecting all six scent channels into one output tube (20mm long), directing the airflow. The end of the nozzle is designed in the way that it can be easily connected to any ≤8mm thick plate with a hole of 9mm in diameter in it. It can also be mounted on a tripod.

8.3.2 Olfactory Interaction Room

If we decide to release scents into a room, we also need to make sure they disappear quickly, to avoid scent habituation, and to be able to release new scents without the problem of scent mixing. For this purpose, a dedicated room design and a setup are

Figure 8.4: Olfactory interaction space: clean room wrapped into a black water repellent fabric with an air extractor E1 and the clean air blower on the top, as well as a scent-delivery device and an air extractor E2 in the bottom-left corner (outside the clean room).

necessary to facilitate research of olfactory interaction. Based on consequences of using olfactory interfaces addressed in [23, 19, 118], we defined a set of requirements. The olfactory interaction room needs to be

i. composed out of materials that do not absorb scents.

ii. independent from the building's centralised ventilation system to enable direct control over the air in the room.

Here we define the specific setup and configurations for the olfactory interaction room we designed and built. We used a former softwall clean room construction (from Connect 2 Cleanrooms Ltd.). Due to the size of this room (H= 2.1m, W= 1.3m, L= 2m), it has the potential to be used for multiple applications (e.g. multisensory cinema for 1-2 users, gaming, driving simulator, or even VR use cases). In this paper, we present a setup that is purpose-made to explore the olfactory interaction parameters (see Figure 8.5), but it can be further extended to any of the applications listed above.

We have removed the clean room's original plastic walls (because of their intense smell) and exchanged them with the black odourless water-repellent fabric (made of polyester, not absorbing scents, see Figure 8.4).

We have equipped our olfactory interaction room with two air extractors (see Figure 8.5): E1 - Torin-Sifan DDC270-270 (550W, 50Hz, 69dB) extractor mounted on the ceiling of the room and E2 - Vent-Axia ACM200 B 17108010C (109W, 50Hz, 38dB) in-line extractor connected through a pipe to a ventilation grid in the surface of the table inside the olfactory room. With such a setup, we were not relying on the building's centralised ventilation system. To motivate installation of two air extractors, it is important to mention that we initially conducted a prestudy 1 with only the extractor E1. In prestudy 1, we carried out a between participants exploration with 23 subjects, with a mean age of 31 years (SD= 6.1 years, 8 females), where 12 participants measured the scent lingering time with the extraction off and 11 with the extraction on. The results of prestudy 1 showed no immediate impact of the extraction on the scent lingering time. We hypothesised that it might have been due to extractor E1 being located too far away from the scent-delivery output and decided to install an additional extractor E2, which would be much closer both to the output and to the participants' nose. Another issue that caused a lot of variability in the data collected in prestudy 1, were the head movements of the participants. For this reason, in the improved setup, we decided to install a chinrest, which would help us fix the position of the head and the nose and keep it constant across trials and subjects. Such an approach has already been applied in olfactory studies [150].

The clean room also came with a clean air blower (Envirco Corporation Mac 10 XL), which is equipped with a high-efficiency particulate air (HEPA) UL900 filter (99.99% efficient at 0.3 Micron), capable of filtering the odour molecules. We have left the exploration of this device for the future work.

The air tank and the scent-delivery device were located outside the olfactory room, and only the plastic tubes of six scent channels were going into the room (Figure 8.5).

8.3.3 Positioning the Output of the Scent-Delivery Device

When deciding on the correct position of the scent-delivery output within the room, it is essential to make sure that

i. the output nozzle does not interfere with user's movements.

ii. the device is capable of sending the scent over the necessary distance from the nozzle to the user's nose.

As we plan to investigate olfactory interaction in a driving simulator, we decided to locate the output nozzle just behind the steering wheel of a driving simulator device (possible occlusions would be prevented applying a distance sensor).

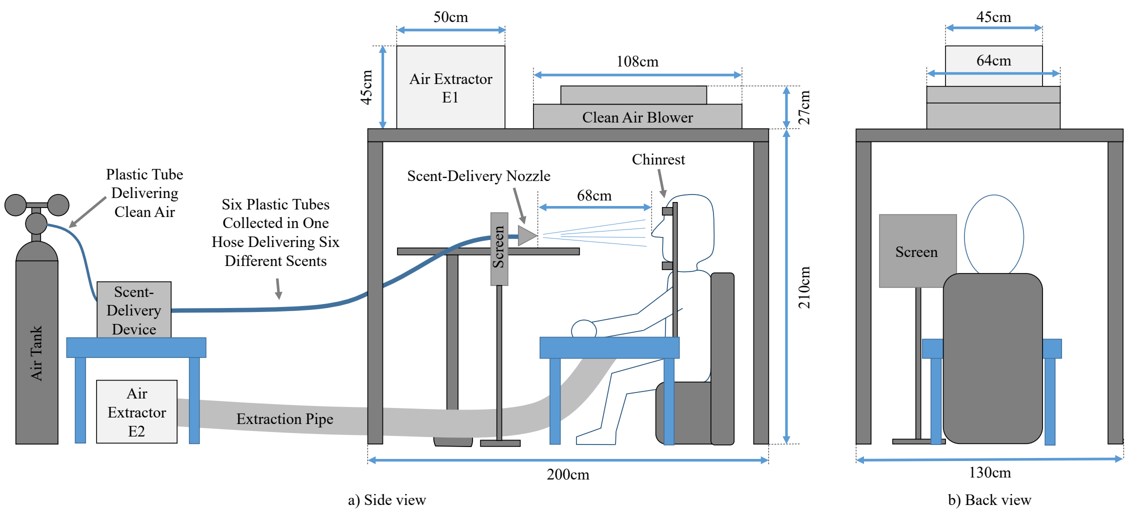

Figure 8.5: Side and back views of the olfactory interaction space with the scent-delivery device connected to an air tank, delivering a scent to the user seated inside the olfactory interaction room. User's head is fixed on a chinrest, and the delivered scent is extracted through a pipe connected under the table. The user is rating the investigated parameters by answering questions on the computer screen. There is an additional air extractor on the top of the room to refresh the air between the interaction sessions. A clean air blower can be applied to propel filtered air in from the outside (an option to explore in the future work).

To identify the distance we will need to deal with in such a use case, we conducted a prestudy 2 with 15 participants, with a mean age of 32 years (SD= 5.2 years, 3 females). In prestudy 2, participants were instructed to adjust the seat of the driving simulator the way they feel comfortable to perform the driving task. When the position of the seat was fixed, we measured the distance from the nozzle to participants' face using the ultrasound distance sensor. The shortest distance recorded in prestudy 2 was 43cm, but the longest 63cm (M= 56cm, SD= 5.15cm). To make sure that our scent-delivery device works in this distance range, we took the distance of 68cm (MAX + SD) for our OSpace exploration study.

8.3.4 Summary

Following the OSpace recommendations, we have built an exemplary olfactory interaction space. The main component of our setup is the scent-delivery device capable of releasing different scents (with different dilution levels), for a customisable time, under various air pressure conditions. We created an olfactory interaction room composed of materials that do not absorb scents (metal, plastic, and water repellent fabric made of polyester). This room is equipped with two extraction fans to help remove the scents released by the device. To explore the scent-delivery and air extraction parameters of our olfactory interaction space, we have also installed a chinrest, which helps to keep the conditions consistent across trials and participants. We summarise all these components in Figure 8.5. In the next section, we present the user study conducted to investigate the above-mentioned parameters. In particular, we focus on the scent detection and lingering time, as well as the hedonic perception of scents (i.e. scent liking, comfort, and intensity).

8.4 THE STUDY

In this section, we present the user study performed to explore the olfactory interaction space designed and built following the requirements set out in the OSpace design phase.

8.4.1 Study Design

We conducted a mixed model study, in which we explored three different air pressure levels (0.5, 1.0, and 1.5 bars [126]) as a between participants condition, but scents (lemon, peppermint, rose), dilution levels (100% pure essential oil, 50% dilution with water), and air extraction (on/off) as within participants conditions. The distance of the scent-delivery (from the output to the participants' nose) was constant: 68cm.

Our dependent variables were scent detection time (when do the participants start perceiving the scent after it has been released) and scent lingering time (when do they stop perceiving the released scent) recorded by a button press. Further dependent variables include the scent liking, comfort, and intensity values (self-report measurements, 7-Point Likert scale).

8.4.2 Choice and Presentation of Scents

The scents of lemon and peppermint have been employed in a number of olfactory studies [97, 15, 130, 170, 220], which supported our choice to apply them. Since both lemon and peppermint are highly arousing, we decided to also include one soothing scent - rose, which has been referred to as relaxing in the related work (see [89]). Other applications (e.g. multisensory cinema) might involve some other scents [196].

For the user study, we filled each jar of our scent-delivery device with 6g of the corresponding 100% pure essential oil, or with 3g of the essential oil and 3g of water to create a 50% dilution of a scent. We used the *"miaroma"* 100% pure essential oils from Holland & Barrett International Limited and tap water for the dilutions.

8.4.3 Participants

A total of 21 participants, with a mean age of 32 years (SD= 7.8, 6 females) volunteered for this study. Participants have reported having no olfactory dysfunctions or adverse reactions to strong smells (e.g. migraines), not suffering from any respiratory problems (e.g. asthma), or from the flu, and not being pregnant. There were seven participants for each between-subjects condition mentioned previously. We have invited participants from different cultures. The countries the participants came from include France, Italy, Spain, Greece, Palestine, Uganda, Vietnam, Japan, Mexico, USA, and UK.

8.4.4 Procedure and Method

Upon arrival, participants were given the information sheet, an explanation of the procedure, and a consent form to sign (the procedure and method of this study were approved by the ethics committee of the University of Sussex).

We then asked the participants to take a seat on the chair inside the olfactory interaction room and to follow the instructions on the screen (17” screen, 60Hz refresh rate). They were instructed to interact with the graphical interface shown on the screen using a mouse (see Figure 8.6). During the experiment, participants wore headphones playing pink noise to cancel the sounds created by the scent-delivery and to avoid potential bias. Below we present different blocks of the study, separated by a break of 30s.

8.4.4.1 Scent Familiarisation Phase

The following message was shown on the screen at the beginning of this first step: *"Welcome to the experiment! In the first 6 trials, you will have a chance to familiarise yourself with all 6 scent stimuli we use in this experiment! Please place your head on the chinrest!"*. After the participant had clicked the *"OK, I’m ready!"* button, the following message appeared on the screen: *"Press ’Start’, when you detect the scent!"* Scent delivery started five seconds after this message appeared on the screen. We delivered the scent to the participants for five seconds in each trial, which is a sufficient time frame to cover at least one in- and one exhalation (according to [155]). As soon as the participant clicked the *"Start"* button, a *"Press ’Stop’, when you stop perceiving the scent!"* message

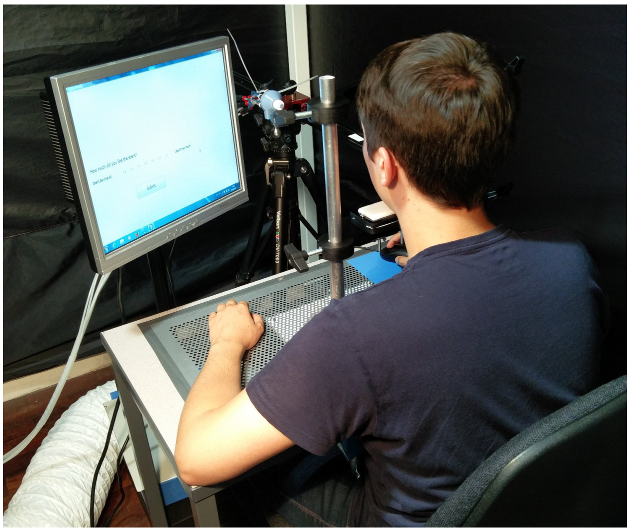

Figure 8.6: A participant inside the olfactory interaction space designed following the OSpace recommendations, to study the scent-delivery and air extraction parameters. During the study, the participants also wore noise-cancelling headphones (not depicted in this figure).

appeared together with the *"Stop"* button. The following three questions were shown to the participant after the press of the *"Stop"* button: *(1) "How much did you like the scent? (1= "Did not like it at all"; 7= "Liked it very much")"; (2) "How would you rate your comfort with this scent? (1= "Very uncomfortable"; 7= "Very comfortable")"; (3) "How would you rate the intensity of this scent? (1= "Not intense at all"; 7= "Very intense")"*.

Participants could answer these questions by clicking the corresponding value (1-7) on the scale and confirming their response by pressing the *"Submit"* button. The six trials of the familiarisation phase included stimulation by all three scents (lemon, peppermint, rose) with two dilutions levels (100% pure essential oil, 50% dilution with water) per each scent. The order of the scents and dilution levels were randomised across the participants based on the Latin square. Air extraction was off in this step of the study. Since the aim of this part was to help the participants compare the scents with each other for more objective scent liking, comfort, and intensity ratings in the remaining part of the study, we did not analyse the data collected in this phase.

8.4.4.2 Explicit Scent Detection and Lingering Time Measurements

In this step of the study, the participants were shown exactly the same instructions as in the familiarisation phase, but this time their button press activities and self-report data were recorded. Participants performed this step twice (once with extractor E2 on, and once with extractor E2 off). Both the order of the scents/dilutions and the air extraction conditions were randomised based on the Latin square. Just like in the previous step, scent delivery started with a 5s delay after the instructions of each trial were displayed.

8.4.4.3 Implicit Scent Lingering Time Measurements

This step of the study started in a similar manner as the two described above, with the difference that clicking the *"Start"* button triggered the appearance of the following question: *"How would you rate the intensity of this scent right now? (1= "Not intense at all"; 7= "Very intense")"*. This question appeared on the screen every 10s (after 0, 10, 20, and 30s), replacing the *"Stop"* button and giving participants a chance to implicitly report the lingering time of the scent. There was a *"Please wait"* message shown between the intensity questionnaires. We introduced this step to help the participants realise when is the scent really not perceivable anymore.

From the participants' feedback collected in prestudy 1, we understood that it was not easy to understand when a scent is really gone because some intense scents were leaving an arousing feeling in the nose, despite not being present anymore. By sampling the lingering time in the chunks of 10s and asking to rate the scent intensity by the end of each chunk, we could see how the intensity drops over the time. Participants were instructed to give the score of 1, if they did not perceive the scent anymore. This step was also performed twice (once with extractor E2 on, and once with extractor E2 off). Both the order of the scents/dilutions and the air extraction conditions were randomised based on the Latin square.

We concluded the experiment with the demographic questionnaire asking the participants to specify their age, gender, and the country(ies) they grew up and lived in.

8.5 RESULTS

In this section, we present the results of our user study: the observed scent detection/lingering times, air extraction issues, and hedonic scent perception (liking, comfort, and intensity).

We performed a normality test before applying parametric statistics [151]. A series of one-way-repeated measures ANOVA tests was performed to analyse the effect of the scent type (independent variable) on each of the dependent variables: scent detection and lingering times, as well as scent liking, comfort, and intensity. We report the results of the user study below.

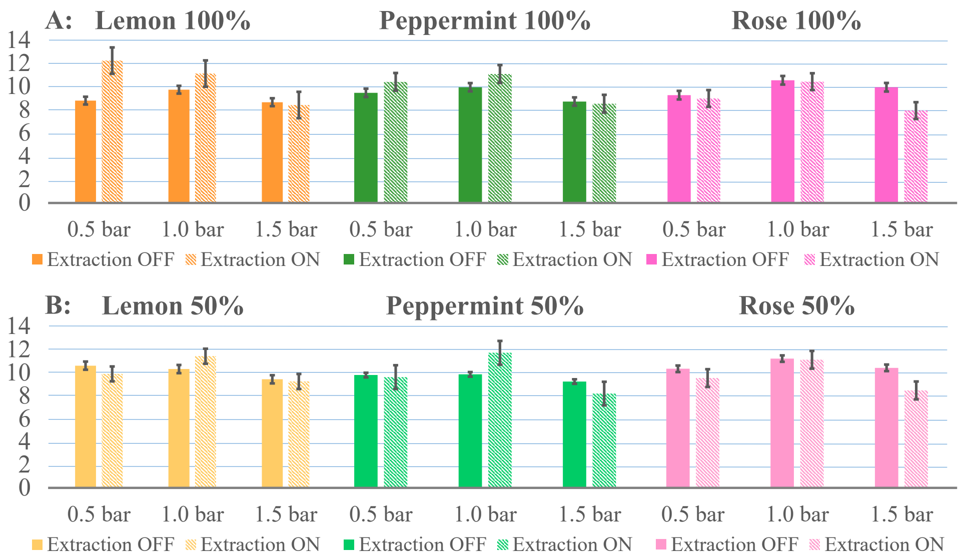

Figure 8.7: Mean Scent Detection times in seconds under the air pressure conditions of 0.5, 1.0, and 1.5 bars, for A: 100% pure essential oils of lemon, peppermint, and rose, and for B: 50% dilutions of lemon, peppermint, and rose essential oils with water. Error bars, ± s.e.m.

8.5.1 Scent Detection and Lingering Times

The results show that any of the three observed scents (lemon, peppermint, rose), with two dilution levels each (100% pure essential oil and 50% dilution with water), can be perceived in no longer than 10s under any of the three air pressure levels (0.5, 1.0, 1,5 bars). These results are summarised in Figure 8.7. It also takes no longer than 9s for a scent to disappear in any of the observed conditions (Figure 8.8). From these two figures, we can also see that there are no significant differences across the detection ($F(11, 198) = 1.10$, $p = .348$) and lingering ($F(11, 198) = 1.31$, $p = .168$) times recorded under all the different combinations of the above mentioned conditions.

8.5.2 Air Extraction Effect

The results from our study demonstrate that the scent detection and lingering times do not change depending on the air extraction conditions (see Figures 8.7 and 8.8). The fact that there are no statistically significant differences in the scent detection ($F(11, 198) = 1.10$, $p = .348$) and lingering ($F(11, 198) = 1.31$, $p = .168$) times between the extraction on and off conditions proves the efficiency of our scent-delivery device. The results confirm that our device releases such a small amount of the scent that there is no need for an extraction system to work in parallel with it. In fact, in both cases, it is enough

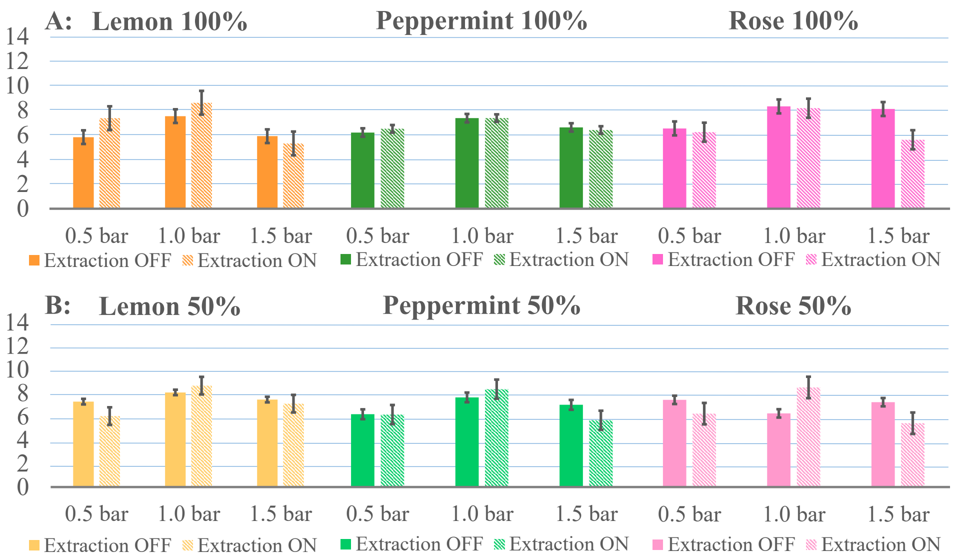

Figure 8.8: Mean Scent Lingering times in seconds under the air pressure conditions of 0.5, 1.0, and 1.5 bars, for A: 100% pure essential oils of lemon, peppermint, and rose, and for B: 50% dilutions of lemon, peppermint, and rose essential oils with water. Error bars, ± s.e.m.

with 10s for the participant to detect any of the explored scents, and with 9s for this scent to disappear.

8.5.3 Hedonic Scent Perception

Further results indicate high mean ratings of the perceived liking (e.g. 5.7 for Lemon, 4.9 for Peppermint, and 5.7 for Rose undiluted essential oils in the 1.0 bar condition, with air extraction off) and comfort (e.g. 5.1 for Lemon, 4.7 for Peppermint, and 5.7 for Rose undiluted essential oils in the 1.0 bar condition, with air extraction off), which suggests that all the explored scents have a big potential in HCI, since users would like them and feel comfortable about interacting with them. In addition to that, there is no need to worry that one scent would be liked less than the other one, or that a choice of the scent might decrease the comfort, since the differences between the perceived liking ($F(11, 198) = 1.16$, $p = .288$) and comfort ($F(11, 198) = 1.16$, $p = .292$) ratings are not significant.

We recorded the increase of the perceived scent intensity with the change of the air pressure (e.g. the mean scores of 2.9 in the 0.5 bar and 4.6 in the 1.0 bar conditions of the rose essential oil diluted to 50% with water, when air extraction was off). Nevertheless, the differences in the perceived intensity ($F(11, 198) = .86$, $p = .652$) were not statistically significant. We discuss what it means and what impact it has on the future research in the coming two sections.

8.6 Discussion

The scent detection and lingering times identified in this study are too slow for real-time applications (unless the target event can be predicted 10s in advance), but open multiple opportunities for feedback and feedforward messages (e.g. olfactory feedback on the objects the user is interacting with in gaming [142, 134] or VR [34, 143], warning feedforward messages in the autonomous driving scenarios). Another application example can be found in the scope of the multisensory cinema (e.g. like in [196]), where a scent accompanies a certain scene of the film, and transitions between the scenes are smooth enough to release a new scent.

As the results suggest, an HCI researcher exploring olfactory interaction might not need to worry about the timing changes depending on the type of the scent or its dilution, when applying our setup. This is supported by the lack of statistically significant differences between the scent detection and lingering times. Nevertheless, this finding still needs to be confirmed by a study with a bigger sample size.

This might reduce the implementation effort and exclude a chance of setting a wrong delivery time of a specific scent or a wrong time-out after it has been delivered. These values could be kept consistent across the stimuli, which would be relevant e.g. for gaming applications [142, 1], or in-car olfactory interfaces [66, 220], where multiple scents are used.

Our results on the air extraction effect, contribute a lot to solving the issues, which so far have been only referred to as a limitation in HCI (e.g. [19, 23, 208, 118]). Our exploration of the air extraction parameters, in relation to the automated scent-delivery, suggests which extraction requirements we need to fulfil for our setup. We hope that other HCI researchers can apply the same strategy for their olfactory interfaces.

The extractor E2 might well be useful for ambient desktop notification systems like [23, 19], but extractor E1 for ambient scenarios on an even larger scale, where there is a need to saturate the entire olfactory room with a scent, e.g. in user behaviour studies under the effect of an ambient scent (like in [15]). Both of these extractors did not demonstrate an effect in this study and the prestudy 1 we conducted earlier, which demonstrates that no extractors were needed for these scenarios and suggests their necessity in other applications.

An olfactory HCI designer might still stay confused about what air pressure to use since it seems to have no impact both on the scent detection speed and the lingering time. Even though the ratings of comfort and liking of each scent are not significantly different, a good suggestion would be to take a look at these ratings for each of the scents necessary for the desired application and to choose the pressure level based on the highest liking/comfort value. The choice could be made depending on what is more important for the intended use case (e.g. comfort might be more important for a multisensory cinema or driving, but liking for gaming or notifications).

To sum up, we can see that our results are promising and create a lot of room for new interaction potentials in HCI.

8.7 Challenges and Future Work

When working with the sense of smell, it is always necessary to acknowledge the challenges. Here we summarise the objectives we will need to further explore in the future.

As an outcome of prestudy 1, we found that extractor E1 had no impact on scent lingering. For this reason, we decided not to use it in the actual study, but we still ran it to refresh the air in the olfactory room between the sessions (when the room was empty). Another challenge of both air extractors installed in our setup was the noise. Even after placing the extractor E2 in a plastic box and covering the inner walls of the box with noise-cancelling materials, one could still hear the extractor running. Since the participants wore headphones, this had no impact on the results of the current study, but it would create an issue for use cases with a "no headphones" requirement.

It is important to acknowledge that so far we have only studied an effect of air extraction (taking contaminated air out of the room through the window) in the exploration of the ventilation issues, even though ventilation also involves blowing fresh air in. In our case, we relied on the fresh air flowing in naturally when air inside the interaction space is extracted. In the future, we might explore the use of the clean air blower (see Figure 8.5), which can be especially useful when there is no access to the fresh air source (e.g. window), as often happens in exhibition booths. The impact of designing such a system in a larger or smaller room still needs to be investigated, however, we do not expect the results to change significantly, if the scent-delivery distance and the locations of the air extractors are the same as in our proposal.

The lack of statistically significant differences in the perceived scent intensity between the different air pressure levels is also understandable. It means that the intensity changes are not perceivable when triggered between subjects, motivating the need of a within subjects solution. Our current setup did not support changing the air pressure within subjects. In the future, we plan to solve this issue with a digital air pressure regulator and are sure that the changes of the intensity will be perceivable when performed within a single session.

The fact that all the recorded mean liking and comfort ratings were equally high (e.g. liking ratings of 5.7 for Lemon, 4.9 for Peppermint, and 5.7 for Rose undiluted essential oils in the 1.0 bar condition, with air extraction off) resulted in no statistically significant differences between them as well. This is not surprising though, since we were only using pleasant scents, which people like to sniff and apply to increase the comfort of their daily life (e.g. through deodorants, air re-fresheners). These results might change in the future studies, if we decide to investigate the effect of unpleasant scents.

In the current study, we have only investigated the interaction at the maximum distance (68cm) necessary for the target application (olfaction-enhanced driving), but in the future we would also explore other distances (e.g. the minimum, or the mean), to see how the perception changes there, and how the scent-delivery parameters should be changed depending on whether the distance grows or decreases.

Finally, it is worth acknowledging that our current setup is not portable. We are now assembling a mobile solution of our olfactory interaction system equipped with a transportable air compressor (Bambi PT24: Maximum Pressure - 8 bar, Noise - 54dB(A), Weight - 25kg, Size - 57×40×40cm), the air flow generated by which is suitable for inhalation. This would also eliminate the need to constantly check the air pressure inside the tank and refill it when it becomes empty.

8.8 Conclusion

Our findings show that with our setup, a scent can be perceived by the user in 10s and it takes less than 9s for the scents to disappear. Our user study confirms that such a performance is maintained also when the air in front of the user is not being extracted, proving that our scent-delivery device can also be applied without additional air extraction solutions. Our OSpace framework presents a novel set of recommendations (addressed in the "Designing an OSpace" section) for olfactory interaction design and creates multiple opportunities for the exploration of olfactory applications in HCI (such as in gaming, multisensory cinema, VR, and simulated driving). Our innovative concept makes the first steps beyond the one-off applications and creates a more generalizable and scientifically valid and rigorous approach for designing, building, and exploring the olfactory interaction spaces. It takes into consideration not only the usefulness of smell for a particular interaction scenario but also suggests ways to understand the details of how the scents can be delivered to the user, including the timing, scent type and dilution level, air pressure values, and air extraction requirements.

9 | What Did I Sniff?: Mapping Scents Onto Driving-Related Messages

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Abstract

The sense of smell is well known to provide very vivid experiences and to mediate a strong activation of crossmodal semantic representations. Despite a growing number of olfactory HCI prototypes, there have been only a few attempts to study the sense of smell as an interaction modality. Here, we focus on the exploration of olfaction for in-car interaction design by establishing a mapping between three different driving-related messages ("Slow down", "Fill gas", "Passing by a point of interest") and four scents (lemon, lavender, peppermint, rose). The results of our first study demonstrate strong associations between, for instance, the "Slow down" message and the scent of lemon, the "Fill gas" message and the scent of peppermint, the "Passing by a point of interest" message and the scent of rose. These findings have been confirmed in our second study, where participants expressed their mapping preferences while performing a simulated driving task.

9.1 Introduction

The sense of smell is the most complex and challenging human sense (see [13, 106, 186]), but at the same time, it is a very powerful interaction medium enabling humans to extract meaningful information [184]. It has been shown that odours trigger automatic and implicit retrieval of mental representations related to the odour source [29], and enable automatic access to terms semantically related to the odours [88]. Moreover, the congruence between visual and olfactory information, and consequently multiple sensory sources, mediates the activation of crossmodal semantic representations stronger than each sensory modality on its own [184]. Considering that driving is a multisensory process, where eyes, ears, and limbs are all coordinated to get the task done, an olfactory component could make multimodal in-car interfaces even more efficient.

The positive effect of smell on driving has been evidenced by a number of user studies [130, 15, 170, 219, 157, 66]. In fact, in 2013 Ford has patented the in-vehicle smell notification system [112], while Mercedes-Benz and BMW have already installed the olfactory interfaces in their S-Class [35] and 7 Series [20] vehicles. The latter two are however mainly used as ambient scent-delivery devices to merely improve the hedonic experiences of the drivers, not fully exploiting the potential of the sense of smell in the context of driving. Our research builds on this work, in particular, to alert the driver about driving-relevant information. We believe that olfaction is interesting with respect to introducing a new semantic layer into interaction design and HCI (such as the mapping between different scents and messages/notifications related to performing the task of driving).

To address the above challenge, it is first of all necessary to define the characteristics of the driving-related messages and scents, and the relationship between them, so as to avoid performing tests with arbitrary scents, and to create an empirically grounded starting point for in-car olfactory interface design. To find out when the use of olfactory stimuli is meaningful in the car, we developed a two-dimensional framework to define driving-relevant messages, which either require "low or high attention" and "slow or fast reaction" from the driver. We account for the level of alertness of information and the required response time. Accordingly, we also selected a set of two alerting (lemon, peppermint) and two relaxing (lavender, rose) scents to carry out our studies. In Study 1, we used a four-step procedure to establish an objective mapping between three messages and four scents. We then extracted three best-rated scents and confirmed the mapping established in Study 1 by asking the participants to express their mapping preferences while performing a simulated driving task in Study 2.

We discuss the findings with respect to the potential of specific scents to convey particular information, considering the perceived alertness, relaxation, and urgency of the informative messages, as well as the alertness and relaxation levels of the scents. Our findings show that the scents of lemon, lavender, and peppermint are useful for alerting and urgent messages ("Slow down" and "Fill gas"), while the scent of rose is linked to relaxing messages ("Passing by a point of interest").

The main contributions of this paper are

i. presentation of a new semantic layer based on an empirical investigation of driving-related messages and scents,

ii. extraction of specific design considerations for guiding smell-based in-car interaction design.

9.2 Related Work

9.2.1 Expanding In-Car Interaction Modalities

Within the driving context, vision is the dominant sense, and any distraction of the driver's visual attention on the road can have fatal consequences [163]. This is especially important to consider with the increasing amount of information the car is sending to the driver. Auditory stimulation can reduce the visual load and even increase the urgency perception of the warnings [54], but also be annoying [14] or even distracting [54]. Application of tactile interaction demonstrated, for instance, a positive effect on users' attention in safety critical environments [189], and faster braking reaction times [127] in simulated driving. However, none of these approaches takes advantage of the sense of smell, in particular of its positive impact on crossmodal correspondences [184], and the relationship between odour detection and semantically congruent cues [68] that it provides. Here, we propose a novel approach investigating the use of odours as an information medium.

No other sensory modality (besides olfaction) has a direct and intense contact with the neural substrates of emotion and memory, which may explain why smell-evoked memories are usually emotionally potent. The emotion-eliciting effect of smell is particularly useful in inducing mood changes because they are almost always experienced clearly as either pleasant or unpleasant [56]. For instance, Alaoui-Ismaïli et al. [2] used the scents of vanillin and menthol to trigger positive emotions in their participants (mainly happiness and surprise), as well as methyl methacrylate and propionic acid to trigger negative emotions (mainly disgust and anger). The understanding of smell established by neuroscientists and cognitive psychologists provides a strong starting point for investigating the relation between specific scents and experiences that they could be able to elicit.

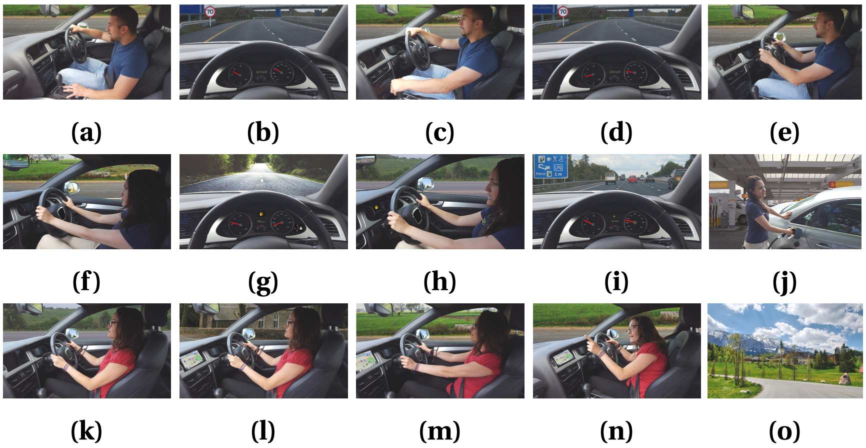

Figure 9.1: "Slow down" (a-e), "Fill gas" (f-j), and "Passing by a point of interest" (k-o) storylines. Each storyline consists of five static images presented one-by-one to the participants in Study 1 to explain the context of each driving-related message.

9.2.2 Establishing a Semantic Layer Through Smell

Previous studies on olfaction in psychology provide valuable insights into the semantics elicited by the sense of smell. For instance, Seigneuric et al. [184] highlighted that odours can affect visual processing by capturing people's attention. This is especially important since congruency between visual and olfactory information mediates the activation of crossmodal semantic representations much stronger than each sensory modality on its own [184]. Previous findings in psychology also showed the arousing [15, 170, 97] and relaxing [137, 125, 89, 65] effects of different scents on humans, which is very important to consider in the design of interactive olfactory interfaces in HCI. This prior work indicates the potential to convey basic, but yet informative messages, to a person (i.e. different levels of alertness, relaxation, and urgency) by means of olfactory stimulation.

The relationship between odour detection and semantically congruent cues has been demonstrated by Gottfried et al. [68]. Castiello et al. [29] have also shown that odours can influence our motor action, giving hints to the task of grasping, because smell triggers automatic and implicit retrieval of a mental representation of the object the scent is coming from [29]. The same effect has been studied in the scope of accessibility of lexical terms [88]. Seigneuric et al. [184] also pointed out that implicit presentation of odours may influence perception and cognition in human adults, and that the sensorium is massively influenced by vision and audition. This opens up new interaction possibilities in the automotive context.

While scent mapping has been studied for decades outside HCI [52], olfactory human-computer interaction gained increased interest only recently [153, 183, 154]. Nowadays we see a variety of scent delivery devices and technologies appearing on the commercial market [154]. Olfaction has been applied for photo-tagging [23] and ambient notifications [19, 208]. These explorations indicated that smell is less disruptive than visual and auditory stimuli. Despite the growing amount of such works in HCI, there have been only a few works tackling olfactory stimulation in the automotive context. The main contributions are targeting drowsiness while driving [220, 66, 157], alertness and mood of the driver [15, 170], and driving performance task [130]. All these previous studies demonstrate the potential of smell to enhance users' experiences, and in particular, introduce a new way of in-car interaction. Nevertheless, none of these studies has explored a mapping between scents and messages.

In this paper, we extend this emerging field of research by establishing an understanding of how olfactory stimulation can be used to transfer specific information to the user, in our case to the driver. For that purpose, our experiments explored the mapping between driving-relevant information and scents.

9.3 DRIVING RELATED INFORMATION

In order to investigate how smell can convey specific driving-relevant information, we defined three typical driving scenarios represented by following three messages: (1) "Slow down", (2) "Fill gas", and (3) "Passing by a point of interest".

These messages were selected based on a two-dimensional framework (see Figure 9.2). We accounted for the level of alertness and required reaction time in the described situation, which characterised the alertness and urgency of the message to be conveyed to the driver. We split the alertness dimension into a "low" and a "high" range, but the reaction time dimension into a "fast" and "slow", dividing our space into four areas. We filled each area, apart from one, with a dedicated driving relevant message. It is not common to have a message with a low level of alertness, which at the same time requires a quick response (high urgency) within a driving context. For this reason, we did not specify a message for that area. For the remaining three areas, we chose "Slow down" for high alertness and fast reaction time, "Fill gas" for high alertness, slow reaction time, and "Passing by a point of interest" for low alertness, slow reaction time, which consequently is the least urgent situation from the driver's primary driving task perspective. The main criteria for choosing these messages was their relatively long

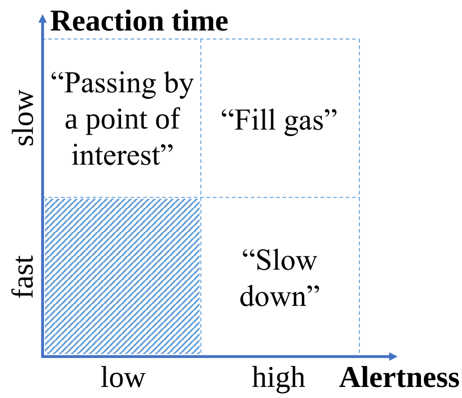

Figure 9.2: 2D framework of message urgency along two axes: alertness (i.e. salience: low-high) and reaction time (range estimation considering the time required to detect a scent: fast(≤10s)-slow(>10s)).

reaction time requirement (not a high priority information, which requires the driver to respond to it in a matter of seconds, considering the time delay between the release and the perception of the scent). In the future, when we know that we can deliver the scent to the user within an even shorter time frame, we will extend the set of messages including high priority information (e.g. an indication of excessive lane deviations or a short inter-vehicle distance).

9.4 Study 1

In the first study, we presented each of the explored driving-related messages to the participants in the form of short storylines [69] to facilitate the storytelling related to each message over the time (Figure 9.1), without yet introducing any novel interfaces or interaction elements related to smell:

"Slow down": (9.1a) Mark is driving on the motorway and at some point, he turns up the volume of the radio to listen to his favourite song. (9.1b) Without noticing, he is speeding up and begins to drive faster than the speed limit. (9.1c) At this point, a scent inside the car is released and reminds Mark to slow down. (9.1d) Mark slows down and is below the speed limit again. (9.1e) Mark continues listening to music.

"Fill gas": (9.1f) Sarah is an occasional driver. (9.1g) She does not need to fill gas every day and has no routine for this activity. (9.1h) Today she drives to work and at some moment a scent is released in the car to notify her about the low fuel level. When perceiving the scent, Sarah knows that it is time to fill gas. (9.1i) After 15min of driving, she sees a "Petrol Station in 1 mile" sign and pulls over in 1 mile. (9.1j) Sarah fills gas.

"Passing by a point of interest": (9.1k) Laura is driving through a new area on the countryside and is eager to explore new sites. (9.1l) She switches on the navigation system, which is showing all the points of interest on the screen, but as she is driving alone, it is easy to miss a sightseeing place, since she has to focus on the road. (9.1m) At some point, a scent is released in the car notifying her about an upcoming landmark worth visiting. (9.1n) A few moments later, Laura notices a beautiful castle on her way. (9.1o) She decides to stop and visit this castle.

9.4.1 Study Design

This study followed a 5(scents)×3(messages) within-participants experimental design, composed of four main steps: (1) Rating of the perceived level of alertness, relaxation, and urgency of the three presented messages; (2) Mapping between the presented messages and five olfactory stimuli; (3) Ranking of all three messages according to each of the five olfactory stimuli; (4) Rating of the perceived level of alertness, relaxation, and liking of each olfactory stimulus (scent or water). All the stimuli were presented one-by-one in a counterbalanced and randomised order. Overall, the study lasted about 30 minutes.

9.4.2 Scent Selection and Presentation

For the olfactory stimuli, we selected two low arousal (lavender, rose), two high arousal scents (lemon, peppermint), and water as a neutral/control stimulus. All scents were *"miaroma"* 100% pure essential oils from Holland & Barrett Int. Ltd.

These five stimuli were selected based on prior work. Lavender and rose demonstrated a relaxing effect on people (see [137, 125, 89, 65]), while lemon and peppermint were used to increase alertness (see [15, 170, 97]). The scents of lemon and peppermint have already been extensively used in a number of simulated driving studies [130, 15, 170, 219, 157, 66].

All olfactory stimuli were presented to participants in the form of five jars. This manual delivery approach was used in previous studies in the fields of neuroscience and experimental psychology, such as by Khan et al. [109] to investigate their odour pleasantness prediction framework, and more recently by Velasco et al. [200] to study the crossmodal effects of music and odour pleasantness on olfactory quality perception.

At this point, it is worth noting that we initially started the experiment by using a commercially available scent-delivery device, however after having completed the pilot study with 10 participants, we noticed that participants had difficulties in discriminating the stimuli due to the mixing of scents caused by the device. We carefully cleaned the device with ethanol (as instructed by the manufacturer), and left it to dry for 2 hours, but it didn't solve the contamination problem. Hence we decided to change the scent presentation mode. We switched to the manual approach and started a new set of data collection. However, we intended to come back to an automated delivery approach for Study 2. We planned to finish building our own scent-delivery device by the beginning of our second study.

To keep the stimulation constant across the participants, each jar was filled with 5g of the essential oil or water, controlling scent intensity and the weight of the jars. Each jar was also wrapped in paper (odourless) to avoid visual cues with respect to the colour of the liquid. The experimenter was passing the jars one-by-one to the participants based on the predefined randomised protocol. The participants could not see the jar until it was handed to them. They were instructed to hold the jar 2cm away from their nose while sniffing and to perform one sniff (2-5s long) for each jar, in each new trial. Such short sniffing time was designed to avoid any potential olfactory adaptation [155]. A break of 20-25s was ensured between the olfactory stimuli [200] to "refresh" participants' scent perception.

9.4.3 Setup

The experiment was set up in a quiet and well-ventilated room. The participants were sitting in front of a 24" screen with 60Hz refresh rate, on which the driving-related messages were presented through an Microsoft PowerPoint® presentation. Each message consisted of five slides showing one picture after another with a short description. Participants used the keyboard to switch between slides.

9.4.4 Procedure and Method

Upon arrival, participants were given the information sheet, an explanation of the procedure, and a consent form to sign.

After the participants had finished viewing each of the three storylines (step 1), they were asked to respond to the following three self-report questions on a 7-Point Likert scale: (1) *"How alerting do you consider the message presented in this storyline? (1= "Not alerting at all"; 7= "Very alerting")"*; (2) *"How relaxing do you consider the message presented in this storyline? (1= "Not relaxing at all"; 7= "Very relaxing")"*; and (3) *"How* *urgently would you react to the message presented in this storyline? (1= "Not urgently at all"; 7= "Very urgently")".*

After having answered these questions, participants were given a jar to sniff and rated the following self-report question on a 7-Point Likert scale (step 2): *"How much do you think this scent represents the message from this storyline? (1= "Very little"; 7= "Very much")".* This was repeated 5 times for each storyline, for a total of five olfactory stimuli.

For step 3, participants were given each jar again and asked to rank the suitability of each message to each scent based on the following instructions: *"If you think of smell as a medium to convey information, which message ("Fill gas", "Slow down", or "Passing by a point of interest") would you assign this smell to? (1= "is the best to convey this message", 3= "is the worst to convey this message"). Please do not repeat the ranks."*

Finally, in step 4, we asked participants to rate each olfactory stimulus (independently from a driving-related message) following three self-report questions: (1) *"How alerting is this scent for you? (1= "Not alerting at all"; 7= "Very alerting")"*; (2) *"How relaxing is this scent for you? (1= "Not relaxing at all"; 7= "Very relaxing")"*; (3) *"How much do you like this scent? (1= "I don't like it at all"; 7= "I like it very much")".*

We designed this questionnaire based on psychometric standard guidelines (self-report based on Likert scale) and used related studies as an example [15, 184]. As conveying information using smell is a relatively unexplored topic, we couldn't adopt any existing questionnaires. We also included typical questions on liking, pleasantness, and relaxation [200, 31]. The experiment was concluded with the demographic questionnaire (age, gender, country(ies) of origin and residence).

9.4.5 Results

In this section, we summarise the main findings from Study 1 following the four main steps described above.

9.4.5.1 Participants

A total of 30 participants, with a mean age of 31 years (SD= 6.60, 6 females) took part in the study. Participants have reported having no olfactory dysfunctions, adverse reactions to strong smells, respiratory problems, or flu, and not being pregnant. They were recruited on an opportunity-sampling basis. The study was approved by the University of Sussex ethics committee. All subjects expressed written consent before the experiment and were rewarded with a £5 Amazon Voucher for their participation.

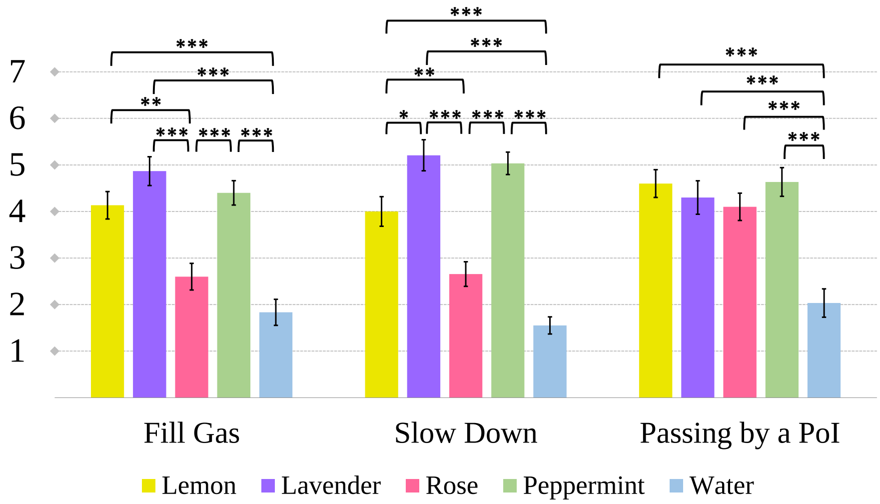

Figure 9.3: Mean scores of how much each scent represents each of the driving-related messages (1= "Very little"; 7= "Very much"). Error bars, ± s.e.m., $*p < .05$; $**p < .01$; $***p < .001$

9.4.5.2 Message Ratings

To understand how participants perceived the messages, we performed a one-way MANOVA test considering alertness, relaxation, and urgency as a dependent and driving-related messages as an independent variable. The Post Hoc comparison was performed following the Bonferroni correction.

The results indicate an effect of driving-related messages on the three dependent variables (alertness, relaxation, and urgency), $F(6, 152) = 10.21$, $p < .001$; Wilks' $\lambda = .508$.

The "Slow down" message (M= 6.10, SD= .80) demonstrated itself as the most alerting (significantly higher than "Fill gas" (M= 5.37, SD= 1.27, p < .05) and "Passing by a point of interest" (M= 4.40, SD= 1.33, p < .001)).

On contrary, the "Passing by a point of interest" message (M= 4.73, SD= 1.34) was chosen as the most relaxing (significantly higher than "Fill gas" (M= 3.00, SD= 1.14, p < .001) and "Slow down" (M= 2.50, SD= 1.45, p < .001)).

Both the "Slow down" (M= 6.26, SD= .86, p < .001) and the "Fill gas" (M= 5.56, SD= 1.30, p < .001) messages were rated significantly more urgent than "Passing by a point of interest" (M= 4.01, SD= 1.55), which matches the Figure 9.2 framework.

9.4.5.3 Scent Mapping

To understand the associations between the driving-related messages and each scent, we performed two-way ANOVA, in which messages and scents were the two independent

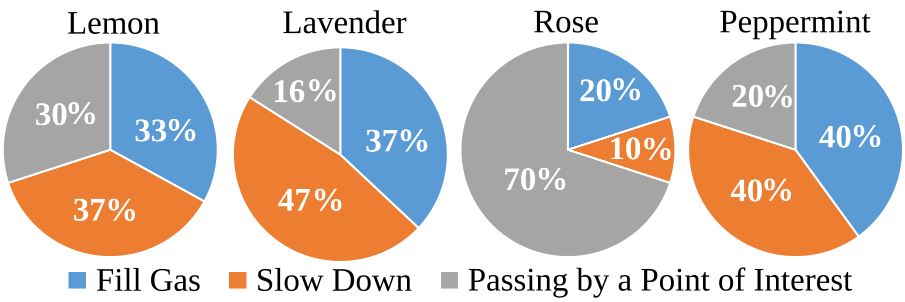

Figure 9.4: Percentage of subjects having ranked the corresponding driving-related message as first (best) for each scent.

variables, but association rating was a dependent variable. The Post Hoc comparison was used following the Bonferroni correction test.

The results indicate a statistically significant interaction between the messages and the scents ($p < .05$) and a statistically significant difference between the scents ($p < .001$).

Mapping results of the "Fill gas" message (see Figure 9.3 (left) for details) demonstrate that this message was best associated with the scents of lemon (M= 4.13, SD= 1.61), lavender (M= 4.87, SD= 1.70), and peppermint (M= 4.40, SD= 1.43). All of these three scents were rated significantly higher than the scent of rose (M= 2.60, SD= 1.57) and water (M= 1.83, SD= 1.53).

Similarly to the "Fill gas" message, "Slow down" was best mapped onto the scents of lemon (M= 4.00, SD= 1.71), lavender (M= 5.21, SD= 1.80), and peppermint (M= 5.03, SD= 1.29), however lavender was also rated significantly higher than lemon (see Figure 9.3 (middle)). Lemon, lavender, and peppermint were all rated significantly higher than the scent of rose (M= 2.66, SD= 1.42) and water (M= 1.55, SD= .98).

Mapping onto the "Passing by a point of interest" message shows that water (M= 2.03, SD= 1.67) is rated significantly lower than the scents of lemon (M= 4.60, SD= 1.63), lavender (M= 4.30, SD= 1.97), rose (M = 4.10, SD= 1.60), and peppermint (M= 4.63, SD= 1.69) (see Figure 9.3 (right)).

9.4.5.4 Scent Ranking

To compare the participants' rankings of the correspondence between each scent and each message, we performed a non-parametric analysis of the data. The results underline statistically significant differences in the scent-message rankings ($\chi^2(4) = 18.77, p < .001$). In particular, rose has been highly ranked in association with the "Passing by a point of interest" message ($\chi^2(2) = 6.21, p < .05$) (see Figure 9.4). The other associations

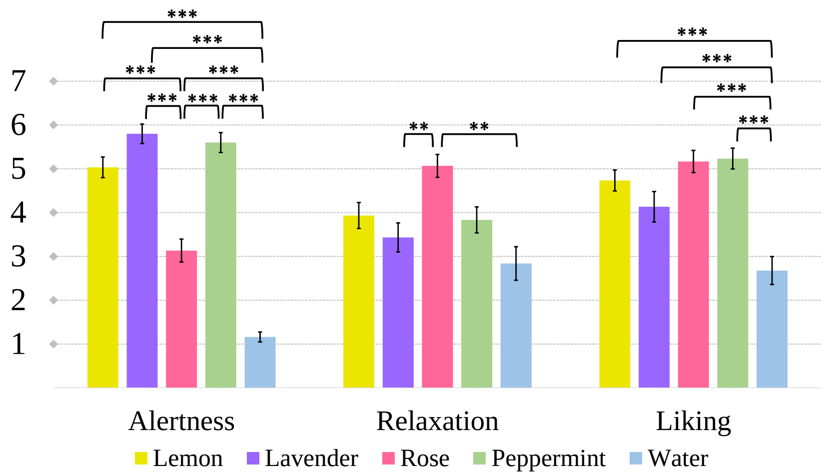

Figure 9.5: Mean scores of scent alertness, relaxation, and liking. Error bars, ± s.e.m., $*p < .05$; $**p< .01$; $***p< .001$

are not providing any clear preference for either the scent of lemon, lavender, or peppermint. Important to mention is that we have taken only the messages ranked first (best) for the data analysis, even though participants were asked to rank the second best, and the worst message for each scent. This was done intentionally, to help the participants think more.

9.4.5.5 Scent Ratings

We evaluated the ratings of the perceived scent attributes (i.e. alertness, relaxation, and liking) performing a one-way MANOVA, considering scents as an independent variable, and alertness/relaxation/liking ratings as a dependent variable. We did the Post Hoc comparison with Bonferroni correction.

The scents of lemon (M= 5.03, SD= 1.30), lavender (M= 5.80, SD= 1.21), and peppermint (M= 5.60, SD= 1.25) were rated significantly more alerting than the scent of rose (M= 3.13, SD= 1.43) and water (M= 1.16, SD= .64) (see Figure 9.5 (left)).

The scent of rose (M= 5.07, SD= 1.44) was rated as a significantly more relaxing scent than both the scent of lavender (M= 3.43, SD= 1.81) and water (M= 2.84, SD= 2.13) (see Figure 9.5 (middle)).

Finally, the scents of lemon (M= 4.73, SD= 1.31), lavender (M= 4.13, SD= 1.90), rose (M= 5.17, SD= 1.39), and peppermint (M= 5.23, SD= 1.30), were all liked significantly more than water (M= 2.68, SD= 1.78) (see Figure 9.5 (right)).

9.4.6 Summary

In this study, we found associations between arousing scents (e.g. lemon, peppermint) and alerting/urgent driving-related messages (e.g. "Slow down", "Fill gas"). On contrary, relaxing scents (e.g. rose) were mapped onto less alerting and urgent messages (e.g. "Passing by a point of interest"). To verify these findings, we did a follow-up study in the driving simulator.

9.5 STUDY 2

In the second study, we asked the participants to express their mapping preferences between the scents and the messages while performing a simulated driving task.

9.5.1 Study Design

This study followed a 3(scents)×3(messages) within-participants experimental design, composed of two main steps: (1) Familiarisation with the messages and the scents by rating the perceived level of their alertness; (2) Mapping the presented scents onto the messages in the process of driving.

All the stimuli (driving-related messages and scents) were presented one-by-one in a counterbalanced and randomised order. Overall the study lasted about 20 minutes.

9.5.2 Scent Selection and Presentation

For the olfactory stimuli, we selected the scents of rose, lemon, and peppermint, because they had the best associations with the driving-related messages in Study 1 and because the scents of lemon and peppermint have already been applied in numerous simulated driving studies [130, 15, 170, 219, 157, 66]. We used essential oils from the same supplier as in Study 1.

We presented the scents in an automated way by means of a self-made scent-delivery device. The device delivered the air from a tank of compressed clean air. This air was propelled though glass jars (using plastic tubes of 4mm in diameter) filled with 5g of 100% pure essential oils (one jar per scent) with the air pressure of 1 bar in order to diffuse the scent into the delivered air. The output of the scent-delivery device was located behind the steering wheel and pointed towards the participants' face. The distance from the output to the face was 42-66cm (M= 58.06, SD= 6.71), depending on

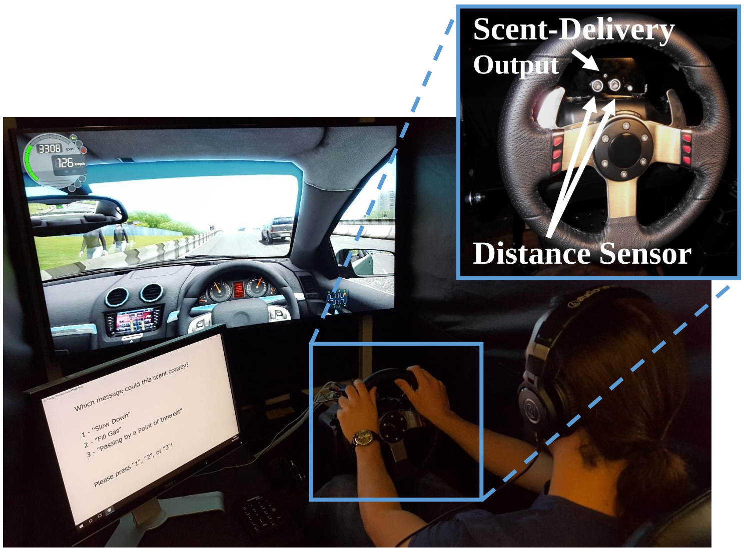

Figure 9.6: Setup of the driving simulator with an integrated system of automated scent-delivery used for the mapping task.

how the participants adjusted their seat. We measured this distance using an ultrasound sensor located just under the output (see Figure 11.1). The flow of air was controlled using electric valves and an Arduino board connected to a computer. Participants wore headphones playing the sound of the driving simulator software, which was cancelling the sound of the scent-delivery.

9.5.3 Setup

The experiment was set up in our olfactory interaction space, which is a former soft wall clean room (Connect 2 Cleanrooms Ltd., H= 2.1m, W= 1.3m, L= 2m), equipped with an air extractor (Torin-Sifan DDC270-270, 550W, 4 pole, 1 speed, 230V, 50Hz, 1 phase). We exchanged its original walls with the black odourless water-repellent fabric, which does not absorb scents.

The participants were sitting in a driving simulator seat (FK Automotive) equipped with the Logitech G27 steering wheel in front of a 55” curved screen with 60Hz refresh rate, on which the view outside the car from driver’s position was rendered. We used the CityCarDriving 1.5 driving simulator software for this purpose. This software was chosen due to the support of left-hand driving and traffic rules. The questions were presented to the participants on a second screen (17”, 60Hz refresh rate) located to the left from the steering wheel (see Figure 11.1). Participants gave their responses to the questions using a numeric keypad located under the second screen.

9.5.4 Procedure and Method

Upon arrival, participants were given the information sheet, an explanation of the procedure, and a consent form to sign.

In step 1, participants were asked to answer three questions about the perceived alertness level of the messages: *"How alerting do you consider the "{Slow Down/Fill Gas/Passing by a Point of Interest}" message? (1= "Not alerting at all"; 7= "Very alerting")"*. Afterwards, another three questions were asked about the perceived alertness level of the scents. Each scent was presented for 5s every time a new *"How alerting do you consider this scent? (1= "Not alerting at all"; 7= "Very alerting")"* question appeared on the second screen. The scent presentation time was enough to make sure that the participants inhale at least once [150]. There were 30s breaks between the questions on scent alertness to avoid scent mixing and lingering (as in [200]). The participants were submitting their ratings by pressing the corresponding key on the numeric keypad and confirming their input by pressing "Enter".

Step 2 started with a *"Please start driving now!"* message shown on the second screen. This was a sign for the participants to start the five minutes long free driving, the purpose of which was to get used to the setup and the driving simulator software. By the end of the free driving phase, the participants received the first scent, which was delivered for 10s. We doubled the delivery time compared to step 1 to make sure the scent reaches participants' nose despite occasional occlusions of the output of the scent-delivery device by participants' hands or parts of the steering wheel. By the end of the scent-delivery, a questionnaire appeared on the second screen: *"Which message could this scent convey? (1-"Slow Down", 2-"Fill Gas", 3-"Passing by a Point of Interest")"*. Participants were giving their responses by pressing the "1", "2", or "3" key on the numeric keyboard. A feedback message was shown on the screen right after the button-press to confirm their input. We instructed the participants about the fact that the scent-delivery was not synchronised with the current driving situation. The same scent-mapping task was repeated two more times (three times in total). There were breaks of two minutes between scent deliveries. To make sure this time was sufficient to avoid scent-mixing and lingering, we included a self-report question at the end of the study, asking the participants if the breaks were long enough to solve these issues. One minute after the third scent-delivery, the *"Please stop driving and leave the simulator!"* message was shown. This meant the participants had to proceed with filling in the demographic questionnaire (the same as in Study 1) outside the simulator.

9.5.5 Results

Here, we present our findings of mapping the scents onto driving-related messages performed in the process of driving.

9.5.5.1 Participants

A total of 17 participants, with a mean age of 31 years (SD= 6.00, 3 females) volunteered for this study (different subjects than in Study 1). Participants have reported having no olfactory dysfunctions, adverse reactions to strong smells, respiratory problems, or flu, and not being pregnant. They were recruited on an opportunity-sampling basis. The study was approved by the University of Sussex ethics committee. All participants expressed written consent before the experiment.

9.5.5.2 Scent Mapping onto Messages

To compare the mapping between scents and the driving-related messages set by the participants while driving, we performed a non-parametric analysis of the data. We found statistically significant differences in the mapping preferences (see Figure 9.7). In particular, the scent of rose has been highly associated with the "Passing by a point of interest" message (χ^2 *(2)= 7.88, p< .01*), which matches the findings of Study 1 (see Figure 9.4). The scent of peppermint has been equally linked with "Fill gas" and "Slow down" messages (χ^2 *(2)= 5.77, p< .05*), while the scent of lemon has mainly been affiliated with the "Slow down" message (not significant).

These findings are consistent with the results of Study 1, where lemon and peppermint scents were associated with the same messages (see Figure 9.3). Such results suggest that both lemon and peppermint are good for either the "Slow down" or the "Fill gas" messages, which is in line with the high alertness level of the two messages (see Figure 9.2) and the alertness ratings of these scents (see Figure 9.5).

9.5.6 Summary

Study 2 has validated the mapping between scents and messages (from Study 1) in the context of driving. This study presents initial findings and creates a new dimension of research within the scope of automotive user interfaces: conveying information by means of the smell inside the car.

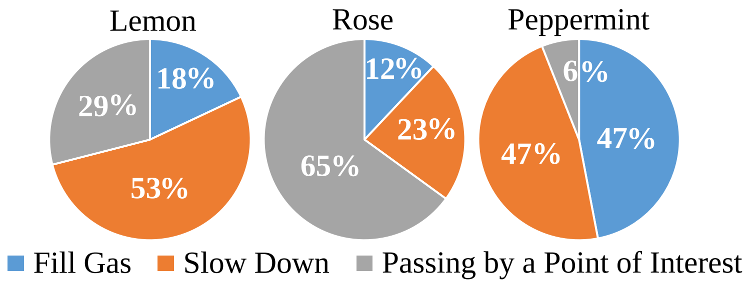

Figure 9.7: Percentage of subjects having mapped the corresponding scent on one of the three driving-related messages.

9.6 Discussion

In this section, we discuss how the results from our studies can inform the design of in-car interaction and experiences.

9.6.1 Levels of Alertness: Clear and Ambivalent Mappings

As expected, the "Fill gas" and "Slow down" messages were clearly perceived as more alerting and urgent than the "Passing by a point of interest" message. Alerting messages were further mapped onto the arousing scents, like lemon and peppermint, which is in line with previous findings on the alerting effect of those two scents [170, 15]. However, despite the expected relaxing effect of lavender [137, 125], in Study 1 participants associated it with alerting and urgent messages. This makes sense, because lavender still is a very intense odour that people can quickly recognise and respond to.

Interestingly, alongside peppermint, lavender was chosen as one of the best scents to convey the "Slow down" message, implicitly advising the driver to calm down (e.g. we speed up when we are too excited or nervous). This thought-provoking effect is in line with the related work on unconscious effects of scents [29, 184]. On contrary, the calming scent of rose clearly showed its relaxing effect. It dominated in the mapping onto the "Passing by a point of interest" message in both of our studies. In Study 1, both this message and the scent of rose were rated most relaxing. Such perception of the rose scent also matches the results from the previous work [89, 65].

It is important to note that the scent of rose was not explicitly dominant in the scent mapping results of Study 1. This could be due to the ambivalent quality of the "Passing by a point of interest" message, which can be interpreted variously. Its exact meaning depends strongly on the context. If I miss one of the points of interest, I might just turn around, or wait for another one. Nevertheless, if the current point of interest is the one I definitely want to visit, I may want an alerting scent to notify me about its proximity. This might be the reason why we found no significant dominance of the rose scent in relation to the "Passing by a point of interest" message at that stage.

A further explanation can be found in the distinction between primary, secondary and tertiary driving tasks. While "Fill gas" and "Slow down" are related to the primary task of driving and are distinctly alerting and urgent, the "Passing by a point of interest" is a message that falls into the category of secondary or even tertiary driving tasks (similar to using the radio described in [162]). A more specific design approach can be considered for such messages (i.e. customised mapping).

9.6.2 Opportunity to Expand the Range of Information

In our studies, we focused on three main messages, which we selected taking into account the level of alertness, and urgency of the information (message) to be conveyed to the driver (see the two-dimensional framework in Figure 9.2). Based on our findings, this set of messages can be further extended and clustered along primary, secondary, and tertiary tasks for the driver. Other primary tasks could include driving related information such as "Ice on road", "Traffic jam ahead", or "Bad weather alert", whereas notifications in relation to secondary and tertiary tasks could be "Favourite radio station available", "Bakery nearby", "New social event invitation" etc. Later, when we know how to deliver scents to trigger an immediate reaction from the driver, we can also explore messages like "Excessive lane deviation" and "Short inter-vehicle distance".

Other scents, interesting to explore in the scope of conveying primary notifications, could be cinnamon and rosemary, which have already proven their alerting effect in [170, 220]. For secondary and tertiary notifications, we might apply vanilla, ylang-ylang, and caramel, which were classified as relaxing in [57, 90, 31]. A different mapping between the scents and the informative messages might emerge out of future empirical investigations. It would be interesting to see if further hints of unconscious scent associations arise. An example case might be as follows: participants perceive the scent of caramel as intense and map it on the alerting "Traffic jam ahead" message, even though, this scent was labelled as "soothing-peaceful" by Chrea et al. [31]. "Traffic jam ahead" does however implicitly say, we should stay calm (despite the stressful situation).

Furthermore, it is important to mention that we focused on indirect associations in our studies, rather than on the literal mapping between a scent and a driving-relevant message (e.g. "Fill gas" and the scent of petrol, or "Slow down" and the scent of burned rubber). Our study is based on previously established classifications of the selected scents as alerting and relaxing, which engage users on an emotional level. It is well known that scents have a strong and direct connection to emotions and memory [179, 177, 88] and can, therefore, be a powerful medium to elicit and convey information. The use of naturally arising odours (e.g. petrol leak, the smell of burning rubber in case of emergency braking) could also have undesirable effects on the user, or act as a safety hazard. Direct mapping is however interesting to explore in further studies.

9.6.3 Practical Application Considerations

In a real car, it might be relevant to train the driver on the meaning of a specific scent, to reinforce a preferred behaviour (e.g. "Take a break"), just like we were trained to associate traffic signs with certain pieces of information [95]. Prior work by Kuang and Zhang [115] suggests that there is a potential of doing so by means of the conditioning, which was proven to work in a smell enhanced visual motion perception study.

Our findings are not intended to present a well established mapping for the design of a semantic messaging system, but rather to highlight the correspondence between the arousal of the scents and the alertness level of the messages. This motivates the application of scents based on how important, relevant, or salient the driving-related message is.

9.6.4 Challenges

Our research provides a necessary starting point to open up a new interaction design space for HCI. Despite promising findings, further research is needed involving an even larger sample size, extended set of scents, and more messages.

Our driving setup did not enable links between the scent-message combinations and the current situation on the road. The effect of the scent might be stronger if its delivery is synchronised with a certain traffic event or a vehicle status update. Improvement possibilities also include replacing the air tank with a compressor (more feasible in a real car [220]).

Working with the sense of smell raises ethical concerns as it involves the handling of chemicals, but also because scents have a strong association with emotions and memories. This emphasises the need to allow for customisation of olfaction-based interfaces. The same applies to personal and cultural preferences. Further challenges may include smell unfamiliarity, persistence, and "the stimulus problem" [11].

Persistent smells could be eliminated through advancements of the "olfactory white" in the future [211]. We also need to consider the challenge of delivering the scent without invading the olfactory space of the co-driver and the passengers [49]. Moreover, to account for are potential scents that people seated in the car (i.e. drivers and passengers) bring in with them.

Even though the effect of smell on the driving performance and experience has been studied [15, 170], there is a need to investigate these factors within the scope of conveying driving-related information by scents (also in a real driving setting).

9.7 Conclusion

Our findings show that using olfactory stimuli as an alternative interaction modality in the car is not arbitrary and that participants are able to establish a mapping between specific driving-related messages and scents. Based on the induced alertness level of both the message and the scent, we demonstrated that it is possible to establish a new semantic layer of information delivery for the driver. These insights open up new opportunities to further explore the topic of conveying information using smell in the context of driving and beyond.

10 | Towards a Framework for Validating the Matching Between Notifications and Scents in Olfactory In-Car Interaction

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Abstract

Olfactory notifications have been proven to have a positive impact on drivers. This has motivated the use of scents to convey driving-relevant information. Research has proposed the use of such scents as lemon, peppermint, lavender and rose for in-car notifications. However, there is no framework to identify which scent is the most suitable for every application scenario. In this paper, we propose an approach for validating a matching between scents and driving-relevant notifications. We suggest a study in which the olfactory modality is compared with a puff of clean air, visual, auditory, and tactile stimuli while performing the same driving task. For the data analysis, we suggest recording the lane deviation, speed, time required to recover from the error, as well as the perceived liking and comfort ratings. Our approach aims to help automotive UI designers make better decisions about choosing the most suitable scent, as well as possible alternative modalities.

10.1 Introduction

Visual notifications dominate in modern vehicles, however, any distraction of the driver's visual attention on the road can have fatal consequences [163]. Sound can reduce the visual load and help the driver perceive the urgency of the warnings [54], but it can also be annoying [14] or even distracting [54]. This has stimulated the exploration of other modalities [153]. Tactile interfaces have been widely studied and have indicated, e.g. a positive effect on users' attention in safety critical environments [189], faster braking reaction times [127] in simulated driving, while also being less annoying [121]. Olfactory stimulation is, still largely unexplored in automotive contexts, even though it could help drivers process information [184].

Olfactory stimulation is the most challenging communication channel to apply in the car, due to scent lingering and interpersonal differences [49]. It has been proven to have a positive impact on the alertness and mood of the driver [15, 170], drivers' braking performance [130], and on keeping drowsy drivers awake [220, 66, 157]. Nevertheless, there are still only very few investigations of using smell as a communication channel [48, 46]. However, considering the increased visual load in modern infotainment and driving assistance systems, coupled with advances in scent-delivery [45, 129, 4, 161], we see a great opportunity to rethink the integration of scent into modern vehicles. A valid approach is necessary to decide what scent matches each specific driving-relevant notification. Our paper proposes the first steps on the way of establishing such a validation framework.

The significance and the originality of our approach can be summarised as follows:

- We propose the first approach to help automotive UI designers make better decisions about choosing the best scent for a specific driving-relevant notification. This is especially important considering the recent olfactory interface tendencies in the automotive industry, involving such manufacturers as Mercedes-Benz [35], BMW [20], and Bentley [18].

- Our approach goes beyond the most relevant previous work in this area. We offer a structured method of choosing the scent for an in-car interaction scenario, by not only taking into consideration the knowledge on the effects of scents from psychology and neuroscience, but also by comparing their efficiency opposed to other modalities (i.e. vision, audition, and touch).

To make sure our method is valid, we built up on the work of Politis et al. [165], who compared different types of visual, auditory, and tactile stimulation as stand-alone and combined notifications to convey driving-relevant information. We extend this work by including the olfactory modality.

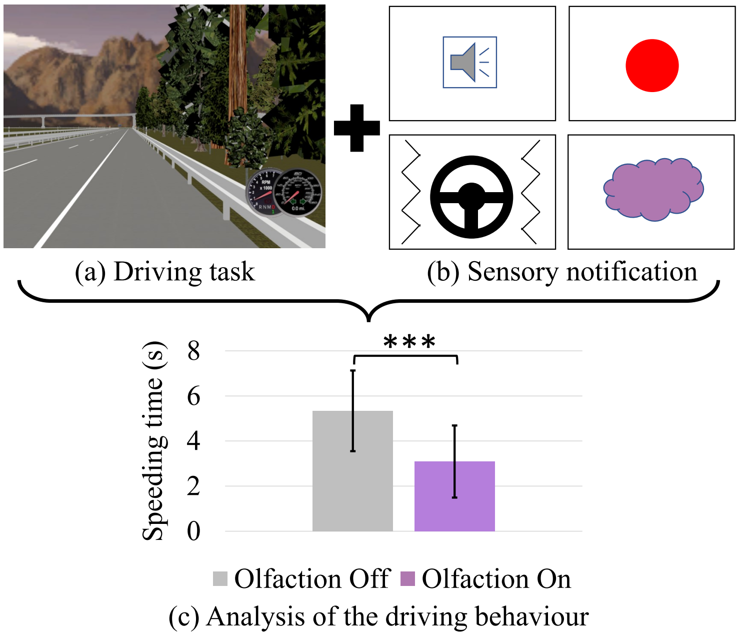


Figure 10.1: Framework for validating the matching between driving-relevant notifications (e.g. "Slow down") and scents (e.g. Lavender). We propose a framework with the following three steps: (a) Selecting a driving task, (b) Displaying a notification (auditory, visual, tactile, olfactory, or combined) relevant to this driving task (e.g. one sensory modality/combination of modalities per condition), and (c) Analysing the driving behaviour based on what is required by the selected task (e.g. mean speeding time in seconds, in case of a "Slow down" notification, error bars ±SD, $***p < .001$).

10.2 Method

Based on the related work, we propose establishing a framework for validating the matching between scents and notifications (by extending the approach of [165]). To do that, we focus only on one scent and one notification, which can be conveyed by this scent (multiple scents could be explored for each notification in the future). To demonstrate our approach, we chose a speeding scenario. The driving task involves overtaking slower vehicles. As there are also oncoming vehicles and pedestrians involved, the participant is likely to go over the speed limit when overtaking. Once this happens, the corresponding "Slow down" notification is displayed as a beep or a circular red symbol (as per [165]), as a vibration on the steering wheel (as per [185]), as a puff of Lavender (a calming and sharp scent associated with slowing down in [48, 46, 215]), or as a puff of clean air (control stimulus). Each of these modalities could be explored as a separate condition in a within- or a between-participants study, depending on the driving task (e.g. short task would enable a within-participants study). To extend the knowledge on multimodal interaction, it is also possible to include combined e.g. visual-olfactory, auditory-olfactory, and visual-auditory-olfactory conditions. Our framework is schematically displayed in Figure 10.1.

We suggest evaluating the matching based on the changes of the driving behaviour (e.g. time required to reduce the speed back to the limit, number of speeding events, mean speed, driving time, braking intensity) and performance (lane deviation). In addition to this data, we also encourage collecting the self-report data on the perceived liking and comfort of interacting with each modality.

10.3 Preliminary Study

For an initial exploration, we conducted a preliminary study to see if a Lavender olfactory notification has a positive impact on the slow down time, mean number of speeding events, the mean speed, and the lane deviation. In this study, the driving task included no other traffic and participants were instructed to stay as close to the speed limit as possible, while driving on a motorway.

10.3.1 Study Design

This study followed a 1(scent: lavender)×2(conditions: scent vs no scent)×2(repetitions) within-participants experimental design, composed of two main steps: (1) Familiarisation with the driving simulator, (2) Driving with or without a scent notification delivered every time the speed limit (70mph/112.654km/h) is exceeded (i.e. two repetitions with a scent and two without). The conditions were randomised and counterbalanced using the Latin square.

10.3.2 Setup and Procedure

For this study, we have assembled and used the scent-delivery device and the olfactory interaction room (made of materials that do not absorb scents, equipped with an air extractor) proposed in [45]. To create a feeling of being seated in a real vehicle, we have used a driving simulator seat from FK Automotive, with the Logitech G27 steering wheel mounted on it. We have used the OpenDS driving simulator software displayed on a 55” curved screen with 60Hz refresh rate. The source code of this software (in Java) was integrated with functions that we wrote to control the scent-delivery device.

Figure 10.2: Participant sitting in the driving simulator, inside the olfactory interaction space.

The output of the scent-delivery device was located behind the steering wheel and pointed towards the participants' face (as in [48]). The distance from the output to the face depended on how each participant adjusted their seat. We measured this distance using an ultrasound sensor located just under the scent-delivery nozzle and the mean distance among all participants was 48.95cm (*SD*= 6.52). Participants wore headphones playing the engine sound, which was cancelling any potential sounds elicited by the scent-delivery (30 dB) or the noise around the experimental space (see Figure 10.2).

In two trials out of four, the scent of lavender was delivered to the participants' noses every time the driving speed reached 72mph (115.873km/h) or more. The tolerance of 2mph (3.219km/h) was introduced to avoid potential frustration caused by going above the limit insignificantly.

In the other two trials, there were no olfactory notifications involved, and the participants were instructed to rely on the speedometer visualised on the bottom-right corner of the screen to check if they were not above the speed limit (just like drivers do on the real road). Before each trial, participants were instructed about which notifications they would receive and in what situations.

Every trial finished automatically when the participants had driven one full lap, which took 2-3 minutes. The trial was restarted in case of a crash (only one participants crashed in one of their trials).

The experiment finished with a questionnaire on the overall experience and the demographic data of the participants, followed by the debriefing. Overall, the study took about 30 minutes. This study was approved by the Cross Schools Research Ethics Committee of the University of Sussex.

10.3.3 Results

This subsection summarises the results of the of the preliminary study described above. The results represent the participants' driving behaviour, by analysing how long it took them to reduce the driving speed back to the limit, how many times they exceeded the speed limit per trial, and what was their mean driving speed.

10.3.3.1 Participants

A total of 21 participants, with a mean age of 31.05 years (*SD*= 6.30, 10 females) volunteered for this study. Their mean driving experience was 10.17 years (*SD*= 6.16). Participants have reported having no olfactory dysfunctions, adverse reactions to strong scents, respiratory problems, or flu, and not being pregnant. All participants expressed their written consent before the start of the experiment.

10.3.3.2 Driving Data

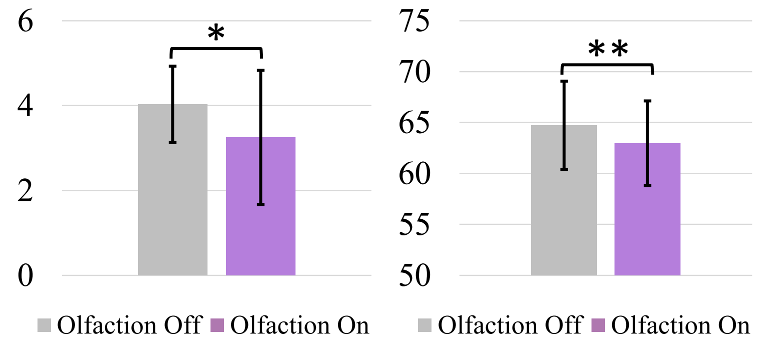
We have performed a two-way repeated measures ANOVA test to compare the driving data collected with and without the olfactory notifications presented to the participants to indicate the speeding event. We will call these conditions: "olfaction on" and "olfaction off" modes.

When receiving olfactory notifications, participants have reduced the speed significantly faster ($F(3, 18) = 10.519, p < .001; Wilks' \lambda = .363$) than without such notifications. It took them $M = 5.34s$ ($SD = 1.79$) to return the car's current speed back to the speed limit in the "olfaction off" mode, but only $M = 3.09s$ ($SD = 1.60$) in the "olfaction on" mode (see Figure 10.1c).

The participants have also exceeded the speed limit fewer times (on average, per trial) in the "olfaction on" ($M = 3.25, SD = 1.58$) than in the "olfaction off" ($M = 4.03, SD = .90$) mode (see Figure 10.3a), which was a statistically significant difference ($F(3, 18) = 3.304, p < .05; Wilks' \lambda = .645$).

To assess the participants' driving performance, we have captured the lane deviation (distance from the centre of the lane in cm). In the "olfaction on" mode, it was lower ($M = 35.80cm, SD = 6.40$) than in the "olfaction off" mode ($M = 37.74cm, SD = 11.02$), but the difference was not significant.

The results also show that with the olfactory notifications, the participants drove significantly slower ($F(3, 18) = 6.675, p < .01; Wilks' \lambda = .473$). The mean speed in the "olfaction off" mode was $M = 64.73mph/104.17km/h$ ($SD = 4.33mph/6.97km/h$), whereas



(a) Mean number of speeding events (b) Mean speed (mph)

Figure 10.3: Driving behaviour data of the "olfaction off" (no olfactory notifications) and the "olfaction on" (with olfactory notifications) conditions: (a) Mean number of times the participants have exceeded the speed limit in each trial, (b) Mean speed in mph ("olfaction off": *M= 104.17km/h* (*SD= 6.97km/h*); "olfaction on": *M= 101.34km/h* (*SD= 6.70km/h*). Error bars, ± SD, $*p < .05$; $**p < .01$

in the "olfaction on" mode it was *M= 62.97mph/101.34km/h* (*SD= 4.16mph/6.70km/h*). These results are presented on Figure 10.3b.

10.4 Conclusion and Future Work

This paper is the first to propose an approach for validating a mapping between scents and driving-relevant notifications. There have been multiple proofs of concepts demonstrating the effectiveness of olfactory stimulation in the automotive context, but none of those indicates a clear procedure for making sure the initial mapping (e.g. as in [48]) is valid considering such driving behaviour measures as lane deviation, mean speed, and the time required to recover from error. Our initial preliminary study demonstrates how such measurements can be taken into account for the validation task. In the future, we plan to carry out the study described in the Method section to perform the complete validation of the mapping between the Lavender scent and the "Slow down" notification. Our preliminary study investigated only one scent. However, our framework does not exclude exploring multiple scents to find the best match with the chosen driving-relevant notification. We also propose using a puff of clean air as a control stimulus. The study we have planed for the future, will reveal advantages and disadvantages of using other modalities (visual, auditory, and tactile) compared to the olfactory channel. We propose exploring other modalities to find driving scenarios in which olfactory notifications are most useful.

11 | I Smell Trouble: Using Multiple Scents To Convey Driving-Relevant Information

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Abstract

Cars provide drivers with task-related information (e.g. "Fill gas") mainly using visual and auditory stimuli. However, those stimuli may distract or overwhelm the driver, causing unnecessary stress. Here, we propose olfactory stimulation as a novel feedback modality to support the perception of visual notifications, reducing the visual demand of the driver. Based on previous research, we explore the application of the scents of lavender, peppermint, and lemon to convey three driving-relevant messages (i.e. "Slow down", "Short inter-vehicle distance", "Lane departure"). Our paper is the first to demonstrate the application of olfactory conditioning in the context of driving and to explore how multiple olfactory notifications change the driving behaviour. Our findings demonstrate that olfactory notifications are perceived as less distracting, more comfortable, and more helpful than visual notifications. Drivers also make less driving mistakes when exposed to olfactory notifications. We discuss how these findings inform the design of future in-car user interfaces.

11.1 Introduction

Olfactory interaction has gained a new momentum recently [153]: it has been proposed for wearable technologies [4, 50], VR/AR [168, 34, 79, 143], multimedia synchronisation [140, 196], multisensory theatres [84, 76], and artworks [132, 119, 118, 8], but less so in a context of performing the task of driving [49]. Scent stimulation could be beneficial to reduce the visual overload of the driver [29]. Furthermore, modern vehicles already have some of the hardware necessary for olfactory stimulation (e.g. air compressor).

The sense of smell is the most complex and challenging human sense [13], but at the same time, it is a very powerful interaction medium [106] enabling humans to extract meaningful information [184]. For example, it has been shown that odours trigger automatic and implicit retrieval of mental representations of information related to the object the scent is coming from [29], and enable automatic access to terms semantically related to odours [88]. Moreover, the congruence between visual and olfactory information mediates the activation of crossmodal semantic representations stronger than each sensory modality on its own [184]. Taken together, this research indicates the potential of smell for introducing a new semantic layer into interaction design and the perception of visual information. Here, we investigate to what extent olfactory stimuli can be used for this in the context of driving. To overcome the scent unfamiliarity problem [19, 107, 207], we introduce olfactory conditioning [115] to instruct drivers on the associations between scents and driving-relevant messages.

To guide the investigation of smell for conveying driving-relevant information, we first need to decide what scent-delivery device to use. Based on the specifications of previously designed devices [219, 142, 8, 48] we extracted the following three requirements for the delivery of three different scents in our study: (1) no scent cross-contamination, (2) no lingering, and a (3) delivery distance of ≥50cm (to avoid interference with the steering task). To meet these requirements, we decided to adapt the device of [45].

Secondly, we need to choose the right scents. Previous work has shown the arousing effect of the scents of peppermint and lemon [170, 15] and the calming effect of the scent of lavender [82, 137] in driving contexts and beyond. Since events like short inter-vehicle distance and lane departure can be classified as highly alerting and requiring fast reaction time [48], we decided to assign them to the scents of peppermint and lemon respectively. The event of speeding is often associated with risky decisions and time pressure [67]. For this reason, we assigned it to the calming scent of lavender (i.e. to potentially help the driver calm down).

In summary, this paper demonstrates for the first time (i) the use of olfactory conditioning in the context of driving (to apply the previously established olfactory mapping [48]) and (ii) the exploration of how multiple olfactory notifications influence the driving behaviour. It also discusses (iii) the opportunities for harnessing the sense of smell when designing for the in-car interaction.

11.2 Related Work

The main focus of olfactory research in the automotive context has been on fighting the drowsiness in driving, where the scents of peppermint [66, 157], and lemon [220, 83] helped to keep drivers awake. However, as we are in the early stage of olfactory research in HCI, we can learn and draw upon prior work in psychology and neuroscience. The most relevant findings are tackling the activation of the central neural system [110, 203, 10]. We build on this work for the investigation of olfactory interaction in a visually loaded automotive context.

Previous findings in psychology particularly show the arousing (see [15], [170], [97]) and relaxing (see [137], [125], [89], [65]) effects of different scents on humans, which is very important to consider in the design of interactive olfactory interfaces. This prior work indicates the potential to convey informative messages to a person (i.e. alerting scents for alerting notifications).

To overcome unfamiliarity with the medium [19, 107, 207] and to let the driver know the meaning of each scent, we propose the use of olfactory conditioning suggested by [115]. We can differentiate between the long- and short-term memory training. Long-term memory training takes 12-18 weeks and requires participants to sniff scents for 5-15s each, two times a day. Examples of such studies can be mainly found in therapeutical contexts [94, 72, 37]. Short-term memory training takes less than 10 minutes. Examples for that have been demonstrated in motion perception [115], chemosensory [194], and verbalisation [104] studies.

To ensure the effectiveness of olfactory conditioning, a success rate needs to be set, which is challenging to define. In long-term olfactory memory studies, there is a well-established training and test procedure [72, 113]. In the research on short-term olfactory memory, different approaches assess participants' performance differently. However, the common success rate is >60% [104].

In olfactory studies, it is crucial to select the right scent-delivery device. Funato et al. [66] has classified such devices as "fixed" and "wearable". Wearable devices are very compact [4, 50], but Funato et al. also points out a very important argument against wearables in the car, namely, their potential to interfere with the driving task (driver's hand movements). For this reason, fixed position devices are more suited for the car-driver interaction. There are several prototypes of this kind (e.g. [219, 7, 150]), but they do not satisfy our three main requirements (no scent cross-contamination, no lingering, ≥50cm delivery distance). So, we decided to adapt the device of Dmitrenko et al. [45].

11.3 The Study

Here, we describe the setup and the procedure of our study. We ran a within-participants study to explore the effect of three notifications ("Slow down", "Short inter-vehicle distance", and "Lane departure") conveyed either as visual only or combined visual-olfactory stimuli (two conditions). The scents of lavender, peppermint, and lemon were used accordingly. The order of the two conditions was randomised.

11.3.1 Setup

The experiment was set up in a dedicated olfactory interaction space, built out of materials that do not absorb scents. It also has a powerful air extractor (*Torin-Sifan DDC270-270, 550W, 4 pole, 1 speed, 230V, 50Hz, 1 phase*, as per [45]).

Participants were sitting in a driving simulator seat (*FK Automotive*) equipped with the *Logitech G27* steering wheel in front of a curved screen (55", 60Hz refresh rate), on which the first-person view from the driver's position was rendered. We used the *CityCarDriving 1.5* simulator software for this purpose, which was chosen due to its support for left-hand driving and traffic rules. The following text was displayed on the right side of the screen (see Figure 11.1): "Comply with the speed limit" (if the participant exceeded the speed limit, e.g. 110km/h on motorway), "Increase the distance" (if the inter-vehicle distance was too short, <10m), "Right/Left turn signal not used" (in the case of a lane departure).

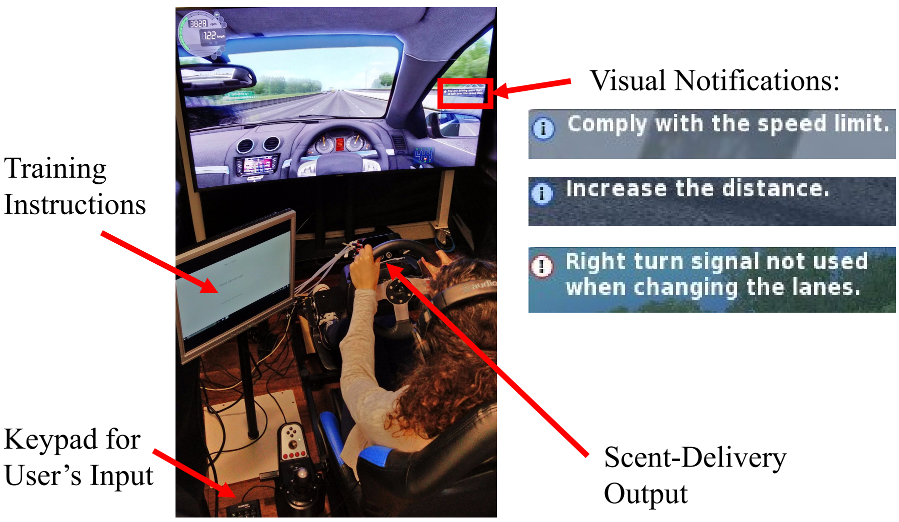

Figure 11.1: Setup of the driving simulator in the olfactory interaction space with a participant.

The olfactory conditioning and test instructions were presented to the participants on a second screen (17”, 60Hz refresh rate) located left of the steering wheel (see Figure 11.1). Participants gave their responses to the questions using a numeric keypad located under the second screen.

We presented the scents in an automated way, adapting a custom-made and fully controllable scent-delivery device [45]. The device delivered the scented air from a tank of compressed clean air. The clean air was propelled through glass jars (using plastic tubes of 4mm in diameter) containing 6g of 100% pure essential oils (*"miaroma"* essential oils from *Holland & Barrett Int. Ltd.*) of lavender (*Lavandula officinalis*), peppermint (*Mentha arvensis*), and lemon (*Citrus limon*) with an air pressure of 0.5 bar, in order to diffuse the scent into the delivered air. The scent-delivery output was located behind the steering wheel and pointed towards the participant’s face. The distance from the output to the face was 38-68cm (M= 50.67, SD= 7.73), depending on how participants adjusted their seat. We measured this distance using an ultrasonic transceiver located just under the output. The flow of air was controlled using electric valves and an Arduino board connected to a computer [45]. Participants wore headphones, playing the sound of the driving simulator, to cancel any external sounds (noise made by the scent-delivery device was 30dB).

11.3.2 Procedure

Upon arrival, participants were given an olfactory screening sheet, the information sheet, and a consent form to sign.

11.3.2.1 Step 1: Olfactory Training and Testing

The experiment started with a single session short-term olfactory memory training procedure (see [194]) followed by a test. We presented all three notifications one-by-one (three times each) in a randomised order (based on the Latin square) for 19s each, where the scent was delivered for the first 5s [45]. For the test, each scent was delivered three times again. After each delivery, participants were asked which notification is the current scent associated with. They responded to these questions using a keypad. If they answered at least six questions out of nine (>60% [104]), they were asked to proceed with the driving task. Otherwise, they were asked to repeat the training. The total of three attempts were given for the participants to score six correct answers. If they failed all three attempts (not occurring in our study), the experiment finished without the driving phase. This step took six minutes without repetitions (in the case of making three or more mistakes).

11.3.2.2 Step 2: Driving Phase

The driving started on a motorway and participants were instructed to drive in any direction, following the traffic rules. We split the nine minutes long driving phase into three chunks (three minutes each). For the first three minutes, participants were given a chance to familiarise themselves with the driving simulator and no data about their driving behaviour was recorded at this stage.

After the first three minutes, we started recording the occurrences of the "Slow down", "Short inter-vehicle distance", and "Lane departure" notifications, which were displayed as text for three seconds (on the right side of the screen, see Figure 11.1) each time participants committed the corresponding driving mistake. At the start of the experiment, participants were instructed on where the visual notifications would appear on the driving simulator's screen and for how long (no participants reported having missed the visual notifications). The method of counting the number of mistakes to quantify the driving behaviour has already been successfully employed in the past [102, 101, 60]. For either the second or the third chunk of three minutes (randomised order), visual notifications were also accompanied by the corresponding scent (lavender, peppermint, or lemon). There was a break of 19s used between scent deliveries (as per [45]) to avoid scent habituation. The driving phase finished with a "Please stop driving" message displayed on the second screen.

11.3.2.3 Step 3: Post-Experiment Questionnaire

When the driving task was finished, participants were asked to complete a self-report questionnaire. It contained questions on how distracting, helpful, and comfortable the visual and olfactory modalities were, as well as how much the participants liked each of the two modalities. The responses were provided on a 7-Point Likert scale (1= "Not at all", 7= "Very much"). The study took 15-20 minutes in total.

11.4 RESULTS

In this section, we present the results of the olfactory test, the driving behaviour evaluation, and the self-reported perception of the visual and olfactory notifications.

11.4.1 Participants

A total of 22 participants (22-43 years old), with a mean age of 31.33 years (*SD*= 5.81, 8 females) volunteered for this study. Participants' driving experience varied between 1 and 28 years (*M*= 9.52, *SD*= 7.91). One participant did not complete the study due to motion sickness and was excluded from the data analysis. Participants have reported having no olfactory dysfunctions, adverse reactions to strong smells, respiratory problems, or flu, and not being pregnant. They were recruited on an opportunity-sampling basis. The study was approved by the local university's ethics committee. All participants expressed written consent.

11.4.2 Olfactory Test

Only one of the 22 participants had to repeat the training procedure to complete the olfactory test with a >60% success rate. All the other participants completed the olfactory test in their first attempt. 76% of participants assigned the scents to the correct messages with no or only one mistake (half of them made one mistake), 10% of the participants made two mistakes, and 14% three.

11.4.3 Driving Behaviour Data

We performed a dependent t-test for paired samples to analyse the number of mistakes the participants made in the process of driving, when receiving visual and combined visual-olfactory notifications (see Figure 11.2).

Participants had significantly fewer instances of exceeding the speed limit (*t(20)= 4.552, P<.001*) when receiving visual "Slow down" notifications accompanied by the scent of lavender (*M*= 4.44, *SD*= .39), than in the case of visual-only notifications (*M*= 7.71, *SD*= .83). They also made significantly fewer mistakes of a short inter-vehicle distance (*t(20)= 4.027, P<.01*) when receiving the corresponding visual notifications accompanied by the scent of peppermint (*M*= 1.41, *SD*= .10), than in the case of visual notifications only (*M*= 2.53, *SD*= .26). Finally, the same effect was observed for the "Lane departure" notification, where participants made significantly fewer mistakes (*t(20)= 7.802, P<.001*) when receiving visual notifications combined with the scent of lemon (*M*= 1.27, *SD*= .07), than in the case of visual notifications only (*M*= 3.07, *SD*= .22). These findings (summarised in Figure 11.2) demonstrate a clear advantage of using olfactory stimuli in combination with visual notifications.

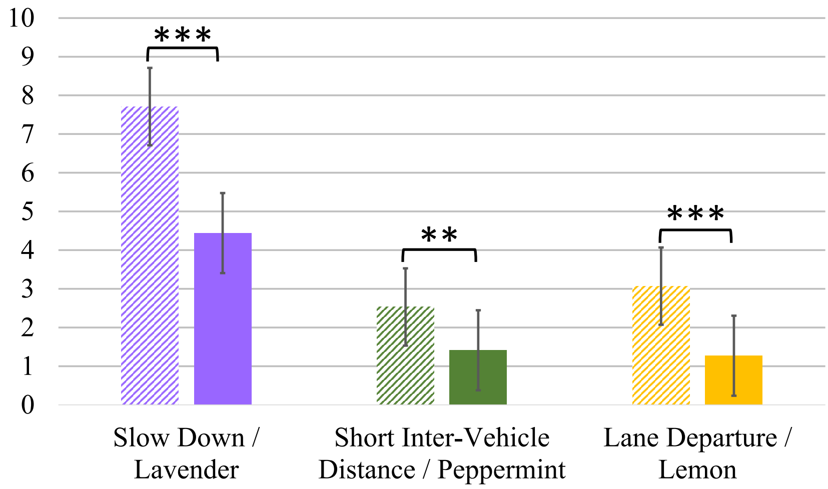

Figure 11.2: Mean number of mistakes made by the participants of the study in the process of driving. Striped bars represent the driving phase in which participants received visual notifications and solid bars represent the driving phase with visual-olfactory notifications. Error bars, ±s.e.m., $**p < .01$; $***p < .001$

11.4.4 Self-Report Data

We performed a dependent t-test for paired samples to analyse the perceived levels of distraction, helpfulness, liking, and comfort of the visual and olfactory modalities experienced in the process of driving (see Figure 11.3).

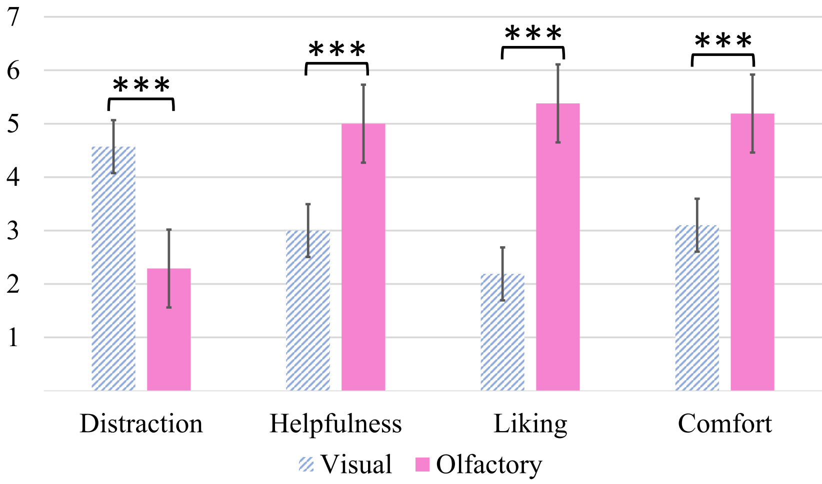

Figure 11.3: Mean ratings of distraction, helpfulness, liking, and comfort of the visual and olfactory modalities (1= "Not at all", 7= "Very much"). Error bars, ± s.e.m., $***p < .001$

The olfactory modality (*M*= 2.29, *SD*= 1.45) has been reported significantly less distracting (*t(20)= 5.510, P<.001*) than the visual modality (*M*= 4.57, *SD*= 1.78). Participants also found the olfactory modality (*M*= 5.00, *SD*= 1.14) more helpful (*t(20)= -5.477, P<.001*) in understanding the notifications than the visual (*M*= 3.00, *SD*= 1.87). Moreover, the olfactory modality (*M*= 5.38, *SD*= 2.19) was liked significantly more (*t(20)= -7.345, P<.001*) than the visual modality (*M*= 2.19, *SD*= 1.40). Finally, the olfactory modality (*M*= 5.19, *SD*= 1.25) was perceived significantly more comfortable (*t(20)= -4.298, P<.001*) than the visual (*M*= 3.10, *SD*= 1.64).

11.5 DISCUSSION

This paper is the first to demonstrate the use of olfactory conditioning to instruct drivers which olfactory notification is assigned to which driving-relevant message (based on the conditioning procedure of [115]). The results show that all participants were able to correctly assign at least six scents out of nine (in line with prior work achieving >60% success rate [104]).

Moreover, the driving behaviour data shows that participants made significantly less mistakes when receiving visual-olfactory notifications. This is in line with previous findings on the positive effect of ambient scents on performing the driving task (e.g. lemon scent promoted better braking performance in [130]). Such results suggest that scents are a promising notification modality in the car.

Furthermore, in our study, olfactory feedback was perceived less distracting, more helpful, and more comfortable than the visual notifications alone. The olfactory modality was also liked more than the visual. This might be because visual notifications were not salient enough. However, the findings on scents match the current automotive trends regarding the wellbeing in the car (e.g. like in a new Mercedes-Benz [35], Bentley [18], or BMW [20].

The driving simulator software we have used does not allow customisation of visual notifications. Results might change if different visual stimuli (e.g. icons) and in a different location on the screen are used. However, there is evidence that the olfactory feedback in combination with the visual information can help us become more aware of notifications without the need to shift our attention. Understanding crossmodal integrations can enable better design of in-vehicle notification systems. More studies on multimodal in-car interaction (e.g. like [164]) should be carried out.

Although olfaction is related to many constraints, including interpersonal and cultural differences, health issues (e.g. adverse reactions to certain scents), and ventilation, our findings underline the benefits of the olfactory modality. When the olfactory stimulation is applied, controlling the delivery parameters [45], we can achieve both a better interaction performance and a better user experience. Such a finding is very important for the design of in-car user interfaces.

11.6 Conclusion and Future Work

The findings of our user study suggest that (when scent-delivery parameters are controlled) olfactory notifications can, not only increase our hedonic experience, but also act as a non-distracting, helpful, and comfortable interaction modality. Moreover, olfactory feedback has the potential to improve our driving behaviour, giving us hints we could have missed when relying on visual stimuli only (e.g. in cases of exceeding the speed limit, short inter-vehicle distance, and lane departure).

Future research can now start investigating scents for more complex driving tasks (e.g. overtaking slower vehicles [121]) and other notifications (e.g. "Traffic jam ahead"). It is also worth exploring olfactory notifications in the presence of a secondary task (e.g. using a radio or a touchscreen [147]) and in combination with other visual (e.g. ambient lights [123]) and auditory [27] stimuli. Finally, studies in a real car interior would demonstrate the effectiveness of olfactory notifications in the presence of other ambient scents and scent absorbing materials.

12 | S(C)ENTINEL - Monitoring Automated Vehicles With Olfactory Reliability Displays

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Abstract

Overreliance in technology is safety-critical and it is assumed that it could have been a main cause of severe accidents with automated vehicles. To ease the complex task of monitoring vehicle behaviour in the driving environment, researchers have proposed to implement uncertainty displays. They allow the driver to estimate whether or not an upcoming intervention is likely. However, presenting uncertainty just visually adds more workload on drivers, who might also be engaged in secondary tasks. We suggest to use olfactory displays as a potential solution to communicate uncertainty and conducted a user study (N=25) in a driving simulator. Results of the experiment comparing both objective (task performance) and subjective (technology acceptance model, trust scales, semi-structured interviews) measures suggest that olfactory notifications could become a valuable extension for calibrating trust in automated vehicles.

12.1 INTRODUCTION

Trust in automation is an important topic for a safe use of automated driving systems (ADSs) [216]. According to the classification of autonomy levels as proposed by SAE [33], ADSs currently available on the market mainly operate on level 2. Here, the driver is fully responsible for monitoring the vehicle's actions and thus the overall safety. However, recent events (such as the fatal crash of a Tesla driver in May 2016, but also less critical situations) indicate that many drivers utilising such systems tend to overtrust them, and do not properly monitor ADSs even in scenarios they were not designed for [206]. This is especially dangerous when systems seem to work flawlessly for a long time and in varying situations [58]. Since monitoring is a challenging task, even for *"highly motivated human beings"* (irony of automation [12]), researchers have proposed to use so-called "reliability/uncertainty displays", that have shown to provide benefits in both level 2 [17] and level 3/4 automated driving (AD) [78]. Such displays are able to reduce the chance of mode awareness failures while increasing situation awareness as well as system transparency, and thereby ultimately lead to better calibrated trust [149]. They present the actual system reliability (or uncertainty, what is the inversion of reliability, but still follows the same concept - which kind of information works better is still an ongoing research [149]) to the user to adjust his/her monitoring behaviour.

However, especially when drivers are visually engaged in secondary tasks, such displays can merely act as "proxy" for the system state – instead of monitoring the vehicle and the environment itself, the driver has to frequently inspect the display, what still demands his/her visual attention. Since future intelligent and multimodal user interfaces should adapt to different types of users [159] while using the full range of human interaction and communication capabilities [198], we claim that there is a need to evaluate other modalities for communicating reliability information. A potential modality in this regard could be the sense of smell, that, in contrast to other typical approaches (such as haptics [116] or auditory cues [114]), is still widely unused, but provides some unique advantages: The sense of smell is a very powerful interaction medium [106] enabling humans to extract meaningful information [184]. For example, it has been shown that odours trigger automatic and implicit retrieval of mental representations of information related to the object the scent is coming from [29], and enable automatic access to terms semantically related to odours [88]. Moreover, scents can be very efficient in activating the central neural system [110, 203, 10], which is essential to keep the driver alert and more attentive on the road [170]. Scents can also act as an arousing (e.g., when the driver is tired or inattentive [220, 66]) or as a calming (e.g., when the driver is stressed [137, 89]) stimulus. In future automated vehicles (AVs), classical perception channels (i.e., visual and auditory) will often be occupied by secondary tasks (such as watching a video, what demands both visual and auditory attention), while olfactory notifications have proven to be a valid way to gain user's attention [19]. Consequently, to the best of our knowledge, our study (see Figure 12.1) is the first experiment including olfactory notifications for trust calibration in AD.

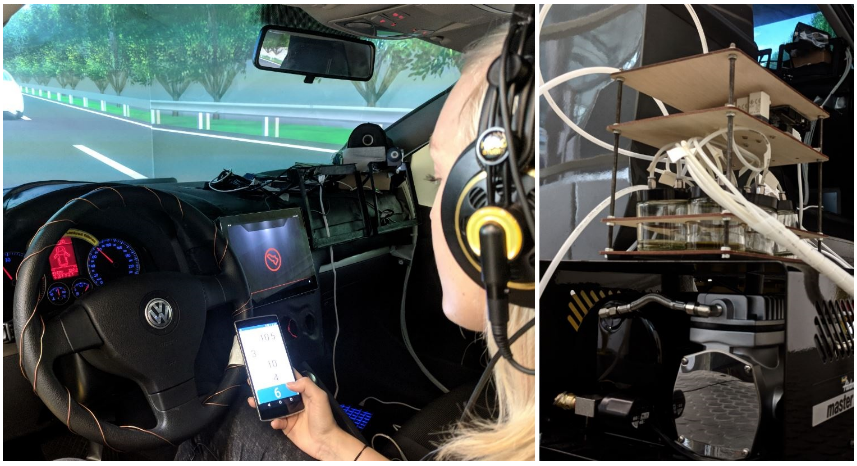

Figure 12.1: Study setup: Participants had to frequently intervene by actuating the brake pedal in case the automated longitudinal system fails (low reliability indicated on the central in-vehicle display), while performing a detection-response task on a smartphone (left). To hide the activation sound of the olfactory device (located outside the vehicle, right), we used noise-cancelling headphones for the sound output of the driving simulation.

12.2 Related Work

Trust in automation can be defined as *"the attitude that an agent will achieve an individual's goals in a situation characterised by uncertainty and vulnerability"* [122], and is a complex construct built by analytic, analogical, and affective processes before (dispositional trust), during (situational trust), and after (learned trust) direct system interaction [87]. To foster safe use of automated systems (and thereby prevent both disuse and misuse [160]), users should adjust their subjective trust levels to fit *"an objective measure of trustworthiness"* (*"calibration of trust"* [139]). Reliability/uncertainty displays should assist in the process of trust calibration (especially to account for the problem of overtrust) by providing decision aids that allow users to estimate an automated system's performance in a given situation [61].

Important groundwork in the domain of AD is the study conducted by Beller, Heesen and Vollrath [17], who demonstrated the potential of a binary reliability display for AVs in a dual-task experiment. Since then, various papers have addressed reliability/uncertainty displays in the driving domain. Helldin et al. could show that such displays can also improve performance and comfort in Take-Over scenarios [78]. Recent studies have addressed potential metrics and design approaches for in-vehicle displays [149], but also augmented reality [117], or less obtrusive modalities such as haptics [116]. The presentation of different levels of reliability/uncertainty became more and more fine grained in these experiments, aiming to provide drivers more detailed information about the system state. However, a problem reliability displays share with any warning information is that, if (due to an offensive warning strategy) users face too many false alarms, they might simply ignore them ("cry wolf effect" [24]). Considering vehicle safety, drivers already seem to often ignore warning lights in vehicles [92]. As in the near future more and more potentially safety critical systems will be operated by everyday consumers [216], overtrust/overreliance is widely debated in the field of robotics [206] and AD [204]. For example, in a recent series of simulator studies conducted by Volvo, nearly 30% of drivers crashed in a provoked accident scenario, despite hands on the wheel and eyes on the road, and the authors conclude that more research is necessary to find out how system limitations can be communicated to drivers more effectively [204]. We claim that olfactory notifications could benefit the driver in such situations, as smell is a sense with a strong emotional component [56, 81, 4].

For example, Baron and Kalsher [15] proved that the scent of lemon increases alertness and the mood of the driver. The emotion-eliciting effect of scents is particularly useful in inducing mood changes because they are almost always experienced clearly as either pleasant or unpleasant [56]. For instance, Alaoui-Ismaïli et al. [2] used scents of vanillin and menthol to trigger positive emotions in their subjects (mainly happiness and surprise), as well as methyl methacrylate and propionic acid to trigger negative emotions (mainly disgust and anger). The scents of lemon, peppermint, rose, and lavender have been shown as efficient in improving the hedonic experiences of the user [48, 46, 168], whereas lemon and lavender have also demonstrated to be a good medium of conveying useful information in the context of driving and beyond [49, 46, 129, 23, 50]. On this aspect, it is essential to keep olfactory stimuli synchronised with other modalities [140]. Further, scents have already been proven to have a positive impact on driving performance/behaviour. Martin and Cooper [130] showed that the scent of lemon can improve drivers' braking performance, while Dmitrenko et al. [46] demonstrated that the scents of lemon, peppermint, and lavender could help to reduce the number of errors. Further, scents of peppermint, rosemary, eucalyptus and lemon have been proven to be useful for keeping drowsy drivers awake [220, 66, 157, 83]. Scents could also help to remind drivers on certain driving-relevant activities, as the sense of smell is known to have a strong link with memories [179, 80, 23].

12.3 DRIVING SIMULATOR STUDY

To find out if olfactory displays can ease monitoring for drivers and thus provide a valuable extension of visual reliability displays, we conducted a dual-task study in a driving simulator. Participants had to drive in a semi-automated (level 2) vehicle while performing a detection-response task (DRT) on a smartphone (see Figure 12.1). To counter potential criticism of our experimental setting (smartphone usage or engagement in secondary tasks is strictly forbidden at level 2 driving in most countries), we want to emphasise that (1) many drivers engage in side activities (for example on mobile devices) despite given legislation [217], and (2) if successful, the underlying concept can be easily adapted to other levels of automation (for example to improve Take-Over requests [78]) or even different safety-critical systems.

12.3.1 Method

Although recent studies on reliability displays often presented multiple levels [117, 149], we chose to utilise a binary display because of two reasons. First, we believed that for an initial evaluation, drivers should not need to distinguish between multiple levels of uncertainty, and second, we wanted to shift the principle from reliability to "responsibility". Currently, drivers utilising ADSs remain the responsible control authority any time. However, to make AD successful in the future, vehicle manufacturers must start taking over responsibility for their vehicles' actions when driving in automated mode (this is a precondition to achieve driving automation above level 2 [33]). Thus, the binary display utilised in our study indicates either, that the vehicle itself takes over full responsibility for the dynamic driving task (green colour, see Figure 12.2), or that the driver him/herself is responsible in case system reliability drops, indicating that a manual intervention is likely (red colour, see Figure 12.2).

While performing the DRT, drivers had to monitor and intervene (if necessary) in the longitudinal control system of the AV. Participants could thereby rely on the given

Figure 12.2: Visual design of the utilised binary reliability display (left: high system reliability, right: low system reliability).

reliability information – as long as reliability was high (green), no manual intervention is necessary, in case of low reliability (red) a system malfunction is likely to occur. Drivers thus had to succeed in two tasks: (1) performing the DRT while (2) monitoring/intervening in longitudinal control of the vehicle. In randomised order, participants thereby faced the following conditions:

- ***Baseline* Condition**: No information about the longitudinal system's performance is presented, participants had to manually adjust their monitoring behaviour.
- ***Reliability* Display**: The reliability for longitudinal control is presented to the user in form of a classical, binary reliability display.
- ***Olfactory*-supported Reliability Display**: In addition to the visual information, an olfactory notification will be issued in case the reliability display changes its status (high to low and vice versa). Drivers thus can keep their visual attention on the DRT until they perceive the olfactory stimulus.

12.3.2 Measurements and Research Questions

For statistical investigation we conducted the following measurements: performance in the DRT (true and false positive rate), braking behaviour/overrides of the longitudinal control system (number of manual interventions, average brake duration, and intensity), as well as subjective scales addressing user acceptance and trust. Therefore, we utilised the trust scale (TS) by Jian et al. [103] (which is widely used among trust researchers and provides sub-scales for both trust and distrust), and the Technology Acceptance Model (TAM) proposed by [38] (that assesses a user's intention to actually use a given system, determined by his/her perceived ease of use, perceived usefulness, and attitude towards using [it] [38]). Since product usage leads to positive/negative emotions [40], and odours have a strong emotional component [4], we also wanted to find out if the presented interface affects participants' emotional response. Therefore, we utilised the Positive/Negative Affect Scale (PANAS, [209],). Additionally, we conducted semi-structured interviews (assessing their perception of the system, potentially changed behaviour, etc.) with all participants after the experiment. By statistical investigation we wanted to answer the following research questions:

- **RQ1:** Can olfactory notifications increase performance in the driving task (quantified by objective measurements assessing braking behaviour)?
- **RQ2:** Can olfactory notifications increase side activity performance (detection-response task, quantified by true/false positive rates)?
- **RQ3:**How are olfactory notifications trusted and accepted by potential users in comparison with visual or the total absence of reliability displays (quantified by standardised scales such as TAM, TS, or PANAS)?

12.3.3 Driving Task

We implemented our driving scenario on the basis of Beller et a. [17], where drivers monitored an adaptive cruise control system. In our setting, participants were driving on the left lane of a straight 2-lane highway segment with 120km/h. Every 30s, the AV encountered a lead vehicle with a lower speed of just 70km/h, thus the system had do slow down, what was followed by the lead vehicle changing to the right lane (as soon as the ego-vehicle reached the same speed as the lead vehicle). Then, the ego-vehicle could accelerate again and continue driving with 120km/h for roughly 30s, before the next lead vehicle appeared. We alternated phases of ca. 2 minutes (i.e., 4 lead vehicles) in either *high* (all vehicles detected and the AV slows down by itself) or *low* reliability (2 out of 4 cars not detected, where the driver had to intervene and brake manually). Each drive included 24 lead vehicles (roughly 12 minutes duration depending on participants' braking behaviour during the 3 phases with manual interventions) and thus 3 alternating phases of high and low reliability (in randomised order).

12.3.4 Reliability Display and Olfactory Device

To communicate the reliability levels (*low* and *high*) we displayed either a green or red status symbol (see Figure 12.2 prominent on a tablet in the vehicle's center console

(Google Pixel C, see Figure 12.1). The symbol changed after clearing the 4th vehicle of every section in the driving task to the new reliability level (condition *reliability*). In condition *olfactory*, we additionally communicated a change in reliability levels using two odors (lemon for a change to *low* and lavender for a change to *high* reliability). We used these two scents as both of them have been used to convey driving-relevant information in the past [48, 46]. Lemon was chosen for the change to *low* reliability, because it is known to keep the driver alert [15, 170] and to have an arousing effect on users [97]. Lavender was chosen for the switch to the *high* reliability level, because it is known to help drivers become aware of information they could have missed when relying only on visual stimuli [46] and because it is one of the most commonly used relaxing stimuli in olfactory research [137, 10, 125].

We presented these scents in an automated way, adapting a custom-made and fully controllable scent-delivery device (see [45] for design details). The device delivered the scented air from an air compressor (*Revell Masterclass*) attached to an air filter (5 micron filter from *Shako Co Ltd.*). The clean air was propelled through glass jars (using plastic tubes of 4mm in diameter) containing 6g of 100% pure essential oils (*"miaroma"* essential oils from *Holland & Barrett Int. Ltd.*) of lavender (*Lavandula officinalis*) and lemon (*Citrus limon*) with an air pressure of 1 bar. The scent-delivery nozzle (output) was located above the glove compartment, pointing towards the participant's face, approximately 1.5m away from the driver's nose (this distance could be shortened, if required by the application scenario [48]). The flow of air was controlled using electric valves (*Norgren T51P0004* 4mm Inline Non-Return Valves) and an Arduino board [45] synchronised with the driving simulation as suggested by [180]. The scent delivery was working with the vehicle's AC system being constantly on.

12.3.5 Detection-Response Task

For the secondary task we implemented an HTML5/JavaScript application running on a OnePlus One 5.5" smartphone.

On white background, each cell of a 3x3 grid was updated every second randomly showing numbers between 0 and 9 (or no number respectively, see Figure 12.1). Every time the number "6" appeared, participants had to press a large button at the bottom of the screen (once, a second button press was dismissed in this case). To evaluate performance in the detection-response task, we calculated the average response time for true positives, the true positive rate, and the false positive rate.

12.3.6 Procedure

Prior to taking a part in the study, all participants were screened for potential olfactory dysfunctions or adverse reactions to string scents. Upon arrival, participants were given a consent form and the experimenter explained the experiment verbally to participants before starting the driving phase(s). Participants were encourages to ask questions, if anything remained unclear. After a short test drive helping participants to get used to the driving simulator, the experiment started with one of the three conditions (*baseline* – no visual and no olfactory stimuli, *reliability* – with visual notifications involved, or *olfactory* – visual notifications combined with the olfactory stimuli). The order of the conditions was randomised. Each condition lasted about 12 minutes and the switch between the reliability levels took place every two minutes. In the olfactory condition, the scent was triggered simultaneously with the switch between the visual stimuli and was delivered for five seconds. Participants were asked to complete a short questionnaire assessing demographics before the driving phases and the set of standardised scales after each condition. At the end of the experiment, we further conducted a five minutes long semi-structured interview with each participant.

12.4 Results

In total, 25 participants aged between 19 and 38 years ($M = 24, SD = 3.98$ years, 10 female, 15 male) voluntarily participated in the study. Participants have reported to have no olfactory dysfunctions, adverse reactions to strong scents, respiratory problems or flu and female participants confirmed that they are not pregnant. They were recruited on an opportunity-sampling basis. All participants expressed written consent.
In the following, we present the results of our statistical evaluation. Effects are reported as statistically significant if $p < .05$, we used *IBM SPSS* Version 24 and (one way) repeated measures ANOVA (Greenhouse-Geisser in case Mauchly's test for sphericity failed) with Bonferroni correction and respectively Friedman ANOVA, if the data did not follow a normal distribution. A summary of descriptive statistics and evaluation results is presented in Tables 12.1 and 12.2).

12.4.1 Objective Measures

To evaluate the objective measures, we have analysed the driving performance and the secondary task performance.

12.4.1.1 Driving Performance

Considering driving performance, we calculated the number of brake pedal actuations, the average duration, as well as the average intensity of braking actions. All three parameters showed no significant differences between the conditions (see Table 12.1 for descriptive statistics). Friedman ANOVA (test for normal distribution failed) resulted in $\chi^2(2) = .427, p = .080$ for the average number of brake actuations, and in $\chi^2(2) = .250, p = .882$ for the average duration of a braking action. A repeated measures ANOVA (assumptions for normal distribution and data sphericity met) for the average intensity of each braking action did not show significant differences ($F(2,46) = 2.844, p = .068$) as well. However, pairwise comparisons using Bonferroni correction would have shown a difference between the conditions *baseline* and *olfactory* ($p = 0.02$, we report this fact as ANOVA just slightly missed the significance level of .05).

	Condition Mean (SD)			Statistics	
	Baseline	*Reliability*	*Olfactory*	F	Sig (η_p^2)
Braking Behaviour					
No of brakes	15.08 (12.89)	13.67 (5.92)	20.33 (26.89)	-	.808 (-)
Avg. duration (s)	2.91 (2.48)	2.46 (.92)	2.33 (1.01)	-	.882 (-)
Avg. intensity (%)	.52 (.19)	.49 (.18)	.46 (.20)	2.844	.068 (.11)
Secondary Task Performance					
Avg. resp. time (s)	.81 (.10)	.80 (.10)	.80 (.12)	-	.68 (-)
True positive rate	.62 (.09)	.63 (.09)	.65 (.09)	3.496	**.039 (.13)**
False positive rate	.0143 (.004)	.0125 (.005)	.0113 (.003)	4.823	**.013 (.17)**

Table 12.1: Descriptive and test statistics of objective data: braking behaviour (number of brakes, average brake duration, average intensity) and secondary task performance (average response time, true positive rate, false positive rate). In case of missing F-values, Friedman ANOVA was utilised. Significant differences are printed in boldface.

12.4.1.2 Secondary Task Performance

To assess the performance in the detection-response task, we evaluated the average reaction time for true positives, as well as the true and false positive rate (see Table 12.1 for descriptive statistics). Only the reaction time did was not normally distributed, however there were no significant differences applying Friedman ANOVA ($\chi^2(2) = .75, p = .687$). For the true positive rate (TP), we found a significant difference using repeated measures ANOVA ($F(2,46) = 3.496, p = .039$), however post-hoc tests using Bonferroni correction showed no individual differences (if any, conditions *baseline* and *olfactory* were slightly above the significance level with $p = .63$, where *olfactory* showed the highest true positive rate). The false positive rate on the other hand resulted in a significant difference ($F(2,46) = 4.823, p = .013$), where post-hoc tests revealed the origin between conditions *olfactory* and *baseline* ($p = .024$, *olfactory* resulted in the lowest false positive rate).

12.4.2 Subjective Measures

To evaluate the subjective measures, we have analysed the self-report data (using standardised scales, see Figure 12.2) and the interview responses.

12.4.2.1 Standardised Scales

Reliability analysis showed acceptable values for Cronbach's alpha (above .722 or higher) for all sub-scales, thus we were able to calculate mean scale values.

Considering the trust scale from Jian et al. [103], we found significant differences for both sub-scales of trust and distrust (average of the respective scale items). Distrust significantly differs with respect to the conditions (Greenhouse-Geisser since failed precondition for sphericity, $F(1.606, 38.550) = 18.508, p < .001$). Post-hoc analysis using Bonferroni correction showed differences between the conditions *baseline* and *olfactory* ($p < .001$), as well as *reliability* and *olfactory* ($p = .001$), but not between *baseline* and *reliability*. Contrarily, in the sub-scale trust ($F(1.454, 34.891) = 22.725, p < .001$), both conditions *olfactory* ($p < .001$) and *reliability* ($p = .001$) significantly differed from the *baseline*. However, no difference between *reliability* and *olfactory* was present here.

In the Technology Acceptance Model (TAM), we were able to find significant differences in all sub-scales. Perceived ease of use (PEOU) significantly differed in the result of the repeated measures ANOVA (Greenhouse-Geisser: $F(1.428, 34.273) = 37.061, p < .001$). Pairwise comparisons (Bonferroni) revealed that the *baseline* differs to both conditions *olfactory* ($p < .001$) and *reliability* ($p < .001$), while there were no differences between the latter two. Exactly the same result was obtained for perceived usefulness (PU, $F(1.348, 32.349) = 17.272, p < .001$). Also here, only the *baseline* differed to *olfactory* ($p = .001$) and *reliablity* ($p = .001$). Regarding the attitude towards using the system (ATT), all conditions have demonstrated significant differences, $F(1.484, 35.615) = 37.061, p < .001$. Condition *olfactory* was rated as highest and showed differences to *reliability* ($p = .01$) and *baseline* ($p < .001$), but also *reliability* was significantly higher then the *baseline* condition ($p = .018$). Since intention to use the system (INT) does

	Condition Mean (SD)			Statistics	
	Baseline	*Reliability*	*Olfactory*	F	Sig (η_p^2)
Trust Scale					
Trust	1.71 (1.08)	2.99 (1.06)	3.35 (1.26)	22.725	**<.001 (.486)**
Distrust	3.93 (1.40)	3.15 (1.08)	2.28 (0.91)	18.508	**<.001 (.435)**
Technology Acceptance Model					
Perceived ease of use	2.38 (1.28)	4.06 (1.02)	4.21 (0.92)	37.061	**<.001 (.607)**
Perceived usefulness	1.32 (1.22)	2.60 (1.41)	2.91 (1.65)	17.272	**<.001 (.418)**
Attitude towards use	1.92 (1.64)	3.11 (1.42)	3.84 (1.62)	15.232	**<.001 (.388)**
Intention to use	1.44 (1.66)	2.52 (1.61)	3.20 (2.00)	-	**<.001 (-)**
Positive and Negative Affect Scale					
Positive Affect	2.82 (1.10)	2.74 (1.08)	3.07 (1.20)	2.038	.141 (.078)
Negative Affect	2.49 (1.57)	2.24 (1.34)	1.67 (1.34)	6.729	**.003 (.219)**

Table 12.2: Descriptive and test statistics of subjective scales (Trust Scales, Technology Acceptance Model, Positive and Negative Affect Scale). In case of missing F-values, Friedman ANOVA was utilised. Significant differences are printed in boldface.

not represent a scale variable, we utilised a non-parametric test (Friedman ANOVA, $\chi^2(2) = 19.3, p < .001$). Here, pairwise comparisons showed that only conditions *baseline* and *olfactory* significantly differed ($p = .002$) from each other. When looking at the results of the Positive/Negative Affect Scale (PANAS), we could not find any differences regarding positive affect (PA, preconditions for repeated measures ANOVA, as well as data sphericity met, $F(2,48) = .280, p = .869$). The negative affect (NA) on the other hand resulted in significant differences ($F(2,48) = .6.729, p = .003$), where post-hoc tests using Bonferroni correction revealed that condition *olfactory* had significantly less negative affect than *reliability* ($p = .036$) and *baseline* ($p = .02$), while there was no differences between *baseline* and *reliability*.

12.4.2.2 Semi-Structured Interviews

In the interviews, all 25 participants have confirmed that they have perceived the scents used in the experiment. They mainly emphasized the fact that the scents were intense enough to get perceived quickly and that this was helpful. For example, *P19* said: *"The scents were always quite intense in the beginning. It was good, because I could always understand when the switch between the reliability levels took place."* Also, all the 25 participant had experienced neither scent lingering, nor cross-contamination during the driving phase. They particularly liked that the timing of the scent-delivery was spot-on, that the scent disappeared quickly, and matched the visual notifications very well. For example, *P12* said: *"The scents were so succinct that they appeared at the right time and were then gone relatively quickly."*

Scents were also perceived as helpful in performing the task of driving and in monitoring the autonomous system. 20/25 participants had mentioned the scents as helpful in perceiving the change between the reliability levels and as supportive in capturing the visual information displayed in the center console. For example, *P14* said: *"The scents helped, especially when there was no eye contact with the display."*. Moreover, 19/25 participants admitted that they had to monitor the display less thanks to the scents. They argued that they had to look on the display less, could rely on scents, and that their attention was grasped by the scents. For example, *P13* said: *"Thanks to the scents, when I was interacting with the phone, I was sure that with this system I can do anything."*

In terms of usefulness, 18/25 participants also mentioned that they find olfactory interaction generally useful in automotive context, considering that the choice of scents is performed carefully, appropriate training is carried out, and the scent-delivery is well controlled. For example, *P11* said: *"It's a good idea, but you need to be careful about the choice of scents."*, whereas *P13* said: *"It's something brand new! It was very nice! You just need to be careful that not too many scents are used... 2-3 very different scents would be good, I think."*

At the end of the interview, we encouraged the participants to suggest further scenarios, in which they consider olfactory feedback to be effective.

5/25 participants recommended using scents as warnings for such non-urgent notifications as a traffic jam or a bad weather alert, and a low petrol level notification. For example, *P21* said: *"I would use scents when there is enough time, when I can decide what I can take over."*

Another 5/25 participants suggested rather using scents for safety critical notifications (also as a support to visual stimuli), such as ACC, inter-vehicle distance, and vehicles passing by on the left/right. For instance, *P4* said: *"Scents could come when you drive too close to a lead car, when a traffic light goes red, or when a child crosses the road."*

Furthermore, 3/25 participants expressed a wish for scents to convey vehicle diagnosis-related data. *P11* mentioned *"vehicle overheating"*, *P15* an *"oil leak"*, and *P19* generalised this to *"problems with the car"*.

Two participants decided that scents are good for *"take a break"* notifications, e.g. *P7* said: *"It makes sense to use scents in the car, because they make the driver awake."*

Finally, 4/25 participants referred to the well-being of the driver, e.g. *P21* said: *"When I get into the car and it smells nice, it contributes to the comfort, of course."*

12.4.3 Summary of Results

Only the combination of visual and olfactory reliability information (condition *olfactory*) showed differences in driving behaviour (less intensive brake pedal actuations) and secondary task performance (lower false positive rate), while the provision of the visual display only (condition *reliability*) did not result in an improvement compared to the *baseline* drive. In subjective scales (TS, TAM, PANAS) a significant difference was visible for both test conditions (*reliability* and *olfactory*) compared to the baseline in most subscales, while *olfactory* notifications showed significantly less distrust (TS) and negative affect (PANAS), as well as a higher attitude towards using the system (TAM) compared to visual *reliability* information only. Participants' positive attitude towards *olfactory* notifications was further confirmed in semi-structured interviews.

12.5 Discussion

The results of our study provide multiple interesting insights and confirm, in general, the potential of olfactory notifications for trust calibration. Regarding driving behaviour (**RQ1**), a statistically significant difference was only present between the condition *olfactory* and the *baseline* (participants showed less average braking intensity and thus braked "smoother"). This difference is only visible in post-hoc tests, while the overall ANOVA result slightly missed to meet the significance level. Although it is often emphasised that pairwise comparisons should only be conducted in case of significant ANOVA results, there is also the view that pairwise differences can be seen as valid even if the global effect is not significant [93]. However, we believe it is necessary to include a larger sample size to either confirm or reject the observed tendency. In the present stage, our study cannot fully confirm the results of Beller et al. [17] regarding strong significant differences in braking behaviour.

Considering **RQ2**, the combination of visual and olfactory reliability display significantly decreased the false positive rate in the secondary task (visual detection-response task) compared to the baseline condition. There also exist some tendencies that condition *olfactory* resulted in a higher true positive rate as compared to the *baseline* condition (ANOVA result significant but post-hoc not, however Bonferroni is known to be conservative in pairwise comparisons [212]). The provision of a visual reliability display only did not significantly improve secondary task performance compared to the baseline, what highlights the potential of combined visual-olfactory notifications.

Regarding standardised subjective scales assessing trust and user acceptance (**RQ3**), we can report increased trust and acceptance towards olfactory notifications. Condition *olfactory* induced significantly less distrust and received significantly higher attitude towards using the system, compared to visual-only provision of reliability. Also, the provision of *olfactory* cues resulted in a significantly lower negative affect in PANAS, thus this modality was not perceived negatively among study participants. Subjects' positive attitude towards olfactory notifications was further confirmed in interviews.

Our observations are in line with the previous findings on multimodal in-car interfaces, where drivers were shown to perform better when assisted by notifications consisting of multiple modalities (e.g., as per [165, 46]). Study results confirm this in the scope of autonomous driving and trust to automation. Our findings are also matching the evidence found in the fields of psychology and neuroscience, where the sense of smell has been demonstrated as an efficient medium of conveying semantically congruent cues [68].

Still, we do not suggest combining olfactory notifications with other modalities permanently, and we would neither suggest the same for any additional form of reliability display. We rather emphasise that olfactory notifications (as other modes of communication such as haptics [116]) are a valuable extension to be included in intelligent user interfaces. To meet the requirements of time-sensitive in-car notifications, olfactory stimuli could be applied as feedback messages, in cases when visual notifications are likely to be missed [46]. As it cannot be guaranteed that drivers can be reached with any given modality due to their engagement in arbitrary secondary activities (that will vary with respect to the demand of different perceptional channels), future interfaces should become context-aware and thereby take both environmental/operational properties of the situation, as well as personal preferences [159] of different drivers into account.

The National Transportation Safety Board (NTSB) reported that in the fatal Tesla accident in 2016, the driver did not respond to multiple visual and auditory warnings issued by the system prior to the accident. We do not claim that olfactory notifications would have made the difference in this situation, but we want to raise the question: what could have happened, if a strong scent, for example the smell of a broken engine, would have been issued to gain the driver's attention? An answer to this question, as well as when and how the support of olfactory notifications yields the best results, should be addressed in future studies and detailed research. However, our study provides initial insights that highlight the potential of olfactory notifications for trust calibration in automated vehicles.

12.6 LIMITATIONS AND FUTURE WORK

As our findings demonstrate promising tendencies in terms of olfactory enhanced reliability displays, it is worth exploring multiple levels of reliability conveyed by scents in the future. This could be achieved by either using two scents of different intensity levels (e.g., as in [45]) or by extending the range of scents (e.g., as in [48, 46]) and assigning a certain scent to every urgency level (e.g., as in [129]). When working with scents, it is important to acknowledge the subjective element of scent perception. For example, four of our participants said in the post-experiment interview that they did not like the scent of lavender. In the future, it would be necessary to explore customisable olfactory interfaces, allowing participants to select the scent of their preference. Also, as the selection of the scents might not work for everyone and in every situation (e.g., not in case of a flu), it would be a good idea to explore other modalities, such tactile [185, 21] and ambient light [123] interfaces for conveying automation reliability-relevant information. We have tested our olfactory interface in a high-fidelity driving simulator, with a real car interior. Interviews conducted with the participants have revealed no scent lingering or cross-contamination artefacts experienced during the experiments. This suggests that the interface is suitable for the use in a real car. However, this would need to be supported by further studies in the real road environment and for an extended time frame. The location of the scent-delivery nozzle and the interference of the scented airflow with the vehicle's AC (or air coming through an open window) would need to be investigated further. This might include positioning the nozzle closer to the driver's nose (as per [45]) or temporarily replacing olfactory stimulation by other modalities (e.g., touch [185]). On-road studies would also help understand how do drivers feel about using scents over a longer period of time, how their sensitivity to the olfactory stimuli changes over time, and if scents get absorbed by the car's interior on long term. Furthermore, such explorations could reveal the efficiency of the olfactory stimuli in the presence of external scents (e.g., coffee or a dog on the rear seat). In terms of neutralising the delivered scents, it would be useful to investigate different ventilation parameters (as per [45]) and to explore the application of the "olfactory white" [211].

12.7 CONCLUSION

In this paper, we have evaluated the potential of an added olfactory UI in supporting reliability displays for trust calibration (or more precise: to prevent overtrust) in automated vehicles. Results of a driving simulator study (N=25) comparing three conditions (visual reliability display only, visual reliability display supported by olfactory notifications, baseline condition without any reliability information) confirm our assumption that olfactory cues can improve performance in a dual-task setting. We can report tendencies that, with support of olfactory cues, participants showed smoother braking behaviour compared to the baseline condition (quantified as brake pedal actuations during manual interventions in case the longitudinal system of a level-2 vehicle failed). Also, adding olfactory notifications to the visual stimuli resulted in significantly higher performance in the secondary task (visual detection-response task). In addition, this (at least in the context of trust calibration) yet unused modality was subjectively preferred by study participants based on subjective evaluation. Participants rated the system with added olfactory cues significantly better in sub-scales of the Technology Acceptance Model (TAM) [202], the Trust Scale [103], and the Positive/Negative Affect Scale (PANAS) [209]. Participants' positive attitude towards olfactory notifications was further confirmed in semi-structured interviews, where, 80% of the participants stated that olfactory cues are helpful in perceiving a change in vehicle reliability levels. Overtrust is an issue that already led to (even fatal) accidents with automated vehicles [216, 206] and could hinder a success of the automated driving technology. Identifying additional methods to calibrate trust is, thus, timely and important [204]. Olfactory cues could become a valuable asset helping to regain attention of drivers that are engaged in secondary tasks (and thus out of the loop), allowing them to more reliably assess and react to unknown and unexpected circumstances.

13 | CARoma Therapy: Pleasant Scents Promote Safer Driving, Better Mood, and Improved Well-Being in Angry Drivers

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Abstract

Driving is a task that is often affected by emotions. The effect of emotions on driving has been extensively studied. Anger is an emotion that dominates in such investigations. Despite the knowledge on strong links between scents and emotions, few studies have explored the effect of olfactory stimulation in a context of driving. Such an outcome provides HCI practitioners very little knowledge on how to design for emotions using olfactory stimulation in the car. We carried out three studies to select scents of different valence and arousal levels (i.e. rose, peppermint, and civet) and anger eliciting stimuli (i.e. affective pictures and on-road events). We used this knowledge to conduct the fourth user study investigating how the selected scents change the emotional state, well-being, and driving behaviour of drivers in an induced angry state. Our findings help designers make better decisions on what scents to choose when designing interactions for angry drivers.

13.1 Introduction

Drivers may experience a whole range of emotions. Nevertheless, research on emotions and their influence on driving is mainly focused around anger [101, 173, 60]. This is understandable, since anger promotes dangerous driving [53], becoming the key reason for road traffic accidents [77]. Anger leads to more errors [101, 55], stronger acceleration [102, 173], and higher mean speed [173] than e.g. in the neutral state. For this reason, interventions for reducing anger should be a research priority.

No other human sense has such a strong link to emotions as the sense of smell [2]. Scents can improve our mood [81] and help us relax [89]. Car manufacturers (e.g. Mercedes-Benz [35], BMW [20], and Bentley [18]) have already started including olfactory interfaces in their high-end vehicles to increase the well-being of the driver and passengers. Nevertheless, the choice of scents, the elicitation of specific emotions, and the impact of olfactory stimulation on the driving behaviour in these products are unknown. Also, the academic research offers only very few insights on the influence of scents on emotions in the driving process [15, 170]. This issue may lead to designers choosing the wrong scent for a specific type of driving behaviour.

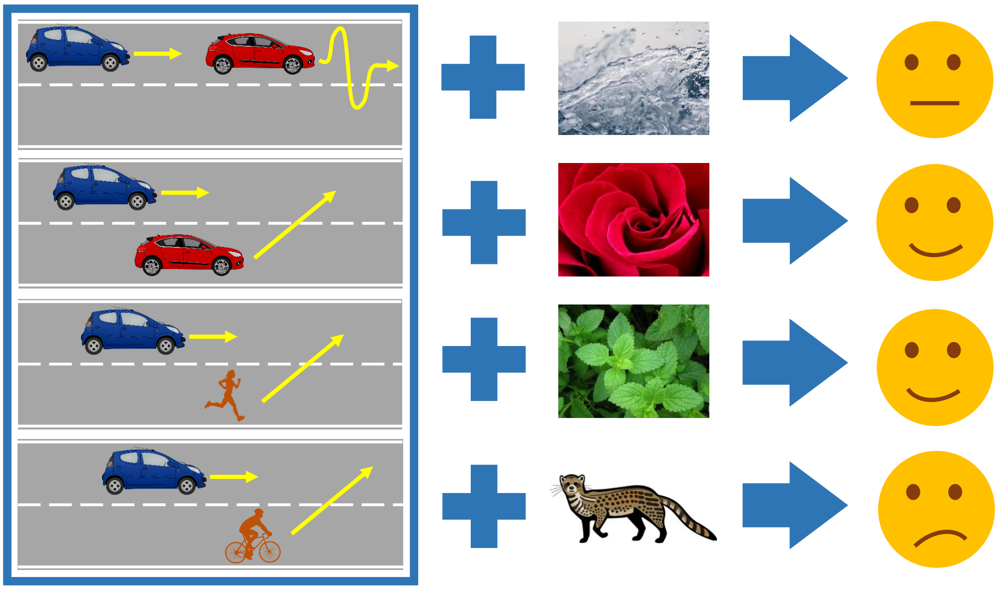


Figure 13.1: After having experienced anger-inducing on-road events (e.g. a car cutting off), drivers describe the valence of their emotional state as neutral in the water (clean air) condition, as positive in the rose and peppermint conditions, and as negative in the civet condition.

To start tackling this problem, we define the following research question: Scents of what arousal and valence levels can reduce the negative emotion of angry drivers? The key contributions of our paper are summarised below:

- Mapping different scents on the arousal/valence circumplex, covering different quadrants of this two-dimensional space.
- Identifications of anger-eliciting IAPS (International Affective Picture System) [120] pictures.
- Identification of anger-eliciting on-road events.
- First empirical evidence for the positive effect of high/low arousal scents on reducing drivers' negative emotions (see Figure 13.1).

13.2 Related Work

We structured the related work around three research areas: (1) emotions while driving, (2) stimulating different senses, and (3) the use of scents while driving. These three areas are presented below.

13.2.1 Emotions While Driving

Following the method proposed by Wilson et al. [214], we looked into the Emotions Circumplex established by Russell [175]. This model helped us gain an understanding of a wider spectrum of emotional labels and their mapping on the four quadrants of the arousal and valence dimensions, to tackle the problem of analysing driver's emotions more efficiently. Anger is an emotions that lies in the "high arousal, negative valence" quadrant. Roidl et al. [173] have found that anger leads to stronger acceleration and higher speed. Jeon et al. showed that anger also leads to more errors [102] and a degraded driving performance [101]. Chan and Singhal [30] demonstrated that distraction charged with negative emotions leads to reduced lateral control and slowed driving speed. Hayley et al. [77] showed that poor emotional control may impede the ability to drive safely. Finally, Eherenfreund-Hager et al. [55] confirmed that the arousing negative affect leads to increased risky driving. This area of research shows how negative emotional states (e.g. anger) are tied to negative driving behaviour. Therefore, minimising these negative emotions is of utmost importance. Olfactory displays are promising for this application due to the strong connection between emotions and scents [2].

13.2.2 Stimulating Different Senses

Prior research on emotions has mainly demonstrated that it is possible to improve the driving performance using visual and auditory stimulation. For example, displaying positive words to participants during the driving resulted in a decreased lane deviation [30]. Drivers who listened to either happy or sad music made significantly fewer errors than those who did not listen to music [60]. It has also been shown that participants drove significantly slower after the music had faded from the front to rear speakers [27].

Positive impact on the driver's emotions can also be achieved by using tactile stimulation. For example, vibrations in the driver's seat have been demonstrated to be less annoying and more appropriate in collision warnings studies [121].

Olfactory stimulation is still little explored [49], despite its potential benefits (e.g. a link to emotions and memories [80]).

13.2.3 The Use of Scents While Driving

Prior studies have revealed that scents can improve drivers' braking performance [130] and have a positive impact on the alertness and emotions of the driver [15, 170]. Moreover, olfactory stimulation has been proven to have a positive effect on keeping drowsy drivers awake [220, 66, 83, 157, 219]. Scents have also been demonstrated to be useful for conveying driving-related information [49, 48, 46].

Initial findings on the effect of scents on drivers' emotions suggest that the scent of lemon results in a significant increment of participants' positive affect [15], and scents of peppermint and cinnamon reduce frustration [170]. Thus far, there are no studies that aim to determine if olfactory displays can be used to reduce negative emotional states while driving. Such a study is, however, essential to help HCI practitioners make informed decisions regarding the choice of scents when designing for driver's emotions.

In summary, while the olfactory interface and experience design, especially in an automotive context, comes with challenges (e.g. confined space, lingering, interpersonal differences [45]), we can build on advances in the understanding of olfaction as an interaction modality [46, 129] and advances in scent-delivery technology [45]. Latest techniques of scent delivery and extraction [48, 45] have shown that it is possible to enable quick detection of scents by the driver (10s), short lingering time (9s), and rapid switching between scents (just 19s is enough to neutralise the previous scent).

In the next sections, we will present the studies conducted to answer the research question. We will start with an overview of the studies and then summarise the process of choosing scents and anger eliciting visual stimuli. We will conclude by explaining how these olfactory and visual stimuli were used to study the participants' emotions, well-being, and driving behaviour.

13.3 Overview of Studies

This paper presents the total of four studies investigating the effects of scents on drivers in an induced angry state:

- **Study 1:** Mapping different scents on the arousal/valence circumplex (i.e. identifying suitable scents).
- **Study 2:** Identifying the anger-eliciting pictures among the negative valence and high arousal IAPS [120] pictures.
- **Study 3:** Identifying anger-eliciting on-road events. Study 2 and Study 3 have been conducted to identify the suitable anger-eliciting stimuli for the main study (i.e. Study 4).
- **Study 4:** Investigating the effects of different arousal and valence scents on emotions, well-being, and the driving behaviour of the participants in an induced angry state.

All four studies were approved by the the Ethics Committee of the University of Sussex. Details of these studies are presented below. All participants were carefully screened to make sure they have no respiratory problems, no scent allergies, no adverse reactions to scents, and that they are not pregnant.

13.4 Study 1: Mapping Scents

We initially conducted an exploratory scent rating study during a public science fair (like in [31]) in which we collected data on valence and arousal of 11 different scents (i.e. black pepper, cedarwood, eucalyptus, juniper, lemon, patchouli, peppermint, pine, rose, vanilla, and ylang-ylang). However, as the results of this study were not conclusive (i.e. no strict borders between valence and arousal quadrants) and not from a lab-based exploration, we decided to validate them in Study 1.

The aim of Study 1 was to validate the mapping of the scents of rose, peppermint, and patchouli on the valence and arousal quadrants. To add a “negative valence, high arousal” scent, we included a civet scent (fragrance oil from *Plush Folly Ltd*) [16].

The idea of this study was not to select specific scents but to pick one scents from each cluster of scents (i.e. arousal and valence quadrant) for further investigation.

13.4.1 Design

We conducted a within-participants study asking the participants to rate four scents (peppermint, rose, patchouli, civet).

13.4.2 Setup

Participants sniffed the scents from identical bottles located on a table. Each bottle contained 10ml of essential oil. They sniffed each bottle for 2s, with intervals of 20s (the way it was done in [109, 200]).

13.4.3 Procedure

After sniffing each scent, participants were asked to rate the valence and arousal of each scent using Self-Assessment Manikins (SAM) [22] on a 5-Point Likert scale (*1= “low/negative”, 5= “high/positive”*, see Figure 13.2).

13.4.4 Results

22 participants, aged 20-38 years (*M= 28.68, SD= 5.38*, 6 females) volunteered to take part in this study.

A normality test showed that the scent ratings were normally distributed. We did a repeated measures ANOVA test to analyse the data and found a main effect of scents on the arousal ($F(3, 19)= 11.26, p< .001; Wilks' \lambda= .360$) and valence ($F(3, 19)= 39.86, p< .001; Wilks' \lambda= .137$) ratings. The results of this study (see Figure 13.2) confirmed that the scent of peppermint has positive valence and high arousal, the scent of rose has positive valence and low arousal, and the scent of civet has negative valence and high arousal. Only patchouli was not rated as expected, landing in the same quadrant as the scent of civet.

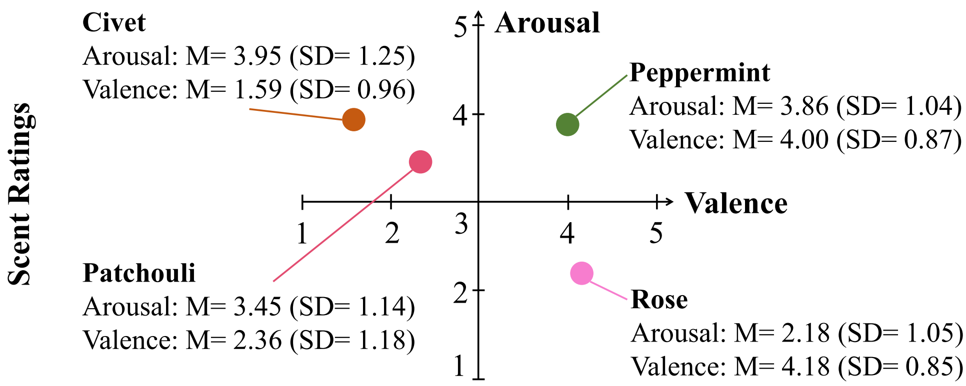


Figure 13.2: Mean Arousal (1= "Low", 5= "High") and Valence (1= "Negative", 5= "Positive") ratings of fours scents.

13.5 Study 2: Identifying Anger-Eliciting Pictures

Related work suggests such approaches of inducing emotions in participants as revisiting an emotional situation from the past [102, 101], showing videos [60, 176], presenting emotionally charged words on traffic signs [55], delivering emotionally charged voice signals during the driving [30], and asking participants to imagine they were late on their way to work [173].

We used IAPS to elicit anger due to three reasons:

i. driving is a highly visual task, and visual stimuli have already been successfully applied for eliciting anger in simulated driving studies in the past [60, 176, 55],

ii. the effect of IAPS is comparable with auditory stimuli [128],

iii. with IAPS we can be sure that we will elicit an emotion of the required arousal and valence levels, as it has been validated through a multitude of studies in HCI (e.g. such as [213, 128]).

IAPS provides information on the arousal, valence, and dominance ratings of each picture. However, it is not clear which "high arousal, low valence" pictures specifically elicit anger. With this study, we were able to find this out.

13.5.1 Design

We conducted a within-participants study in which each participant had to observe and rate ten different IAPS pictures.

13.5.2 Setup

With a few exceptions for the pictures showing traffic accidents, most of the IAPS pictures are not related to driving. We chose ten negative valence and high arousal pictures (see Table 13.1) to be rated on a computer screen.

13.5.3 Procedure

Participants saw each picture for 5s and rated them by answering the following question: *"How angry does this picture make you feel?" (1= "Not angry at all", 7= "Very angry").*

13.5.4 Results

28 participants, 23-53 years old (*M= 30.25, SD= 5.92*, 16 females) volunteered for this study. A Shapiro-Wilk test showed a significant departure from normality for all the variables. We conducted a Friedman test and found a statistically significant difference in the effect of pictures on anger ratings (χ^2 *(9)= 99.7, p< .001*). Three pictures with the highest mean anger ratings (i.e. #6212, #6313, and #9410) were chosen to induce anger in participants before the driving task (see Table 13.1).

Picture	**Description**	**Anger rating: M (SD)**
#6212	**Soldier pointing a gun at a child**	**6.07 (1.67)**
#6313	**Man attacking a woman**	**5.90 (1.65)**
#6563	Gun pointed at a teenager's head	5.55 (1.74)
#9040	Person suffering from starvation	5.59 (1.97)
#9250	Medical staff with an injured person	4.52 (2.16)
#9410	**A man carrying an injured child**	**6.00 (1.79)**
#9413	Two men about to be hanged	5.55 (1.76)
#9635_1	Person being set on fire	5.62 (1.90)
#9908	Traffic accident	3.90 (2.04)
#9921	Fire-fighters saving a person from fire	4.28 (2.09)

Table 13.1: IAPS pictures studied to establish anger-eliciting stimuli, with the corresponding ratings. Three pictures that got selected for the main study are highlighted in bold.

13.6 Study 3: Identifying Anger-Eliciting Events

Besides inducing anger in participants before the driving phase, it is important to keep them angry throughout the driving. We conducted a study to investigate which on-road events make drivers angry. The related work showed that displaying emotional stimuli on signs [55] and making drivers wait [173] helps keep them angry. We wanted to explore further scenarios.

13.6.1 Design

We ran a between-participants study with two conditions. In the first condition, participants experienced 12 different anger-eliciting on-road events. In the second condition, before experiencing the 12 anger-eliciting events, participants also viewed three IAPS pictures (see Table 13.1) before the driving phase.

13.6.2 Setup

We developed the course using the *IPG CarMaker* software. The participants were sitting in a driving simulator seat (*FK Automotive*) equipped with the *Logitech G27* steering wheel in front of the main screen (55”, 60Hz refresh rate), on which the view outside the car from driver’s position was rendered. The dashboard was presented on an additional screen (17”, 60Hz refresh rate), in front of the main screen (see Figure 13.3).

Figure 13.3: Participant sitting in the driving simulator.

13.6.3 Procedure

In the condition with IAPS pictures shown before the driving, pictures were shown on the simulator's main screen, in its full height. Pictures appeared in a randomised order, for 5 seconds each.

In both conditions, during the driving phase, there were no anger-eliciting events in the first 90s, so that participants could become familiar with the simulator [165]. After this stage, one of the 12 events (see Table 13.2) took place every 30s.

Event	**Anger rating in two conditions:**	
	1: M (SD)	**2: M (SD)**
IAPS picture #6212 on a billboard	4.86 (1.95)	3.86 (1.68)
IAPS picture #6313 on a billboard	5.14 (2.27)	4.29 (1.80)
IAPS picture #9410 on a billboard	4.14 (2.12)	4.86 (1.35)
30s waiting time at a traffic light	3.14 (1.35)	2.57 (1.13)
Car cutting off	5.43 (2.07)	**5.29 (2.06)**
Slow zigzagging lead vehicle	4.57 (2.30)	**5.71 (2.21)**
Cyclist cutting off	5.14 (2.19)	**5.00 (1.53)**
Pedestrian suddenly crossing the road	4.00 (2.31)	**5.00 (1.53)**
Child playing with a ball on the street	3.86 (1.68)	2.43 (1.13)
Sheep suddenly appearing on the road	3.86 (1.68)	2.29 (1.89)
Unmarked roadworks site	3.57 (1.72)	3.57 (2.23)
30mph limit on a straight rural road	4.29 (1.38)	3.71 (2.36)
Overall experience	*4.43 (1.81)*	*4.57 (1.81)*

Table 13.2: Anger-eliciting on-road events studied to select stimuli for the driving phase of the main study in two conditions: (1) without and (2) with anger-eliciting IAPS pictures shown to the participants prior to the driving phase. Events chosen for the main study are shown in bold.

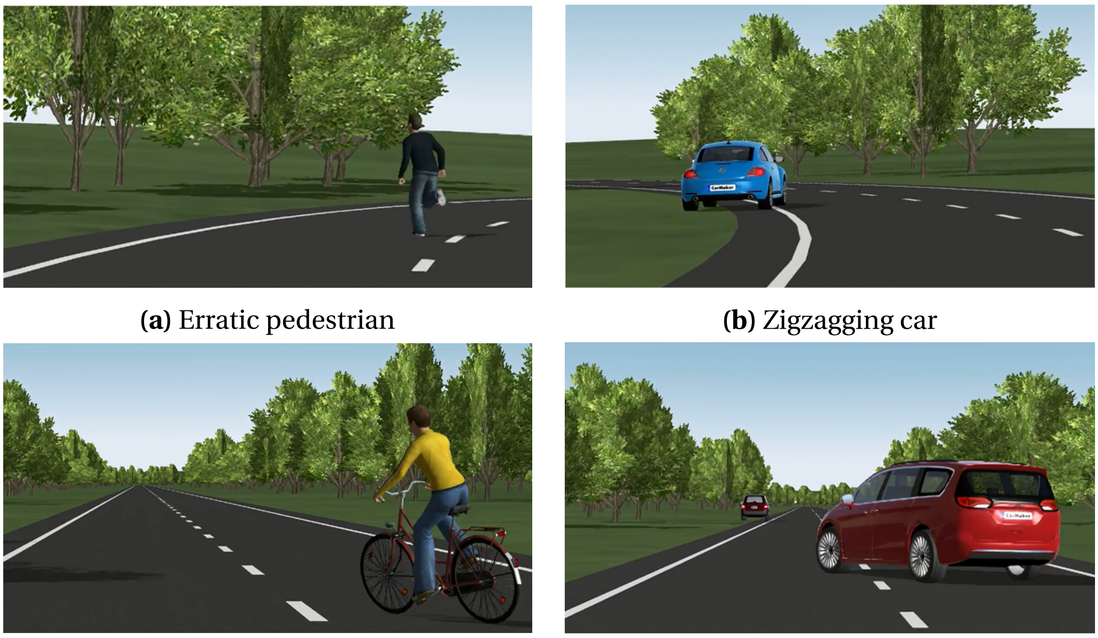
After the driving phase, the participants were asked to rate how angry each event, and the drive as a whole, made them feel, on a 7-Point Likert scale (*1= "Not angry at all", 7= "Very angry"*). Such a rating procedure has been chosen in order not to interrupt the driving task [188]. This study took 10 minutes to complete.

13.6.4 Results

14 participants (seven per condition, three females in each) in the age of 23-43 years old (*M= 30.14* years, *SD= 6.06*) volunteered for this study. Participants' driving experience varied between 2 and 23 years (*M= 8.93*, *SD= 6.18*).

We ran a normality test and found that data was normally distributed. After confirming the normality, an independent t-test was conducted to determine if there was a difference in average anger ratings between the two conditions (IAPS pictures followed by on-road events and just on-road events). The results showed no significant differences in the anger ratings of the different events between the two conditions and also within each condition. As the anger rating of the overall driving experience was slightly higher for the condition where the IAPS pictures were displayed before the driving, we decided to use this approach in the main study and exclude pictures from the billboards.

For further exploration, we decided to use only the four most highly rated events (see Table 13.2, highlighted in bold and Figure 13.4): a car cutting off, a slow zigzagging lead vehicle, a cyclist cutting off, and a pedestrian suddenly crossing the road.



(a) Erratic pedestrian

(b) Zigzagging car

(c) Cyclist cutting off

(d) Car cutting off

Figure 13.4: Four anger-inducing on-road events: (a) a pedestrian suddenly crossing the road, (b) a slow zigzagging car that needs to be overtaken, (c) a cyclist cutting off, (d) a car cutting off.

13.7 Study 4: Investigating the Effects of Scents

In Studies 1-3, we chose a set of scents representing different quadrants of the arousal and valence dimensions, a set of anger-inducing IAPS pictures, and a set of anger-inducing events.

13.7.1 Design

This study followed a 1(emotional state: anger)×4(scents: rose, peppermint, civet, water/clean air as a control stimulus) mixed model experimental design, with three main steps:

i. Familiarisation with the driving simulator.

ii. Inducing anger in participants by displaying three emotionally charged IAPS [120] pictures (see Table 13.1).

iii. Driving through a course composed of anger-inducing events (see Figure 13.4) under an effect of one of the four scents (rose, peppermint, civet, or clean air).

We used the mean lane deviation (vehicle's deviation from the centre of the lane in metres) as a measure of the participants' driving performance. The mean steering angle (in radians), the average speed (in mph), and the number of collisions were used to assess the driving behaviour. We also analysed the catastrophic road excursions (as per Mok et al. [136]) - events of the ego car leaving the road.

13.7.2 Setup

13.7.2.1 Driving Simulator

Here, we used the same driving simulator setup as in Study 3. The course was built using the *IPG CarMaker* software, based on the four anger-inducing events extracted from Study 3. The software used to log the driving data (using the *CarMaker API*) and to control the scent-delivery device was written in C.

13.7.2.2 Scent-Delivery Device

For this study, we have assembled and used a scent-delivery device (as per [45]). The study was conducted in an olfactory interaction room (as per [45]).

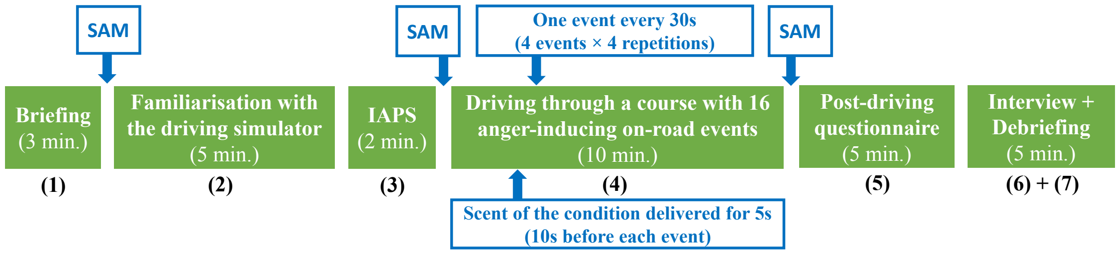


Figure 13.5: The timeline of the Study 4 procedure.

Our scent-delivery device contained four scent chambers. The first two were filled with 6g of 100% pure essential oil of rose and peppermint (from *Holland & Barrett Int. Ltd.*), chamber three contained 6g of the civet scent (from *Plush Folly Ltd*), and chamber four was filled with 6g of water (odourless water used as a neutral stimulus). The scent was delivered with the air pressure of 0.5bar.

The output of the scent-delivery device was located behind the steering wheel and pointed towards the participants' face (as in [48]). Participants wore headphones playing the engine sound to cancel any potential external sounds.

13.7.3 Procedure

In this section, we will cover the procedure (see Figure 13.5) of this study, which consisted of the following seven steps:

13.7.3.1 Briefing

Upon arrival, participants were given the information sheet, driving instructions, and a consent form to sign. The driving instructions contained clear guidance regarding the driving rules, such as the speed limits and the rule of overtaking a slower vehicle. Participants were then asked to rate their current emotional state using the SAM [22] questionnaire and take a seat in the driving simulator.

13.7.3.2 Familiarisation With the Driving Simulator

Participants then became familiar with the driving simulator by driving on a rural highway for approximately five minutes. The study continued with a session, in which the participants were asked to drive for five minutes through a rural setting and familiarise themselves with the driving simulator. No anger-eliciting events were occurring on this stage, only normal traffic with a few cars and pedestrians.

13.7.3.3 Inducing Anger Using IAPS Pictures

Next, participants were shown three IAPS pictures. Participants were provided information about the graphic content in the Information sheet given at the beginning of the study. The three IAPS pictures (see Table 13.1) were displayed taking the full height of the screen. Each picture appeared for 5s, and the order of their presentation was randomised. After this, participants were again asked to rate their emotional state by filling in the SAM questionnaire.

13.7.3.4 Driving Through an Anger-Inducing Course

After the anger induction stage, participants were asked to drive straight, through a rural setting, respecting the speed limits (40-60 mph, shown on signs), until the simulation ended. They were instructed to expect traffic on the road, but no information on critical events was given.

The course consisted of four anger-eliciting events (see Figure **??**). One of these events appeared every 30s after the start of the driving phase. Each event was repeated four times (16 events in total), and the order of their occurrences was randomised. Ten seconds before each event, a scent of the condition was released, which is the time necessary for the scent to get perceived by the user in such a setup, as suggested by [45]. Each scent-delivery event lasted five seconds, in order to ensure that participants inhaled each scent [155]. Each participant received only one scent (a between-participants condition): rose, peppermint, civet, or clean air (control stimulus). As the events appeared every 30s, the scent-delivery frequency was 30s too, enough to neutralise the previously delivered scent [45, 150].

13.7.3.5 Post-Driving Questionnaire

After the driving phase, participants were asked to rate their emotional state one more time by completing the SAM questionnaire. Participants were also asked to answer questions on the liking, comfort, and intensity of the scent (as per [48]), as well as about their demographic data.

13.7.3.6 Post-Driving Interview

The experiment finished with a short semi-structured interview conducted to gain additional insights about how the participants felt. The interview was audio-recorded and structured around the following four questions:

i. How did the pictures make you feel?

ii. How did the on-road events make you feel?

iii. How were your emotions influenced by the scent?

iv. How was your driving behaviour influenced by the scent?

13.7.3.7 Debriefing

After the end of the interview, participants received a Debriefing Sheet and a £5 Amazon Voucher for their participation. Overall, the study lasted about 30 minutes.

13.7.4 Results

In this section, we summarise our results on the participants' emotions, driving performance/behaviour, negotiation of critical events, and their experience with the scents.

13.7.4.1 Participants

A total of 40 participants were recruited for the study (10 per condition, four females in each). The age ranged from 19 to 59 years (*M= 30.73, SD= 9.11*). Their reported driving experience ranged from 1 to 41 years (*M= 9.28, SD= 9.07*).

13.7.4.2 Emotions Before Driving

A Shapiro-Wilk test showed a significant departure from normality for all the variables. We ran a Wilcoxon-Signed-Ranks test to compare the means between two variables. We compared the valence of the emotions before the experiment with its value after the IAPS pictures were shown. The same comparison was done for the corresponding arousal ratings. Concerning the valence ratings, the test indicated that the valence before the experiment (*mean rank= 17.52*) was significantly higher than after viewing the IAPS pictures (*mean rank= 11.00, Z= -4.058, p<.001*). Concerning the arousal ratings, the test indicated that the arousal before the experiment (*mean rank= 10.33*) was statistically lower than after viewing the IAPS pictures (*mean rank = 13.22, Z= -2.611, p< .01*).

This means, at the start of the study, all participants were calm (as per [175]). After viewing the IAPS pictures, participants' self-reported emotional state shifted towards the negative valence and high arousal quadrant (see Figure 13.6), which also contains the anger emotion (as per [175]).

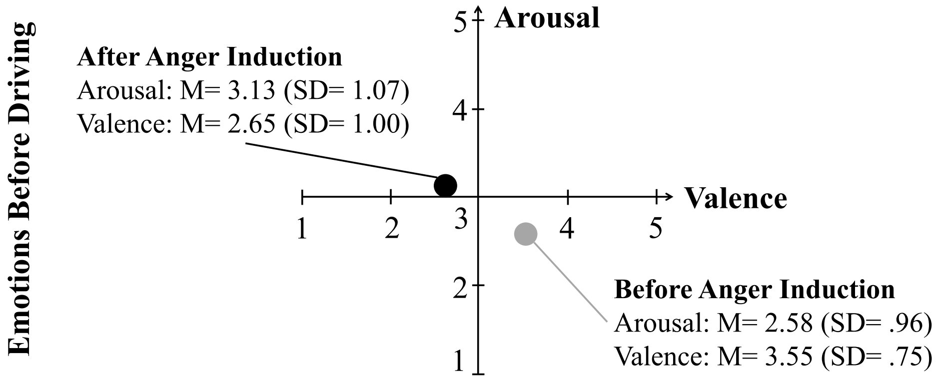


Figure 13.6: Mean Arousal (1= "Low", 5= "High") and Valence (1= "Negative", 5= "Positive") ratings of the participants' self-reported emotional state before and after anger induction.

13.7.4.3 Emotions After Driving

After the driving, participants reported still being aroused (all mean arousal ratings were above three on a 5-Point Likert scale). The emotions were distributed over the negative and positive valence quadrants (see Figure 13.7), however, this was not supported by the statistics. A Shapiro-Wilk test showed a significant departure from normality for all variables. The Kruskal Wallis test showed no significant differences in the arousal (χ^2 *(3)= 5.39, p= .145, median= 3.0, 25th quartile= 2.0, 75th quartile= 4.0*) and valence (χ^2 *(3)= 2.87, p= .412, median= 3.5, 25th quartile= 3.0, 75th quartile= 4.0*) ratings. We also checked for the changes of the self-reported emotions between the three points of time: before the experiment, after viewing the IAPS pictures, and after driving. The Friedman test showed a statistically significant effect of timing on the arousal (χ^2 *(1)= 6.76, p< 0.01*) and valence (χ^2 *(1)= 5.76, p< 0.05*) ratings. There was no significant interaction between the time and the scent for the arousal (*p= .320*) and valence (*p= .104*).

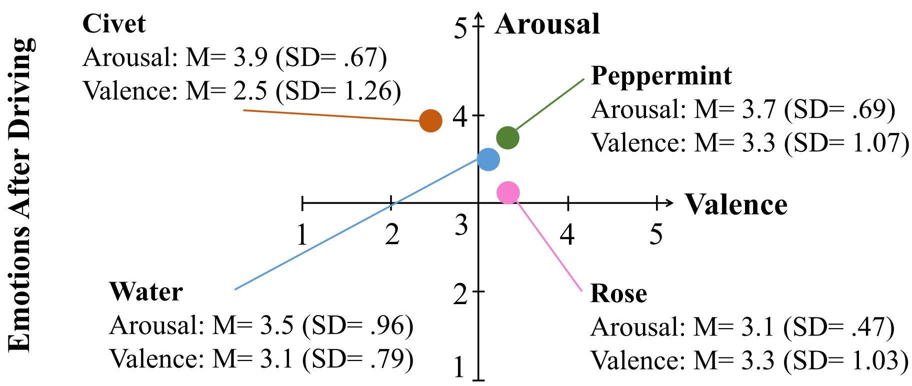


Figure 13.7: Mean Arousal (1= "Low", 5= "High") and Valence (1= "Negative", 5= "Positive") ratings of the participants' self-reported emotional state after driving in each scent condition.

	Condition Mean (SD)			
	Water/Clean Air	*Rose*	*Peppermint*	*Civet*
Lane Deviation (m)	.44 (.11)	.52 (.26)	.71 (.50)	.73 (.33)
Steering Angle (rad)	.09 (.01)	.10 (.03)	.09 (.02)	.11 (.03)
Average Speed (mph)	46.68 (6.95)	42.95 (7.41)	44.63 (6.71)	48.83 (7.47)

Table 13.3: Mean scores of the objective driving performance and behaviour data.

13.7.4.4 Driving Performance and Behaviour

The Shapiro-Wilk Normality Test showed ($p = .02$) for the lane deviation and the steering angle, and ($p = .04$) for the average speed. For this reason, we compared the means of the four conditions using the non-parametric Kruskal-Wallis H Test (as per [135]). The test showed no significant differences (see Table 13.3) for lane deviation ($\chi^2(3) = 6.15$, $p = .11$), steering angle ($\chi^2(3) = 2.86$, $p = .41$), and average speed ($\chi^2(3) = 4.99$, $p = .17$).

13.7.4.5 Negotiating Critical Events

While experiencing critical events (e.g. car cutting off), it was important for the participants to avoid collisions. However, only five participants out of 40 (three in rose and two in peppermint conditions) were able to complete their driving without colliding into another vehicle, a bicycle, or a pedestrian. A Shapiro-Wilk test showed a significant departure from normality for all the variables in this dataset. The Kruskal Wallis test showed statistically significant differences in the number of collisions between the scents ($\chi^2(3) = 26.27$, $p < .001$, $median = 1.0$) with the highest number of collisions in the civet condition (see Figure 13.8).

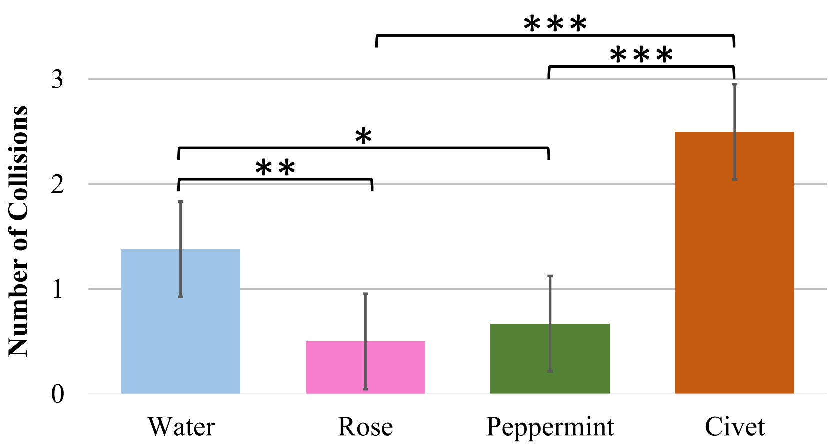


Figure 13.8: The mean number of collisions in the water (clean air, control), rose, peppermint, and civet conditions. Error bars, ± s.e.m., $*p < .05$; $**p < .01$; $***p < .001$.

However, no significant differences were found in the binary measures of catastrophic road excursions (χ^2 *(3)= 7.13, p= .068, median= .0*). No excursions were recorded in the rose condition. There were two such occurrences in the water (clean air, control) and peppermint conditions. Finally, half of all 10 participants in the civet condition had experienced an excursion.

13.7.4.6 Scent Comfort and Liking Ratings

After the experiment, participants were asked to rate how much they liked interacting with the scent and how comfortable that was on a 5-Point Likert scale (*1= "Not at all", 5= "Very much"*). A Shapiro-Wilk test showed a significant departure from normality for all the variables in this dataset. The Kruskal Wallis test showed no statistically significant differences in the scent liking ratings (χ^2 *(3)= 6.32, p= .097, median= 4.0*) and a significant effect of scents on the comfort ratings (χ^2 *(3)= 7.81, p= .05, median= 4.0*) with rose rated significantly higher than civet (see Figure 13.9).

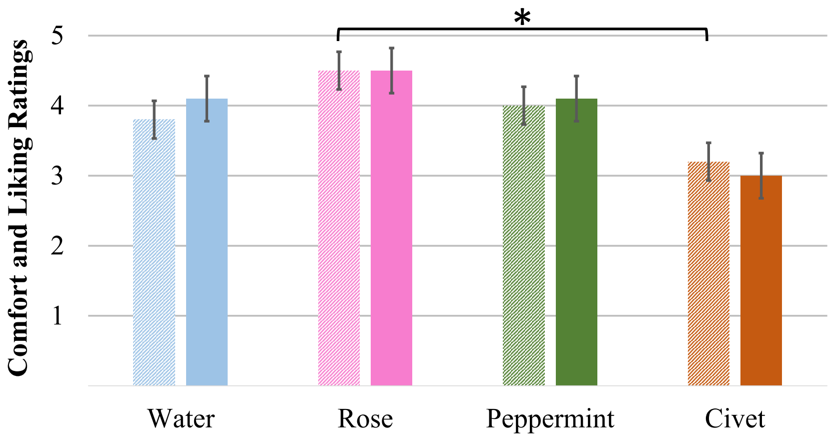


Figure 13.9: Mean Comfort (left bar) and Liking (right bar) ratings (1= "Not at all", 5= "Very much") of interacting with the scents. Error bars, ± s.e.m., $*p < .05$.

13.7.4.7 Interview Responses

All interviews were transcribed and open coding was used to analyse the data. Below we summarise participants' impressions on the anger-induction procedure and the effects of scents on their emotions and driving.

85% of participants had confirmed being negatively affected by the anger-inducing pictures shown at the very beginning of the experiment. These participants have described their emotional state as disturbed/distressed/upset/uncomfortable (17), angry/frustrated (16), sad (16), not happy/not positive/negative/bad (5), unpleasant/irritated/disgusted (5), disappointed/discouraged (2), confused (2), insecure (1) and stressed (1). For example, *P20* described their emotions in the following way: *"These are not very pleasant pictures. Especially the last two were a bit disturbing because there were young kids involved in a war... They made me feel mostly angry."* Those who did not report being affected by the pictures (15%) explained this by the fact of being exposed to such content regularly. For example, *P31* said: *"I have not been touched much by those pictures... Nothing special... The content is really strong, but that is something I am used to seeing through news, movies, and social media."*

93% of participants had confirmed being negatively affected by the on-road events (i.e. a pedestrian suddenly crossing the road, a slow zigzagging car, a bicycle cutting off and a car cutting off) experienced in the driving simulator. They described their feelings as angry/frustrated/furious/annoyed/pissed off/irritated/impatient (25), having experienced something unexpected/unpredictable/crazy/unsafe/random/hectic (15), stressed (7), anxious/worried (3), upset/distressed/discouraged (3), confused (2) and cautious (1). For example, *P15* said: *"I felt a little annoyed by the pedestrians. They were everywhere and unexpected. Drivers were like drunk, and they made me angrier than the pictures."* Those, who said they did not feel affected, explained this by either knowing that they are in a safe simulator environment, or having had similar virtual experiences in the past, or generally being a very calm person. For example, *P18* said: *"I did not really feel anything. If they were real, in a real-life situation, where they would put my life under threat, then I am sure I would be very annoyed."*

As the descriptors used by the participants lie in the "anger" (high arousal, negative valence) quadrant of the emotions circumplex [175] and the number of affected participants went up after having experienced anger-eliciting on-road events, the anger-induction procedure can be considered successful.

13.7.4.7.1 Perceived Emotions

Here, we summarise the interview responses on the participants' emotions during the experiment (see Figure 13.10).

All 10 participants who smelled rose said this scent made them feel less nervous (1), more relaxed/peaceful/settled/soothed (5), positive (1), attentive (1), positively affected (1), and less emotional (1). For example, *P35* said: *"It made me feel more relaxed... It was nice to have it in the car."* and *P9* said: *"It did positively affect me, it slowed me down."*

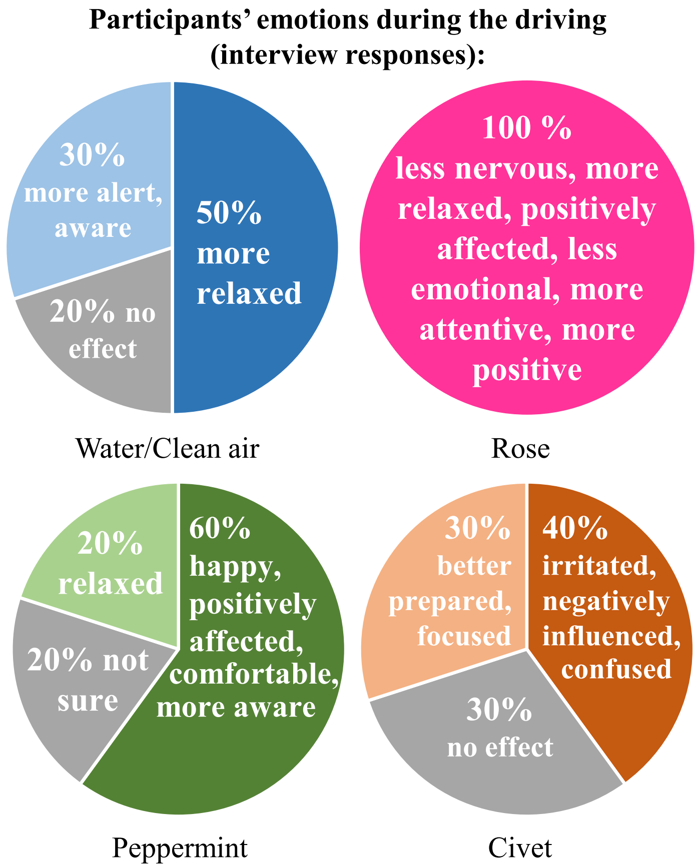


Figure 13.10: Percentage of participants having experienced each emotion while driving.

6/10 participants who smelled peppermint highlighted the arousing and hedonic properties of this scent. They said that it made them positively affected (1), happy (1), more attentive/aware (3) and comfortable (1). For example, *P33* said: *"One thing for sure is that I was more aware of the events because of the scent."* 2/10 participants claimed the scent made them more relaxed because it acted as a notification and prevented them from speeding or crashing. For example, *P11* said: *"It made me calmer... If there was no smell, I would crash four times!"*

4/10 participants who smelled civet underlined the negative effect of this scent. They said that the scent made them irritated/ annoyed (2), negatively influenced (1), and confused (1). For example, *P5* said: *"I felt a strong negative influence. I was nervous and not relaxed."*, whereas *P38* said: *"When I got the smell, I was really annoyed, and I wanted to finish the driving faster."* 3/10 participants reported being better prepared (1), more focused (1), and able to rethink the situation (1) with the help of the scent. For example, *P28* said: *"There was a moment when the smell arrived just while I was passing or when I was doing a curve, and I was going too quick... That was an occasion to* *rethink what has happened."* However, these responses do not tell us much about the participants' emotional state. Surprisingly, two of these participants reported that they liked this scent (despite the low mean liking rating).

In the control (clean air/water) condition, 5/10 participants felt more relaxed (e.g. due to fresh air). For example, *P7* said: *"It was relaxing. It might have been just the airflow."* 3/10 participants reported being more alert. For example, *P17* said: *"When it was coming through, I was thinking... OK, what's up ahead? It was like a warning to me."*

13.7.4.7.2 Perceived Driving Behaviour

Here, we summarise the interview responses on the participants' perceived driving behaviour (see Figure 13.11).

5/10 participants who smelled rose claimed they drove in a much more considered, cautious, and focused fashion thanks to the scent, which makes sense considering its calming effect [48]. For example, *P35* said: *"In this particular case, I was more aware to see if there is a dangerous situation or at least a dangerous setting for a situation, like when a car would be on the side of a road, and somebody could just jump out..."* 3/10 participants felt that they drove in a more relaxed way due to the scent. For example, *P26* said: *"It was quite a soothing and relaxing smell... and an enjoyable one. The time I smelled it, it helped me relax."*

7/10 participants who smelled peppermint said that the scent made them more awake and activated on the road, leading to both positive (e.g. preventing crashes) and negative (e.g. speeding) consequences. For example, *P31* said: *"When you are driving long ways, it could make you more aware, activate you."* and *P37* said: *"There was one moment when I thought I drove faster when the smell came."* 2/10 participants could only highlight the hedonic advantages of the scent by saying that it made their driving more comfortable. For example, *P27* said: *"If there is a good smell, I just feel comfortable."*

What it comes to the effect of civet scent on the driving, then only 3/10 participants reported being influenced by its unpleasant properties. Participants said that they became more irritated drivers, that their driving was negatively affected, and that they were doing a lot of "illegal stuff". For example, *P5* said: *"The scent influenced my driving negatively, I was exceeding the speed, I was not driving smoothly; there was no positive effect."* Surprisingly, 5/10 participants argued they felt that they became more attentive, focused, and alert drivers. However, the quantitative data showed that participants had more crashes in this condition (see Figure 13.8).

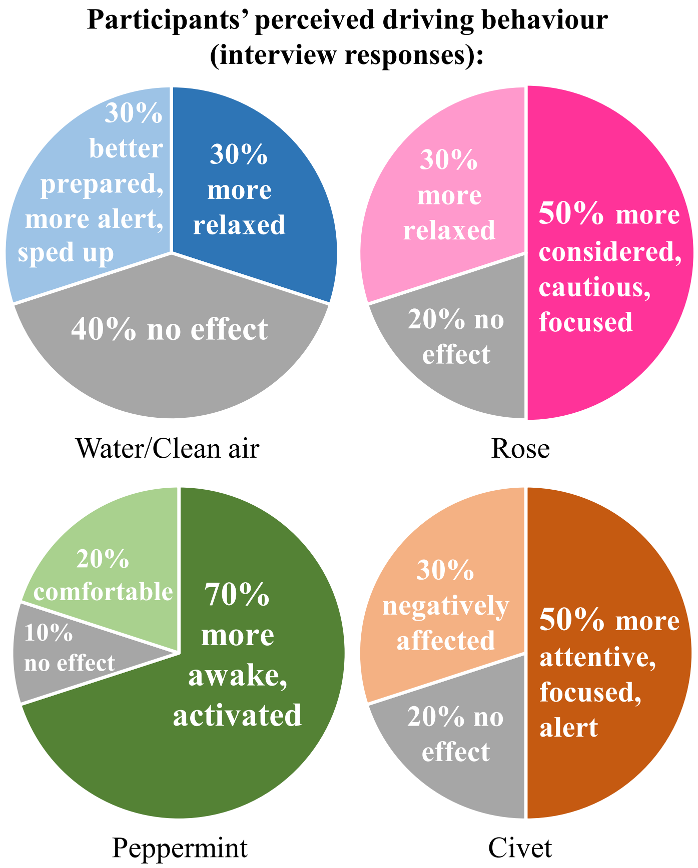


Figure 13.11: Percentage of participants having experienced each driving behaviour change.

The fact that 5/10 participants in the civet condition reported finding this scent helpful might be due to its arousing property, disregarding the negative valence of this unpleasant scent.

Undoubtedly, there is an activating effect in delivering the scent of civet. It is, for example, reflected in a response from *P22*: *"When you are driving, it's very repetitive. When you get a smell, you think... Oh! It pitched me up a little bit!"* However, the outcome of such a pitch might not be positive.

In the control (clean air/water) condition, 4/10 participants were not conclusive about any noticeable effect of the scent, which was expected. However, 3/10 said that it made them drive in a more alert way, be better prepared for the on-road events, and speed up. Finally, the remaining 3/10 participants found the scent relaxing. For example, *P32* said: *"When I got the smell, it helped me relax and do the turns a little bit better, a little bit less wobbly."* This might be due to fresh air, as revealed in the responses on the emotional state.

13.8 Discussion

Anger is one of the most dangerous emotions that a driver can experience, leading to aggressive driving [53] and crashes [77]. Finding a way of reducing anger might become crucial in lowering the number of traffic accidents. The results of Study 4 led to a discussion on how the scents of rose, peppermint, and civet influence the driving behaviour of participants in an induced angry state, as well as how these scents affect their emotions and well-being. We conclude with possible implications for design beyond an automotive context.

13.8.1 Scents and Driving Behaviour

Our study has shown that the scent of rose resulted in the lowest average speed (among all conditions) and a lane deviation that is comparable to the control condition. In the rose condition, participants also had no crashes and reported being more cautious and relaxed due to this scent. This finding is in line with the research on the relaxing effect of the scent of rose [89]. This also means that if the scent of rose is used to notify the driver about something (e.g. a "Passing by a point of interest" event [48]), then, in addition to acting as a notification modality, it could help the driver relax.

The scent of peppermint helped the participants maintain the same speed as in the control condition and the participants have reported being more activated thanks to this scent. If we think of this scent as a notification modality for angry drivers (e.g. to say "Fill gas" [48]), then it could fit also this purpose. However, as it seems to be increasing the lane deviation, it needs to be applied carefully. Potentially, it could be useful on an empty road, but not in heavy traffic. Raudenbush et al. [170] has demonstrated the scent of peppermint to increase the driver's alertness. In this study, peppermint helped participants focus on the driving task and improved their reaction time. This finding seems not to be true for angry drivers, though, as, in our study, the number of crashes was not significantly different between the peppermint and clean air conditions.

Punishment has been demonstrated to enforce correct behaviour [187]. That made us assume that a negative scent of civet might be perceived by the participants as a punishment, motivating them to be more careful on the road. However, we saw that this scent resulted in a significantly higher number of collisions. Moreover, it led to an increase in both the lane deviation and the average speed. This finding suggests that the civet scent is not a good choice for stimulating angry drivers. This finding is in line with the conclusion of Ilmberger et al. [97], who argued that strong unpleasant scents could negatively influence people's performance. Moreover, it is known that arousal through music leads to better driving performance if, and only if, the driving task is under-stimulating (arousal increased to an optimal level) [25]. This finding could explain why adding an scent with high arousal and negative valence (like civet) to an already arousing and frustrating driving environment leads to worse driving behaviour (over-stimulation). Adding a scent which counters the driving situation with low arousal and/or positive valence (like rose or peppermint) leads to better driving behaviour.

13.8.2 Scents and Driver's Emotions

For peppermint and rose, there was a clear shift of the self-reported emotions towards the positive valence (both in the qualitative and the quantitative data). As also expected, emotional state in the peppermint condition was rated as more aroused than in the rose condition. These findings are in line with previous work [48]. The present study confirms that arousing and calming effects of scents also work for angry drivers (i.e. reduce their negative emotional state). Both peppermint and rose could make angry drivers happier (positive valence), but they would still stay activated (high arousal).

As expected, participants in the civet condition reported the highest negative valence and the highest arousal. The interviews confirmed this with nearly half of participants describing their emotional state as highly aroused and a high negative valence. That was expected, as civet is a strong and very unpleasant scent. This is in line with previous research [111], where participants' self-reported mood in the unpleasant scent condition (e.g. dimethyl sulfide) was worse than in a pleasant scent condition (e.g. lavender). It is, however, important to consider the challenge of personal preferences here. In the interview, 20% participants in the civet condition reported liking this scent. This finding indicates, there might be drivers who choose to have this unpleasant scent in their cars. Nevertheless, the results of our study suggest that, if a driver is angry, the scent of civet might only worsen their emotions, irrespective of their personal preferences.

The arousal rating of the driver's emotions in the control condition fell between the ratings of the peppermint and rose conditions (i.e. in the higher range), and its valence stayed neutral (see Figure 13.7). If we compare this to the self-reported emotions before driving (see Figure 13.6), we can see that the valence has shifted away from the negative range. As revealed in the interviews, this might be due to an effect of fresh air, found relaxing by a half of the participants in this condition.

Our findings suggest that, when designing olfactory experiences to reduce anger in drivers, HCI practitioners should avoid civet. Peppermint and rose could help improve the driver's mood. It might be possible to achieve the same mood improvement effect by using scents of the comparable valence and arousal levels (e.g. vanilla instead of rose and lemon instead of peppermint). Such a swap might help solve the problem of inter-personal differences, which we also observed in our study. For example, interview responses revealed that 20% of participants in the peppermint condition claimed that this scent made them calmer (e.g. because it is associated with something *"nice"* and *"comforting"*). Therefore, we suggest developing customisable olfactory interfaces (as suggested in [215]). With such an interface, a driver could be offered a selection of positive valence scents (e.g. lavender, vanilla, rose, peppermint, lemon) and would then be asked to indicate which ones they find calming and which ones arousing/activating. This could help some drivers avoid scents that they do not like and still find scents suited for anger reduction.

13.8.3 Scents and Well-Being of Angry Drivers

As expected, the scents of rose and peppermint appeared to be the most suitable to increase the well-being of angry drivers, as the comfort ratings of these two scents were the highest. The scent of civet, on the contrary, had the lowest comfort rating, also correlating with the worst driving behaviour.

On this point, it is interesting to project our findings on the current trends in the automotive industry. Unfortunately, there is very little information available on what scents the vehicle manufacturers use and how their choices were made. For example, the official website of Mercedes-Benz [35] suggests that they have four different fragrances to modulate drivers' well-being, but not many details are provided. It seems though that these fragrances are sophisticated blends of odourants. In one of the recent interviews [86], Annabelle Kanzow-Coffinet, a fragrance designer of BMW [20], said that commonly used scents (e.g. lavender) are "too well known" for a car. She argued that an in-vehicle scent should be "unbiased". This statement makes sense in light of the related work on the perception of luxury experiences, which says that a luxury product (such as a high-end vehicle) should provide a unique experience associated with a unique ritual (as per [70]). With this in mind, our recommendation is to use peppermint and rose (or scents of the same arousal and valence levels) as base notes of in-car fragrances used to increase the driver's well-being. What it comes to unpleasant scents (e.g. civet), then car manufacturers would most likely not want a bad scent to be associated with their vehicles. It might, however, be that an unpleasant scent proves itself useful as a warning, motivating its choice as a suitable stimulus. Nevertheless, this statement requires further investigation.

13.8.4 Applications Beyond Automotive Context

Our findings can be useful also outside the context of driving a vehicle, e.g. in such areas as multisensory cinemas, gaming, VR/AR, desktop applications, and interacting with well-being wearables.

For example, if a user has had a very tense VR experience or watched an aggressive scene of an action movie in a multisensory cinema, they might need a whiff of a pleasant low arousal scent (e.g. rose) in a transition to a calmer scene. This could contribute to the research on multimedia synchronisation [140] or combining visual content with olfactory stimulation [196, 218]. On the contrary, if a player wants to have a richer gaming experience, content creators could design experiences in such a way that they regulate or modulate the user's state using scents. In such a case, even an unpleasant scent (e.g. civet) could match some of the situations in a game (as in [79, 1]). On the other note, a pleasant arousing scent (e.g. peppermint) could be used to, e.g. improve the user's well-being while maintaining their performance in a game (like in [98, 134]) or a desktop application (like in [23, 129]). Finally, in case of wearable well-being devices [50, 3], if the system detects that the user is angry, it could deliver a pleasant scent (e.g. rose or vanilla).

13.8.5 Limitations

In our study, we investigated only one scent per valence and arousal quadrant. It could be that e.g. the scents of vanilla and lavender have similar effects as the scent of rose (e.g. as suggested by [48, 47]), whereas lemon and cinnamon have similar effects as peppermint (e.g. as suggested by [215, 170]). Also, our experiment was limited to a lab environment and a small sample size. Moreover, despite having a racing seat and a separate screen for the dashboard, our driving simulator is still quite low-fidelity. The results could have changed if a higher fidelity simulator was used. Finally, we only had 10 participants per condition which is quite a small sample size. More participants would be needed to strengthen our findings.

13.9 Conclusion and Future Work

It is dangerous to feel angry while driving a car. Anger leads to aggressive driving behaviour [53] and crashes [77]. A strategy for changing anger to a positive emotion might become crucial in reducing the number of road traffic accidents. Our findings suggest that pleasant scents (such as rose and peppermint) can shift the mood of the driver towards the positive valence. However, in terms of emotions and well-being, it would be necessary to calibrate the choice based on the driver's personal preferences. From its properties, the scent of peppermint is much more arousing than the scent of rose. Nevertheless, our interview data reveals that some people still find it calming, as peppermint is associated with comforting experiences. In terms of driving behaviour, our findings show that an unpleasant scent (i.e. civet) is not a good choice for stimulating angry drivers, as it results in a significantly higher number of collisions. On the contrary, pleasant scents of rose and peppermint could help calm the driver down. A slightly increased lane deviation in case of the peppermint scent indicates that pleasant high arousal scents might not be suitable for high-density traffic. We suggest that car producers create customisable olfactory interfaces, where a driver is offered a set of scents, that are known to have a positive effect, and is asked to choose one from them. In the context of high-end vehicles, it is also important to consider the uniqueness of the used scent. Therefore, if a scent is very familiar to a driver (e.g. peppermint), it could be slightly modified by a perfumer, by adding other notes to it. In the future, we plan to extend this study by also investigating other common driving emotions, such as anxiety, fear, happiness, and a normal state.

Part III

Bibliography

14 | Bibliography

[1] ABID, S., LI, Z., LI, R., AND WALEED, J. Heat based odors delivery apparatus for interactive game playing. *International Journal of Multimedia and Ubiquitous Engineering* (2015).

[2] ALAOUI-ISMAÏLI, O., ROBIN, O., RADA, H., DITTMAR, A., AND VERNET-MAURY, E. Basic emotions evoked by odorants: comparison between autonomic responses and self-evaluation. *Phys. & Beh.* (1997).

[3] AMORES, J., HERNANDEZ, J., DEMENTYEV, A., WANG, X., AND MAES, P. Bioessence: A wearable olfactory display that monitors cardio-respiratory information to support mental wellbeing. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (2018), IEEE.

[4] AMORES, J., AND MAES, P. Essence: Olfactory interfaces for unconscious influence of mood and cognitive performance. In *CHI '17* (NY, USA, 2017), ACM.

[5] ANDERSON, A. K., CHRISTOFF, K., STAPPEN, I., PANITZ, D., GHAHREMANI, D. G., GLOVER, G., GABRIELI, J. D. E., AND SOBEL, N. Dissociated neural representations of intensity and valence in human olfaction. *Nature Neuroscience 6*, 2 (Jan. 2003), 196–202.

[6] ANDERSON, C., HUANG, J., TAKASHIMA, K., AND KITAMURA, Y. Light-tracing: Ray-casted movement for improved character control in platform virtual reality gaming. In *SIGGRAPH Asia 2017 VR Showcase* (New York, NY, USA, 2017), SA '17, ACM.

[7] ANDO, H. Development of an olfactory display system capable of instant switching between aromas. *New Breeze* (2013).

[8] ANDO, H., LIU, J., AND KIM, D. Multi-sensory interaction technology and its system application. *Journal of the National Institute of Information and Communications Technology* (2010).

[9] AROMAJOIN. Aroma Shooter. `http://www.aromajoin.com/`, 2016. [Online; accessed 15-January-2016].

[10] ATSUMI, T., AND TONOSAKI, K. Smelling lavender and rosemary increases free radical scavenging activity and decreases cortisol level in saliva.

[11] AUFFARTH, B. Understanding smell - the olfactory stimulus problem. *Neuroscience & Biobehavioral Reviews 37*, 8 (2013).

[12] BAINBRIDGE, L. Ironies of automation. In *Analysis, Design and Evaluation of Man–Machine Systems 1982*. Elsevier, 1983, pp. 129–135.

[13] BAKALAR, N. Sensory science: Partners in flavour. *Nature* (2012).

[14] BALDWIN, C. Verbal collision avoidance messages during simulated driving: Perceived urgency, alerting effectiveness and annoyance. *Ergonomics 54*, 4 (2011).

[15] BARON, R., AND KALSHER, M. Effects of a pleasant ambient fragrance on simulated driving performance: The sweet smell of... safety? *Environment and Behavior 30*, 4 (1998).

[16] BELKIN, K., MARTIN, R., KEMP, S., AND GILBERT, A. Auditory pitch as a perceptual analogue to odor quality. *Psychological Science 8*, 4 (1997).

[17] BELLER, J., HEESEN, M., AND VOLLRATH, M. Improving the driver–automation interaction: An approach using automation uncertainty. *Human factors 55*, 6 (2013), 1130–1141.

[18] BENTLEY. Personalising Your Bentley, and Your Life. `https://www.bentleymotors.com/en/world-of-bentley/mulliner/personal-commissioning/personalising-your-bentley.html`, 2019. [Online; accessed 14-June-2019].

[19] BODNAR, A., CORBETT, R., AND NEKRASOVSKI, D. Aroma: Ambient awareness through olfaction in a messaging application. In *ICMI '04* (NY, USA, 2004), ACM.

[20] BOERIU, H. She created the smell of the all-new BMW 7 Series. `https://www.bmwblog.com/2015/07/03/she-created-the-smell-of-the-all-new-bmw-7-series/`, 2015. [Online; accessed 14-June-2019].

[21] BOROJENI, S., WALLBAUM, T., HEUTEN, W., AND BOLL, S. Comparing shape-changing and vibro-tactile steering wheels for take-over requests in highly automated driving. In *AutomotiveUI '17* (New York, NY, USA, 2017), ACM.

[22] BRADLEY, M., AND LANG, P. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry 25*, 1 (1994).

[23] BREWSTER, S., MCGOOKIN, D., AND MILLER, C. Olfoto: Designing a smell-based interaction. In *CHI '06* (New York, NY, USA, 2006), ACM.

[24] BREZNITZ, S. *Cry wolf: The psychology of false alarms.* Psychology Press, 2013.

[25] BROADHURST, P. Emotionality and the yerkes-dodson law. *Journal of experimental psychology 54*, 5 (1957).

[26] BURGESS, M. We got sprayed in the face by a 9D television. `https://www.wired.co.uk/article/9d-television-touch-smell-taste`, 2016. [Online; accessed 16-July-2019].

[27] BURNETT, G., HAZZARD, A., CRUNDALL, E., AND CRUNDALL, D. Altering speed perception through the subliminal adaptation of music within a vehicle. In *AutomotiveUI '17* (New York, NY, USA, 2017), ACM.

[28] CAO, Y., CASTRONOVO, S., MAHR, A., AND MÜLLER, C. On timing and modality choice with local danger warnings for drivers. In *AutomotiveUI '09* (2009), ACM, pp. 75–78.

[29] CASTIELLO, U., ZUCCO, G., PARMA, V., ANSUINI, C., AND TIRINDELLI, R. Cross-modal interactions between olfaction and vision when grasping. *Chemical Senses 31*, 7 (2006).

[30] CHAN, M., AND SINGHAL, A. Emotion matters: Implications for distracted driving. *Safety Science 72* (2015).

[31] CHREA, C., GRANDJEAN, D., DELPLANQUE, S., CAYEUX, I., LE CALVE, B., AYMARD, L., VELAZCO, M., SANDER, D., AND SCHERER, K. Mapping the semantic space for the subjective experience of emotional responses to odors. *Chemical Senses* (2008).

[32] CHREA, C., VALENTIN, D., SULMONT-ROSSÉ, C., NGUYEN, D. H., AND ABDI, H. Semantic, typicality and odor representation: A cross-cultural study. *Chemical senses 30*, 1 (2005), 37–49.

[33] COMMITTEE, S. O.-R. A. V. S. Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems, 2014.

[34] COVARRUBIAS, M., BORDEGONI, M., ROSINI, M., GUANZIROLI, E., CUGINI, U., AND MOLTENI, F. Vr system for rehabilitation based on hand gestural and olfactory interaction. In *VRST '15* (New York, NY, USA, 2015), ACM.

[35] DAIMLER. A fragrance for the new S-Class. `https://www.mercedes-benz.com/en/mercedes-benz/innovation/a-fragrance-for-the-new-s-class/`, 2019. [Online; accessed 14-June-2019].

[36] DALEAIR. DaleAir Vortex Activ USB. `http://www.daleair.com/dispensing/dispensers/`, 2016. [Online; accessed 15-January-2016].

[37] DAMM, M., PIKART, L. K., REIMANN, H., BURKERT, S., GÖKTAS, Ö., HAXEL, B., FREY, S., CHARALAMPAKIS, I., BEULE, A., RENNER, B., HUMMEL, T., AND HÜTTENBRINK, K. Olfactory training is helpful in postinfectious olfactory loss: a randomized, controlled, multicenter study. *The Laryngoscope* (2014).

[38] DAVIS, F. D. User acceptance of information technology: system characteristics, user perceptions and behavioral impacts. *International journal of man-machine studies 38*, 3 (1993), 475–487.

[39] DENNIS, C. Neuroscience: The sweet smell of success. *Nature 428*, 6981 (2004).

[40] DESMET, P. M., AND HEKKERT, P. Framework of product experience. *International journal of design 1*, 1 (2007), 57–66.

[41] DI CAMPLI SAN VITO, P., BREWSTER, S., POLLICK, F., AND WHITE, S. Thermal in-car interaction for navigation. In *ICMI '17* (New York, NY, USA, 2017), ACM.

[42] DI CAMPLI SAN VITO, P., BREWSTER, S., POLLICK, F., WHITE, S., SKRYPCHUK, L., AND MOUZAKITIS, A. Investigation of thermal stimuli for lane changes. In *AutomotiveUI '18* (New York, NY, USA, 2018).

[43] DI CAMPLI SAN VITO, P., SHAKERI, G., BREWSTER, S., POLLICK, F., BROWN, E., SKRYPCHUK, L., AND MOUZAKITIS, A. Haptic navigation cues on the steering wheel. In *CHI '19* (New York, NY, USA, 2019), ACM.

[44] DMITRENKO, D., MAGGIONI, E., BRIANZA, G., HOLTHAUSEN, B., WALKER, B., AND OBRIST, M. Caroma therapy: pleasant scents promote safer driving, better mood, and improved well-being in angry drivers. In *CHI '20* (2020), ACM.

[45] DMITRENKO, D., MAGGIONI, E., AND OBRIST, M. Ospace: Towards a systematic exploration of olfactory interaction spaces. In *ISS '17* (NY, USA, 2017), ACM.

[46] DMITRENKO, D., MAGGIONI, E., AND OBRIST, M. I smell trouble: Using multiple scents to convey driving-relevant information. In *ICMI '18* (NY, USA, 2018), ACM.

[47] DMITRENKO, D., MAGGIONI, E., AND OBRIST, M. Towards a framework for validating the matching between notifications and scents in olfactory in-car interaction. In *CHI EA '19* (2019), ACM, New York, NY, USA.

[48] DMITRENKO, D., MAGGIONI, E., VI, C., AND OBRIST, M. What did i sniff?: Mapping scents onto driving-related messages. In *AutomotiveUI '17* (New York, NY, USA, 2017), ACM.

[49] DMITRENKO, D., VI, C., AND OBRIST, M. A comparison of scent-delivery devices and their meaningful use for in-car olfactory interaction. In *AutomotiveUI '16* (New York, NY, USA, 2016), ACM.

[50] DOBBELSTEIN, D., HERRDUM, S., AND RUKZIO, E. inscent: A wearable olfactory display as an amplification for mobile notifications. In *ISWC '17* (2017), ACM.

[51] DRAVNIEKS, A. Odor quality: Semantically generated multidimensional profiles are stable. *Science 218*, 4574 (1982), 799–801.

[52] DRAVNIEKS, A. *Atlas of odor character profiles.* ASTM DATA SERIES, 1985.

[53] DULA, C., AND BALLARD, M. Development and evaluation of a measure of dangerous, aggressive, negative emotional, and risky driving1. *Journal of Applied Social Psychology 33*, 2 (2003).

[54] EDWORTHY, J., LOXLEY, S., AND DENNIS, I. Improving auditory warning design: Relationship between warning sound parameters and perceived urgency. *Human Factors 33*, 2 (1991).

[55] EHERENFREUND-HAGER, A., TAUBMAN-BEN-ARI, O., TOLEDO, T., AND FARAH, H. The effect of positive and negative emotions on young drivers: A simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour 49* (2017).

[56] EHRLICHMAN, H., AND BASTONE, L. Olfaction and emotion. In *Science of olfaction*. Springer, 1992.

[57] EHRLICHMAN, H., BROWN KUHL, S., ZHU, J., AND WRRENBURG, S. Startle reflex modulation by pleasant and unpleasant odors in a between-subjects design. *Psychophysiology 34*, 6 (1997).

[58] ENDSLEY, M. R. Autonomous driving systems: a preliminary naturalistic study of the tesla model s. *Journal of Cognitive Engineering and Decision Making 11*, 3 (2017), 225–238.

[59] ENRIQUEZ, M., MACLEAN, K., AND CHITA, C. Haptic phonemes: basic building blocks of haptic communication. In *Proceedings of the 8th international conference on Multimodal interfaces* (2006), ACM.

[60] FAKHRHOSSEINI, S., LANDRY, S., TAN, Y., BHATTARAI, S., AND JEON, M. If you're angry, turn the music on: Music can mitigate anger effects on driving performance. In *AutomotiveUI '14* (NY, USA, 2014), ACM.

[61] FINGER, R., AND BISANTZ, A. M. Utilizing graphical formats to convey uncertainty in a decision-making task. *Theoretical Issues in Ergonomics Science 3*, 1 (2002), 1–25.

[62] FIRESTEIN, S. How the olfactory system makes sense of scents. *Nature 413*, 6852 (Sept. 2001).

[63] FLEXPOINT. Flexpoint Sensor Systems (FLXT). `https://www.flexpoint.com/`, 2019. [Online; accessed 17-July-2019].

[64] FORUM8. Human Factors Research. `https://www.forum8.com/solutions/drive-simulation/human-factor-research/`, 2020. [Online; accessed 09-Feb-2020].

[65] FUKADA, M., KANO, E., MIYOSHI, M., KOMAKI, R., AND WATANABE, T. Effect of "rose essential oil" inhalation on stress-induced skin-barrier disruption in rats and humans. *Chemical Senses 37*, 4 (2012).

[66] FUNATO, H., YOSHIKAWA, M., KAWASUMI, M., YAMAMOTO, S., YAMADA, M., AND YANAGIDA, Y. Stimulation effects provided to drivers by fragrance presentation

considering olfactory adaptation. In *Intelligent Vehicles Symposium 2009* (2009), IEEE.

[67] GABANY, S., PLUMMER, P., AND GRIGG, P. Why drivers speed: The speeding perception inventory. *Journal of Safety Research 28*, 1 (1997).

[68] GOTTFRIED, J., AND DOLAN, R. The nose smells what the eye sees: Crossmodal visual facilitation of human olfactory perception. *Neuron 39*, 2 (2003).

[69] GREENBERG, S., CARPENDALE, S., MARQUARDT, N., AND BUXTON, B. The narrative storyboard. telling a story about use and context over time. *Interactions* (2012).

[70] GRIGORIAN, V., AND PETERSEN, F. Designing luxury experience. *ESMT 14*, 04 (2014).

[71] HADDAD, R., MEDHANIE, A., ROTH, Y., HAREL, D., AND SOBEL, N. Predicting odor pleasantness with an electronic nose. *PLoS Computational Biology* (2010).

[72] HAEHNER, A., TOSCH, C., WOLZ, M., KLINGELHOEFER, L., FAUSER, M., STORCH, A., REICHMANN, H., AND HUMMEL, T. Olfactory training in patients with parkinson's disease. *PloS one 8*, 4 (2013).

[73] HAEUSLSCHMID, R., FORSTER, S., VIERHEILIG, K., BUSCHEK, D., AND BUTZ, A. Recognition of text and shapes on a large-sized head-up display. In *DIS '17* (2017), ACM, pp. 821–831.

[74] HAQUE, U. Scents of space: an interactive smell system. In *ACM SIGGRAPH 2004 Sketches* (2004), ACM.

[75] HART, S., AND STAVELAND, L. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Human Mental Workload*, P. A. Hancock and N. Meshkati, Eds., Advances in Psychology. North-Holland, 1988.

[76] HASEGAWA, K., QIU, L., AND SHINODA, H. Midair ultrasound fragrance rendering. *IEEE Transactions on Visualization and Computer Graphics 24*, 4 (2018), 1477–1485.

[77] HAYLEY, A., DE RIDDER, B., STOUGH, C., FORD, T., AND DOWNEY, L. Emotional intelligence and risky driving behaviour in adults. *Transportation Research Part F: Traffic Psychology and Behaviour* (2017).

[78] HELLDIN, T., FALKMAN, G., RIVEIRO, M., AND DAVIDSSON, S. Presenting system uncertainty in automotive uis for supporting trust calibration in autonomous driving. In *Proceedings of the 5th international conference on automotive user interfaces and interactive vehicular applications* (2013), ACM, pp. 210–217.

[79] HERRERA, N., AND MCMAHAN, R. Development of a simple and low-cost olfactory display for immersive media experiences. In *ImmersiveMe'14* (2014), ACM.

[80] HERZ, R., AND ENGEN, T. Odor memory: Review and analysis. *Psychonomic Bulletin & Review 3*, 3 (1996).

[81] HERZ, R. S. Influences of odors on mood and affective cognition. In *Olfaction, Taste, and Cognition*. Cambridge University Press, 2002.

[82] HIRAMATSU, M., KASAI, J., AND TAGUCHI, M. Effects of fragrance on workload in driving activity.

[83] HIROIKE, S., DOI, S., WADA, T., KOBAYASHI, E., KARAKI, M., MORI, N., KUSAKA, T., AND ITO, S. Study of olfactory effect on individual driver under driving. In *ICME '09* (2009).

[84] HIROTA, K., ITO, Y., AMEMIYA, T., AND IKEI, Y. Presentation of odor in multi-sensory theater. In *Virtual, Augmented and Mixed Reality. Systems and Applications* (2013), Springer Berlin Heidelberg.

[85] HO, C., AND SPENCE, C. *The multisensory driver: Implications for ergonomic car interface design.* CRC Press, 2017.

[86] HOBERG, F. Dufttricks der Autoindustrie: Morgens riecht der Wagen nach Meer, abends nach Wüste. `https://www.spiegel.de/auto/fahrkultur/bmw-mercedes-und-co-wie-hersteller-innenraeume-beduften-a-1272068.html`, 2019. [Online; accessed 13-June-2019].

[87] HOFF, K. A., AND BASHIR, M. Trust in automation: Integrating empirical evidence on factors that influence trust. *Human Factors 57*, 3 (2015), 407–434.

[88] HOLLAND, R., HENDRIKS, M., AND AARTS, H. Smells like clean spirit nonconscious effects of scent on cognition and behavior. *Psych. Science* (2005).

[89] HONGRATANAWORAKIT, T. Relaxing effect of rose oil on humans. *Natural Product Communications* (2008).

[90] HONGRATANAWORAKIT, T., AND BUCHBAUER, G. Relaxing effect of ylang ylang oil on humans after transdermal absorption. *Phytotherapy Research 20*, 9 (2006).

[91] HOWLAND, K., GOOD, J., AND ROBERTSON, J. Script cards: A visual programming language for games authoring by young people. In *VL/HCC'06* (2006), IEEE.

[92] HPI. How long do you leave your dashboard lights on? Online, August 2018. Retrieved October 01, 2018 from `https://goo.gl/dMf99W`.

[93] HSU, J. *Multiple comparisons: theory and methods*. Chapman and Hall/CRC, 1996.

[94] HUMMEL, T., RISSOM, K., REDEN, J., HÄHNER, A., WEIDENBECHER, M., AND HÜTTENBRINK, K. Effects of olfactory training in patients with olfactory loss. *The Laryngoscope 119*, 3 (2009).

[95] HURTADO, S., AND CHIASSON, S. An eye-tracking evaluation of driver distraction and unfamiliar road signs. In *Automotive'UI 16* (New York, NY, USA, 2016), ACM.

[96] ICHIKAWA, S., TAKASHIMA, K., TANG, A., AND KITAMURA, Y. Vr safari park: A concept-based world building interface using blocks and world tree. In *VRST '18* (New York, NY, USA, 2018), ACM.

[97] ILMBERGER, J., HEUBERGER, E., MAHRHOFER, C., DESSOVIC, H., KOWARIK, D., AND BUCHBAUER, G. The influence of essential oils on human attention. i: Alertness. *Chemical Senses 26*, 3 (2001).

[98] ISHIBASHI, Y., HOSHINO, S., ZENG, Q., FUKUSHIMA, N., AND SUGAWARA, S. Qoe assessment of fairness between players in networked game with olfaction. In *Proceedings of the 11th Annual Workshop on Network and Systems Support for Games* (2012), IEEE Press.

[99] ISHIKAWA, M., HAGIWARA, T., TAKASHIMA, K., AND KITAMURA, Y. Viblock: Block-shaped content manipulation in vr. In *SIGGRAPH ASIA 2016 VR Showcase* (New York, NY, USA, 2016), SA '16, ACM.

[100] J.D.POWER. J.D. Power Car Ratings. `https://www.jdpower.com/cars`, 2020. [Online; accessed 16-Feb-2020].

[101] JEON, M., WALKER, B., AND YIM, J. Effects of specific emotions on subjective judgment, driving performance, and perceived workload. *Transportation Research Part F: Traffic Psych. and Beh.* (2014).

[102] JEON, M., YIM, J., AND WALKER, B. An angry driver is not the same as a fearful driver: Effects of specific negative emotions on risk perception, driving performance, and workload. In *AutomotiveUI '11* (New York, NY, USA, 2011), ACM.

[103] JIAN, J.-Y., BISANTZ, A. M., AND DRURY, C. G. Foundations for an empirically determined scale of trust in automated systems. *International Journal of Cognitive Ergonomics 4*, 1 (2000), 53–71.

[104] JÖNSSON, F., MØLLER, P., AND OLSSON, M. Olfactory working memory: effects of verbalization on the 2-back task. *Memory & cognition* (2011).

[105] KADOWAKI, A., SATO, J., BANNAI, Y., AND OKADA, K. Presentation technique of scent to avoid olfactory adaptation. In *ICAT '07* (2007).

[106] KAY, L. Olfactory coding: Random scents make sense. *Current Biology 21*, 22 (2011).

[107] KAYE, J. Making scents: aromatic output for hci. *interactions* (2004).

[108] KERN, D., AND SCHMIDT, A. Design space for driver-based automotive user interfaces. In *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (2009), ACM.

[109] KHAN, R., LUK, C., FLINKER, A., AGGARWAL, A., LAPID, H., HADDAD, R., AND SOBEL, N. Predicting odor pleasantness from odorant structure: Pleasantness as a reflection of the physical world. *J. Neuroscience 27*, 37 (2007).

[110] KIECOLT-GLASER, J., GRAHAM, J., MALARKEY, W., PORTER, K., LEMESHOW, S., AND GLASER, R. Olfactory influences on mood and autonomic, endocrine, and immune function. *Psychoneuroendocrinology 33*, 3 (2008).

[111] KNASKO, S. Ambient odor's effect on creativity, mood, and perceived health. *Chemical senses 17*, 1 (1992), 27–35.

[112] KOLICH, M. In-vehicle smell notification system, May 28 2013. US Patent 8,448,739.

[113] KOLLNDORFER, K., KOWALCZYK, K., HOCHE, E., MUELLER, C., POLLAK, M., TRATTNIG, S., AND SCHÖPF, V. Recovery of olfactory function induces neuroplasticity effects in patients with smell loss. *Neural plasticity 2014* (2014).

[114] KOO, J., KWAC, J., JU, W., STEINERT, M., LEIFER, L., AND NASS, C. Why did my car just do that? explaining semi-autonomous driving actions to improve driver understanding, trust, and performance. *International Journal on Interactive Design and Manufacturing (IJIDeM) 9* (2015).

[115] KUANG, S., AND ZHANG, T. Smelling directions: Olfaction modulates ambiguous visual motion perception. *Scientific Reports 4* (2014).

[116] KUNZE, A., SUMMERSKILL, S., MARSHALL, R., AND FILTNESS, A. J. Preliminary evaluation of variables for communicating uncertainties using a haptic seat.

[117] KUNZE, A., SUMMERSKILL, S. J., MARSHALL, R., AND FILTNESS, A. J. Augmented reality displays for communicating uncertainty information in automated driving. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (2018), ACM, pp. 164–175.

[118] LAI, M. Universal scent blackbox: Engaging visitors communication through creating olfactory experience at art museum. In *SIGDOC '15* (New York, NY, USA, 2015), ACM.

[119] LAI, M. The scent of digital art: Yesterday, today, and tomorrow. In *ARTECH2017* (New York, NY, USA, 2017), ACM.

[120] LANG, P. International affective picture system (iaps) : affective ratings of pictures and instruction manual. *Technical Report* (2005).

[121] LEE, J. D., HOFFMAN, J. D., AND HAYES, E. Collision warning design to mitigate driver distraction. In *CHI '04* (USA, 2004), ACM.

[122] LEE, J. D., AND SEE, K. A. Trust in automation: Designing for appropriate reliance. *Human factors 46*, 1 (2004), 50–80.

[123] LÖCKEN, A., HEUTEN, W., AND BOLL, S. Supporting lane change decisions with ambient light. In *AutomotiveUI '15* (NY, USA, 2015), ACM.

[124] LORIG, T., ELMES, D., ZALD, D., AND PARDO, J. A computer-controlled olfactometer for fmri and electrophysiological studies of olfaction. *Behavior Research Methods, Instruments, & Computers 31*, 2 (1999), 370–375.

[125] LUDVIGSON, H., AND ROTTMAN, T. Effects of ambient odors of lavender and cloves on cognition, memory, affect and mood. *Chem. Sen.* (1989).

[126] LUNDSTRÖM, J., GORDON, A., ALDEN, E., BOESVELDT, S., AND ALBRECHT, J. Methods for building an inexpensive computer-controlled olfactometer for temporally-precise experiments. *Int. J. of Psychophysiology* (2010).

[127] LYLYKANGAS, J., SURAKKA, V., SALMINEN, K., FAROOQ, A., AND RAISAMO, R. Responses to visual, tactile and visual-tactile forward collision warnings while gaze on and off the road. *Transportation Research Part F: Traffic Psychology and Behaviour 40* (2016).

[128] MAGGIONI, E., AGOSTINELLI, E., AND OBRIST, M. Measuring the added value of haptic feedback. In *QoMEX '17* (2017).

[129] MAGGIONI, E., COBDEN, R., DMITRENKO, D., AND OBRIST, M. Smell-o-message: integration of olfactory notifications into a messaging application to improve users' performance. In *ICMI '18* (2018), ACM, New York, NY, USA.

[130] MARTIN, G., AND COOPER, J. Adding zest to difficult journeys: Odour effects on simulated driving performance. In *The British Psychological Society Annual Conference* (2007).

[131] MCGOOKIN, D., AND ESCOBAR, D. Hajukone: Developing an open source olfactory device. In *CHI EA '16* (New York, NY, USA, 2016), ACM.

[132] MCGOOKIN, D., MAYE, L., CHEN, L., AND KYTÖ, M. An initial study of multisensory interaction for outdoor heritage sites. In *CHI EA '18* (New York, NY, USA, 2018), ACM.

[133] METATLA, O., MAGGIONI, E., CULLEN, C., AND OBRIST, M. "like popcorn": Crossmodal correspondences between scents, 3d shapes and emotions in children. In *CHI '19* (2019), ACM, New York, NY, USA.

[134] MOCHIZUKI, A., AMADA, T., SAWA, S., TAKEDA, T., MOTOYASHIKI, S., KOHYAMA, K., IMURA, M., AND CHIHARA, K. Fragra: a visual-olfactory vr game. In *ACM SIGGRAPH 2004 Sketches* (2004), ACM.

[135] MOK, B., JOHNS, M., MILLER, D., AND JU, W. Tunneled in: Drivers with active secondary tasks need more time to transition from automation. In *CHI '17* (New York, NY, USA, 2017), ACM.

[136] MOK, B., JOHNS, M., YANG, S., AND JU, W. Reinventing the wheel: Transforming steering wheel systems for autonomous vehicles. In *UIST '17* (New York, NY, USA, 2017), ACM.

[137] MOSS, M., COOK, J., WESNES, K., AND DUCKETT, P. Aromas of rosemary and lavender essential oils differentially affect cognition and mood in healthy adults. *Int. J. of Neuroscience* (2003).

[138] MUADDI, N. Audi's 'Nose Team' Battles 'New Car Smell'. `http://www.thehogring.com/2015/05/27/audis-nose-team-battles-new-car-smell/`, 2015. [Online; accessed 19-June-2019].

[139] MUIR, B. M. Trust between humans and machines, and the design of decision aids. *International Journal of Man-Machine Studies 27*, 5-6 (1987), 527–539.

[140] MURRAY, N., MUNTEAN, G., QIAO, Y., AND LEE, B. *Olfaction-Enhanced Multimedia Synchronization.* Springer International Publishing, 2018.

[141] MUSTAFA, M., RUSTAM, N., AND SIRAN, R. The impact of vehicle fragrance on driving performance: What do we know? *Procedia-Social and Behavioral Sciences* (2016).

[142] NAKAMOTO, T., OTAGURO, S., KINOSHITA, M., NAGAHAMA, M., OHINISHI, K., AND ISHIDA, T. Cooking up an interactive olfactory game display. *IEEE Computer Graphics and Applications 28*, 1 (2008).

[143] NARUMI, T., NISHIZAKA, S., KAJINAMI, T., TANIKAWA, T., AND HIROSE, M. Augmented reality flavors: Gustatory display based on edible marker and cross-modal interaction. In *CHI '11* (New York, NY, USA, 2011), ACM.

[144] NAVARRE, D., PALANQUE, P., AND BASNYAT, S. A formal approach for user interaction reconfiguration of safety critical interactive systems. In *International Conference on Computer Safety, Reliability, and Security* (2008), Springer.

[145] NEWREALITY. Tree - a VR Experience. `https://www.treeofficial.com/`, 2019. [Online; accessed 16-July-2019].

[146] NG, A., AND BREWSTER, S. Investigating pressure input and haptic feedback for in-car touchscreens and touch surfaces. In *Automotive'UI 16* (New York, NY, USA, 2016), ACM.

[147] NG, A., BREWSTER, S., BERUSCHA, F., AND KRAUTTER, W. An evaluation of input controls for in-car interactions. In *CHI '17* (New York, NY, USA, 2017), ACM.

[148] NHTSA. Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey. `https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812506`, 2018. [Online; accessed 07-Jan-2020].

[149] NOAH, B., GABLE, T., CHEN, S., SINGH, S., AND WALKER, B. Development and preliminary evaluation of reliability displays for automated lane keeping. In *AutomotiveUI '17* (New York, NY, USA, 2017), ACM, pp. 202–208.

[150] NOGUCHI, D., SUGIMOTO, S., BANNAI, Y., AND OKADA, K. Time characteristics of olfaction in a single breath. In *CHI '11* (NY, USA, 2011), ACM.

[151] NORMAN, G. Likert scales, levels of measurement and the "laws" of statistics. *Advances in health sciences education : theory and practice* (2010).

[152] OBERHAUSER, M., DREYER, D., CONVARD, T., AND MAMESSIER, S. Rapid integration and evaluation of functional hmi components in a virtual reality aircraft cockpit. In *Advances in Ergonomics in Design*. Springer, 2016.

[153] OBRIST, M., TUCH, A., AND HORNBAEK, K. Opportunities for odor: Experiences with smell and implications for technology. In *CHI '14* (2014), ACM.

[154] OBRIST, M., VELASCO, C., VI, C., RANASINGHE, N., ISRAR, A., CHEOK, A., SPENCE, C., AND GOPALAKRISHNAKONE, P. Sensing the future of hci: Touch, taste, and smell user interfaces. *interactions 23*, 5 (2016).

[155] OHTSU, K., SATO, J., BANNAI, Y., AND OKADA, K. Scent presentation technique of pulse ejection synchronized with breathing. In *Ninth Annual International Symposium on Applications and the Internet, 2009. SAINT '09* (July 2009).

[156] OPHONE. oPhone DUO. http://www.indiegogo.com/projects/ophone-duo/, 2016. [Online; accessed 15-January-2016].

[157] OSHIMA, C., WADA, A., ANDO, H., MATSUO, N., ABE, S., AND YANIGADA, Y. Improved delivery of olfactory stimukus to keep drivers awake. In *Workshop on DSP for in-Vehicle and Mobile Systems* (2007).

[158] OWIDGETS. What is OWidgets? https://www.owidgets.co.uk, 2017. [Online; accessed 07-July-2019].

[159] PAN, S., BRDICZKA, O., CARENINI, G., CHAU, D. H., AND KRISTENSSON, P. O. What's hot in intelligent user interfaces. In *AAAI* (2016), pp. 4333–4334.

[160] PARASURAMAN, R., AND RILEY, V. Humans and automation: Use, misuse, disuse, abuse. *Human factors 39*, 2 (1997), 230–253.

[161] PATNAIK, B., BATCH, A., AND ELMQVIST, N. Information olfactation: Harnessing scent to convey data. *IEEE transactions on visualization and computer graphics* (2019).

[162] PEREZ, M. Safety implications of infotainment system use in naturalistic driving. *Work 41* (2012).

[163] PETERS, G., AND PETERS, B. The distracted driver. *Journal of The Royal Society for the Promotion of Health 121*, 1 (2001).

[164] PFLEGING, B., SCHNEEGASS, S., AND SCHMIDT, A. Multimodal interaction in the car: Combining speech and gestures on the steering wheel. In *AutomotiveUI '12* (New York, NY, USA, 2012), ACM.

[165] POLITIS, I., BREWSTER, S., AND POLLICK, F. To beep or not to beep?: Comparing abstract versus language-based multimodal driver displays. In *CHI '15* (New York, NY, USA, 2015), ACM.

[166] PRICE, J. Olfactory system. *The human nervous system* (1990).

[167] Rajan, R., Selker, T., and Lane, I. Effects of mediating notifications based on task load. In *AutomotiveUI '16* (2016), ACM, pp. 145–152.

[168] Ranasinghe, N., Jain, P., Thi Ngoc Tram, N., Koh, K., Tolley, D., Karwita, S., Lien-Ya, L., Liangkun, Y., Shamaiah, K., Eason Wai Tung, C., Yen, C., and Do, E. Season traveller: Multisensory narration for enhancing the virtual reality experience. In *CHI '18* (USA, 2018), ACM.

[169] Ranasinghe, N., Karunanayaka, K., Cheok, A., Fernando, O., Nii, H., and Gopalakrishnakone, P. Digital taste and smell communication. In *Proceedings of the 6th international conference on body area networks* (2011), ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

[170] Raudenbush, B., Grayhem, R., Sears, T., and Wilson, I. Effects of peppermint and cinnamon odor administration on simulated driving alertness, mood and workload. *N.A.J. of Psychology* (2009).

[171] Robertson, J., and Good, J. Story creation in virtual game worlds. *Communications of the ACM 48*, 1 (2005), 61–65.

[172] Rogers, Y., Sharp, H., and Preece, J. *Interaction Design: Beyond Human - Computer Interaction*. Interaction Design: Beyond Human-computer Interaction. Wiley, 2011.

[173] Roidl, E., Frehse, B., and Höger, R. Emotional states of drivers and the impact on speed, acceleration and traffic violations-a simulator study. *Accident Analysis and Prevention* (2014).

[174] Rümelin, S., Gabler, T., and Bellenbaum, J. Clicks are in the air: How to support the interaction with floating objects through ultrasonic feedback. In *AutomotiveUI '17* (New York, NY, USA, 2017), ACM.

[175] Russell, J. A circumplex model of affect. *Journal of personality and social psychology 39*, 6 (1980).

[176] Sani, S., Tabibi, Z., Fadardi, J., and Stavrinos, D. Aggression, emotional self-regulation, attentional bias, and cognitive inhibition predict risky driving behavior. *Accident Analysis and Prevention 109* (2017).

[177] SAVIC, I. Processing of odorous signals in humans. *Brain research bulletin 54* (2001).

[178] SCENTEE. Scentee for Mobile Devices. `http://www.scentee.com/`, 2016. [Online; accessed 15-January-2016].

[179] SCHAB, F., AND CROWDER, R. *Memory for odors.* Psychology Press, 2014.

[180] SCHARTMÜLLER, C., WINTERSBERGER, P., AND RIENER, A. Interactive Demo: Rapid, Live Data Supported Prototyping with U.S.E. In *Adjunct Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Oldenburg, 2017), ACM, pp. 239–241.

[181] SCHMIDT, A., SPIESSL, W., AND KERN, D. Driving automotive user interface research. *IEEE Pervasive Computing 9*, 1 (Jan 2010), 85–88.

[182] SCHNEIDER, O. *Haptic experience design: tools, techniques, and process.* PhD thesis, University of British Columbia, 2017.

[183] SEAH, S., MARTINEZ PLASENCIA, D., BENNETT, P., KARNIK, A., OTROCOL, V., KNIBBE, J., COCKBURN, A., AND SUBRAMANIAN, S. Sensabubble: A chrono-sensory mid-air display of sight and smell. In *CHI '14* (New York, NY, USA, 2014), ACM.

[184] SEIGNEURIC, A., DURAND, K., JIANG, T., BAUDOUIN, J.-Y., AND SCHAAL, B. The nose tells it to the eyes: Crossmodal associations between olfaction and vision. *Perception 39*, 11 (2010).

[185] SHAKERI, G., NG, A., WILLIAMSON, J., AND BREWSTER, S. Evaluation of haptic patterns on a steering wheel. In *Automotive'UI 16* (New York, NY, USA, 2016), ACM.

[186] SHEPHERD, G. Smell images and the flavour system in the human brain. *Nature 444*, 7117 (2006).

[187] SIDOWSKI, J., WYCKOFF, L., AND TABORY, L. The influence of reinforcement and punishment in a minimal social situation. *The Journal of Abnormal and Social Psychology 52*, 1 (1956).

[188] SIRKIN, D., MARTELARO, N., JOHNS, M., AND JU, W. Toward measurement of situation awareness in autonomous vehicles. In *CHI '17* (New York, NY, USA, 2017), ACM.

[189] SKLAR, A., AND SARTER, N. Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. *Human Factors 41*, 4 (1999).

[190] SMITH, M., STREETER, J., BURNETT, G., AND GABBARD, J. Visual search tasks: The effects of head-up displays on driving and task performance. In *AutomotiveUI '15* (New York, NY, USA, 2015), ACM.

[191] SODHI, R., POUPYREV, I., GLISSON, M., AND ISRAR, A. Aireal: Interactive tactile experiences in free air. *ACM Trans. Graph. 32*, 4 (July 2013), 134:1–134:10.

[192] STEAM. Drive Megapolis. `https://steamcommunity.com/app/514970`, 2016. [Online; accessed 12-July-2019].

[193] STEAM. Euro Truck Simulator 2. `https://steamcommunity.com/app/227300`, 2019. [Online; accessed 12-July-2019].

[194] STREETER, N., AND WHITE, T. Incongruent contextual information intrudes on short-term olfactory memory. *Chemosensory Perception* (2011).

[195] SUNDSTRÖM, P., BAUMGARTNER, A., BECK, E., DÖTTLINGER, C., MURER, M., RANDELSHOFER, I., WILFINGER, D., MESCHTSCHERJAKOV, A., AND TSCHELIGI, M. Gaming to sit safe: The restricted body as an integral part of gameplay. In *DIS '14* (New York, NY, USA, 2014), ACM.

[196] SUZUKI, R., HOMMA, S., MATSUURA, E., AND OKADA, K.-I. System for presenting and creating smell effects to video. In *ICMI '14* (New York, NY, USA, 2014), ACM.

[197] TRÖSTERER, S., WURHOFER, D., RÖDEL, C., AND TSCHELIGI, M. Using a parking assist system over time: Insights on acceptance and experiences. In *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (New York, NY, USA, 2014), AutomotiveUI '14, ACM, pp. 22:1–22:8.

[198] TURK, M. Multimodal interaction: A review. *Pattern Recognition Letters 36* (2014), 189–195.

[199] TWILLEY, N. Will Smell Ever Come to Smartphones? `https://www.newyorker.com/tech/annals-of-technology/is-digital-smell-doomed`, 2016. [Online; accessed 18-July-2019].

[200] VELASCO, C., BALBOA, D., MARMOLEJO-RAMOS, F., AND SPENCE, C. Crossmodal effect of music and odor pleasantness on olfactory quality perception. *Frontiers in Psychology 5*, 1352 (2014).

[201] VENGUST, M., KALUŽA, B., STOJMENOVA, K., AND SODNIK, J. Nervteh compact motion based driving simulator. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct* (2017), pp. 242–243.

[202] VENKATESH, V., MORRIS, M. G., DAVIS, G. B., AND DAVIS, F. D. User acceptance of information technology: Toward a unified view. *MIS quarterly* (2003), 425–478.

[203] VERNET-MAURY, E., ALAOUI-ISMAÏLI, O., DITTMAR, A., DELHOMME, G., AND CHANEL, J. Basic emotions induced by odorants: A new approach based on autonomic pattern results.

[204] VICTOR, T. W., TIVESTEN, E., GUSTAVSSON, P., JOHANSSON, J., SANGBERG, F., AND LJUNG AUST, M. Automation expectation mismatch: Incorrect prediction despite eyes on threat and hands on wheel. *Human factors* (2018), 0018720818788164.

[205] VOKRINEK, J., SCHAEFER, M., AND PINOTTI, D. Multi-agent traffic simulation for human-in-the-loop cooperative drive systems testing. In *AAMAS '14* (2014).

[206] WAGNER, A. R., BORENSTEIN, J., AND HOWARD, A. Overtrust in the robotic age. *Communications of the ACM 61*, 9 (2018), 22–24.

[207] WARNOCK, D., MCGEE-LENNON, M., AND BREWSTER, S. The impact of unwanted multimodal notifications. In *ICMI '11* (2011), New York, NY, ACM.

[208] WARNOCK, D., MCGEE-LENNON, M., AND BREWSTER, S. Multiple notification modalities and older users. In *CHI '13* (USA, 2013), ACM.

[209] WATSON, D., CLARK, L. A., AND TELLEGEN, A. Development and validation of brief measures of positive and negative affect: the panas scales. *Journal of personality and social psychology 54*, 6 (1988), 1063.

[210] WEBER, M., GIACOMIN, J., MALIZIA, A., SKRYPCHUK, L., AND GKATZIDOU, V. Automotive emotions: An investigation of their natures, frequencies of occurrence and causes. *Engineering and Technology International Journal of Industrial and Systems Engineering* (2018).

[211] WEISS, T., SNITZ, K., YABLONKA, A., KHAN, R., GAFSOU, D., SCHNEIDMAN, E., AND SOBEL, N. Perceptual convergence of multi-component mixtures in olfaction implies an olfactory white. *Proceedings of the National Academy of Sciences* (2012).

[212] WEISSTEIN, E. W. Bonferroni correction.

[213] WILSON, G., AND BREWSTER, S. Multi-moji: Combining thermal, vibrotactile & visual stimuli to expand the affective range of feedback. In *CHI '17* (New York, NY, USA, 2017), ACM.

[214] WILSON, G., DOBREV, D., AND BREWSTER, S. Hot under the collar: Mapping thermal feedback to dimensional models of emotion. In *CHI '16* (New York, NY, USA, 2016), ACM.

[215] WINTERSBERGER, P., DMITRENKO, D., SCHARTMÜLLER, C., FRISON, A., MAGGIONI, E., OBRIST, M., AND RIENER, A. S(c)entinel: monitoring automated vehicles with olfactory reliability displays. In *IUI '19* (2019), ACM, New York, NY, USA.

[216] WINTERSBERGER, P., AND RIENER, A. Trust in technology as a safety aspect in highly automated driving. *i-com 15*, 3 (2016), 297–310.

[217] WINTERSBERGER, P., RIENER, A., SCHARTMÜLLER, C., FRISON, A.-K., AND WEIGL, K. Let me finish before i take over: Towards attention aware device integration in highly automated vehicles. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (2018), ACM, pp. 53–65.

[218] WU, B., MENG, Q., HOU, H., ZENG, M., AND QI, P. An olfactory display system integrated with video content recognition. In *2018 13th World Congress on Intelligent Control and Automation (WCICA)* (2018), IEEE, pp. 1641–1646.

[219] YANAGIDA, Y., KAWATO, S., NOMA, H., TOMONO, A., AND TESUTANI, N. Projection based olfactory display with nose tracking. In *Virtual Reality, Proceedings. IEEE* (March 2004).

[220] YOSHIDA, M., KATO, C., KAKAMU, Y., KAWASUMI, M., YAMASAKI, H., YAMAMOTO, S., NAKANO, T., AND YAMADA, M. Study on stimulation effects for driver based on fragrance presentation. In *MVA2011 IAPR* (2011).