ScentHaptics: Augmenting the Haptic Experiences of Digital Mid-Air Textiles with Scent

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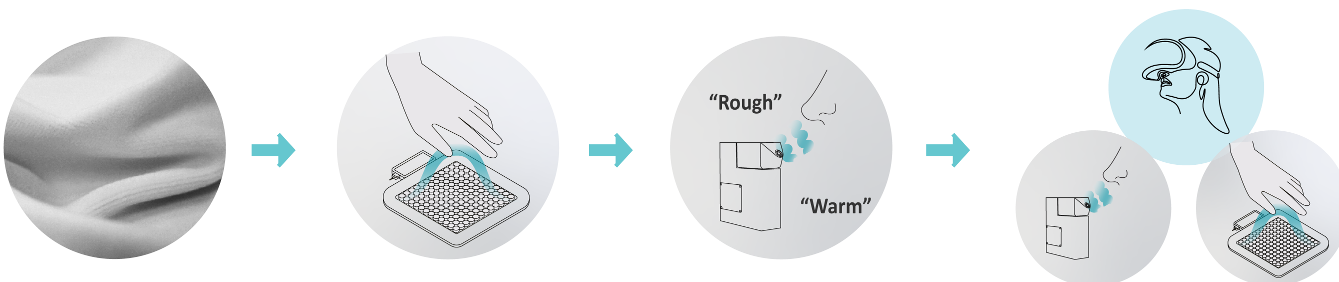

Figure 1: Our paper investigated how the touch experience of digital textiles, presented using ultrasonic mid-air haptics, could be augmented by scents. In Study 1, we identified scents associated with tactile dimensions (e.g., "Rough" or "Warm") based on user ratings. In Study 2, users explored two different digital textiles while these scents were presented in a Virtual Reality environment.

ABSTRACT

Human perception of touch is a complex interplay of sensory inputs, extending beyond tactile stimuli to include visual and auditory cues. Yet, the potential of olfactory cues (e.g., scents) to enrich our understanding and experiences of digital touch remains largely unexplored. This paper explores the integration of scent with digital haptic feedback, specifically focusing on the perception of textiles using an ultrasonic mid-air haptic device. In an initial validation study, we identified scents associated with the tactile properties of roughness, smoothness, coldness, and warmth based on participant ratings (n = 31). In a subsequent immersive Virtual Reality (VR) experiment, we explored how these scents might affect perceptions of digital textiles presented using ultrasonic mid-air haptics (n = 32). Our results suggested that while scents did not affect the tactile properties of digital textiles, participants reported the sensations feeling more realistic and more arousing according to the scent delivered. This multimodal integration of scent with digital haptic stimuli can open up the creation of more immersive experiences and more in-depth understanding of digital material properties.

CCS CONCEPTS

• **Human-centered computing → User studies**.

KEYWORDS

Multisensory, Scent, Haptics, Virtual Reality, Textiles, Digital Touch, Mid-Air Haptics, Olfaction, Immersive Digital Experiences

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1 INTRODUCTION

As digital environments become more pervasive, there is a growing need to replicate complex real-world sensations to create more immersive and meaningful experiences. Human-Computer Interaction (HCI) has traditionally focused on visual and auditory modalities, but recent advances have expanded its scope to include touch, smell, and even taste [15, 56]. The digitisation of touch, while explored through various haptic devices, remains challenging due to the intricate nature of tactile interactions, which encompass tactile, thermal, proprioceptive, and kinaesthetic elements [44], in addition to device size, cost, and system complexity [44]. Pseudo-haptics, a field that augments touch experiences by capitalising on multimodal sensory inputs [47], offers a promising alternative to conventional haptic technologies by potentially bypassing the limitations of physical devices. To date, pseudo-haptic research has predominantly focused on visual and auditory cues, largely neglecting the potential of olfactory cues, which may significantly enhance the realism and emotional depth of digital interactions [44]. With advancements in olfactory technology facilitating controlled scent delivery [9, 14], we now have the means to systematically explore how integrating olfactory cues with tactile feedback can create more nuanced and realistic multimodal interactions.

This paper presents a novel exploration into augmenting digital touch with olfactory cues within a VR setting, utilising novel olfactory and haptic technologies, including ultrasonic mid-air haptics [2]. We focus on the digital representation of textiles — a medium highly relevant to scent augmentation and previously explored in the context of pseudo-haptic feedback [74]. Textiles are particularly pertinent in HCI due to their complex properties, which no single haptic device can currently replicate fully, making them a key target for pseudo-haptic augmentation. Moreover, our experience with textiles is inherently multisensory [75], necessitating a multimodal approach to understand and fully replicate their properties in digital spaces. A fuller understanding and digital representation of textiles in virtual environments would allow for remote design opportunities [75], greater digital exploration of limited physical samples of innovative textiles, and may create more informative interactions and purchasing decisions during online shopping, being in-line with aims to reduce textile e-commerce waste [52].

To achieve this, we conducted two studies. From Study 1, we selected scents associated with tactile texture-related features such as roughness, smoothness, coldness, and warmth based on ratings by 31 participants. In Study 2, we presented these scents while participants explored different mid-air textiles in an immersive VR environment (n = 32, See Figure 4). Our results revealed that while olfactory cues did not directly alter tactile perceptions (such as roughness or warmth), they significantly enhanced the realism and emotional engagement of the digital textiles experienced by users. This finding highlights scent as a novel pseudo-haptic method to enhance digital interactions, emphasising the potential of integrating the often-underutilised sense of smell alongside traditional sensory modalities.

2 RELATED WORK

In this section, we first delve deeper into the significance of touch, efforts in the literature to digitise touch, and why bringing it into the digital realm is important. Next, we review how researchers have augmented touch experiences through other modalities. Finally, we highlight the absence of scent-based augmentations of touch and highlight the opportunities around integrating scent and touch.

2.1 Importance of Touch and its Digitisation

The sense of touch is fundamental to human perception, enabling us to navigate, manipulate, and understand our environment effectively [48]. It is deeply tied to emotional and social communication; for example, comforting contact between humans and between humans and animals or robots can foster bonding and pro-social behaviours [22, 46, 70]. Touch also helps us discern the material properties of objects, with tactile variations prompting detailed explorations that enhance emotional connections, influence purchasing decisions, and bolster confidence in our judgments [57–59]. Effectively rendering digital touch can enhance the realism and emotional reaction to virtual objects, environments, and interactions [63, 65], improve user engagement and interaction efficiency [51, 69], and increase the effectiveness of virtual communication and social interactions [28].

The need for digital touch has led to the development of various wearable devices. However, these devices, such as vibrotactile motors, force-feedback devices, and Peltier modules, often stimulate only single sensory pathways — vibration, pressure, kinesthetic sensations, or temperature changes. Embedding all these devices into practical applications is not feasible [43], leaving a gap in comprehensive haptic feedback needed for precise manipulation and understanding of objects and others. Moreover, these wearable devices come with limitations related to comfort, weight, hygiene, and practicality [35, 43]. Alternatively, recent touchless technologies like ultrasonic mid-air haptics use ultrasonic waves to create touch sensations through focal points on the skin, stimulating rapid pressure changes and light touch, but they fail to affect slow-adapting mechanoreceptors responsible for detecting static pressure, texture, and skin stretch [34, 48, 62, 71].

In the digital realm, textiles as a touch medium offer a particularly rich case for the exploration of touch. Textiles evoke a diverse range of sensations and emotions [75], encompass a broad spectrum of haptic properties such as smoothness, weight, and warmth, and communicate our identity and cultural values. They also represent a key sustainability target [52]. Moreover, our understanding and exploration of textiles is inherently multisensory, requiring multimodal input to replicate our rich decision-making processes in the physical world [59]. Previous work has effectively augmented textiles presented using mid-air haptics with multimodal inputs, capitalising on the unrestricted exploration needed for textile appraisal [60]. Yet, the range and specificity of tactile stimulation these devices can provide remains notably constrained [30, 74]. The integration of textiles with mid-air haptics creates a compelling scenario, merging the ease of using touchless haptic technologies with the enriched tactile sensations afforded by multimodal principles [60]. One promising direction is the integration of pseudo-haptics with other sensory modalities to create more convincing sensory experiences.

2.2 Augmenting Touch with other Modalities

Pseudo-haptics, extensively reviewed by Kurzweg et al. [44], involves stimulating haptic sensations using other modalities, thereby reducing system complexity [61]. These illusions can alter our perception of proprioception, geometry, weight, stiffness, and surface texture or even cause phantom sensations [44]. Pseduo-haptic research has gained increasing attention in recent years but has almost entirely focused on visual and auditory cues to augment tactile perceptions [44].

A frequent approach is to combine haptic stimulation with corresponding visual representations of the intended texture [6, 25]. Visual information often dominates tactile perception when evaluating material properties [66], reinforcing the sense of touch with congruent visual cues. This multisensory dominance can be influenced by both the information's relevance and reliability [24]. For instance, darker and heavier-looking objects (e.g., metal vs wood) can be perceived as heavier simply based on their appearance [49]. In terms of our sense of hearing, the sounds produced during the exploration of object surfaces significantly influence our perception of texture [20, 53, 68]. Augmenting these sounds can re-shape our touch experiences [21, 32, 54, 74], such as changes in pitch or frequency and adding white noise to explorations altering our perception of roughness [23, 27, 38, 72, 74]. The integration of auditory and visual cues can even produce more pronounced sensations, as demonstrated in augmented reality applications, where congruent auditory and visual oscillations can intensify the perception of vibration [43]. The integration of scent to augment touch perception in digital interactions remains largely unexplored [44]. Brooks et al. used scents to influence perceptions of temperature in Virtual Reality (VR) settings, increasing feelings of cold with eucalyptol and warmth with capsaicin [10]. While promising, the potential of scents to enhance the perception of digital objects, especially when combined with other sensory feedback like haptic sensations, is poised for deeper study [44].

2.3 Integrating Touch and Scent

In recent years, there has been a renewed focus on our sense of smell, alongside the development of new olfactory interfaces and design frameworks [4, 9, 14, 50]. With these advancements and the removal of previous hardware/software limitations, it has become more practical to explore how scents can enhance our experiences. Given this progress, how might scent influence our sense of touch?

Scents are often described using descriptors related to sensory or bodily features that are not directly related to smell, such as feminine or masculine, or sweet, sour or spicy [7, 76]. We might use tactile descriptors as well [8, 42, 67, 76]. For example, we may describe lemon as soft, vanilla as smooth, or eucalyptus as sharp [67]. In Table 1, we review previous work using olfactory cues to manipulate tactile properties. In cosmetic research, scents can augment the texture, smoothness, stickiness, and greasiness of products [12, 31, 40] and even increase their perceived efficacy [16, 29, 31, 40, 45]. In wider research, the effect of scent on touch experiences is less consistent. For example, civet scent has been found to reduce touch pleasantness from a robotic arm [17] and jasmine to decrease ratings of stiffness from a force-feedback device [55]. Interestingly, while lemon increased ratings of textile softness relative to an 'animal' scent [19], a later study found lemon did not affect smoothness ratings of sandpaper [41].

While this literature is somewhat inconsistent in terms of whether scent may affect touch, several points may explain this inconsistency. Firstly, the temporal and spatial congruence between stimuli (e.g., scent and touch) is critical for crossmodal correspondences [11, 39]. Moreover, past studies have often presented ambient odours rather than embedding scents within stimuli, which would give a greater indication of the material's properties (e.g., an intensely fragranced cream may suggest a high concentration of active ingredients). Moreover, using a scent irrelevant to the stimuli may mean it is not considered during appraisal [20]. Indeed, this is consistent with lemon increasing the smoothness of scented textiles [19], but not of sandpaper when delivered ambiently [41].

Table 1: Summary of previous work presenting or embedding scents in touch interactions

Scent	Dimension assessed
Pleasant-Unpleasant	Civet [17]*, Rose [17], and Floral [16]*.
Hard/Rough-Soft/Smooth	Lemon [19, 40]* [41], Lavender [19]*, Rose [41], Masculine [36], Feminine [36], Ethanol [41], Animal [19]*, Jasmine [55], Peppermint [55], Indole [41], Floral [31]*, and Fennel [31]*.
Stiff-Soft	Jasmine [55]* and Peppermint [55]
Greasiness/Oiliness	Fennel [31]* and Floral [31]*
Ability to spread (cream)	Fennel [31]* and Floral [31]*
Tackiness	Fennel [31]*
Stickiness	Vanilla [40]

***Note**: * indicates the scent significantly affected touch.*

2.4 ScentHaptics Research Opportunity

While studies suggest that olfactory cues may be able to augment ambient temperature and physical touch [10, 12, 17, 31, 40], the potential of scent to enhance digital touch remains unexplored, highlighting a significant gap in multimodal research. Moreover, many studies deliver scents ambiently and refer to objects with minimal relevance to olfactory cues, which may limit the impact of pseudo-haptic effects [11, 20, 39]. In response, our work investigates the effect of embedding carefully selected scents into digital touch experiences, in our case, digital textiles, to augment their tactile and affective properties.

To explore this novel interaction opportunity, we adopted two existing innovative technologies, one to accurately deliver scents and another to convey mid-air textiles using an ultrasonic mid-air haptic device. To do so, we conducted two studies. Our first study aimed to identify and select scents associated with the tactile dimensions of roughness-smoothness and cold-warmth according to user ratings. We chose these properties for their relevance in previous mid-air haptic [3, 74] and physical touch research (see Table 1). Our second study aimed to explore the effect of presenting these scents during the exploration of digital textiles in an immersive VR environment. Both studies in this paper were approved by the University's Ethics Committee Review Board.

3 STUDY 1: VALIDATION OF SCENT SELECTION

Our first study aimed to find two scents associated with smoothness, two with roughness, one with coldness, and another with warmth due to these properties' potential to be augmented in mid-air haptics [74] and frequency in past work (Table 1). We then assessed the pleasantness of these chosen scents as pleasantness has previously

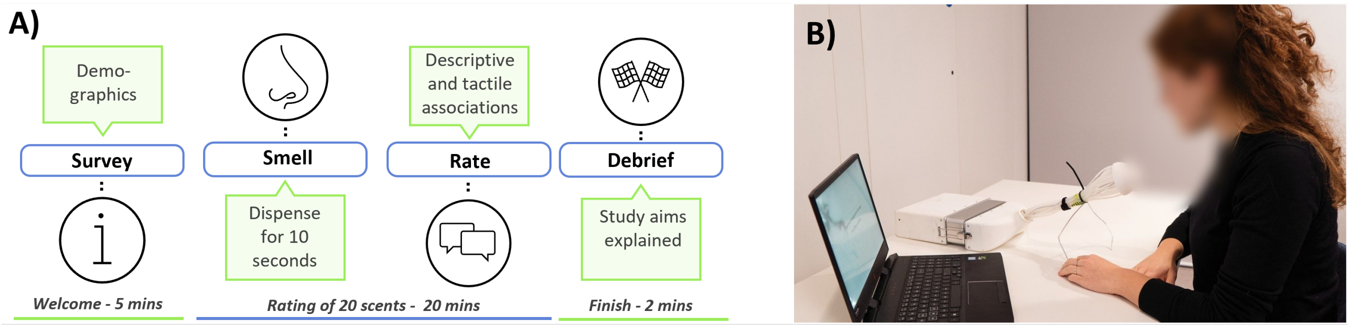

Figure 2: A) Procedure of Study 1. After answering background information about themselves, participants were asked to rate 20 different scents on their tactile, affective, and descriptive properties. B) Setup of Study 1. We used a scent delivery device to present olfactory cues at a distance of 30cm. Participants sat in a quiet room for the experiment.

been suggested to be influential [17]. To do so, participants rated 20 different scents on their descriptive, affective, and tactile properties, as described below. We hypothesised that different scents will be significantly associated with the tactile descriptors of roughness-smoothness and coolness-warmth.

3.1 Scent Selection and Delivery

We selected nine scents based on the literature presented in section 2.3 and a further 11 novel scents for exploration we considered fabric-relevant. Ten of these were expected to relate to smoothness (rose, lemon, jasmine, lavender, fresh linen, baby powder, clean cotton, vanilla, cocoa absolute, and coffee), and the other ten to roughness (eucalyptus, sandalwood, indole, civet, ethanol, peppermint, black pepper, castoreum, teak, and cedar). Scent suppliers, chemical components, and concentration details can be found in Supplementary Table A. We eventually removed ethanol from the analysis, as the scent was imperceptible after 24 hours due to evaporation. The scents were delivered using a digital scent delivery device developed by OW Smell Made Digital[1]. The device pumps air through individually separated scent channels. We added 250 microlitres of each scent to a cellulose sponge (25mm x 10mm x 1mm) placed into the device.

3.2 Measures

We asked participants to rate the descriptive, tactile, and affective properties of the 20 scents. These items are presented below alongside the rating scales used to make assessments:

- Rating scales: 0% (Not at all) - 100% (Extremely): woody, intensity, familiarity, and liking.
- Bipolar adjective scales: 0 (Left pole) - 100 (Right pole): rough-smooth, cool-warm, hard-soft, sharp-dull, natural-artificial, delicate-bold, and heavy– light.
- Self-Assessment Mannequin (SAM): valence (negative-positive) and arousal (low-high) dimensions [5].

3.3 Procedure

As outlined in Figure 2A, users rated the 20 scents on the above measures. All questions and scents were presented in a randomised order, with all question initial anchor points on the continuous scales set to halfway (50% = no association). Participants were asked to rate the scent intensity as 0% if they did not smell anything, which we later used to exclude trials from the analysis.

3.4 Participants

Thirty-one participants were recruited (Mean age = 28.1 years [SD = 7.50, range = 18 - 60], 19 cis-gendered females and 11 cis-gendered males). The participants' first language was primary English (10) or Mandarin/Chinese (10), but all were proficient in English. All participants had no history of neurological disorders, were non-smokers, and did not suffer from any form of smell/touch loss. All participants were compensated for their time with a £5 gift voucher.

3.5 Study Results

Trials with an intensity rating under 5% or identified as outliers (according to the median ± 3.0 × the Median Absolute Deviation) were removed. For the analysis, ratings of each scent were compared to a null value of 50% on the 0% - 100% bipolar scales, representing no association. We used Linear Mixed-Effects (LME) models to analyse responses (similar to repeated-measures ANOVAs) and applied False Discovery Rate (FDR) correction to follow-up tests. As we aimed only to identify up to six total scents for the main study (a number less likely to cause olfactory fatigue), we only analysed the top and bottom three scents for each question. These associations would then be validated in Study 2.

3.5.1 Tactile association. For roughness-smoothness, planned t-tests compared ratings against a null value of 50 (no association), finding that Civet (36.8, SE = 3.97, p = .007) and Black Pepper (37.7, SE = 3.97, p = .014), but not Castoreum (46.3, SE = 3.71, p > .999) were significantly associated with roughness. Next, Clean Cotton (75.8, SE = 3.84, p < .001), Chocolate (77.9, SE = 4.30, p < .001), and Baby Powder (75.8, SE = 3.77, p < .001) were all significantly associated with smoothness. These relationships are illustrated in Figure 3. We selected Civet and Black Pepper as "Rough" and Clean Cotton and Chocolate as "Smooth" based on these results.

3.5.2 Thermal association. The scents of Peppermint (11.6, SE = 3.54, p < .001), Eucalyptus (21.1, SE = 3.40, p < .001), and Baby Powder (35.3, SE = 3.29, p < .001) were all significantly rated as

[1]OW Smell Made Digital: https://www.ow-smelldigital.com/

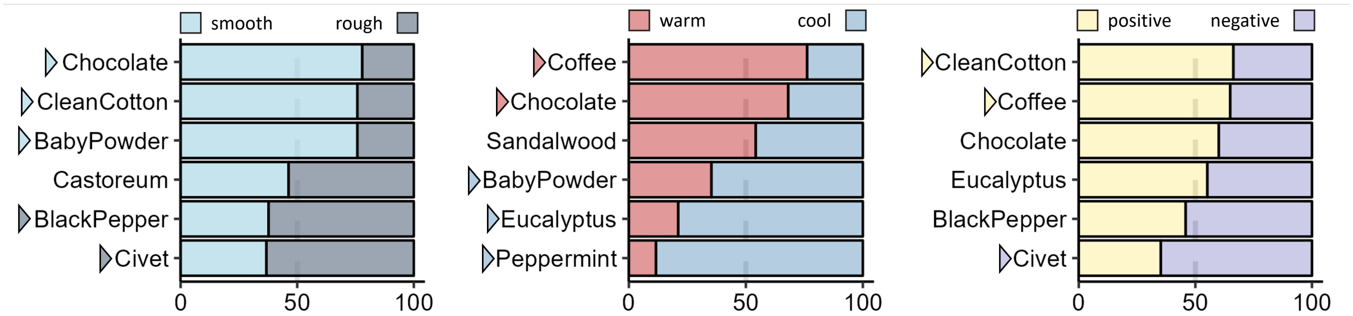

Figure 3: Study 1 results. From participant ratings of 20 different scents, we identified Civet and Black Pepper as associated with Roughness, Chocolate and Clean Cotton as Smooth (*Left*), Coffee as Warm, and Eucalyptus as Cool *(Middle)*. Analysing these six scents also suggested Civet was unpleasant, while Clean Cotton and Coffee were pleasant scents (*Right*). Note: arrows represent a significant effect compared to a null rating of 50 (no association).

cool. Conversely, the scents of Chocolate (68.1, SE = 3.40, $p < .001$) and Coffee (76.2, SE = 3.53, $p < .001$) were rated as warm. However, there was no association for Sandalwood (54.2, SE = 3.34, $p > .999$). From these results, we selected Coffee to represent warmth and Eucalyptus to represent cold. While Peppermint was rated colder, participants in the current and our previous studies (which were primarily UK and Chinese nationals) more commonly agreed that Eucalyptus is most easily recognised.

3.5.3 Affective. Only Civet was rated as having a negative valence (35.2, SE = 4.29, $p < .001$). Both Clean Cotton (66.3, SE = 4.09, $p < .001$) and Coffee (64.9, SE = 4.29, $p = .004$) were found to have a positive valence. The scents of Black Pepper (45.8, SE = 4.09, $p < .999$), Eucalyptus (55.1, SE = 4.03, $p > .999$), and Chocolate (60.0, SE = 4.09, $p = .094$) were not significantly associated with valence.

4 STUDY 2: THE EFFECT OF SCENT ON TOUCH EXPERIENCES IN VR

Building on the results of Study 1, we selected scents representing touch properties, including Civet and Black Pepper for roughness, Clean Cotton and Chocolate for smoothness, Eucalyptus for coolness, and Coffee for warmth. Study 2 investigates whether these scent-touch associations may enhance the tactile perception of digital textiles during VR interactions. We hypothesised that scents associated with a specific touch dimension (e.g., smoothness) would increase ratings of that dimension in mid-air haptic textures when paired with the scent, compared to textures with no scent delivery.

4.1 Study Design and Setup

We used a repeated-measured design with two variables: Scent (the 6 scents identified in Study 1 and an unscented control condition) and Textile (digitised Velvet [smooth] and Buckram [rough]). Users rated their touch experiences of the digital textiles on tactile properties, including rough-smooth, soft-hard, and cool-warm; affective properties of valence and arousal; and how realistic the touch experience felt. Below, we explain the study details and setup.

4.1.1 VR Environment and Interaction. The virtual environment was designed using the Unity Game Engine and presented via a Meta Quest Pro headset, providing a resolution of 1800 × 1920 pixels per eye (72Hz). The headset's native hand-tracking facilitated interactions, and we used each controller as an object tracker for the table and the haptic board, ensuring appropriate haptic delivery. We modelled the virtual environment on the simple physical lab where the study took place to reduce novelty effects and cognitive load. This was a small room with a kitchenette used for multisensory studies, where participants sat at a desk with the researcher sitting opposite.

4.1.2 Haptic Delivery. Velvet and Buckram were selected to be digitised, representing a smooth and rough textile [75]. We delivered mid-air haptic textures to participants using the Ultraleap STRATOS Explore Development Kit (16 × 16 transducer array boards). Participants' hand movements were tracked with a Leap Motion Controller LM-010. We employed the mid-air haptic textures of Buckram and Velvet used in our previous study [74], created using algorithms by Beattie et al. [3] and Montano-Murillo et al. [53].

4.1.3 Scent Delivery. A smaller six-channel scent delivery device, again by OW Smell Made Digital, provided the scent delivery. The scent was directed to the user's nose via a custom 3D-printed attachment for the headset, which held six 2-meter-long polyurethane tubes approximately 10cm away from the user's nose. The device interfaced with Unity through a serial port connection and delivered the scent in short bursts of 100ms followed by a 900ms break to reduce that tactile stimulation on the face.

4.2 Measures

We asked for the same demographic information as Study 1. For digital touch assessments, we chose a subset of questions used in Study 1 and additionally asked participants how realistic the haptic sensation was:

- Bipolar adjective scales: rough-smooth, hard-soft, cool-warm, realistic-unrealistic
- Self-Assessment Mannequin (SAM): valence and arousal

We reduced the scale size from 0% - 100% to 0 - 10 for simplicity within VR.

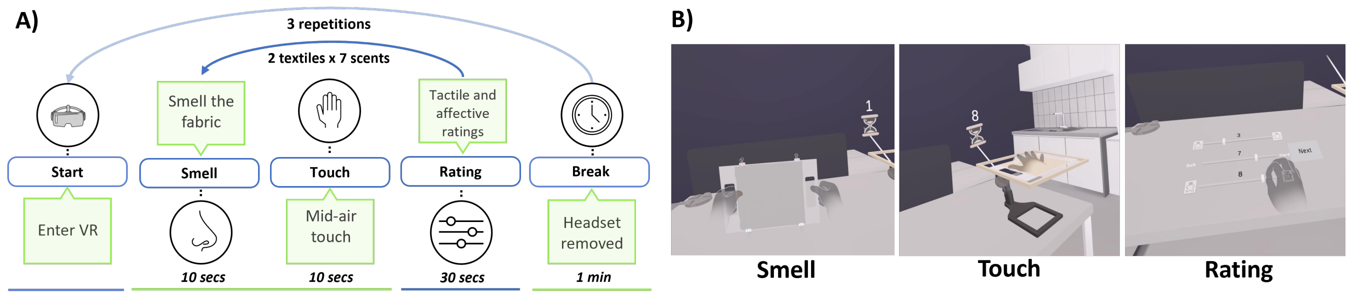

Figure 4: A) Procedure flow of Study 2. There were 14 combinations of textiles and scents presented in a randomised order. Each set of 14 combinatons were rated three times with a break in-between, with the order re-randomised after each repetition B) VR task used in Study 2. Each trial began with the user grabbing a digital textile, holding it close to their nose, and smelling it while the scent was delivered for 10 seconds. Next, they placed the textile into the 'haptics zone' and explored its touch properties delivered by a mid-haptic device for 10 seconds. We also delivered shorter bursts of fragrance during the touch interaction to facilitate multisensory integration. After touching for 10 seconds, rating scales appeared in VR, and users rated their experience on tactile and affective dimensions

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4.3 Procedure

Study 2 began with demographic data collection, followed by the VR task where users explored digital textiles while the scents were presented, a replication of the scent rating task outlined in Study 1 to confirm our previous results, and open-ended feedback.

4.3.1 Introduction. After explaining the overall process of the study (see Figure 4), it was made clear to participants that they would be rating their feelings towards the textiles, not just the scent or haptic in isolation. Next, the haptic device was introduced to participants and a physical representation of the textile they would see in VR was shown. This was simply an A4 piece of card with a textile swatch attached, covered by a removable layer of muslin that masked the visual of the textile underneath. It was explicitly explained to participants that we wanted to remove the visual impact of the textile on their assessments, with the textiles in VR also shielding their visuals similarly. It was explained that the scent would come from the textile swatch underneath the cover.

4.3.2 VR Task. The VR task began with participants sitting at a virtual desk. They saw a digital version of the haptic zone in mid-air, represented by a glowing hollow square. The task began with a 1-minute video explaining the procedure. Each trial began with a digital version of the textile appearing in front of the participant (see Figure 4B, left). Participants were then told to grab the digital textile with both hands and bring the textile close to their nose until a 10-second virtual timer ran out. Critically, scents were only delivered if the digital textile was within 10 cm of the digital nose, reinforcing that the scent came from the textile, not the environment. Once completed, a voice-over asked participants to move the textile to the haptic zone and let go (see Figure 4B, middle). Upon release, the textile snapped into place, and an animation played, removing the clips and muslin cover and 'revealing' the textile underneath. The textile was depicted as a glowing square, and the voice-over explained, *"Remember, the real visual of the textile has been digitally changed, so all textiles will look like this, but they are not all the same. Now run your hand across the textile until the 10-second timer runs out"*. At this point, the appropriate haptic sensation (Buckram or Velvet) was delivered. We also delivered two puffs of scent during the haptic exploration at seconds 3 and 7 to facilitate multisensory integration and mimic real-life exploration. After the timer ran out, the haptic sensation stopped and virtual versions of the survey questions appeared so that participants could rate their experiences. Users clicked a 'Next' button to submit their answers. The process was then repeated. The 14 trial combinations of textiles and scents were randomised within each of the three repetitions, totalling 42 trials. Each repetition took approximately 15 minutes, with a 1-minute break between each repetition.

4.3.3 Scent Validation and Post-Task Feedback. After a short break, participants took part in a replication of the scent rating task in Study 1, assessing only the six scents they just experienced. To ensure consistency with their perception within VR, scents were delivered through the same device and attachment held 10cm from their face. After the 5-minute task, participants gave feedback to open-ended questions regarding how they felt about the task more generally and whether they smelled any scents during the VR condition. Participants were then debriefed and allowed to withdraw their data anonymously before leaving.

4.4 Participants

A total of 32 participants were included. The sample had a mean age of 28.3 years (SD = 8.59, range = 18 - 50) and a gender balance of 22 cis-gendered females, 10 cis-gendered males, and one self-identified transgender male. In terms of background, 17 were British nationals, and eight were from China or Hong Kong, with the remainder scattered more widely. Similarly, the first language was primarily English (16) followed by Manadarin or Cantonese (11). All participants met the same criteria as the pre-study and were offered £15 compensation.

4.5 Data Processing and Analysis Strategy

One participant requested the removal of their data, leading to our final sample of 32 participants. For our second scent rating task, we applied the same outlier criteria and analysis as Study 1, but no trials fell outside this criteria. For the VR task, where users rated the touch experiences of the mid-air textiles, 7 blocks of trials were not completed due to technical issues with the headset. We also screened responses for outliers in the same manner as the scent rating tasks, removing 1.5% of extreme responses. We again applied LME models to compare the ratings of our six dependent variables between our unscented control condition and the six scents (FDR corrected). We also assessed the variable of trial number to determine if responses may change over time (e.g., as novelty effects/cognitive load reduced). However, our following results were unaffected by the inclusion of this control variable.

4.6 Results: Scent Rating Task

We began the analysis by assessing user associations between the six scents and tactile and affective properties. These ratings were given after the VR task, where the participants experienced the scents from the device without haptic stimulation. Please see Supplementary Figure 2 for a visualisation of the below results.

4.6.1 Rough-Smooth. We replicated that Clean Cotton was rated as smooth (70.0, SE = 3.86, $p < .001$, $d = 1.001$), but the remaining scents presented no significant association (all $p > .119$, $d < .397$).

4.6.2 Cool-Warm. Interestingly, we found that all scents were related to coolness (all $p < .001$, $d > .679$), with the exception of Coffee (49.7, SE = 3.47, $p = .921$, $d = .020$). Eucalyptus was not rated cooler than the other scents (all $p > .523$, all $d < .253$).

4.6.3 Valence. Clean Cotton was rated with positive valence (69.2 SE = 3.90, $p < .001$, $d = 1.001$), whereas the remaining scents were not significantly associated with valence (all $p > .157$, all $d < .395$)

4.7 Results: Ratings of Digital Touch Experience

Next, we analysed the effect of scent on participant ratings of the mid-air textiles. These ratings refer to those in the VR environment. We began by investigating the effect of textile type (Buckram or Velvet) on the six outcome variables.

4.7.1 Mid-air haptics. Overall, we found that the two textiles of Buckram and Velvet were not significantly different on any of the outcome variables (all $p > .171$). As a result, we did not investigate interactions between Textile and Scent. However, we added Textile as a control variable in the following analyses. See Supplementary Figure 1 for graphs of these relationships.

4.7.2 Unrealistic - Realistic. There was a significant main effect of Scent ($F(6,1198) = 3.746$), $p = .001$), wherein the scents of Clean Cotton ($p = .002$), Black Pepper ($p = .001$), Chocolate ($p = .018$), Civet ($p = .002$) and Eucalyptus ($p = .001$) all increased the realism of touch relative to the unscented control. Coffee did not significantly affect ratings ($p = .130$).

4.7.3 Valence and Arousal. The effect of Scent on Valence was significant ($F(6,1195) = 2.319$), $p = .032$); however, follow-up t-tests did not survive correction for multiple comparisons (all $p > .117$), indicating valence was largely unaffected by scent. The effect of arousal was also significant ($F(6,1196) = 2.611$), $p = .016$), wherein the scents of Black Pepper ($p = .003$) and Eucalyptus ($p = .013$) significantly increased the arousal of touch interactions. The remaining scents were all non-significant (all $p > .083$).

4.7.4 Touch Properties. The effect of Scent was non-significant for the variables roughness-smoothness ($F(6,1198) = 0.889$), $p = .501$), softness-hardness ($F(6,1195) = 0.725$), $p = .629$), or cool-warm ($F(6,1195) = 1.07$), $p = .379$).

5 DISCUSSION

This paper investigated the potential of scents to augment digital touch experiences through ultrasonic mid-air haptics. Even though scents did not alter the tactile properties of the digital textiles, they significantly enhanced touch realism and emotional response, highlighting the potential of scent to enrich digital interactions.

5.1 Augmented Touch Realism and Emotional Engagement with Scent

In Study 2, we demonstrated that incorporating scents during digital touch interactions with mid-air textiles significantly enhances touch realism and emotional engagement. These findings are consistent with broader digital scent research, which emphasises the role of scent in enhancing immersion, presence, and engagement in digital environments and interactions, as well as bridging physical and digital elements in mixed-reality settings [1, 33, 64, 73, 77]. Our research extends the existing literature — which typically focuses on ambient factors — to discrete interactions such as textiles, enriching the user experience with nuanced sensory inputs. These implications reach far beyond our textile case study. For instance, the tactile sensation of rain on our faces could be made more vivid with the scent of petrichor, and the realism of digital weapons in gaming can be enhanced with the scent of gunpowder, perhaps even improving interaction efficiency through enhanced touch naturalism. Additionally, personal interactions in digital settings can be deepened, such as enhancing the touch of a long-distance loved one's hand with their personal scent. More broadly, integrating scent with touch offers new pathways for accessibility, providing alternative sensory interactions for individuals with sensory loss [51]. Utilising scent as a pseudo-haptic method may also address some limitations of haptic devices, such as system complexity [44], especially given the rise of simple, open-source, and affordable VR scent delivery prototypes [26, 37].

Regarding design recommendations, our findings suggest that the type of scent was not directly correlated with increased touch realism. However, increasing the recognisability of scents (which is often challenging when visual cues are absent, as in Study 2), might strengthen the association to tactile properties [67]. Interestingly, only Black Pepper and Eucalyptus were found to increase emotional arousal, possibly due to their unique activation of trigeminal pathways rather than through scent recognition alone.

Despite the enhanced touch realism and emotional engagement through scent demonstrated in our work, scents did not significantly affect the tactile properties or pleasantness of digital textiles. This contrasts with findings from the cosmetic industry, where scents are known to alter tactile and affective properties of products like creams, as documented in Table 1. However, our results align with other research examining the role of scent in touch interactions, such as studies involving robotic brushing touches [17, 36, 41].

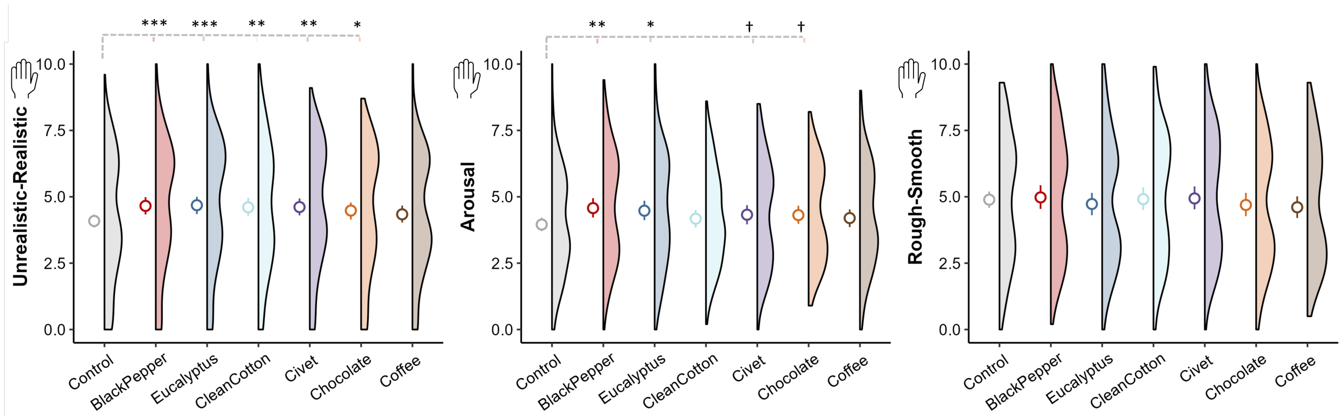

Figure 5: Participant ratings of the mid-haptic textiles while one of the six scents were presented. We found that while tactile dimensions such as roughness-smoothness did not significantly differ, users reported higher arousal when touching digital textiles scented with Eucalyptus and Black Pepper. Participants also reported that the digital textile felt more realistic when any scent, with the exception of Coffee, was presented. Note: * = $p < .05$, ** = $p < .01$,* = $p < .001$. Error bars reflect %95 BCa CI.**

Furthermore, our study replicated the limited tactile and affective differentiation among various mid-air textiles [74]. This may have hindered effective cross-modal correspondences, as congruence between sensory inputs is essential [42], such as combining a smooth scent with a smooth mid-air haptic. The digital nature of the experience may have inhibited the application of multisensory knowledge. For instance, in real-life scenarios, the scent of fabric softeners may signal the care or quality of textiles, but digital scents do not have a direct or tangible link with the virtual textiles they aim to enhance, potentially explaining their limited impact in a VR setting [13, 18]. Although it might be expected that the limited scent-touch associations in Study 2 (e.g., chocolate-smooth) could explain our findings (see 4.6), it is noteworthy that Clean Cotton was rated as highly smooth and pleasant while being highly relevant to textiles. If any scent were likely to have an effect based on these properties, Clean Cotton would be a prime candidate. Moreover, 31 out of 32 participants stated the scent was detectable, estimating a median of 5 scents were present in the experience, suggesting scent delivery is an unlikely contributor.

5.2 Strengths, Limitations and Future Work

This study benefits from several methodological strengths that enhance its reliability and precision. Firstly, we assessed the associations between scent and touch in two studies and used these findings to inform our study design, enhancing its robustness. Secondly, the use of temporally and spatially precise smell delivery systems, coupled with task-relevant stimuli, promoted the potential of cross-modal associations to affect touch. Additionally, the diversity of scents tested expanded the scope and applicability of our results. However, the impact of scent in touch perception in our study may have been greater if users could have explored the fabrics in a more naturalistic manner, such being able to touch and smell while close to the nose or exploration in an online shopping experience. Moreover, alternative haptic methods with greater sensation variability may have been a better catalyst for cross-modal correspondences.

Looking forward, there are several promising directions for future research. Expanding on the scent rating task of Studies 1 and 2, future studies could include free-recall scent associations to better understand the causal mechanisms linking scent and touch. Moreover, qualitative interviews may give greater insights in the User Experience beyond the quantitative dimensions assessed. Similarly, a larger sample would allow for investigation as to whether culture and language affect these associations, which may inform design methods in terms of tailoring scent selection. Moreover, data should be collected on whether users recognised the scents used, which may be critical for cross-modal associations to be effective. Future work could consider whether the increased touch realism afforded by scents may improve the sense of ownership, agency, and care for digital textiles and other objects more broadly. In the context of e-commerce sustainability, increased realism of digital touch may aid consumers to better under digital textiles, potentially leading to reduced e-waste through more accurate purchasing decisions.

5.3 Conclusion

This research highlights the utility of scent in augmenting digital touch experiences, creating more realistic and emotionally engaging interactions. Extending beyond the current literature that focuses predominantly on ambient scent applications, this work illustrates the impactful role of scent in discrete interactions — such as enhancing the emotional depth of digital touches with a loved one or increasing the realism of experiencing rainfall on the face. We also suggest reasons why these augmentations did not extend to tactile properties such as temperature, in which future work may employ a greater variation of haptic stimulations or activate scent-associated memories by informing participants about the scents they are experiencing. This research marks just the beginning of exploring scent as a pseudo-haptic tool, opening numerous possibilities for deeper, more meaningful multisensory integration in digital spaces. There is a vast landscape to explore in the realm of scent-enhanced digital interactions, signaling an exciting frontier for future technological advancements and sensory research.

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