Investigating Expressive Tactile Interaction Design in Artistic Graphical Representations

MARYAM AZH and SHENGDONG ZHAO, National University of Singapore
SRIRAM SUBRAMANIAN, University of Sussex

In this article, a design research approach is taken to investigate expressive design of tactile interactions. Most research efforts to date on designing and exploring the representational aspects of tactile interfaces have focused on usability and task-oriented scenarios. Yet, there is limited knowledge on how to aid the design of tactile interfaces that support the design of expressive or user-experience-oriented tactile interactions. We address this gap by studying tactile designs in a multisensory context, where the tactile interface augments works of visual art. The expressive and artistic context introduces new opportunities to extend on previous work, and identify new design and interaction potentials with tactile interfaces in graphical multisensory scenarios. During one-on-one guided design sessions, visual artists were asked to create tactile design prototypes that augmented one of their existing works. Each element of the overall tactile design, regarded as a *tactile feature*, was analyzed using both the bottom-up and top-down approaches. The results discovered through grounded theory are presented and discussed with respect to semiotic theory. Accordingly, *tactile constructs* and *tactile intents* define the "form" and "meaning" components of each tactile feature, respectively. Overall analysis of the findings indicates associations among the identified categories and between the two components, leading to design implications for expressive tactile interfaces. Insights from the *tactile intents* suggest a set of affordances for expressive visuotactile interactions, which we introduce under the notion of *expressive roles*. Additionally, implications from the *tactile constructs* indicate a design space for an expressive tactile augmentation design tool, based on which a user interface architecture is proposed. Findings from this research can assist in developing systems and tools for expressive tactile interface design and inspire research in user experience and behavior in multisensory tactile interaction scenarios.

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Authors' addresses: M. Azh and S. Zhao, Department of Computer Science, National University of Singapore, 15 Computing Dr., 117418 Singapore; emails: maryam@u.nus.edu, zhaosd@comp.nus.edu.sg; S. Subramanian, Department of Informatics, University of Sussex, Brighton BN1 9RH, UK; email: Sriram@sussex.ac.uk.

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1. INTRODUCTION

As tactile technologies are becoming an integrated part of everyday devices, a growing research interest has been emerging in tactile interfaces. Research in this area has evolved from usability and human-factor issues toward subjects related to user experience and affective interactions. Especially, tactile cues integrated with graphical information at the user interface have raised interesting research questions concerning interactions under multisensory settings. Many of the previous studies have focused on investigating the role of tactile interactions on improving usability in graphical interfaces, especially in mobile interaction scenarios [Brewster and Brown 2004] or enhancing user performance in virtual object interactions [Paneels and Roberts 2010]. With user-experience paradigm being adopted in tactile interaction research, engaging and affective interactions have been the subject of alternative approaches to tactile interaction research, beyond productivity and performance [Bailenson et al. 2007]. With this paradigm shift, subjective experiences with tactile interfaces have been the focus of recent research [Obrist et al. 2013], with emerging interest in virtual interpersonal interactions [Akshita et al. 2015], interactive arts [Bialoskorski 2009; Gumtau 2005; Schiphorst 2009], or storytelling [Israr et al. 2014].

Meanwhile, despite research attempts in developing interaction design guidelines [MacLean 2008; Paneels and Roberts 2010], there remains a need for a systematic investigation of the capabilities of tactile modality from a design perspective, especially with respect to expressivity and user experience. In particular, one that defines a design space and describes a set of affordances in an open-ended and creative context that inspires maximum expressive capacity under minimal technological constraints that may compromise the richness of communication [MacLean 2008].

This work takes a design research perspective [Zimmerman 2007] to investigate the various physical aspects of expressive tactile interfaces in addition to meaning-making potentials of the modality in an artistic visual multisensory scenario. Visual arts was arguably the ideal candidate to serve as the graphical space for ideation and expressive tactile designs due to the wide variety of styles, highly creative visual foundation, and home to expressivity [Sullivan 2010]. In one-on-one guided design sessions with visual artists, low-fidelity tactile design prototypes were developed using a methodology influenced by the staged creativity process [Lubart 2001]. Tactile design prototypes were then analyzed to extract single elements of a tactile interface, regarded as *tactile features*. Taking a grounded theory approach and inspired by semiotic theories, the tactile features were investigated on both their physical form as well as intended meanings, presented under *tactile constructs* and *tactile intents*, respectively.

The implications of this work on analyzing *tactile intents* include a spectrum of expressive meanings that can take the form of touch at different levels of abstraction. The intents further suggest the many ways in which tactile interfaces can extend aesthetic interactions with visual artworks. Thus, under the notion of *expressive roles*, a set of affordances is considered with respect to *interactional* and *cognitive* aspects of multisensory tactile interaction scenarios with visual artworks. The proposed set of expressive roles can be further extended in defining a systematic set of affordances for tactile interfaces in expressive multisensory scenarios, where user experience lays at the heart of the interaction. On the other hand, *tactile constructs* suggest a set of attributes that define the physical aspects of expressive tactile designs. Inspired by design requirements of creativity support tools [Shneiderman 2007], the attributes extend the existing scopes of tactile design space and can motivate the design of tools for creating expressive or artistic tactile interactions. Accordingly, the proposed user interface architecture sets the layout for developing systems to support expressive tactile interaction design, especially in visual multisensory settings.

The overall purpose of this work is therefore two-folded: to highlight the alternative ways in which tactile modality can be used as an expressive medium to convey a variety of meanings in an artistic multisensory environment, and to identify a collective set of characteristics that explain the variety of forms those meanings take. The aim of this research is not to offer comprehensive and generic implications for tactile interaction design but rather to introduce alternative areas where tactile interfaces can be utilized and possibly benefit existing interactions in expressive multisensory scenarios.

2. RELATED WORK

The related body of work includes the existing areas where tactile interfaces are used as a meaning-making medium under different interaction scenarios. As such, the variety of meaning association with tactile features is discussed with respect to four main areas: general graphical user interface interactions, data visualization and virtual object interactions, remote interpersonal communication, and finally, representation and expression. The discussion of the implications to representative capabilities of the tactile modality involves both task-oriented and non-task-oriented scenarios, including interactions at the desktop or in mobile scenarios, in addition to interpersonal and expressive settings.

2.1. Graphical User Interface Interactions

Tactile cueing is predominantly used in graphical user interface elements to provide feedback on user interactions, often aimed at improving usability through delivering more information on the tactile sensory channel, or as sensory substitution to the visual user interface [Brewster and Brown 2004]. Haptic cues in force feedback or tactile form often accompany user interface elements such as graphical icons and features [Enriquez and MacLean 2003], common tasks such as text entry [Brewster and Brown 2004], selection and menu navigation [Yatani and Truong 2009; Luk et al. 2006], or aided browsing [Rotard et al. 2008]. It has been argued that regardless of the application, haptic cueing of user interfaces follows three main objectives [MacLean 2008]: *functional feedback*, where haptic cues work as a notification channel to represent feedback on system status [Luk et al. 2006]; *interactional feedback*, where haptic feedback is an indicator of the affordances of the interface, such as verification of the accuracy or appropriateness of the interaction [Brunet et al. 2013]; and tactile feedback is commonly used in everyday mobile devices to represent *topological relationships* [Brewster and Brown 2004], indicative of different characteristics of the source of information, such as priority [Brown et al. 2005], recency, urgency, and the like [Saket et al. 2013]. In such productivity-oriented scenarios, haptic feedback enhances routine interactions by increasing speed and precision as well as supports the reduction of fatigue caused by sensory overload [Brewster and Brown 2004; Yatani and Truong 2009].

2.2. Data and Virtual Object Interaction

With specific attention to data representation rather than feedback on user interface interactions, haptic rendering of data visualizations emphasizes on user interactions with a variety of static or spatiotemporal forms of information in order to increase user accessibility and performance in haptic-only or multisensory interaction scenarios [Paneels and Roberts 2010]. Haptic data representation applies to a wide variety of graphical information ranging from letters [Lévesque et al. 2005], digits [Töyssy et al. 2008], and graphical data visualizations, such as statistical charts [Wall and Brewster 2006] or structures, to relationships in hierarchical representations [Osawa 2006; Jay et al. 2008], 3D graphics [Lundin et al. 2005] and maps [Jacob et al. 2010], or navigational cues and directional instructions [Park et al. 2012; Spelmezan et al. 2009].

Further, with more focus on object representation rather than illustration of data in the virtual world, haptic cues embedded in virtual reality applications facilitate exploration and manipulation of virtual objects in both performance- and user-experience-oriented applications. Tactile interfaces enhance a user's perceptual and cognitive capabilities for virtual object recognition and manipulation [Lederman and Klatzky 2009]. At the same time, in more experience-oriented scenarios, haptic interfaces improve user experience for comprehension and appreciation of virtual objects in cultural heritage [Styliani et al. 2009], education [Basdogan et al. 2004], or entertainment [Israr and Poupyrev 2011; Sodhi et al. 2013] applications. Haptic cues designed for virtual interactions mostly involve representation of detailed realistic object properties including surface features, such as stickiness [Yamaoka et al. 2008], roughness and smoothness [Klatzky et al. 2013]; thermal properties [Jones et al. 2008]; or attributes related to object structure, such as hardness [Lawrence et al. 2000], stiffness [Basdogan et al. 2004], form, and size [Samur et al. 2007; Najdovski and Nahavandi 2008]. Recent attempts argue that tactile cues targeted at skin level are sufficient to simulate sensation of mass [Minamizawa et al. 2007] in virtual object interactions.

Representations with tactile modality are not limited to user interface notifications and realistic virtual representations, but also include a wider range of representational or metaphoric designs applied in virtual social interactions and expressive meaning-making.

2.3. Remote Interpersonal Interactions

In the conventional physical form, interpersonal touch on different body parts has been used as a form of real-time non-verbal communication [Gallace et al. 2007] to increase information bandwidth [Haans and Ijsselsteijn 2006] or to improve user experience [Li et al. 2008]. Tactile cueing in virtual collaboration scenarios [Chan et al. 2008] or remote conversations [Bailenson et al. 2007] have shown to enhance task performance and improve user experience, borrowing a social metaphor from physical interpersonal touch [Haans and Ijsselsteijn 2006]. As well, tactile interactions help to facilitate remote affective interactions by communicating certain emotions [Smith and MacLean 2007; Hoskins et al. 2010; Salminen et al. 2008] or delivering intimate gestures [Samani 2012; Teh et al. 2008]. Even though in remote interpersonal communication scenarios, expression and interpretation form the essential components of a tactile interaction, some research attempts have focused specifically on expression with tactile modality beyond one-to-one interpersonal interactions.

2.4. Representation and Expression

A unique capability of tactile interfaces, which is also a trending area in human-computer interaction (HCI) research, is supporting remote interpersonal interactions in one-to-many scenarios, such as in public spaces, or allowing for more complex representational meaning-making. This area proposes new opportunities for self-expression and representation in integration with other interaction modalities, including audio, text, graphics, or even tangibles. Areas such as interactive arts [Joy and Sherry 2003; Schiphorst 2009; Bialoskorski et al. 2009] or musical performance [Gumtau 2005] have attracted research on interaction design with tactile interfaces. Research shows that tactile metaphors effectively represent various musical expressions, such as pitch height, volume, instrumental timbre, and vibrato, with implications for improving engagement and enhancing aesthetic appreciation [Eitan and Rothschild 2010].

Furthermore, by incorporating multiple tactile points [Israr and Poupyrev 2011] or increasing controllability of the interface [Ochiai et al. 2014; Sodhi et al. 2013], a larger output space in turn offers more degrees of freedom for increased expressivity and complexity in meaning mappings with tactile interfaces. For instance, integration

Table I. Overview of the Areas of Representational Meaning-Making with Tactile Interfaces in the Literature

Domain	Application area	Representational meaning	Example
Interface interaction	General user interface	Functional cues [Enriquez and MacLean 2003; Luk et al. 2006; Brewster and Brown 2004]	Icons, features, tasks, browsing information
		Interactional cues [Rotard et al. 2008; Brunet et al. 2013; Yatani and Truong 2009]	Accuracy verification, appropriateness of interaction
		Topological relationships [Brown et al. 2005; Saket et al. 2013; Brewster and Brown 2004]	Priority, recency, urgency
	Data and virtual object interaction	Text and digits [Lévesque et al. 2005; Töyssy et al. 2008]	Alphabet, time, value
		Statistical data [Lundin et al. 2005; Osawa 2006; Jay et al. 2008; Wall and Brewster 2006]	Graphical trajectories, data segments, edges, hierarchies, relationships
		3D graphics [Park et al. 2012; Spelmezan et al. 2009; Jacob et al. 2010]	Edges, altitude, navigational cues
		Object attributes [Styliani et al. 2009; Samur et al. 2007; Najdovski and Nahavandi 2008; Lawrence et al. 2000; Basdogan et al. 2004; Minamizawa et al. 2007; Lederman and Klatzky 2009]	Stickiness, roughness, temperature, hardness, stiffness, form, size, mass
Interpersonal interactions	Remote interpersonal interactions	Social communication [Gallace et al. 2007; Bailenson et al. 2007; Chan et al. 2008; Haans and Ijsselsteijn 2006]	Force, gender, affective expressivity, emphasis, turn-taking, mimicking behavior
		Intimate cues [Hoskins et al. 2010; Salminen et al. 2008; Samani et al. 2012; Teh et al. 2008; Smith and MacLean 2007]	Emotions: positive and negative affects Gestures: kiss, hug
	Representation and expression	Metaphors and game events [Israr et al. 2014; Sodhi et al. 2013; Kim et al. 2009; Israr, and Poupyrev 2011]	Precipitation, motion, heartbeat, collision, motion
		Musical expressions [Gumtau 2005; Eitan and Rothschild 2010]	Pitch height, volume, instrumental timbre and vibrato
		Aesthetics [Joy and Sherry 2003; Schiphorst 2009; Hoshi 2012; Bialoskorski et al. 2009]	Abstract meanings in interactive arts
		Textures, shapes, materials [Gumtau 2005]	Organic materials, physical textures

of spatiotemporal cues for motion representation [Israr and Poupyrev 2011], mid-air tactile feedback for a variety of gaming events [Sodhi et al. 2013; Kim et al. 2009], real-time feedback on free-form gestures [Hoshi 2012], or context-based metaphorical tactile cues to augment storytelling [Israr et al. 2014].

Table I demonstrates a summary of related work. It can be implied from the literature that tactile interface design follows two dominant trends: one concerning enhancement of usability of interaction and performance improvement at the user interface, and the other regarding tactile interfaces as a sensory enrichment of virtual interactions between people. The latter perspective considers a more intermediary role for tactile modality as a representational or expressive communication medium, with an actively engaged human on at least one side of the interaction, compared with the goal-oriented view in the former interaction context.

Despite the efforts in utilizing tactile interfaces in different contexts, few attempts have been made in defining a comprehensive design space for representational or expressive capabilities of tactile modality. Research suggests a rough layout for the potential design space of haptic representations, where two key design challenges for designing haptic representations are proposed as using the correct metaphors for appropriate meaning association and exploring the right hardware parameters for haptic behavior design [Swindells et al. 2005]. Most guidelines suggest practical implications on the perceptual design space of specific tactile interface technologies [Lederman and Klatzky 2009] or indicate generic interaction design guidelines for the end-user [MacLean 2008; Luk et al. 2006]. Thus, there is a need for a systematic definition of expressive design possibilities with tactile interfaces that ideally spans over both application trends, in particular, empirical methodologies for defining a design space and a set of meaning-making potentials for tactile interfaces. This research benefits from a design perspective to address this research opportunity from an open-ended and expressive angle.

3. USER STUDY

We conducted a user study in the form of creative design sessions in order to investigate the underlying characteristics of expressive tactile designs within a visual context. During one-on-one design sessions, visual artists iteratively created low-fidelity prototypes of tactile designs to augment an existing artwork of their own. *Tactile features* were then derived from the augmented tactile designs as an independent unit of expression and analyzed for a systematic investigation of the attributes that together delineate an element of an expressive tactile interface.

3.1. Methodology

Four methodological factors guided our design of the study: the choice of visual arts as the creative context for expressive tactile designs; sketching as the approach for early-stage conceptual tactile designs; the creative process that guides the artists to ideate and develop the tactile designs; and finally, the choice of a suitable *tactile technology* based on the requirements set by the previous factors.

3.1.1. Visual Arts as the Context. One of our challenges was the choice of an appropriate graphical context not targeted at usability- or performance-oriented interaction scenarios, which also inspired a large variety of creative ideas suitable for representational meaning-making with tactile modality. After careful consideration, visual arts was chosen as the graphical context in our study. On the one hand, two-dimensional visual arts has been recognized as an expressive platform for design [Sullivan 2010] and has inspired many works in HCI research [Ryokai et al. 2004], while on the other, the skillset of visual artists as designers comply with the established definition of a designer, with both background in related education and extensive practical experience in creative design [Zimmerman et al. 2007].

3.1.2. The Creativity Process. Ideating and generating designs for artifacts that represent indirect touch interactions for visual art objects was both an unfamiliar concept and a new way of thinking about visual art interaction. In order to prompt design thinking for generating tactile design artifacts, we considered how to best inspire

Table II. The 5-Stage Guided Design Process

Phase	Objective	Expected outcome
Setting	Guide the participant to select the context	An instance of the first modality
Staging	Establish the context via elaboration	Comprehension of the selected instance
Evoking	Evoke unlimited creative thinking for design ideas	Unlimited free-form designs
Enacting	Conceptually introduce the modality constraint to refine the design ideas	Free-form designs of the new modality
Exposure	Practically introduce the modality constraint for the final design	Conformed designs of the new modality

creativity and ideation in the design process. Motivated by the models of the creative process, we adopted a reverse-engineered approach to guide the augmented tactile designs. The expressive tactile designs could be inspired from a creativity process *as the sequence of thoughts and actions that leads to novel, adaptive productions* [Lubart 2001]. A variation of the stage-based model of creativity process was deployed as the guide for inspiring tactile designs, shaping natural transitions between several steps of creativity [Johansson 2005; Warr and O'Neill 2005]. The original stage-based model of creativity process involves four phases including *preparation*, *incubation*, *illumination,* and *verification*, which describes how an innovative product results from interrelated stages of creative thinking [Warr and O'Neill 2005].

The stage-based process has been previously applied to guide exploratory design sessions [Johansson 2005], where the three-step process suggests steps for guiding the participatory design process: situating an existing situation as the stage for ideation, evoking creativity for imaginary possible futures, and finally, confining ideas within a boundary of limiting constraints—*staging*, *evoking,* and *enacting,* respectively. The use of stage-based guided design demonstrated a practical application of the creativity process model for organized design sessions, leading to effective design outcomes.

The current proposed methodology particularly considers an active role for technology in constraining and verifying design ideas. Accordingly, tactile modality as the design constraint is introduced in the design process at two levels: First, tactile modality as a *conceptual constraint* limits the free-form ideas generated during *evoking*, and secondly, the ideas are further scoped down by introducing the technology as the *practical constraint* [Biskjaer et al. 2014]. Thus, the last two steps of the original model, *illumination* and *verification*, are restructured into three stages: *evoking*, where the designer is inspired to freely develop unlimited creative expressions without any constraints; *enacting*, where designs are shaped from the creative expressions under the designer's interpretation of a *conceptual constraint* (e.g., tactile modality); and finally *exposure*, where the final design is developed with further refinements after physically experiencing the tactile cues on an enabling technology. The process is summarized in Table II.

3.1.3. Low-Fidelity Prototyping for Conceptual Tactile Designs. The next methodological challenge involved an appropriate technique for representing tactile designs, a new form of user interface which our target designers had limited background on. A low-fidelity prototyping technique would work as a natural way for designing novel and alternative user interface concepts [Gross and Do 1996]. It has been suggested that conceptual design techniques such as free-hand drawings are fundamental to ideation and design and allow the designer to express ideas without considering the complications of implementation [Landay and Myers 2001; Buxton 2010]. Sketch-based prototyping techniques are fast, easy to refine, analyze, and interpret, and are an effective way

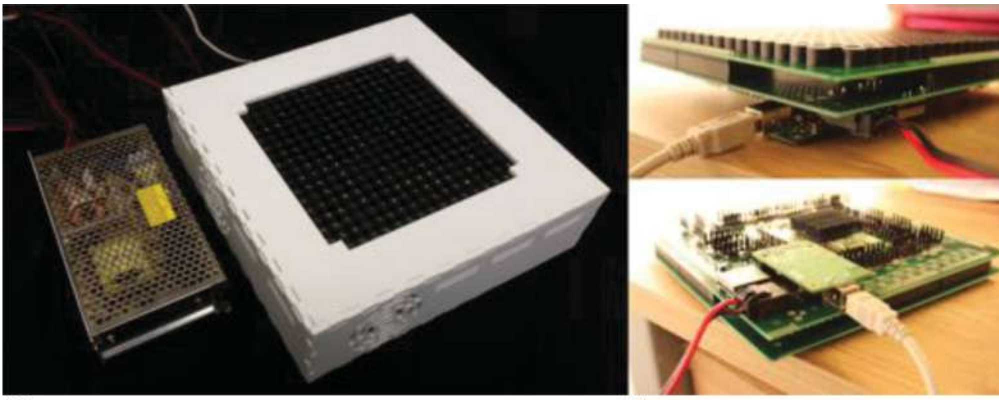

(a) (b)

Fig. 1. The ultrasound-operated tactile technology used in the study. (a) The device in a box, connected to a PC as used during *exposure*. (b) The different layers of the board, including the mounted actuators (top) and the main board with drivers and controllers (bottom).

of getting the *right design* through early stages of user interface design [Tohidi et al. 2006].

Thus, a sketch-based technique in the current augmented design context allows the designer to easily refer to the base modality (visual art pieces) and reflect their designs of a new modality in an unobtrusive way. We used acrylic sheets overlaid on a printout of the artwork to support sketched tactile designs directly on top of a copy of the artwork with no intervention of technology in the creativity process. Of course, verbal elaborations and gestural explanations accompanied the design sketches to compensate for other aspects of the tactile designs as described further.

3.1.4. Tactile Device. The role of the device in the study was to familiarize the designer with a tactile interaction enabler and to help inspire creation of ideas for the guided design process during the *exposure* stage. An ideal scenario for tactile interaction with visual artworks first requires no direct touch on the artwork surface, and second, demands that the user can easily interact with the multisensory artifact with no physical barrier (e.g., a worn or held device) [Lee et al. 2011]. Existing technologies such as air-jet [Suzuki and Kobayashi 2005] and ultrasonic tactile displays [Hoshi et al. 2010] can enable such unobtrusive interactions.

The device deployed for this study creates tactile sensations using ultrasound waves [Carter et al. 2013] and offers more degrees of freedom to control over the 3D space and tactile surface area compared to the air-jet display. As demonstrated in Figure 1, the form factor involves a surface of 285 ultrasound transducers that creates focal points of air-pressure above the perception threshold of the human hand. The principle behind this technology is driven by acoustic radiation pressure that is created as a result of controlling the spatial distribution of the sound pressure of the ultrasound waves. Phase delays induced in simultaneous emission of ultrasound at 40KHz by all transducers results in generation of a single focal point that can be sensed on the human skin. The radiation pressure at the focal point is proportional to the square of the number of transducers, root-mean-squared average sound pressure of ultrasound, and the reflection coefficient of the contact surface—in this case, human skin [Hoshi et al. 2010]. In principle, at higher frequencies, the focal point becomes smaller and the energy of the acoustic pressure is partially lost. However, within a range of 40cm above the device surface, more than 90% of the energy is sustained at all times.

Table III. Background Information of the Participants

ID	Education	Preferred style (selected art form)	Years active
A1	Degree	Non-figurative Abstract (Painting)	25
A2	N/A	Expressionism (Painting)	30
A3	Certificate	Expressionism (Illustration)	5
A4	Degree	Surrealism (Illustration)	8
A5	Degree	Figurative (Photography)	6
A6	Degree	Non-figurative Expressionism (Mixed media)	10
A7	N/A	Victorian figurative (Painting)	31
A8	Degree	Natural subject matter (Print making)	5
A9	Degree	Non-figurative (Painting)	5
A10	Degree	Found still life (Photography)	40
A11	Degree	Architectural (Illustration, Print making)	6
A12	Degree	Pop-art (Illustration, Print making)	10
A13	Certificate	Digital media (Illustration)	6
A14	Degree	Figurative (print-making)	12

The emission of ultrasound at 40KHz is modulated at 10 distinct frequencies in order to create distinguishable vibration sensations: 1, 2, 4, 8, 16, 32, 63, 125, 250, and 500Hz [Carter et al. 2013]. The system supports multiple points of pressure in the 3D space, with variable intensity values, and can produce contours of pressure along a given shape or filled areas. The sensations can be explained as weak air-pressure on the skin when modulated at lower frequencies or as a smoother flow of air toward the higher end [Obrist et al. 2013; Wilson et al. 2014].

3.2. Participants

A total of 14 (8 female) visual artists from various disciplines, ages ranging from 23 to over 60 years old (mean 35–45) participated in this study. Participants were recruited through artist communities, working studios, and art galleries via email. Participants had on average 14 years of active experience as professional visual artists (SD = 12) with a range of 5 to 40 years of experience. Participants were asked to bring along a portfolio of their two-dimensional artworks and were informed to expect creative thinking during the session. Most participants had an academic background (degree or certificate) in a fine arts discipline, with at least 5 years of professional experience.

In order to make a more generalizable conclusion on the visually augmented tactile expressions independent of art movement and style, the experiment was exposed to a large variety of two-dimensional visual arts. Therefore, artists practicing photography, painting, illustration, or mixed-media visual arts served as creative designers for augmented tactile expressions. Table III shows artist profiles in more detail. The IDs are used throughout the article when referring to a quote, tactile design prototype, or a tactile feature associated with that artist.

3.3. Setup

The setup involved video and audio recorders for data-gathering purposes. Depending on the design stage, other materials were provided during the design sessions, such as a printout of the selected artwork and transparent acrylic sheets for conceptual designs. During the *exposure* step, the ultrasonic tactile device was provided for sensing a variety of tactile effects. A laptop (running Windows 7) was used to control the device, and earphones were provided for the pink noise. From all of the available tactile technologies, a challenge was to identify one that would suit the potential interaction scenario for which the tactile designs were intended.

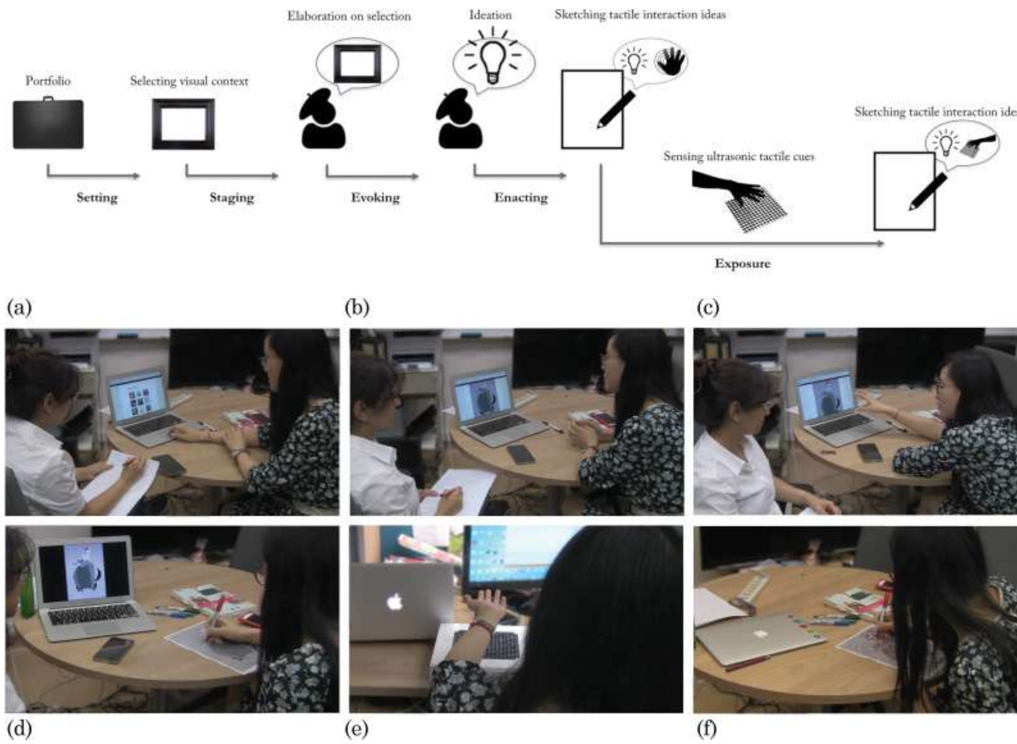


Fig. 2. Experimental procedures using the *Augmented Multimodal Design Process*. (a) *Setting*: selecting an artwork as the visual context. (b) *Staging*: elaborations on the selected context. (c) *Evoking*: open-ended brainstorming on enhancing/changing the existing expressions. (d) *Enacting*: developing and conceptually designing ideas within the scope of a tactile creation. (e–f) *Exposure*: developing a hands-on experience of tactile sensations and modifying the previous designs for the final conceptual tactile design.

3.4. Procedures

Sessions were conducted separately with each participant. The sessions began with inquiring about the participant's academic and professional background, art creation process, use of technology, perceived impact of audience interaction, and feedback on the art creation process. The design session continued with the 5-stage *guided design process* (see Figure 2) as described below.

Setting: The purpose of the first step was to pick one piece of artwork as the context for inspiring and augmenting the tactile designs [Herring et al. 2009]. Our pilot results showed that designer's choice of the graphical context from their own existing works gives a deeper understanding of the existing expressions and intentions of the graphical context, which encourages more expressive designs with tactile modality. Furthermore, guiding the designer to select the context reduces researcher interference with the results.

The designer was therefore first asked to briefly go through their portfolio, including a short description of each piece. They were then asked to identify common themes among their works and to try to categorize their portfolio according to some distinguishable characteristics. This helped the designer develop an abstract overview of his/her own portfolio. The designer was then prompted to identify some pieces that could be further extended in terms of adding an expression or changing some aspects of the piece. After developing ideas on a few pieces, they were asked to pick a final piece as the graphical context for the study.

Staging: After the context was set, the designer was asked to examine the context by elaborating on the selected artwork, verbally describing the piece in detail, including the motivation, history, overall expression, creation time, used materials, creative process, and meaning of the different elements. This step helped the designer with reconstructing memories of the art creation process, rethinking and discovering facts about the artwork as a method for inspiring creativity for the next stage [Zhang et al. 2012].

Evoking: At this step, the designer was invited to explore design possibilities for the artwork with an open-ended, exploratory perspective, and unbounded freedom of expression. The following question template was used during this step to help saturate any design ideas that could complement the artwork:

> Is there any quality you may like to express more or like the audience to appreciate in the piece that might otherwise be missed? Now let's imagine a world inside the artwork with infinite possibilities. What features would you like for or imagine the piece to possess? Imagine you'd be able to enhance or change something in this artwork, what would that be?

The ideas resulting from this brainstorming activity helped form the basis for tactile design ideas.

Enacting: During this step, tactile modality was introduced as the conceptual constraint into the design thinking process. The designer was asked to first think out loud of all the different meanings they would associate with the word "tactile"; then develop design ideas similar to the previous step, this time within a constrained scope for their imagination that only includes what is tactile (according to their own interpretation of the concept). Describing different scenarios where touch sensations could be felt from the piece, designers were asked to develop design ideas and visualize them on acrylic sheets overlaid on a copy of their artwork and to elaborate on their designs.

Exposure: This step involved introducing tactile technology as the *practical constraint* to the design process by having the designer experience a variety of tactile stimuli and then creating a final tactile design similar to the enacting step, augmenting the artwork. The final design could involve additional comments on the previously developed design sketch or emerge as an entirely new design on a separate sheet. The 10 tactile frequencies were presented to the participant in a random sequence under pink noise, and the designer was invited to think out loud about their tactile sensory experience. The next stimulus was played upon request, which allowed the designer the needed time to deliberately explore each cue. Following that, the configurable design space of the device, including amplitude, plurality of the sensation points, 3D interaction space above the device surface, and possibility of a scalable workspace were demonstrated to the participant.

The final conceptual design of a graphically augmented tactile artifact in the form of low-fidelity prototypes together with accompanying verbal and gestural elaborations on each artwork constituted a *tactile design* as the product of the guided design process.

3.5. Analysis

Analysis of the data, including the transcribed audio recordings and tactile designs, started with the first four participants. Both bottom-up and top-down approaches were taken for analyzing the design artifacts. In order to distinctly identify single units within each of the tactile design prototypes, a *tactile feature* was formally defined as one with a uniquely described set of attributes and an exclusive associated meaning that corresponded to a part of its graphical context (i.e., the artwork). The particulars of the attributes and the specifics of the meaning were the questions further sought. Applying a bottom-up grounded theory approach for coding, 32 tactile features were extracted from the four tactile designs, which led to six code themes that formed the basis for the high-level categorization of tactile features. A top-down approach inspired by semiotic theory was then applied for a systematic representation of the findings [Danesi 2007]. Below, a brief overview to the theory and its relevance to this study are presented.

Semiotics, as the *science of signs*, is a scientific discipline concerned with how meanings are articulated and interpreted in different forms of media [Chandler 2007]. While traditionally applied to language and verbal communication, recent perspectives to semiotics are *concerned with everything that can be taken as a sign* to create meanings or represent reality [Enriquez and MacLean 2003]. Semiotic theory identifies two components pertaining to any *sign*: first, the perceivable form (i.e., something that can be seen, heard, touched, smelled, or tasted) for which a meaning is created, referred to as the *signifier*; and second, *a mental image, concept, and a psychological reality* [De Souza and Leitão 2009] that is created in the subjective mind, which constitutes the meaning associated with the signifier, known as the *signified*. In other words, the sign takes the form of the signifier to refer to a meaning or concept as the signified [Chandler 2007], and therefore a sign is the whole that results from associating the signifier to the signified.

Semiotics has recently attracted research in the area of HCI. In the context of HCI, the sign model is applied to and even suggested as a substitute for the notion of *affordances*, mainly due to its systematic structure for explaining an important aspect of user interface design [Najdovski and Nahavandi 2008]. There, user interface elements act as signs of different forms, such as text, images, and the like, to deliver meaningful cues, with special regards to the conventions and under the context they are used at. In Norman's approach and other similar perspectives [Andersen 2001; De Souza and Leitão 2009], the two semiotic components of the user interface element as a sign are distributed between the two subprocesses of communication. In other words, the designer is only responsible for creating the physical form of the sign (signifier), while the meaning of the sign as an indication to a system state or response (signified) is held by the end-user. Although differentiation between the two notions of perceived- and real-affordances attempt to compensate for this disintegration of the semiotic model, it can be argued that the role of the designer in the meaning-making process is overlooked.

Similarly, the semiotic perspective within the scope of this research considers an equally significant role for the designer as the creator of the interface element within a complete sign model. First, on the designer's side, a *tactile expression* is created as a sign by the designer, which is then received and interpreted by the user as a *tactile experience*, both composed of the signifier (referred to as *tactile constructs*) and the signified (designated as *tactile intents*). The effective perception of the signifier and interpretation of the intended message determines a successful communication. Although it is interesting to evaluate the full tactile communication circuit, within the scope of this research, the focus is on the *tactile expression*, the sign system created at the designer's side (Figure 3).

From a top-down semiotic approach, a tactile feature as a unit of expression is regarded as a sign and is composed of the two semiotic components: the *construct component*, a set of attributes that together constitute the physical form of the tactile feature; and the *intent component*, the meaning(s) represented by or embedded into the *construct* from the designer's point of view [Danesi 2007]. Bottom-up grounded theory approaches [Corbin and Strauss 1990] were taken to separately analyze the physical constructs and embedded meanings in the tactile representations. We began

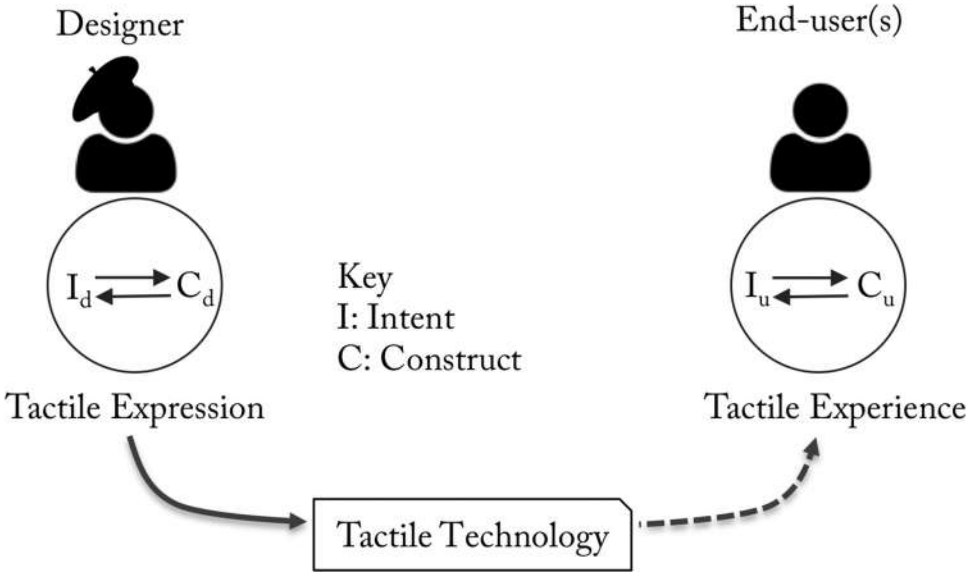


Fig. 3. Semiotic approach to tactile expressions inspired by Saussurean semiotic theory [Chandler 2007]. Indices d and u correspond to the designer and the user, respectively. The dashed arrow indicates that a tactile experience as the sign model on the receiver's side may vary from the original expression, due to technology limitations or noise, in addition to cultural and social differences. The left side of the figure corresponding to a *tactile expression* indicates the focus of this article.

with transcribing and open coding as early as the first session data, while axial coding and categorizations began with the data from the first four participants. The audio and video recordings were transcribed using DataVyu,[1] a qualitative audio/visual data analysis tool. After rounds of open coding, we derived categories through axial coding of the open codes. Taking into account the two main components of semiotic theory, we grouped the codes as construct codes or intent codes. These categories formed the basis of the analysis of the data in its entirety.

Accordingly, six code themes identified with the small subset of results constituted the model for analyzing the tactile features; the features corresponding either to the aspects of *tactile constructs* or to the variety of meaning-associations-*tactile intents*. The dimensions of *tactile constructs* were hinted by clues such as "feels like," "is," "has," and the like, and three dimensions of *tactile intents* were implied by descriptions such as "express," "because," "represents," "shows," and the like. More details on the construct and intents emerged as a result of rounds of open and axial coding on the segmented designs and transcribed data from all the participants.

4. FINDINGS

In total, 14 *tactile designs* were generated at each session, taking on average 156 minutes (SD = 54.2), with 77 distinct tactile features in total. Each augmented artwork as the final outcome of a design session consisted of one or more *tactile features* with an average of 5.5 (SD = 4.8) distinct features per tactile design. For 43% of artworks, 3 or less tactile features were designed, while only 21% of the tactile design prototypes had 10 or more tactile features. No correlation was observed between the duration of the sessions and the number of tactile features.

[1]www.datavyu.org.

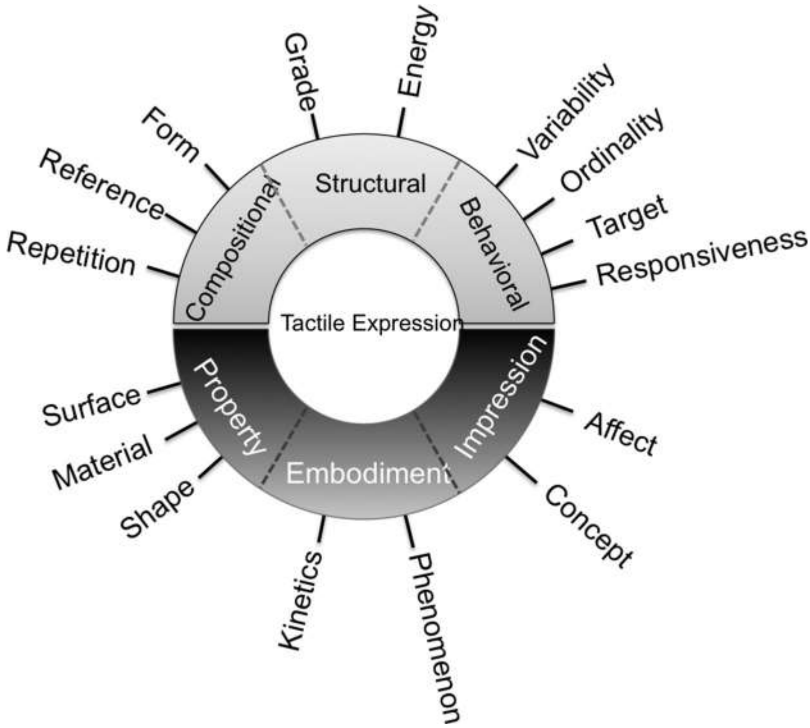


Fig. 4. Overview of the findings. Tactile expression as a sign model: The upper semicircle shows the *constructs* with respect to the three dimensions, and the lower demonstrates the *intents* within the three aspects, comprising the two components of a sign model.

Each tactile feature works as an independent unit of representation, which is evaluated in terms of its *constructs* and *intents* as the conforming elements of a tactile expression. Tactile constructs are analyzed with respect to three dimensions: *compositional*, *structural,* and *behavioral* constructs, each form a different aspect of the perceptual attributes of a feature. Similarly, for each feature, tactile intents are analyzed in three dimensions: *property*, *embodiment,* and *impression* intents define the meanings associated with the tactile expression at different levels of abstraction. An overview of the findings is shown in Figure 4. The quotes from the artists, tactile designs, and individual features cited in the following sections are referred to using the corresponding artist IDs (e.g., A1.3 indicates tactile feature number 3 on the artwork by artist ID A1).

4.1. Tactile Constructs

Each tactile expression as a sensory augmentation of its visual counterpart is composed of a set of attributes that define its physical characteristics, identified as the tactile constructs. The constructs are defined with respect to three dimensions as *compositional, structural*, and *behavioral*, as illustrated in Table IV. Accordingly, for each tactile expression, the compositional constructs provide details on the form and placement of the tactile feature on the visual correspondence, the *structural* constructs give information on the sensation of the tactile feature, and the *behavioral* constructs describe any changes to the sensation of the tactile feature at spatial and/or temporal dimensions.

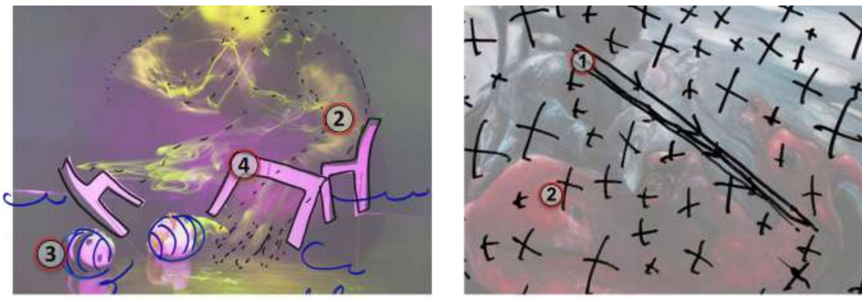
Table IV. Tactile Constructs with Respect to the Three Dimensions

Construct dimension	Construct (frequency)	Description	Variations
Compositional	Form	Spatial configuration of the tactile feature	Points (10%) Contours (17%) Areas (73%) In 2D(88%) or 3D(12%)
	Reference	Visual or non-visual reference on the corresponding part of the artwork	Concrete (68%) (object, line, color, and so on.) Indefinite (32%)
	Repetition	Number of instantiations of the same tactile feature to more than one reference	Single (66%) Multiple (34%)
Structural	Grade	Number of *tactile qualities* that describe a feature.	Zero (14%) Single (22%) Composite (64%)
	Energy	Sum of squared values assigned for the tactile qualities of a feature.	Low (64%) Medium (31%) High (5%)
Behavioral	Variability	Variation(s) along spatial and/or temporal dimensions	Temporal (21%) Spatial (8%) Spatiotemporal (25%) Non-variable (56%)
	Ordinality	The relative order of appearance for a tactile feature	Transitional (pilot only) Sequential (25%) Non-ordinal (75%)
	Target	The body part where the tactile feature acts upon	Non-hand (8%) (Torso, head, arm, and so on.) Hand (4%) Not specified (88%)
	Responsiveness	The type of user movement that activates the tactile feature	Proximal (12%) Gestural (4%) Positional (84%)

4.1.1. Compositional Constructs. The details on the form and placement of the tactile feature in relation to the image are denoted by its *compositional constructs*. In other words, the spatial distribution of a tactile feature including its *form*, *reference,* and number of *repetitions* are elaborated below.

Form: The physical configuration of each tactile feature is identified by its *form*. Often defined within a planar tactile surface, the form variations include points, contours, or areas that can be felt in front of the image (Figure 5). While most features were described in planar forms (A5.4; see Figure 5(a)), some were designed with volumetric forms, meaning the tactile feature would be felt all along the frontal part of the image rather than at a specific distance: *What I thought might be interesting would be if the height can be controlled...so that [the tactile feature] can give [a sense of the human figure's] 3D form...almost like touching the person's body* (A5.1, 2; see Figure 5(a)). Here, the form of the tactile feature is described as a 3D area resembling the facial features of the figure as well as indicating the tactile sensation of the figure's arm being closer to the user, compared to the rest of the tactile plane.

Reference: As visually augmented sensory features, the tactile features often were described as a sensation referring to a particular location or visual correspondence, mostly within the frame of the image. Thus, the *reference* of a tactile feature is an indication of the corresponding part of the artwork, which the tactile feature would act upon. The *reference* was either concretely defined by a depicted visual element or otherwise roughly suggested as an indefinite part of the image (Figures 5 and 7(b)). The



(a) (b)

Fig. 5. Compositional constructs. (a) Indefinite volumetric tactile areas suggested by dotted lines (A5.2), and concrete tactile areas with two repetitions on table and chairs (A5.4) indicated by solid lines. (b) Angled 2D contours (A2.1) and 3D points (A2.2), with two and "infinite" repetitions, respectively. Angled lines indicating an indefinite area between the two depicted characters (A2.1), and crosses indicating volumetric tactile points surrounding the contour (A2.2). Random temporal variability results in instances of A2.2 to hit the user at different depths.

latter implies that there is no particular visually depicted object to which the tactile feature is applied. For instance, in Figure 5(b), a sparse volumetric tactile area is only suggested with reference to another tactile form: *All around the outside of the stroke, there are columns of air coming at you* (A2.2).

While most reference indicators involved a visual element, a concrete visual correspondence could also be defined as the area with other indicators rather than the object outlines such as color: *It would be really nice to feel the warmth underneath the canvas and a bit more pressure, because I'm thinking of the color. . .* (A6.10; see Figure 8(b)). Such types of reference were only rarely observed.

Repetition: Some features were applied to more than one distinct reference. *Repetition* therefore refers to the number of assignments of the same tactile expression (i.e., the same tactile attributes and same meanings to more than one distinct reference of similar form). We observed 25% of features with three or less repetitions, while 5% had infinite instantiations of the same expression. Tactile features such as A5.4 demonstrated in Figure 5(a), or A2.2 in Figure 5(b), have repetitions of three and *infinity,* respectively. On the other hand, repetition does not apply to multiple sectioning of the same visual reference (e.g., A8.1–A8.3; see Figure 10).

4.1.2. Structural Constructs. The quality of the sensation of a tactile feature on the skin is described by its *structural constructs*. The structure of a tactile feature is identified by the specific value(s) assigned to one or more *tactile qualities* associated with that feature. Artists used different descriptors for labeling tactile qualities using real-world examples, such as *smooth* and *flabby, like mussel*, *smelly,* and *textured like seaweed* (A4); or referred to common tactile attributes, such as *smooth*, *cold*, *dry*, *wet*, and the like. Descriptions of the tactile features could also be linked with reference to the sensations felt on the ultrasound device, where tactile qualities were either stated with technical characteristics, or inferred from the subjective experience of the tactile cues. For instance, *high frequency vibration* (A3) and *the one that felt like an engine* (A5) implied *smooth* and *rough* values, respectively, for the roughness quality. The variety of observed qualities is demonstrated in Table V.

Accordingly, the structure of a tactile feature is discussed under two constructs: the *grade* as the number of tactile qualities defined for the feature, and the *energy* as a measure of the value(s) assigned to the quality. While dampness, temperature, and roughness categories each refer to a similar physical perception, amplitude refers to

Table V. Tactile Qualities Pertaining to Structural Constructs, with Frequency of Observation Per Quality

Tactile quality (frequency)	Definition	Value range
Amplitude (39%)	Intensity of the tactile sensation	Gentle, mild, strong
Roughness (60%)	Roughness of the tactile feature	Smooth, rough, coarse
Hardness (38%)	Flexibility to imposed pressure	Soft, resisting, hard
Stickiness (35%)	Tendency to adhere to the touch	Slippery, mid-range, sticky
Sharpness (9%)	Pointedness of tactile feature	Rounded(sparse), dull, sharp(dense)
Temperature (23%)	Relative heat of the tactile feature	Cold, neutral, warm/hot
Dampness (17%)	Level of moisture of the tactile feature	Dry, damp, wet

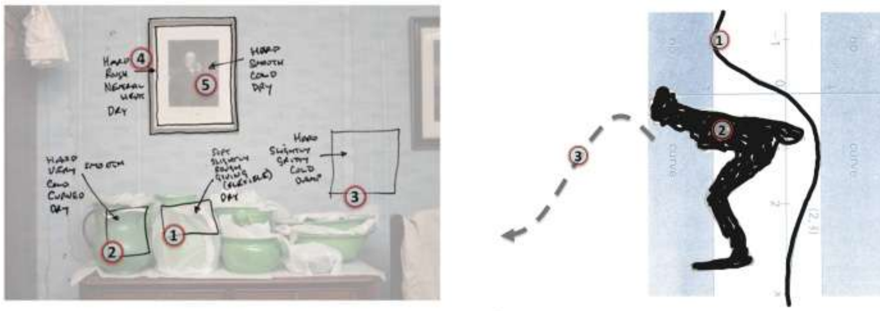
the perceived intensity of the tactile feature, and sharpness indicates how pointy or dense a tactile feature is felt on the skin.

Grade: A tactile feature was sometimes described with more than one quality. The *grade* construct explains the number of the tactile qualities for which a value is assigned. For instance, for the tactile features described as, *The vase, I want it to be hard, so it's going to resist quite strongly and it's going to be smooth, so as I move my fingers, the position of the surface changes but the hardness doesn't* (A11.2), a grade of 2 is considered for the qualities hardness and roughness. Tactile features with grade 1 are referred to as *single-structured*, and grade 2 and above as *composite-structured*. Features with grade 0 indicate that the precise physical sensation of the tactile feature was not a significant factor to the design.

Considering 86% of the features with a specified structural construct, tactile grades of 1, 2, and 3 were equally observed for 22% of the features. A grade 4 accounted for 17%, and maximum grade of 5 was observed in 3% of all features. Stickiness accounted for the most frequent quality to independently describe 35% of single-structure tactile features, while roughness–amplitude, roughness–hardness, and roughness–stickiness were the top-three most frequent couplings observed among the composite structures. Additionally, sharpness never appeared in single-structured features. Similarly, amplitude and dampness seldom independently described a feature.

Energy: The *energy* of a feature provides a comparable measure of the assigned values for the allocated tactile qualities as the sum of squared values of each quality. Any tactile quality is considered to take a relative value, with the lowest referring to the minimum, second referring to the mid-range, and third value to the maximum that the tactile quality can take. A fourth value is considered to account for inconsistencies in the tactile quality, which contribute to a *spatial* variability behavior (see Table V). *There was a sensation it felt as if all over your hand, that could be used, and there was one just after that which was completely the opposite, was more concentrated on the center of the hand, that could be the centralized sensation, starting from [the bottom] and moving on to the more open one* (A6.4; see Figure 8(b)). The feature described as *hard* and *smooth* (A11.2), the energy equivalent of 10 is derived as the sum of squared values 3 for *hard* and 1 for *smooth*. Overall, with a normalized mean value of 0.3, lower tactile energies were more common and a declining trend can be observed at higher energy levels.

4.1.3. Behavioral Constructs. The way in which the tactile feature acts determines its *behavioral constructs*. Behavioral constructs concern the dynamic aspects of a tactile feature as an active entity or with respect to the user. Four constructs are identified pertaining to the behavior of a tactile feature: *variability* construct defines how a particular feature acts with respect to time and space, *ordinality* of a feature determines whether any sequence of appearance is considered for that feature during interaction



(a) (b)

Fig. 6. Behavioral constructs. (a) Non-variable behavior with composite structures, such as hard, dry, cold, and smooth (A11.5). Responsiveness is assumed for A11.1, simulated by a resisting response as a result of imposed pressure from the user. (b) Non-variable behavior of single-structures such as resisting (A9.1) or no specified structure (A9.2). A9.3 is composed of a sensation without a visual correspondence and out of the visual boundaries, which also demonstrates spatiotemporal variability.

time, and finally, *responsiveness* and *target* specify how the tactile feature reacts in response to the user. In other words, behavioral constructs delineate the dynamic attributes of augmented tactile features, where *variability* or *ordinality* constructs consider a passive role from the user, while *responsiveness* and *target* require more active involvement of the user during the interaction.

Variability: Although the majority of the tactile features possessed a constant sensation of their structural construct (Figure 6), particular spatial and/or temporal characteristics were associated with 44% of the tactile features, designating variable behavior. Variations in at least one tactile quality across the tactile composition pertain to a *spatial* behavior; time-based inconsistencies constitute a *temporal* behavior, and variability along both spatial and temporal dimensions implies sensation of motion referred to as *spatiotemporal* behavior. The non-static categories are not mutually exclusive (e.g., a *spatiotemporal* feature can also have *spatial* variability with respect to a tactile quality).

A *temporal* variability refers to temporal inconsistencies in the tactile feature within fixed structural constructs and with no variation over the space dimension. Assignment of a tempo value of either rhythmic or random was set for most of the temporal tactile features. Additionally, a relative speed value was set in some of the temporal features to relatively describe the tempo as fast or slow (Figure 7). Some examples of temporal variability demonstrate more complex and unexpected effects. For instance, a variability was labeled *as firing up*, implying tactile quality variations in time and with regards to the tactile quality: *the little sparkles on the top... fire up and dot about for a while* (A1.1; see Figure 8(a)). The designer indicates the intensity starts weak and then becomes stronger with time, while consequently demonstrating rhythmic variability. Such variations of tactile quality and tempo for the same feature indicate two dimensions of temporal variability, both structure-wise and temporal.

Tactile features with variations in time and space resembling movement possess a *spatiotemporal* variability. In particular, a spatiotemporal feature is associated with a sense of linear or non-linear (e.g., circular) motion along a certain direction. Motions could also be defined to appear recursively in either linear or circular configurations (A3.1, A3.2; see Figure 7(a)). Additionally, a relative value indicating the speed of movement can be associated with a spatiotemporal feature (A1.4; see Figure 8(a)).

Finally, a tactile feature with *spatial* behavior demonstrates inconsistencies in one or more tactile qualities across the defined tactile form, with no variability over time.

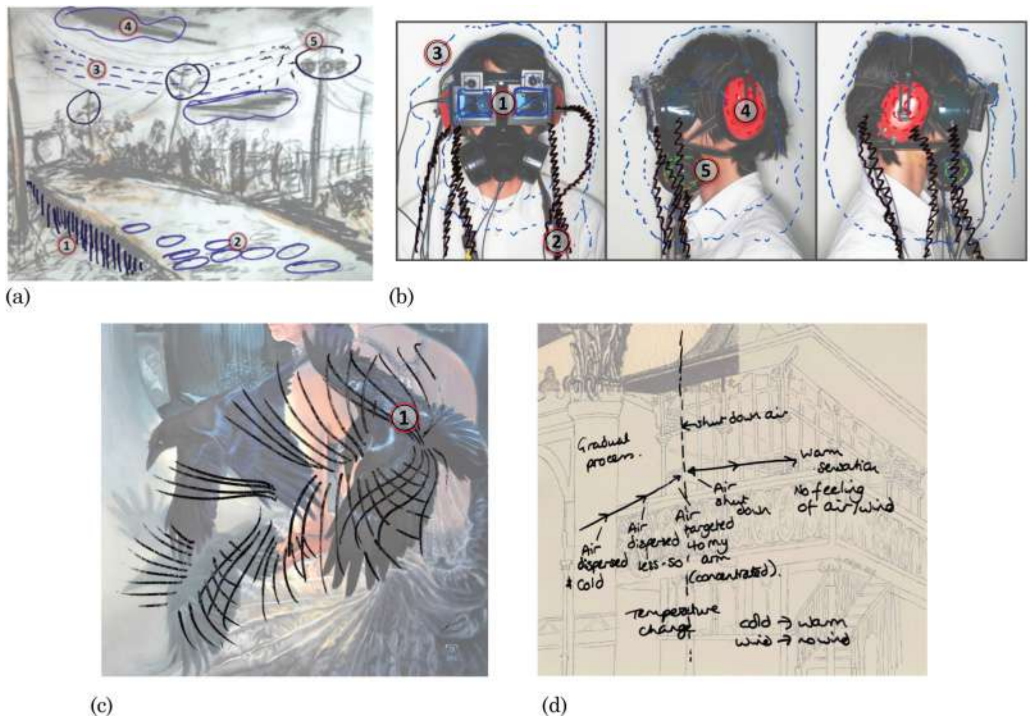


Fig. 7. Variability. (a) Spatiotemporal, (b) temporal, (c) spatial and spatiotemporal, (d) spatial. (a) Recursive motion for spatiotemporal features of different types: A3.1 shows infinite instances of tactile contours with linear vertical motions, while A3.2 shows multiple instances of contours with circular motion. Additionally, in A3.1, the tactile area corresponding to visual depictions in the perspective can be felt according to distance of the user's hand from the image surface. (b) Features vary randomly over an indefinite space (A12.3), or in a controlled rhythmic fashion (A12.1, A12.2, A12.4, A12.5) within the visual reference. A12.2 also depicts spatiotemporal variability in downward direction. (c) Amplitude of the tactile feature diminishes from right toward bottom left of the image in A7.1. (d) Density of A13.1 gradually increases from left toward top right of the suggested tactile area, while thermal quality remains unchanged. A13.2 demonstrates uniform behavior.

In other words, a change of value is observed for one or more tactile qualities along a certain direction of the assigned form of the tactile feature. The number of varying tactile qualities for that feature determines the *type of* spatial behavior. The most common variable tactile quality in spatial features was amplitude, followed by sharpness and roughness. The spatial features in our observations all had composite structures, and concurrently appeared together with other types of variability.

Co-occurrence of spatial and spatiotemporal variability accounted for 67% of spatial variability observations, and spatial and temporal pairs constituted the rest. For instance, A7.1 demonstrates spatial variability with respect to the amplitude of the tactile feature together with a spatiotemporal behavior: *feeling of the air as it comes off from the wings. . .it starts along this path on the top right and diminishes on the way down to the bottom left* (A7.1; see Figure 7(c)). Here, the decreasing windy sensation of the air from *flapping wings* implies concurrent spatial and spatiotemporal variabilities. Likewise, in A13.1, the sharpness or density of a windy sensation changes across the *form*. *It would be windy over here. The air would be dispersed here and cold, there air [becomes] dispersed but less so, and here will be targeted to my arm so it will be concentrated. . .a gradual process* (Figure 7(d)). Here, the spatial variability in a composite tactile structure can involve only one of the tactile qualities, while others

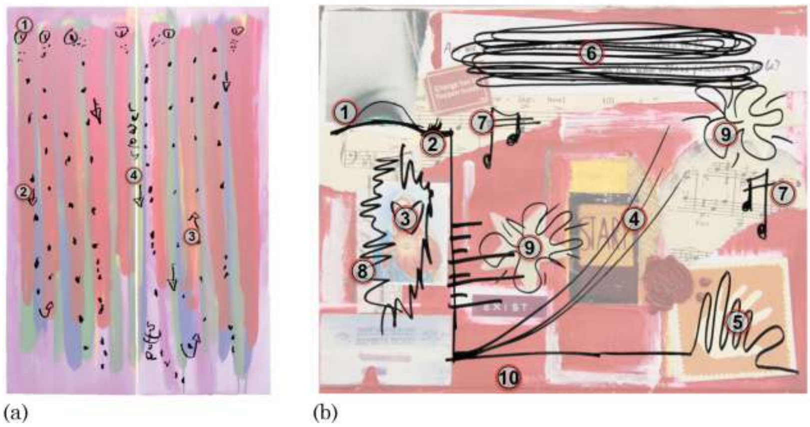


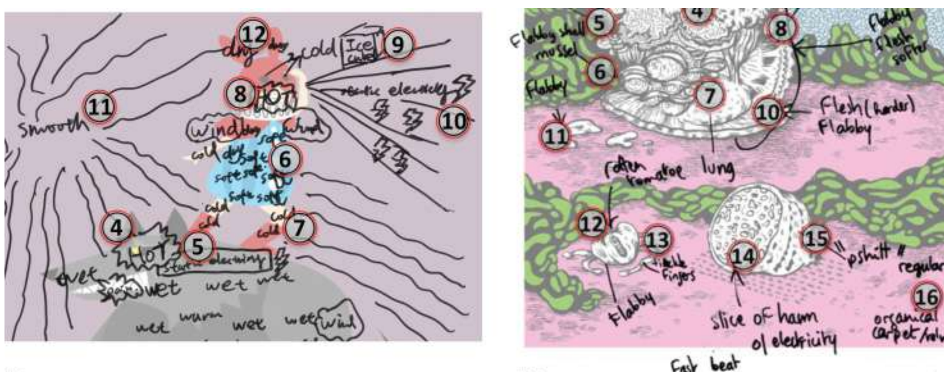
Fig. 8. Sequential ordinality. (a) The sequence starts with repetitions of A1.1 with temporal behavior, followed by downward motion of A1.2 repetitions, followed by instances of A1.3 moving upward. This sequence is set to occur in an infinite loop. The spatiotemporal behavior of A1.4 is independent from the sequence and the speed of movement is slower. (b) Sequence starts at A8.1 with more than one end point at A6.5 or A6.4. Other features such as A6.6 and A6.10 are not included in the ordinality. This sequence appears directional rather than in a loop.

remain uniform. In general, features with mixed-variability as such constitute 21% of non-uniform behaviors.

Ordinality: The ordinality of a tactile feature is determined by any arrangement in the timing of appearance of a feature in relevance to other features. Two categories of ordinality were identified as either a *transitional* effect in multiple tactile features with the same visual reference or *sequential* appearance among independent tactile features. In particular, a *transitional* ordinality behavior refers to when two or more tactile features are assigned to the same visual reference. In this case, tactile features are activated one after another on the same reference, creating a sensation that changes over time. This effect was only observed in the results from the pilot studies: *the sensations are very arbitrary at the beginning, but when the [user] comes back to it after a few minutes, it is going to change to a peaceful sensation* (P3.2). A transition from random temporal pulsations to a uniform behavior was described by P3.

Sequential ordinality on the other hand refers to the order of activation of a particular tactile feature in relation to other features. This effect was more commonly observed among 25% of all tactile features and in about a third of all tactile design prototypes. For instance, A9 (Figure 6(b)) is composed of three sequences, with A9.1 appearing first, followed by A9.2, and the last sequence only involving A9.3. Sequential ordinality can involve only two tactile expressions, one happening after another (A13; see Figure 7(d)), or result in an iterative loop (Figure 8(a)). Although assigning the order of appearance occurs independent of the other constructs as a high-level post process, this behavioral construct supports designing a wide range of complex representations, interconnecting multiple features (Figure 8(b)), which is later discussed under expressive roles.

Target: The user's body part intended as the contact point for the tactile feature is referred to as the *target*. This construct was specifically set for only 22% of tactile features (although arguably due to the relatively small size of the tactile device, in addition to the A4-sized print out of the artworks, most of the tactile features by default would be associated with part of the frontal side of the hand including finger(s) or palm). Alternative body parts were designated as the target, including arm (A13) and torso (A2, A9): *I want it to reach-out to the viewer, across the viewer's chest at the*



(a) (b)

Fig. 9. Responsiveness. (a) A14.9 shows variation in stickiness in response to a pull gesture from the user's finger. (b) A 'flabby' sensation responds to a push gesture (A4.12, A4.10, A4.11, and so on.).

angle (A2.1; see Figure 5(b)). At the same time, the design prototypes were all sketched on an A4-sized copy of the artwork, while the user interaction may happen on a larger scale and consequently target other body parts than the hand. More detailed analysis of a feature's target requires a higher fidelity prototype in a future study.

Responsiveness: The design of some tactile features had more active consideration of user interaction. The user action types that activate the tactile feature delineate its *responsiveness*. As a tactile sensation is only locally perceivable at the contact site, tactile features are by default activated according to the planar positioning of the target. However, some features were designed to only be activated when the user reaches a specific distance from the visual image (Figure 7(a)) or act in response to the user's actions (Figures 9(b) and 6(a)).

Pull and push gestures were often used to describe virtual tactile interactions with visual objects of their physical counterparts. *You need to be able to push it to feel the tissue paper. You can feel it going up and down. . .[it] can move away as you press it.* (A11.1; see Figure 6(a)). *[The little riding hood's eyes]* can *stick to your finger. . .it's very painful when you move away your finger from the eye, it sucks your finger like an ice-cube* (A14.9; see Figure 9(a)). Here, a magnetic effect is created as a response to user's proximal motion of the finger, as if "pulling away." On the other hand, responsiveness to the *target's* distance from the visual surface in the mid-air implies a depicted perspective in the image. *The user needs to bring their hand closer to feel the sensations on the farther perspective* (A3.1; see Figure 7(a)). Tactile features were also designed to respond to user's specific hand gestures, such as pointing, or stroking with back of the hand. Responsive behavior design to other types of gestures may emerge in a design tool.

Ultimately, the *constructs* work together to form a physical entity that carries expression(s) or conveys meaning(s). Such intended meanings are analyzed under the notion of *intents*, the second component of a tactile expression.

4.2. Tactile Intents

The intents correspond to the variety of meanings assigned to a tactile feature, ranging from representation of physical properties of objects to expressing mediated or direct sensory experiences to conveying abstract concepts or emotions. Accordingly, tactile intents fall into three dimensions, namely *properties*, *embodiments*, and *impressions*. The *property* dimension aims to imitate physical tactile attributes in the virtual space

Table VI. Tactile Intents with Respect to the Three Dimensions

Intent dimension	Intent (frequency)	Definition	Examples
Property	Surface (34%)	Represent surface properties of objects	Textures, temperature, wetness
	Material (32%)	Refer to material properties of objects	Hardness, stickiness
	Shape (16%)	Imply a tactile expression of edginess or shape properties	Sharpness, curviness, flatness
Embodiment	Kinetics (20%)	Indicating a deliberate action of a live being, or a motion of an object in the image	Swimming, swarming, flapping, stroking, reaching
	Phenomenon (36%)	Represent a sensation of a static state or flow of sensory phenomena	Sound, smell, light, water, wind, electricity
Impression	Concept (26%)	Represent an abstract and non-sensory concept	Steadiness, mess, order
	Affect (16%)	Express a particular personality trait or emotion	Sadness, happiness, anticipation

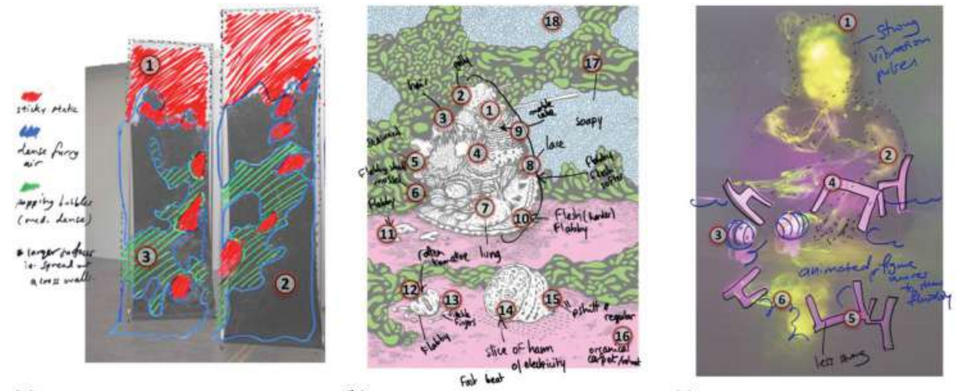
including *surface*, *material,* and *shape* intents. *Embodiment* on the other hand simulates a tactile representation of non-tactile sensory experiences including both *kinetics* of an action or motion, or a *phenomenon* of other sensory channels, such as a sound. Lastly, *impression* denotes the designer's sense of the non-sensory nature of a *concept* or the emotional experience of an *affect* in tactile form. Table VI provides an overview to the intents with respect to the three dimensions.

It is noteworthy to mention that the model is not a solid framework of mutually exclusive classes to which each tactile feature should strictly and uniquely be assigned. Rather, the presented descriptive model works as a guide in identifying the differences and commonalities among the meaning associations, implying the levels of abstraction in meaning-making with tactile creations, as further discussed in the Section 5.3.

4.2.1. Property Intents. Intents of the properties dimension associate tactile features with physical object attributes. *Surface*, *material*, and *shape* are the three intents under this dimension, each focusing on representing a different aspect of a physical tactile attribute in virtual modality. Intents of the *property* dimension were observed the most common compared with others, being expressed in 62% of tactile features and 64% of the tactile designs.

Surface: Tactile features with *surface* property intent are aimed at expressing those attributes that can be inferred from probing the surface of an object without imposing force or resulting in any change to the structure of the object. *Surface intents*, in our observations, were aimed at conveying a variety of textures, temperature, or dampness of their visual correspondence.

Assigning tactile values such as *wet*, *warm*, *cold*, *dry*, or *smooth* (shown in Figure 9(a)), or actual textures such as *hair* or *lace* (Figure 10(b)) are examples of attributing tactile properties from the real-world surfaces to convey a tactile representation for the visual depiction. Figure 6(a) shows more complex structures used in surface representations. Additionally, indirect implications of certain texture properties were conveyed using alternative tactile qualities. For example, sharpness and roughness were used in expression of surface dryness along the perspective. *Patterns with periodic vertical motion that reduce in size towards the [background] and increase towards*



(a) (b) (c)

Fig. 10. Surface, material, and shape intents. (a) Material intents: demonstrating variety of density using tactile qualities such as stickiness (A8.1), spatiotemporal air flow (A8.2), or temporal 3D points "*popping bubbles*" (A8.3). (b) Material and surface intents expressed with reference to real-world examples such as lace, seaweed, and the like. (c) Materials and shapes demonstrating hardness (A5.4) in contrast with graphical depictions of bendable paper-cut shapes; the sensations were also compared with a weaker reflex of the material (A5.5). Both features also demonstrate "sharpness" at the edges as shape intent. See also "shape" of the hand (A5.2) and "material" of the soft toys (A5.3).

the front... to imply things growing on the side of the road (A3.2). The spatial and spatiotemporal variability of this feature together contributed to creating a tactile sense of perspective in the flat image.

In total, 34% of tactile features were observed with surface intent, and 43% of the 14 tactile design prototypes had at least one tactile feature with a surface intent. Categorical data analysis shows some trends in the constructs of the surface intents. In particular, most of the surface intents had a concretely defined visual reference and mostly appeared as two-dimensional areas. Furthermore, surface intents were often identified with a uniform behavior and seldom held a spatiotemporal or spatial behavior. Surface representations had the structural constructs set in 96% of the cases, with no variability configurations in 81% of the cases. While about two-thirds of the features had a composite structure, *roughness* and *hardness* were the most frequent tactile qualities defined for surface intents, and stickiness was of the least interest when defining a tactile surface property. Compared with other property intents, surfaces had the lowest energy values. Finally, features with surface intent were mostly designed to respond to user hand position in a planar surface in front of the image.

Material: A material intent refers to the intention for expressing properties related to the substance of an object via the tactile cue (Figure 10), such as rigidity, density, or stickiness. The difference between surface and material intents lies within the deformability of the material in reaction to probing or applied pressure from the user. Expressions of both *surfaces* and *materials* were usually observed several times throughout the designs (Figure 6(a)). *More or less everything is flabby, organic and alive, so most of [the image] feels as an organic texture* (A4; see Figure 9(b)). This demonstrates the use of tactile modality to convey a particular dominant characteristic in the overall visual image.

A tactile material was the intended expression in 32% of all features and among 36% of the design prototypes, with more than half of all the material intents were associated with A4, representing an imaginary organic environment with many tactile features possessing *soft* or *resisting* tactile qualities (Figure 10(b)). Materials were the most concretely defined compared with other property intents. Structural constructs were specified for all features with material representation, with 92% composite structures. The trend in the energy construct, similar to surface intents, showed a declining trend in higher values, while at the same time, the highest energy value was assigned to material intents within the *property* dimension. Additionally, material intents had more variability compared to other property intents, mostly of temporal variation. Spatial behavior was rarely used and spatiotemporal behavior was never observed in expression of material intents. Additionally, no ordinality was observed in the behavioral constructs of this category, while both gestural and proximal interaction considerations were sparsely observed.

Shape: Expressing a *shape* intent refers to designing tactile features to particularly represent edge or face properties of physical objects, such as pointedness (A5.4), flatness (A3.2), or curvedness (A9.1, A11.1). The shape intent could be targeted at a particular object or a roughly suggested area. *I want to be able to touch and feel the curve, not just the hardness of the surface, rather the shape*, where curvedness of an object was represented together with surface and material intents in a volumetric tactile area (A11.1; see Figure 10(b)). Similarly, tactile contours represented *defined edges* of objects in A5.4 and A5.5 (Figure 10(c)).

Tactile shape intents did not always target a curved or pointy object. A volumetric form was used to represent the contour of a curve in order to emphasize its influence through the user's skin: *you could feel the curve in three dimension in the air, so that as you come up against it, it would give you some resistance* (A9.1; see Figure 6(b)). Tactile qualities such as amplitude and sharpness were relatively more frequently used to represent tactile shapes as opposed to other properties, while hardness and stickiness were the qualities relatively less used to describe a tactile feature of this group. While most shape intents were represented with static tactile stimulation showing a uniform behavior, variability was observed for some shape intents: *horizontal ovals to show the level of ground, also with circular motion to imply holes on the road* (A3.2), where multiple horizontal tactile shapes with circular motion showed a flat rough surface. Finally, interactions with tactile shapes could vary depending on their physical *form*. For instance, in order to get a tactile sense of a curved area, the interaction requires probing a curved virtual surface in the 3D space, but no particular action was required from the user to interact with a whole body experience of a volumetric curved contour as in A9.1.

In total, 16% of the tactile features conveyed a shape intent, while expressed in 50% of all tactile prototypes. The relatively more common observation of volumetric forms compared with surface or material intents is in line with the nature of shape perception in interaction in physical reality. Spatiotemporal behavior was the variability construct most frequently assigned to shape representations, and highest value of ordinality in property intents was observed for shape representations.

4.2.2. Embodiment Intents. The second intent dimension, defined as *embodiments*, suggests a common theme among those tactile intents that convey sensory experiences of an action or motion, or an active state or flow of sensory phenomena. Accordingly, *kinetic* and *phenomenon* are identified as the two intent categories of this dimension. Tactile *embodiments* were expressed among 51% of the tactile features and in 93% of tactile design prototypes.

Kinetics: Tactile features that convey a tangible experience of an action or motion are those identified with a *kinetics* intent. In other words, a feature with kinetics intent represents a tangible experience of a deliberate action of its *reference* or describes a tactile sensation of a motion happening in some part of the image. *To get a sensation of the jump, we can animate how [the figure] completes the dive and swims away*

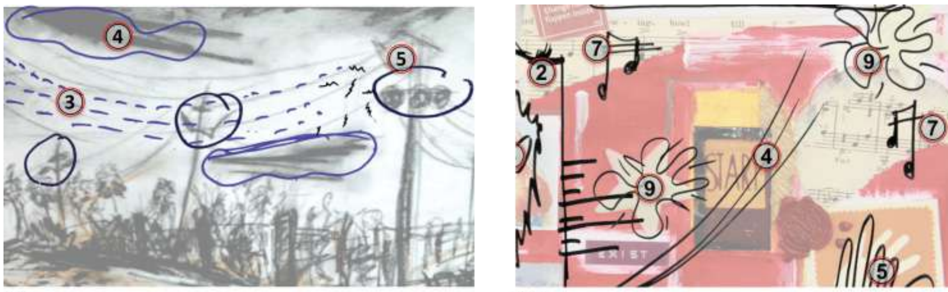
(a) (b)

Fig. 11. Kinetics and phenomenon intents. (a) A7.1 conveys flight path of a bird as a motion using spatiotemporal and spatial behaviors. The *descending flow* of the bird is conveyed by a diminishing sensation of *wind* via *spatial variability* with decline in amplitude. (b) A2.1 conveys both the kinetics of the direction of tension in the rope, as well as an emotional relationship between the two depicted characters. Phenomenon intent in A2.2 shows elemental forces surrounding A2.1.

(A9.3). The tactile expression here is describing an action initiated by the depicted human figure with spatiotemporal behavior that moves along a trajectory beyond the original scope of the visual image. Here, the *reference* of the tactile feature is an area that suggests the path along which the action takes place (Figure 14). Similarly, the tactile feature in A5.2 represents an arm *reaching* outward from the image surface (Figure 5(a)). Although the action of *reaching* does not involve any spatiotemporal characteristics, it is represented by a volumetric tactile *form* that exists along the frontal part of the image.

A kinetics intent was also associated with non-human live-beings, such as a bird flapping its wings. *To get a sense of what it feels like when a bird flaps its wings against [someone's] hand, not touching the wings, but feeling of the air as it comes off from the wings, as the bird is going down towards the left corner of the picture* (A7.1). This indicates a close relationship between the visual and tactile components, where the tactile *form* integrates multiple visual representations into one (Figure 11(a)). Some kinetic characteristics were metaphorically associated with non-live objects such as *tickling* fingers, *breathing* (A4.7), *jiggling* (A4.2), and *swarming* (A4.13) associated with imaginary creatures (Figure 10(b)). Similarly, motion of a live-being is metaphorically assumed for an abstract art theme in A1. *It's all about breathing…in the beginning, it feels like [inhale] to keep it high, to keep [the vertical lines] so they are up here. And with exhale, [the sensations] are going down. Then some of them are coming back up again, so down and up* (Figure 8(a)). Here, *ordinality* creates strong interdependencies among the features to achieve the tactile metaphor in full.

A kinetics intent was represented in 20% of the tactile features and among 64% of tactile designs. Analysis of the constructs shows *planar contours* as the most common form in this category, with 67% possessing spatiotemporal and 27% spatial variability types. At the same time, tactile kinetics had similar frequencies at low energies, compared with medium and high ranges. About 56% of the kinetic features were described by more than two tactile qualities, which implies a relatively more complex structure compared with phenomenon intents. Tactile qualities such as stickiness, dampness, and temperature less commonly occurred in the structural constructs of tactile kinetics.



(a) (b)

Fig. 12. Phenomenon intent. (a) A3.3 and A3.5 convey a tactile sensation of electricity, while A3.4 is expressing a sensory representation of the clouds. (b) A6.4 shows a sensation of wind (a phenomenon) to further indicate "passage of time," while A6.9 demonstrates glowing in the stars, and A6.7 represents rhythm of music. Both A6.9 and A6.7 occur with two repetitions.

Phenomenon: Tactile features with a *phenomenon* intent attempted to convey a tactile experience of an active state or flow of non-tactile sensory phenomena, such as representation of a gaze (A14.4 or A10.1; see Figures 13 and 14, respectively), sound (A6.5, A6.7; see Figure 12(b)), electricity (A3.3, A14.5), warmth (A13.2; see Figure 7(d)), flow of wind (A13.1; see Figure 7(d)), or general forces of nature (A2.2; see Figure 11(b)). The intended objective here is to create a sensory tactile form for non-visual or non-tactile phenomena. For instance, a sensation of the rhythm in the musical notes (A6.7), sound of *a velvety voice softly reading the text* (A6.6; see Figure 12(b)), *sound of electricity* emissions from the *power poles* (A3.5; see Figure 12(a)), and *smell of dampness in the room* (A11.3) are examples of sensory information other than visual or touchable attributes that are represented with tactile modality.

Some phenomenon intents were observed having no particular visual correspondence. For instance, sense of atmospheric ambiance such as flame or fluidity (A5.1, A5.6; see Figure 5(a)), warmth (A13.2) and dryness (A3.4; see Figure 12(a)), or flow of air (A13.1) or electricity (A3.3, A12.2; see Figure 7(b),(c)) are mid-air phenomena represented by tactile features that did not particularly refer to specific visual objects, but rather corresponded to roughly defined areas in the picture. In general, phenomenon intents were aimed at creating a direct sensory experience by sharing the designer's sensory impression of a scene or object with the end-user: *it's about me going into that building (A13), I want the user to experience what I was feeling there* (A3).

Phenomenon intent was represented in 36% of tactile features and across 79% of all the tactile design prototypes, the highest compared with all other intents. The most significant observations in the constructs of phenomenon intents include the commonly planar form of the features mostly appearing as areas in 60% of the cases. Structural constructs involved fewer tactile qualities, and certain tactile qualities such as *dampness, stickiness*, and *hardness* were less popular for expressing tactile phenomena. Additionally, both uniform and non-uniform variability were commonly observed in this category. The highest *target* and *responsiveness* values observed for this category suggest the user was taken more into account when designing interactions with tactile phenomena.

4.2.3. Impression Intents. Finally, tactile features intended for expressing a tactile *impression* of an abstract idea or affective information constitute the third intent dimension in the tactile intent model. Compared with the first two dimensions, features with an *impression* intent impose an overall expression of a subjective opinion onto the designs. Tactile features in this dimension in particular convey abstractions of a non-physical idea or *concept*, or express a positive or negative *affect*. Tactile impressions in general constitute 38% of the expressed intents among the tactile features and were conveyed in 86% of the tactile design prototypes.

Concept: A tactile feature intended to express an impression of a concept or a particular mental representation is identified with a *concept* intent. Our observations show examples of chaos (A2.2, A4.18), shelter (A13.2), liveliness (A10.1, A14.1), flee (A9.3), and so on. Such conceptions or mental representations are entangled with subjective understanding and no precise designation in the sensory reality. For instance, the passage of bird (A7) conveyed an abstract representation of *getting old*. Another example shows tactile expression of *energy* as an abstract concept realized by a sensory experience of electricity surrounding the figure in A12. At the same time, *liveliness* as an abstraction of several indicators was represented together with expressions of surface attributes of a live-being depiction: *with the [skin] being warm and wet, you feel it's animatic...roughness also expresses feature of the wolf's body, and overall [these attributes] give a hint to the audience it's an animal and it's alive* (A14.1). Similarly, in A2, a *relationship* is described by means of a gentle stroke (A2.1) surrounded by elemental forces: *being chaotically pummeled by primordial forces, to show the struggle between life and death* (A2.2) refers to a phenomenon intent, on the one hand to express chaos, and death on the other. Other concept representations as well accompanied intents of other dimensions as the basis to impose on a subjective opinion. This notion is discussed further in Section 5.2.

In total, 26% of the tactile features conveyed a concept intent among 64% of the design prototypes. Most of the concept intents appeared as planar tactile forms with the least number of concrete reference observations. This is in line with the non-concrete nature of abstract mental representation in tactile form. Additionally, more than half of the features had single-structures, which implies a single tactile quality can sufficiently convey a tactile concept. Additionally, the high average energy can be explained by frequent observations of medium and high-energy ranges, as well as many features with spatial variability. Accordingly, behavioral constructs in this category were mostly composed of spatiotemporal and spatial variability together with commonly designed ordinality construct compared with other intent types.

Affect: Lastly, the tactile features carrying an *affect* intent represent a tactile impression of a personality trait or emotional state, which could be either directly related to a representation of a human figure, or intended to generate a negative or positive affective response for the end-user. For instance, expressing aggressiveness or emotionlessness (A14.5, A14.9) from the gaze of a figure's face is intended to represent a particular affective state of the depicted character, while the tactile sensation felt from the face with a visually neutral expression in A10.1 is designed to generate a sense of fear for the user (Figure 13). *Around the head feels like static electricity to express that the wolf is not in a good mood, it's full of hatred* (A14.5, see Figure 9(a)). Here, the affect intent is embedded into the representation of electricity as a phenomenon intent.

While very few features uniquely expressed an affect intent, most accompanied other intent categories. Expression of a *concept* often accompanied many of the features with this intent category. For instance, strong emotional expression was embedded into the representation of the *relationship* in A2.1: *the relationship between the man and the horse...the man's hands are expressing comfortness and tenderness and that's what I like to show with the stroke* (A2), where the stroke of touch describes an emotional relationship happening in the visual image as tender and loving. Affective expressions were also observed to accompany *property* intents, such as surface temperature: *I really like the idea of if you touch that piece you'd feel the cold, because he's quite a cold character* (A11.8). Or material rigidity: *the soft toys should be quite comforting* (A5.3).

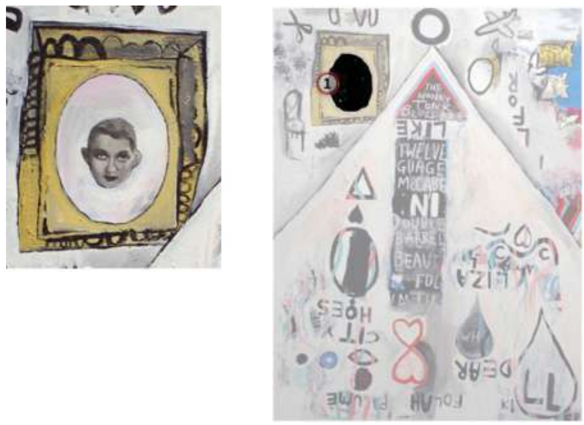


Fig. 13. Phenomenon and affect intents. Uniform sensation of a volumetric point in A10.1 conveys the gaze of the depicted figure with a phenomenon intent. By drawing attention to the gaze of the figure (on the left), the representation is further intended to generate a sense of fear for the user, as an affect intent.

Affect intents were observed for 16% of the tactile features among 43% of the tactile design prototypes. The tactile constructs of this category suggest commonly planar forms with non-concrete reference composition. The affects had the most relative undefined structures among all the tactile intents, implying more abstract and non-concrete nature of emotional information. At the same time, less repeating features were seen in tactile affects category compared with concept. All tactile qualities were used in expression of affect intents; however, smaller tactile grades were more common, and features gradually become infrequent in grades higher than 2. Additionally, the lowest average energy value was observed for tactile affects compared with all other intent categories, which is also in line with the lack of observations of spatial variability construct. The behavioral constructs in this category were mostly composed of uniform variability as well as few spatiotemporal features. The tactile interactions were not intended for alternative body parts, and responsiveness construct was only embedded in only one feature (A14.9; see Figure 9(a)). Similar to the concepts category, tactile features with affect intent commonly express intentions in integration with other intent categories. Again, this notion implies the need for a materialistic representation that works as the infrastructure to express a tactile affect intent, as further discussed.

5. SUMMARY AND DISCUSSION

This section presents an overview and discussion of the findings, including insights from the adopted methodology as well as both tactile components—*constructs* and *intents*.

5.1. On The Impact of The Methodology on Expressive Tactile Designs

The stage-based guided design process had both benefits and drawbacks for interface design of a new modality. Most importantly, the guided design methodology helped to implicitly study the impact of the tactile technology on expressive tactile interaction design. Also, being able to freely sketch design ideas allowed for an open mind for design without any feasibility concerns, which informs important aspects of an expressive tactile interface. Additionally, the initial divergent ideation saturation followed by gradual narrowing down of ideas helped achieve a relatively matured final outcome in the form of final tactile design prototypes.

During the design sessions, we learned how artists take different approaches to realize their design goals given the capabilities of the output device and assuming the limitations of low-fidelity prototyping. While exposure to the tactile device somewhat clarified the output capabilities, some implementation-level ambiguities resulted in either adjusting the designs according to presumed limitations or completely ignoring any technical challenges. Some final designs only became more concrete from the initial ideations during the evoking stage, with tactile features following the composition of the visual background (A1, A11, A14) or a few more features being added to complete the tactile composition (A2; see Figure 11(b), A4; see Figure 15). Others were simplified in their composition including the number of features and precision of the form (A7, A8; see Figure 15(c)). Some designs were adapted to the affordances of the technology after the exposure stage, by specifying the qualities as felt on the device (A5, A8; see Figure 15(b), (c)) including illusory sensations of heat or wind (A13).

Nevertheless, not all tactile qualities had a direct corresponding variable in the current design space of the tactile output device. Mapping qualities such as amplitude or roughness could be more explicitly derived from sensations of ultrasonic cues with different frequency and intensity values, but no variable in the ultrasonic tactile space could explain tactile qualities such as stickiness, dampness, or hardness. Similar to sensation of temperature, such qualities were sometimes perceptually considered for the ultrasonic tactile cues or instead designed regardless of the technical limitations imposed by the technology. In particular, lower modulation frequencies such as 2 or 4Hz were reported to feel *warm* or have a *burning sensation* (A3, A5, A9), whereas higher frequencies implied *cold wind* for some (e.g., A2, A3, A13). Additionally, ultrasound cues felt more diffused than sharp at high frequencies (A3, A5, A8). This finding is in line with encounters in previous research [Obrist et al. 2013], which is found to be due to absorption of the sound waves through skin tissue [Hoskins et al. 2010]. Other qualities such as stickiness or dampness initially emerged during the enacting stage and were kept for the final designs regardless of the capabilities of the tactile device.

Adjustments were also observed at *behavior* level, mostly caused by the sketch-based prototyping technique. For instance, A10 initial design was directly targeted at the end user, not originating from any visual element on the image. It was later altered to initiate from the depicted human face on the painting, when asked to sketch the tactile design on the painting overlay. Similarly, some elements in A2, A9, and A12 were also adjusted to initiate from the image. Nevertheless, we argue that despite the modifications to the final physical attributes of the design products at construct level, design goals aimed at creating intended user experiences were sustained through the tactile intents. We will further discuss those under the notion of expressive roles.

As discussed above, the artist's design intention for each tactile expression was sustained regardless of the final physical properties of the tactile design. On the other hand, within an approximately 2 to 3 hour session and with only one artwork, it was not possible to achieve a full excavation of all design ideas. Investigating how tactile designs evolve as a result of practice was also not possible during the single-session study. Finally, the short duration of physical *exposure* to the technical constraint, limited capabilities of the tactile device, and no demonstration of sample creations may have limited the designer's creative capabilities or prohibited the design of more complex physical structures for the tactile artifacts. Nevertheless, the findings as the first research attempt in this area of tactile interface design offers new insights for designing tools that can further enhance the expressive capabilities of tactile designs. Furthermore, we will discuss below that many final designs did not necessarily comply with the limitations imposed by the methodology and suggest the need for an enabling system with support for the design requirements.

Table VII. Tactile Constructs Per Intent Category. In Each Row, the Frequency of Observations is Demonstrated for Each Construct

Construct	Surface	Material	Shape	Kinetics	Phenomenon	Concept	Affect
Form (% non-planar)	4	16	33	13	7	5	17
Reference (% concrete)	85	88	67	66	64	55	58
Repetition (% multiple)	19	24	42	33	50	32	33
Grade (% composite)	73	92	50	73	54	36	67
Energy (norm. mean)	0.27	0.34	0.30	0.39	0.23	0.31	0.20
Variability (% non-uniform)	19	32	17	87	54	50	25
Ordinality (% any type)	12	0	42	47	25	45	17
Target (% non-hand)	4	8	25	20	36	35	25
Responsiveness (% non-positional)	4	8	8	13	36	10	8

5.2. From Construct-Intent Relationships to *Spectrum of Expressivity*

Looking further into each of the intent categories, we observed attributes from the constructs commonly shared for representations of similar kinds, as shown in Table VII. In The construct-intent relationships lead to interesting insights on how people understand and design for tactile interactions. Below, first high-level implications from intents are presented, followed by the most substantial of these shared attributes with respect to each intent theme.

The intent categories correspond to representation of physical properties of objects, expressing mediated or direct embodied sensory experiences, or conveying abstract meanings through the sense of touch. Tactile intents with real-world imitations of physical object *properties* objectively express certain tactile qualities in real life, indicating property intents have the lowest level of subjectivity in representing a true duplication of a real-world tactile sensation. Additionally, for a tactile representation of the *property* intent, often a strong connection or direct mapping between the tactile constructs and its meaning can be observed. On the other hand, at a less tactile level, *tactile embodiments* possess a tactile representation of something that happens in the physical world but is not necessarily tactile. Although generating an objective expression of motions or actions means regenerating a more or less truthful representation of a flow or rhythm, conveying different sensory phenomena asks for a subjective expression of an individually perceived experience. Finally, as there is no direct tactile value or physical reference to describe a *concept* or *affect* intent, the expressions are at maximum level of subjectivity, where meanings are highly imaginative and are formed as a result of mental abstraction.

In other words, compared with the previous intent themes, the meanings embedded in tactile impressions convey subjective understanding of a mental rather than physical notion. Insights from the construct attributes of each intent theme can suggest the dominant physical aspects of the tactile interface for creating meanings at different levels of abstraction.

Properties: Observations of this theme showed features with commonly concrete references and uniform behavior, mainly targeting the user's hand with no complex responsive behavior to user actions. These characteristics imply a realistic approach to designing tactile simulation of physical properties without much subjective opinion involved at the construct level. In other words, whether the tactile *property* gives a realistic or non-realistic representation of its visual counterpart, compositional and behavioral constructs remain very close to their physical world equivalent.

In general, tactile properties take advantage of composite structures to provide more information about the physicality of the visual reference in tactile modality. Conversely, many property representations were not designed for the sole purpose of a perceptual representation; more than half also expressed intents of other themes.

Embodiments: Higher energy values were observed for the embodiment intents mainly sourced by the *kinetic* intents. More planar forms and less concrete references were observed for tactile embodiments as opposed to properties. More complex design of the behavioral constructs, including non-uniform variability and ordinality, in addition to alternative target body parts and responsiveness consideration, all imply more interactive and user-oriented designs as opposed to intents of the *property* dimension. This set of characteristics is in line with the active nature of motions, actions, or phenomenal happenings in the real world.

Furthermore, we observed creative ways for describing tactile attributes for non-tactile sensory information. For instance, designing a spatiotemporal tactile feature to represent stars glowing (A6.10) or creating the sensation of running water to express embracing a hand (A6.5). We therefore argue that tactile embodiments in general tend to reveal or introduce an aspect of representation that is inaccessible to the eye or not possible to convey in a static image, by either direct or indirect means of expression.

Impressions: Tactile features in this dimension had the lowest average grade and energy mean compared with other intent dimensions. This difference indicates a simpler structure and relatively less common use of intense or user-oriented behaviors for expressing a physical impression of a non-sensory and non-physical subject. Additionally, tactile *impressions* were almost always expressed in combination with intents of other themes, with just under less than half of tactile embodiments also expressed an impression. This implies the need for more physically sensible representations as the infrastructure to express concepts and emotions: *...emotion is the key tactile quality in the painting, you can be touched physically and feel an emotional impact* (A2). Additionally, about one third of all features with *property* intent were also expressing an embodiment intent; *The character is not a human being, but it's very hard to express that... it's something that doesn't really have emotion like human; it's cold touching this person's heart, opposite to the [wolf's] warm body, she has a cold heart* (A14). Thus, the expression of more abstract or metaphorical tactile intents can be achieved by imposing an abstract meaning on a more physical experience that the end-user can easily relate to and is probably of lower cognitive demand.

The non-exclusive relationship among the different intent themes implies a hierarchy in the level of abstraction in the meanings represented by tactile expressions and indicates a spectrum rather than a solid classification for the variety of meanings that can be expressed with tactile modality. In other words, starting from the *property* intent theme, tactile representations are more mimetic of a real world correspondence, while more imagination and expressivity is involved in representing abstract ideas in tactile modality toward the *impressions* intent. A *spectrum of expressivity* can identify this trend with low and high expressivity at properties and impressions side, respectively. More research can evaluate different aspects of such proposition with more quantifiable metrics.

5.3. An Extended Design Space for Expressive Tactile Interfaces

Overall, tactile constructs collectively demonstrate the different physical aspects that a tactile feature can take in isolation, together with other features, or in response to user interaction. While *compositional* constructs focus on the association between the possible configurations of a tactile feature, *structural* constructs imply the relationship between the virtual sensations with a similar tactile correspondence in the reality. Even though many of the current tactile structures have aspects in common with real-world examples, the amount of information needed to describe a tactile structure indicates that despite the device not being able to fully support the described constructs, fairly satisfactory results may be achievable even with the limited technical design space of the ultrasound tactile device. Additionally, the *behavioral* constructs demonstrate novel aspects of tactile features that are also less explored in tactile interaction research. As well, further thoughts indicate that both *responsiveness* and *target* constructs that specifically account for user involvement during interaction can form a separate group of construct dimension that focuses on the *interactivity* rather than *behavior* of the tactile features. Despite the observed variations in the current study, deeper understanding of such user-oriented constructs requires more thorough investigation beyond the scope of this article.

Findings from tactile constructs confirm similar previous research and propose new aspects of tactile interaction design space. Previously suggested taxonomies mostly present a space for tactile interfaces based on heuristics and configurable properties of the device, as well as the context of application [Brewster and Brown 2004; Lederman and Klatzky 2009; Yatani and Truong 2009], and incorporate aspects from all three construct dimensions including form [Huisman et al. 2013; Najdovski and Nahavandi 2008; Jacob et al. 2010; Styliani et al. 2009], structure [Lawrence et al. 2000; Basdogan et al. 2004; Minamizawa et al. 2007], and behavior [Brewster and Brown 2004; Spelmezan et al. 2009; Yatani and Truong 2009]. Examples of these works include construct properties such as tactile points or contours for guiding the user in virtual environments, synthetic surfaces of different types, or rhythmic or spatiotemporal behavior for differentiating non-verbal notifications, each proposing distinct aspects of the tactile space. Some studies have attempted to bring together most of the heuristically determined predominant tactile attributes together [Brewster and Brown 2004], often leading to tool development that supports a particular output device, such as desktop-based Hapticon editor [Enriquez and MacLean 2003] or FeelCraft [Schneider et al. 2015], commercially available Immersion Haptic studio [Immersion.Com 2015], or more recent gesture-based tools such as the haptic sleeve [Huisman et al. 2013] or the handheld device by Rantala et al. [Rantala et al. 2011]. While they generally assume the restrictions pertaining to the design space of the specific technology (mainly vibrotactile actuators), attributes such as form and position, frequency and intensity of the output, and some level of variability are often supported.

Empirical studies focusing on the expressive aspects of tactile interface design are mostly aimed at investigating user behavior with existing tools and tactile output technologies under controlled conditions, and do not attempt to allow full exploration of the space or to explore new variables in a pre-defined design space [Gumtau 2005; Bailenson et al. 2007]. The restraining factors such as researcher-defined design space or outcome, as well as the preset experimental control conditions, in addition to predefined output mapping mechanisms restrict novel attributes from emerging in the experiments.

Compared with other previous taxonomies, the proposed design space illustrated under tactile constructs is the outcome of bottom-up approaches resulting from research through design, as opposed to a technology- or form factor-based approach for classification of the configurable attributes or supported capabilities. Our findings from the expressive tactile designs in low-fidelity prototype format propose a less biased design space for augmented tactile interfaces, with minimal influence of the constraints imposed by specifics of the tactile technology, design tools, input techniques, and mapping mechanisms. During the implementation of conceptual designs, more detailed aspects of the input and output would impose specifics of each attribute. Even though the current results are established under a visual multisensory environment, they demonstrate how the addition of a sensory modality can influence new aspects of the design space to emerge with respect to the context or the end-user.

The findings from tactile intents also compare with the previous works in defining a design space for expressive meaning-making with tactile interfaces [Haans and

Ijsselsteijn 2006; MacLean 2008; Gumtau 2005], as discussed in the related work section. While most of the previous findings are derived from surveying the literature, they argue for a more high-level and larger range of meaning-making potentials. Specifically, in a comprehensive set of application areas and interaction scenarios suggested for tactile interfaces [MacLean 2008], expressivity and affective communication are briefly discussed but deeper analysis of the underlying aspects of meanings is left for the reader to explore. Little empirical efforts [Gumtau 2005; Park et al. 2012] only roughly suggest groups of expressive intentions without detailed explanation or high-level analysis or implications of the meanings or their relationships with their physical counterparts. The open-ended design-based methodology in this work, however, provides empirical evidence and concrete examples of meaning association with specific focus on expressive tactile interfaces. The current findings also indicate some prominent aspects of form–meaning relationships and imply how the identified themes relate with each other in forming a spectrum of meaning. Design implications can be further implied from both aspects as presented in the following section.

6. DESIGN IMPLICATIONS

This section presents a high-level set of implications relevant to the context of human-computer interaction, in particular expressive tactile user interface design. The discussion addresses two main questions pertaining to expressive tactile design as an augmentation to existing visual artworks: What artists aim to achieve by adding the tactile layer and what requirements need to be supported in a tool to aid the creation of the interaction in a user-experience-oriented visuotactile multisensory context.

Accordingly, two sets of roles are considered for end-user interactions with expressive tactile augmentation of visual artworks, mainly derived from tactile intents. Guidelines are also presented for designing an expressive tactile augmentation tool implied from the tactile constructs, inspired from design principles of creativity support tools [Shneiderman 2007]. Finally, a corresponding user interface architecture is laid out for the design of future tools

6.1. Expressive Roles for a Visually Augmented Tactile Layer

The ultimate design objective for developing an augmented tactile interface integrated into existing visual art pieces is to offer alternative interaction opportunities for the end-user and create novel user experiences through a multisensory environment. At the same time, the design objectives of such user-experience-oriented context may deviate from a conventional set of affordances in a performance or productivity-oriented interaction scenario. As such, a variety of design objectives are identified for tactile interaction implied by design intents, and we propose *expressive roles* rather than *affordances* for interaction scenarios composed of tactile augmentation of visual imagery, referred to as *visuotactile interaction*. Consequently, two sets of roles for tactile interfaces are assumed: those more related to interaction at a perceptual level and others more specifically targeted at the user's cognitive interpretation from the interaction.

6.1.1. Interactional Roles for Expressive Visuotactile Interfaces. The following interactional roles describe the various ways in which an integrated tactile interface modifies the default visual interaction in the multisensory visuotactile scenario.

Perceptual switch: As technology becomes an intermediary for tactile perception, tactile and visual interaction spaces become detached. While tactile interaction occurs in the 3D space on the user's body, the visual plane lays at a proximal distance to the user. Consequently, due to the novelty of interaction opportunities, it is foreseen from a design perspective that the tactile overlay is expected to somewhat attenuate attention from the multisensory context and instead guide cognitive reliance solely to the tactile perceptual channel. Though the visual artwork in its original form suggests visual modality as the central source of information, with introduction of an additional channel, user's cognition may lean towards the tactile interface, which offers more intimate and physically present sensory input.

On the other hand, tactile sensory perceptions occur in response to user's deliberate action and intended engagement, meaning the user can intentionally block tactile perception and switch attention to the visual interface. Thus, the tactile interface acts as a perceptual switch, allowing the user to consciously divert attention from one modality to another, changing the central cognitive reliance from visual to tactile and vice versa.

Invisibility and unexpectedness: The immediacy of visual perception provides a global view of the art piece. In contrast, the sense of touch allows a limited field of perception defined by the area of contact or specific *target*. With the static visual interface providing no priming effect as per what to expect on the tactile channel, tactile cues will only be perceived at physical body locations, without any prior expectation or global overview. Thus, tactile sensations remain in an unexpected status until they are locally discovered on the user's body part. Additionally, the sensations remain at a personal level, where the same sensation is available to one user at a time, hidden to other users. This sense of surprise and intimacy of interaction is particularly a novel aspect of interaction with locally perceivable sensory modalities such as tactile and gustatory.

Dimension and perspective: The augmented tactile features introduce an opportunity to actively engage with visual information. With interactions happening mid-air in front of the graphical interface, the tactile interface invites the user to perceive a flat surface in the third dimension. Depending on the type of responsiveness defined for the interface, user interactions with the tactile layer can occur within a single plane or at different depths to offer virtual interactions with the depicted perspective, as shown in Figure 7.

De-framing: The tactile interface works as an invisible sensory medium to extend the interactions beyond the original scope of the visual image. Consequently, interactive experiences with the tactile interface will no longer be bound by the visual frame; instead, with the new sensory information, the interaction space is penetrated without compromising the original form. Figure 14 shows a representative instance of a tactile feature de-framing the scope of the artwork.

Desaturation: When the original visual interface is saturated with information, the tactile interface offers an alternative channel for intensifying an existing visual expression. *Adding a new layer and takes them away from the original goals. You don't want to be disturbed by new things, rather you only want to focus on specific visual elements* (A14). Therefore, instead of introducing new objectives, the tactile interface can highlight the significant visual information that might otherwise be missed.

6.1.2. Cognitive Roles for Expressive Visuotactile Interfaces. Visuotactile interactions are intended to leave deeper impact on the user at a more cognitive level. The following *cognitive roles* are therefore envisioned for tactile interfaces in a visuotactile interaction scenario.

Sensory knowledge: The tactile interface was considered by artists as a platform for learning. *I realized I'm only appealing to [peoples'] visual literacy and...they are used to seeing colorful, moving images that kind of spoils how the look at [unconventional visual encounters], and it takes repeated exposure and very deliberate focus to pick up other tastes. So maybe [tactile interaction] is one way to communicate that you don't solely rely on visual sense which is so compromised...Because many of them may not be*

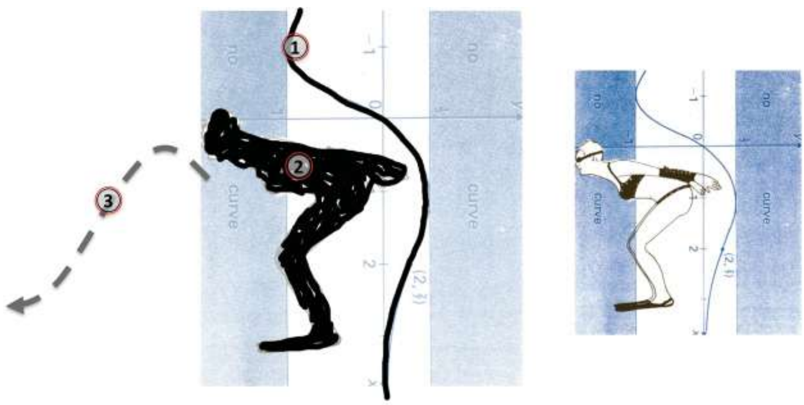


Fig. 14. Concept intents indicating notions such as *boundedness* or *restriction* (A9.1, A9.2), as opposed to *escape* or *flee* (A9.3), demonstrate contrasting meanings expressed in the overall tactile design. A *sequenced ordinality* embedded in the tactile design starts with A9.1, a uniform volumetric contour, continuing with both A9.1 and A9.2 as two simultaneously present features. The sequence ends with spatiotemporal feature A9.3, a tactile motion that diminishes in intensity. A9.3 has no visual reference in the graphical image. The original artwork is shown on the right.

used to or aware of being sensitive to it, it will make them more sensitive to materiality, they will realize that when they move their hand over it, things change, and they want to know why and where it changes (A8).

Similar results found in interactive arts [Joy and Sherry 2003] indicate the impact of embodied experiences in forming a non-quantifiable form of knowledge, which is necessary for learning. This notion of sensory knowledge can be extended beyond art appreciation and suggest educational potentials for tactile interaction for learning through tactile experience.

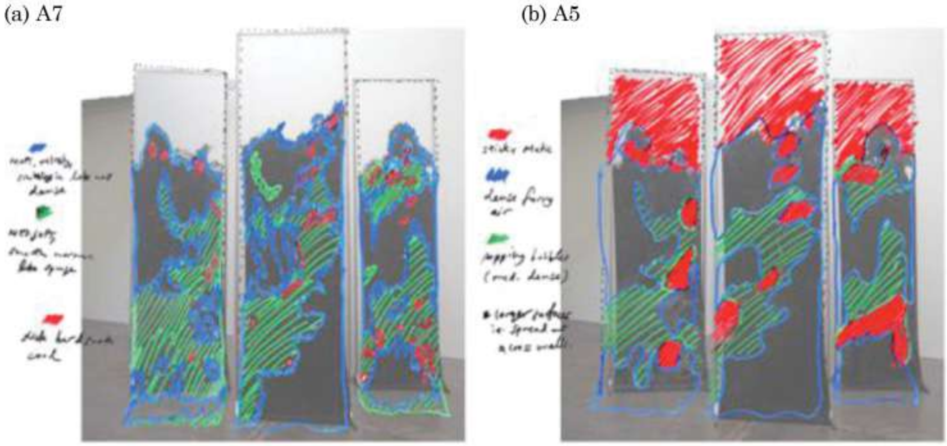
Meaning distribution: As a consequence of the *perceptual switch* effect as discussed earlier, tactile modality can be designed to control over the visual meaning. For example, as the image demonstrates a particular aspect of a depiction as visually significant, tactile interaction highlights another aspect of the same visual reference as more substantial. An example can be found in A11.1, where different physical aspects of a depicted object were expressed via the two modalities: *The green to me looks as if [the vase] should be organic, but it's definitely not...This shade of green in particular, that looks as if [the vase] should be soft to the touch but it isn't*. This effect can distribute the meaning over the two sensory channels depending on the designer's decision on modality fit for a particular expression. This notion is consistent with existing literature on multimodal interfaces [Kress 2009]. As suggested, in a multimodal representation, there is a *role distribution* among the different semiotic systems corresponding to the roles considered for each of the sensory modalities.

While information encoded in the visual media is more understandable because of the broad academic literacy on written text and graphics, the physicality and intimacy of interaction special to the sense of touch offers a new set of roles that can generate novel interactions opportunities when integrated with visual modality.

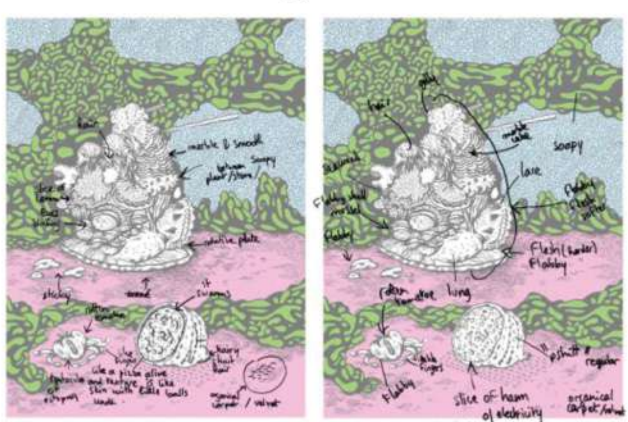
Multisensory narrative: The tactile interface can work as a sensory guide to take the user through the visual imagery. For instance, the collection of tactile features with embedded *ordinality* or *variability,* such as in A6 or A11 (Figures 8(b) and 6(a)), are concerned with inventing a tactile storyline within the graphical interface or leading the user through a trajectory within the visual image.

(a) A7

(b) A5



(c) A8



(d) A4

Fig. 15. Conceptual tactile designs at *enacting* (left images) and *exposure* (right images) stages, showing (a) form simplification from 3 to 1 feature and added dynamics of spatial and spatiotemporal variability; (b) pulsating vibrations replacing thermal qualities and lightness replacing solidity; (c) area initially described as smooth, warm, soft, adjusted to pupping bubbles with medium density; (d) the final design mostly remaining the same with only a few added features.

Ambiguity and imagination: Because of the essential invisibility of a tactile interface, ambiguity is an inseparable part of a tactile interaction. In the visual multisensory context, this sense of uncertainty for interpreting a meaning from a tactile sensory input can be further enhanced or compensated by the visual reference. Contrasting or unfamiliar sensations from each sensory channel may increase the cognitive load of the user to make sense of the multisensory artifact. *Sometimes there's a brain demand to have concrete meanings explained in words, and that goes against the spirit of making a non-words piece of work* (A5). A precise interpretation of the designer's intent is then not the main objective of the multisensory interaction; rather the interaction is motivated by creating ambiguity and imagination. For instance, designing tactile interaction following the motto *what you see in, not what you feel* can be deployed as a source of inspiration for imagination and creative thinking.

Interpersonal bridge: Taking advantage of the unique communicative characteristics of tactile modality, including physical intimacy and whole-body perceptual field, tactile interactions enable a sense of remote interpersonal touch [Haans and Ijsselsteijn 2006]. Tactile augmentation of a visual interface can also benefit from this affordance, especially where direct touch is not applicable or appropriate for interaction. *The interaction will help them appreciate what I was feeling when I took the picture* (A11). The tactile interface then offers a platform for sharing one's own experiences or impressions with others directly onto the user's skin. Tactile modality then creates a sensory bridge between the two sides of communication as a way to physically reach the user in a more intimate way.

These sets of roles are derived from designer's input during low-fidelity prototyping of expressive tactile designs in an artistic visual context, which may vary in other scenarios. Differences in user experiences with visuotactile interfaces may result in variations in comprehension of the multisensory representations during the interaction. Cognition and meaning-making would then depend on the individual perceptual capabilities of the user as well as cultural and social norms and practices, which may still vary between the designer and the user, and even among users. What is then interesting to investigate here is the difference between *real* and *perceived* affordances, where the construction of meaning on the designer's side refers to the *real affordances* or the constraints of the interface imposed by the designer, and *perceived affordances* are designated as the interpretations made out of the interaction from the user's perspective [Najdovski and Nahavandi 2008]. In this case, comparing the *real* and *perceived* affordances in terms of meaning-making and role distribution among the modalities would be something to investigate as a future direction for research.

Although the expressive roles may not provide a comprehensive overview of the full space of the expressive affordances of visually augmented tactile interaction, the aim is to open perspectives and shed light on interaction opportunities in expressive visuotactile multisensory scenarios. Despite the envisioned roles, many designers expected that user's access to the design objectives would be rather unpredictable and that the ability to decode the meanings or even invent new meanings depended on the subjective perception of individuals with different backgrounds. They also stressed the importance of how the interaction opportunity is presented to the user and argued that a minimum level of priming is needed to create awareness or clarify the high-level aims.

6.2. Guidelines for Designing an Expressive Tactile Augmentation Design Tool

An expressive approach to augmented tactile interface design highlights the need for designing tools and improving technologies in order to better support rich tactile interaction design. Taking into account the insights derived from tactile constructs, a set of guidelines is suggested for designing tools to support expressive tactile interaction design. Inspired by design principles for creativity support tools [Shneiderman 2007], we extracted essential design considerations with respect to *objectives*, *techniques*, *processes,* and *evaluation* specific to the designer goals and needs in the existing context of art and expressivity.

6.2.1. Objectives. First and foremost, the objectives of an expressive tactile interface design tool lies within its ability to support a wide range of possibilities at both input and output levels. The major lesson learned from this study was that regardless of any technical affordances or limitations of the tactile output, the final tactile augmentation reflects the initial design intention set by the artist and technology constraints only result in adjustments or simplification of the designs with the design goals sustained throughout the process. Some artists also brought attention to the need for creating co-experiences among different users or more advanced effects across multiple artworks, suggesting scalability considerations for more complex settings. Accordingly, we identified the following factors to mainly drive the design objectives of an expressive tactile augmentation tool.

Creating tactile user experiences: The ultimate goal of the expressive tactile interaction design tool is to enable end-user interactions with multisensory tactile environments, mainly focused on creating an aesthetic sensory experience in addition to the visual, as discussed under the expressive roles. The tool design requirements are therefore driven by this fundamental prerequisite, indicating both a visual context as the basis for tactile designs and the interaction support for target users: artists and designers.

Creativity support: The intention to create expressions of a new and less-explored modality implies many unknowns in the design process, including the offered degrees of freedom for manipulating the outcome or the most effective techniques for creating the desired effect. In that respect, compositional and structural constructs may satisfy the essential components of a tactile feature, while behavioral constructs add value to the expressivity of the design or personality of the experience. Nevertheless, the creative process demands a less linear and more open structure for a user interface workflow. Thus, applying the principle of "creative exploration" [Shneiderman 2007], further investigation can evaluate the relative significance of each of the three constructs in supporting the designer needs at implementation.

Scalability: The enabler of expressive tactile interaction design must take into account both the emerging creativity of the designer as well as his or her expertise level as two independent system scalability determinants. However, this does not necessarily mean the need for a larger design space or higher precision over the parameters, but rather can indicate the most preferred tool capabilities and the right degrees of freedom within the design space that guarantee the highest user experience. For instance, a larger number of supported tactile modes (e.g., combination of thermal, vibrotactile) may be preferred over more editable parameters, or the need for distributed effects across multiple artworks or end-users may be more compelling to use, compared to support for complex behavioral constructs. Therefore, tool scalability for designing such creative artifacts needs to be structured with the capacity to support human discovery and innovative design ambitions in either direction, for both simpler and more complex creations.

6.2.2. Techniques. The second aspect of an expressive tactile interface design tool involves the choice of interaction techniques for generating the desired tactile feature in terms of the physical output. Although the low-fidelity design strategy in the current study did not take into account the specifics of interactions for configuring the parameters, each of the constructs implies a variety of input interaction possibilities and mapping mechanisms for generating the output, with specific regards to the expressive context. Here, we discuss two important considerations with respect to this factor.

Interaction strategy: The current approaches to tactile interaction design such as GUI-based or gesture-based techniques [Enriquez and MacLean 2003; Schneider et al. 2015; Panëels et al. 2013; Rantala et al. 2011] demonstrate both the benefits and drawbacks of different levels of directness of manipulation. The limited research done in this area shows that while GUI-based interfaces allow for a wider range of parameter setting, gesture-based techniques propose the possibility of simultaneous manipulation of multiple tactile parameters. Depending on the context of application, configurable degrees of freedom, and intended complexity of the final tactile design, one or a combination of techniques may be deemed more suitable to serve the purpose. Therefore, a tool or system can take advantage of diverse interaction strategies at the input level for an increased space of expressivity that offers maximum flexibility and a full range of options for the designer.

Synergy of input: The supported variety of configurable parameters on the tool often challenges system designers with issues such as menu hierarchy or visibility. At the same time, the current creative context proposes opportunities for taking advantage of alternative interaction techniques to manage such tool design challenges. For example, the design prototypes show form and reference constructs as highly interdependent parameters of the design space, or the repetition construct indicates the need for a simple copy/paste mechanism. Input mechanisms can be designed to allow for natural and efficient manipulation of such integrated parameters while taking into account the open space for freedom of expression. For this particular example, though sketching seems natural to the end-user and appropriate for the visual context, other input techniques may work as well or even better in serving the same purpose.

6.2.3. Processes. Thirdly, the system workflow must be designed in such a way that supports the highly creative design process while offering the system capabilities in an unobtrusive way. As creativity and expressivity are introduced into the context of tactile interface design, choice of workflow and input techniques might be needed to satisfy designer needs. For instance, prioritizing the order of design steps for behavioral, structural, and compositional constructs in the tool design may influence the creativity process and thus the design outcome.

Integrated process: Due to the diversity of styles and design preferences, a generic best workflow cannot be prescribed for the expressive tactile design process. Therefore, while achieving a best workflow design may not be possible or intended at all, the tool must support easy switching between construct configurations so that the creativity process is not compromised. For example, to enable configuration of interactive behaviors such as target and responsiveness, parameters such as end-user distance or specific actions can be set in a simulated environment rather than directly with an external sensing technology, and further configurations of the actual interaction would be postponed to curation time.

Iterative design: Designing expressive tactile features as the product of a creative process requires iterative prototyping. While tactile interaction is inherently physical, the designer needs to go through rounds of self-assessment in order to find the right outcome. Especially with artists and designers as the target users, this requirement becomes even more vital to a successful outcome. Whether GUI-based or gesture-based, the user interface needs to therefore include the tactile hardware component for such iterative design process. At the same time, the tactile interaction design tool needs to support a mechanism to translate the designer inputs into tactile sensory information at the physical level. Thus, interfacing with the hardware layer must be carefully done in such a way as to enable real-time or ad-hoc feedback during the design process.

6.2.4. Evaluation. Evaluation of tactile designs as domain-specific creative products can be quite a challenging and subjective matter to assess. Furthermore, exclusive evaluation of user-generated design products of tactile modality has proven difficult and inconclusive [Obrist et al. 2015]. Nevertheless, objective and subjective perspectives can give a broad understanding of how successful the augmented tactile designs were in achieving their goal. Exploring the literature, three approaches can be proposed for assessing the expressive tactile interaction designs from different angles: evaluation of the tool or mechanism in successfully supporting creation of the desired effects, self-evaluation of the designs, and lastly evaluating the final design products at interaction time externally with end-users.

Creativity support tool evaluation: Recent interdisciplinary works have attempted to bring about a measure to evaluate the ability of a creativity support tool in assisting a user engaged in creative task [Cherry and Latulipe 2014]. Although the metric is mainly designed to compare creativity success across different tools, a customized version can still give insights into strengths and weaknesses of a single tool scenario. Additionally, this method can inspire research to further explore the impact of workflow and interaction design on the creative design outcomes.

Self-evaluation: Even though this method can be regarded quite subjective considering the established design goals we have discussed above, the final physical designs can be compared against both the design goals and the initial conceptual sketches during post-design surveys and interviews. Although satisfaction can be highly influenced by the technological limitations, especially on the output side, this method provides insights on to what extent the final design itself is successful in expressing the designer's intents.

End-user evaluation: Often above the designer's own satisfaction with the outcome, end-user experience can be considered an ultimate goal of the design process. However, in a fine arts context, the aims of design can vary significantly: *Lots of artists say they want the viewer to be affected in this way, or that. But people will do and think what they want whether you like it or not... only some hate, a very few love - and almost all just don't care* [A10]. Consequently, when evaluating a visuotactile design or art piece, one needs to take into account the end-user's preconceptions and any prior experience that might influence their subjective judgment. For instance, in a gallery setting, the interactions may be influenced by the unavoidable noise produced by common tactile technologies, but at the same time, asking the user to wear headphones with pink noise may not be appropriate. Therefore, a careful choice of the evaluation setting, tactile technology, and evaluator's background with respect to tactile interactions and even sensory health are essential to fairer evaluation of visuotactile design outcomes.

6.3. UI Architecture for an Expressive Tactile Augmentation Design Tool

Taking the design implications into consideration, a user interface architecture can be laid out for an expressive tactile augmentation design tool, as shown in Figure 16. The tool supports the functionalities discussed above under tactile constructs and is composed of a main *design module* that interacts with three external modules. The *design module* handles the tactile feature design at two levels and interfaces with the *tactile actuation module*, the tactile device, to enable iterative feedback during the design process. A *sensing module* is integrated with a subset of the interface to

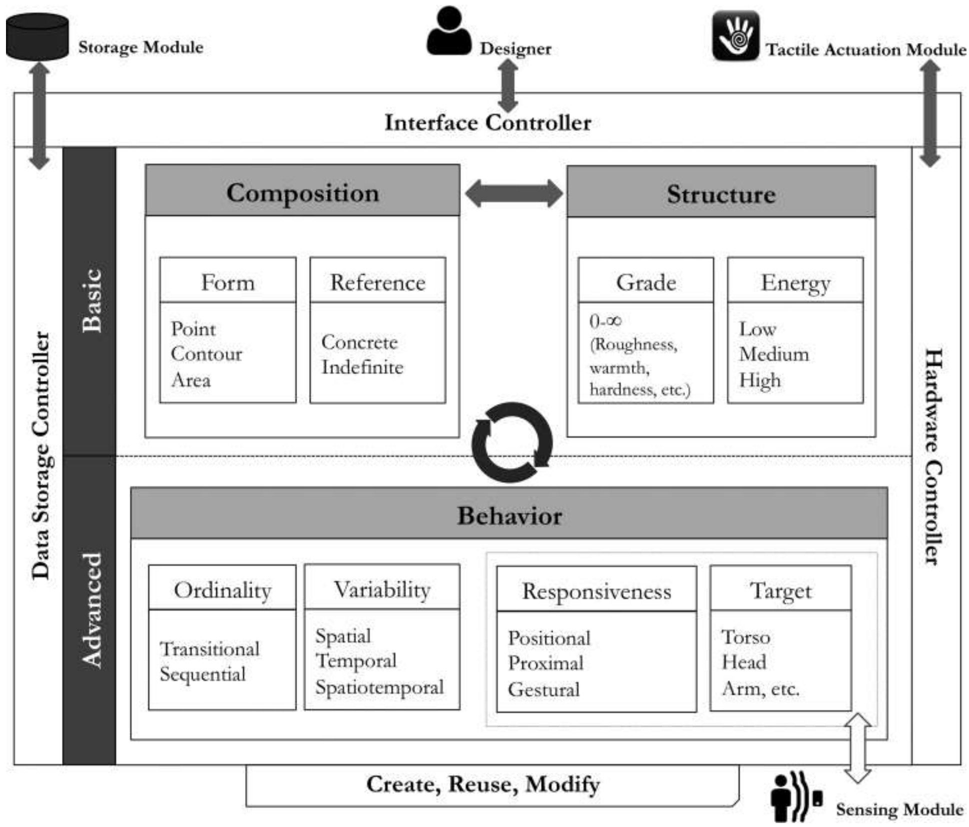


Fig. 16. User interface architecture for a *Tactile Interaction Design Tool*. The tool enables creation, reuse, and modification of tactile features. The *basic* interface components can work independent of the *advanced* layer; the tool actively interacts with the tactile module during iterative prototyping. Active interaction with a motion-sensing module is essential for setting the interactivity behaviors.

support interactive configurations. Finally, a *data storage module* enables reuse and modification of tactile features.

The design module is composed of two layers to support novice and expert use. The *basic* layer provides the essential capabilities for building simple tactile features that include a constant tactile sensation at a particular position in relevance to the visual background. Compositional and structural constructs therefore, constitute the basic layer. The advanced interface layer offers additional functionalities for manipulating more complex tactile attributes, such as spatiotemporal settings, ordinal interrelationships among multiple tactile features, or interactive components that are directly concerned with the user. The four behavioral constructs are thus included in the advanced tactile design layer.

In the basic layer, the two constructs interact with each other in defining the relationships between the tactile sensory attributes and its spatial form factor. While the basis layer can work independent of the advanced layer, the behavioral constructs need to interact with the basic layer to generate the effects. In particular, configuring temporal *variability* requires adding irregularities to the tactile qualities, whereas spatial *variability* requires manipulation of the structural constructs with respect to the form. As well, adding spatiotemporal dynamics means further handling motion-like effects through modifying energy values in time within the compositional constructs.

Ordinality, *responsiveness,* and *target* all occur at high-level interactions with the basic interface layer. *Ordinality* configurations are only defined for multiple tactile features in the same design project, where transitions or sequence of appearance is defined for each feature. In contrast, *responsiveness* and *target* both require more complex handling of reactive behavior with respect to the user's motions or body part. There, a motion-sensing module cooperates with the interface for setting the tactile response accordingly. Computer vision algorithms need to be further integrated with the tool in order to support such interactive capabilities. The tactile actuation module may support real-time or ad-hoc tactile feedback during the design process, which is handled by an integrated hardware interface, while data-storage module formats and stores the tactile parameters for reuse or editing purposes. The tactile features can be later retrieved from the storage for end-user tactile interaction.

The proposed architecture can be used for developing a tactile augmentation design tool for a given visual background, where specifics of the interaction techniques or output tactile capabilities at the front-end can be further determined with regard to the suggested guidelines. Incorporating this architecture in tools with different input types requires adapting the interface controller to offer access to both layers, such as designing input gestures to control the output value of a tactile quality [Rantala et al. 2011]. Additionally, the modules can be highly customized by partial or full implementation of the advanced capabilities. For instance, creating a *variable* tactile feature or adding ordinality among multiple features are relatively simpler advanced capabilities that the tool can support without the need for any additional hardware. The goal of the interface architecture is mainly to introduce a system layout for the design space identified for the expressive multisensory tactile augmentation context. Of course, more research needs to be conducted to further investigate the impact of particular interaction techniques or tactile output device capabilities on the workflows, designer's experience, and the final design artifacts.

7. CONCLUSION AND FUTURE WORKS

Technology advancements and the ubiquity of their use introduce alternative interaction opportunities beyond performance and productivity towards creating novel user experiences with less conventional modes of interaction. In this article, a design-through-research approach was taken to explore the expressive aspects of tactile interfaces under visually augmented multisensory scenarios. The novelty of this work lies within the niche in the context, where tactile interactions are found relevant for augmentation of artistic visual artifacts and a broader space for expressivity can be explored. Additionally, this work can be considered as a primary attempt in collaboratively developing a design space for multisensory tactile interfaces with direct participation and less-biased perspective of traditional visual media professionals. Despite some overlap with previous findings in the construct components, the conclusions from this study provide a systematized view on a new perspective on tactile interaction design with user-experience-oriented focus and in a visual multisensory context.

The creative design sessions with visual artists using the guided design process inspired tactile design ideas for existing graphical artifacts in an open-ended and creative environment. Through empirical evidence, a design space was inspected and meaning-making potentials were investigated for a multisensory expressive tactile interface design. The theory of semiotics as the guiding principle helped systematically organize the prominent aspects of a *tactile expression*. Consequently, a comprehensive analysis of the "form" and "meaning" embedded within each tactile feature were recognized as *tactile constructs* and *tactile intents*, respectively, as the main two components of a tactile expression. To further demonstrate the relevance of the findings to tactile interaction design, a set of *expressive roles* was presented that demonstrate the designer-intended affordances for tactile modality in visual art augmentations. The identified *interactional* and *cognitive* roles can further be evaluated from the end-user perspective. Furthermore, findings from the design sessions together with insights from creativity support tools suggest a set of design implications for future enabler systems that support design of expressive tactile augmentations for visual multisensory environments. Consequently, a user interface architecture was inferred from tactile constructs that describes the various components of a tactile augmentation design tool. The design implications together with the proposed architecture can be utilized as a guide for developing enabler systems for creating expressive visuotactile interactions.

Finally, extending and exploring further into the various aspects of the expressive tactile designs is possible at multiple aspects of this work. In particular, it would be interesting to study tactile designs under variations of the current methodology. As different participants developed their own criteria for selecting the candidate graphical context for tactile creations, it is therefore interesting to study more deeply the criteria for candidate expressive tactile design contexts: *I think what happened is that I tried to think of a piece that maybe I wanted to do something with. Maybe I didn't quite understand, or maybe it wasn't quite finished* (A1). Interesting implications may also emerge from comparing tactile designs as in-process multisensory creations of touch and vision, as opposed to post-process augmentation of existing graphical artifacts. Future research can also look into higher fidelity augmented tactile designs and quantitatively investigate trends or divergences in construct-intent associations, or investigate workflow effectiveness, interaction techniques, or tactile technologies for expressive tactile interface design tools. Lastly, having the end-user experience set as the ultimate goal of this research, studying user interactions with multisensory *visuotactile* artifacts is conceivably an exciting area to explore.

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