Sensorial Interfaces

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ABSTRACT

Sensorial interfaces are based on augmenting existing physical objects with digital information. We propose sensorial activity theory to relate multi-sensory mappings to the context of device physicality and rituals of use. We share a design process for creating *sensorial mappings,* relationships between digital information and sensory information.

We present and analyze some design projects: musicBottles, LumiTouch and comTouch, which illustrate the idea of sensorial interfaces. By utilizing the physical constraints of an object and creating *sensorial mappings* these devices offer novel ways for efficiently interacting with digital information. We believe the principal result enhances the user's sensory experience of the object. Finally, we discuss perspectives and limitations of our sensorial interface design process.

Author Keywords
Sensorial interfaces, tangible user interfaces, sensorial activity theory, sensorial mapping, design research

ACM Classification Keywords
H.5.2 [Information Systems]: Information interfaces and presentation (H.5) (I.7)--User Interfaces (D.2.2, H.1.2. I. 3.6) Evaluation/methodology; Theory and Methods H.5.1 Multimedia Information Systems (evaluation/ methodology)

INTRODUCTION

As technology becomes smaller, and invisible, and computers become more ubiquitous—product designers strive to make information and functionality more easily understood by the general public. The advantage of smaller and faster computing has led to increases in functionality within small devices. One existing solution is to increase the information capacity of display surfaces, by squeezing more information into the pixel space. Meanwhile, the increase of functionality contrasts directly with the decreasing physical volume (see Figure 1). The interaction elements, namely the buttons and overall dimensions of the devices, are getting smaller. However, our physical ability (the size of our hands, and the dexterity of our fingers) to manipulate the explosion of complexity in the interface has remained relatively constant (see Figure 2).

Figure 1. Today's mobile phone (right, the Motorola RAZR from 2004) allows more applications (scheduling, datebook, internet browser) to fit on the phone than its ancestor (left, the Motorola StarTac from 1996), while reducing the size of available interaction elements (keypad areas).

We propose to address the limitations on these interactive surfaces by offloading digital information to other modalities. We present a design method for designing *sensorial mappings*, or multi-sensory mappings, a methodology for incorporating sensory design across physical and digital interaction design. We believe this approach to designing sensorial mappings will enhance device interaction by fostering active discussion on the information flow between sensory channels during the product development process.

A traditional process in product design is to separate the mechanical design from graphical interface design. In general, the product designer is tasked with the aesthetic design of the physical keypads, buttons, and tactile space, while the user interaction (UI) designer is focused on the visual screen space. Although there has been research to examine the quality of interaction by utilizing qualities

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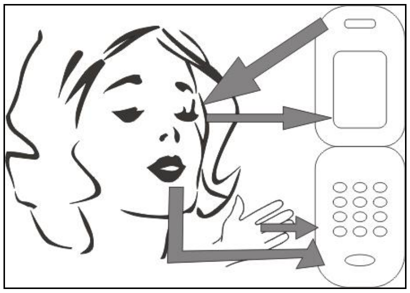

Figure 2. The sensory mapping between a user's senses and a mobile phone. Note that although the amount of information in the handset continues to increase, the sensory channels have remained unchanged.

inherent in the physical embodiment of the device [10], there has been little research examining the design process for multi-sensorial experiences in the context of device interaction.

SENSORIAL INTERFACES

We define a new class of interfaces, called *sensorial interfaces*[1], which articulate information expression across modalities. *Sensorial interfaces* are digital augmentations of *existing* physical objects through the addition of sensory mappings. Designers of these interfaces are less concerned with designing *new* physical forms for manipulation of digital information, but rather, are concerned with expanding the expressive capability of familiar artifacts.

Sensorial interface design results in new mappings within the real world, rather than mappings within a virtual world. As a consequence, the designer must leverage the existing physical and aesthetic constraints provided by the device. The design process of sensorial interfaces relies on three main considerations: understanding the senses, understanding the physical semantics of an object, and understanding the rituals of use of the object. These considerations provide criteria by which to judge designs.

MOTIVATION

We note a trend for interfaces to move toward the creation of innovative platforms, by enabling novel mappings of data to abstract physical forms [14]. These platforms enable users to manipulate large datasets by coupling graphical visualization with physical interaction. While these interfaces have contributed significantly to a vision of HCI where databases and simulations are more intuitive, there has been little done to retroactively upgrade *existing interfaces*. We feel that another perspective on designing interfaces is to couple digital information to sensory stimulation to enhance ordinary physical objects.

Although much prior work in interface design have grasped the importance of incorporating, or maximizing sensory stimulation into device design, we have seen interface designs that sometimes miss the mark of user-friendliness. Other key design criteria are just as important, namely the consideration for usage rituals, interface embodiment, and the appropriateness of the action to the higher-level usage of the artifact. We will revisit these criteria in our discussion of examples of sensorial interface designs from our research in the Tangible Media Group at the MIT Media Lab.

In later parts of this paper, we will present an augmented version of activity theory, *sensorial activity theory*, to engage readers in the process of designing sensorial mappings. We will present a methodology and evaluate some of our own projects in the context of sensorial design criteria. We hope these tools will help to clarify the use of sensorial mappings.

BACKGROUND

Much of our work is influenced by research in both academia and corporate product design. Designers and researchers have been exploring the wealth of available input-output mappings for demonstrating exploratory combinations of various interface modalities [12].

Dunne and Raby's *Bench* object describes benches that map presence to the quality of a shared audio channel to create a sense of virtual presence [9]. In *Virtually Living Together,* Tollmar projected the awareness of remotely located people onto everyday objects[33]. We were particularly attracted to their notion of *sensorialism*, the concept that people utilize sensory channels to meaningfully relate to their environment. The integrated stimulation of our five basic senses: touch, taste, hearing, sight and smell causes our cognition to be more fully engaged[2]. This implies that the overall sensory integration results in a more meaningful, emotional, and personal experience.[28,33] Another mechanism called *Passage* by Streitz, et al, [31] emphasizes the potential digital relevance of everyday physical objects in the workspace, such as a ring, pen, or keychain to store and retrieve digital information. The artistic embodiment of abstract objects, such as scented bowls and floating feathers were used to evoke awareness of a remotely located person [32].

In corporate design, we noticed a similar interest toward exploring the use of sensorialism to represent information. Phillips Design and Research describes the notion of ambient intelligence for *sensorial expression* [1] in tables and community displays. Motorola has developed lighting and vibration-enhanced phones for expressive vibe-light ringtones [8]. We also took special notice of small, mobile embodiments, such as the Kiss Communicator by IDEO,

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[1] *A note on terminology:* We have been asked about the terminology "sensorial" versus using the familiar term "multimodal". From our survey of HCI literature, "multimodal" in the field often implies *audio* augmentation, rather than a full integration of all senses. We prefer the term sensorial, because the subject matter of discussion is about sensory interaction.

Modalities	Relationships	Digital Medium
Vision	Status Change (state changes from off, to standby, different stages of activity)	• Lights, areas • Colors • Temporal effects (flickering) • Text • LCDs, LEDs, other displays
Audition	Directly Proportional (user action parallels digital medium)	• Sound, noise • Music selection • Volume • Number of lights
Touch (haptics and kinesthetic)	Inversely proportional (as user action decreases, digital medium increases… or vice versa)	• textures • manipulations • temperature • kinesthetic, motion • position • shape change • force feedback • vibration
Smell	Additive (persistence)	Smell flavor, intensity
Taste	Temporal (impulse fades with time)	Taste, texture, heat, flavor, intensity

Table 1. Sample Descriptors for Sensorial Mappings

which used the action of kissing an object to display colorful lights on a similar remote object[5].

In our own experience, particularly when evaluating student designs, we found that there were many design cases where the user experience conflicted directly with the digital embodiment. In our yearly class on teaching graduate students tangible interface design, we have begun to realize that this disparity might be due to a lack of guidelines for the *design of sensorial interfaces and experiences*. In order to codify more of our design intent and to foster tangible interface design techniques, we present a sensorial activity methodology, design criteria for evaluation, and discussion of project examples.

SENSORIAL ACTIVITY THEORY

Traditional activity theory breaks down a proposed goal into lower level actions and operations[24,26,29]. Our method of activity theory incorporates a simplified sensory layer, where a *sensory mapping* is described in terms of the operations and actions. Table 1 lists sample elements (modalities, various types of relationships, and digital components) for creating different sensory mappings. By relating the cultural context of artifacts to how the objects stimulate our senses, the designer is explicitly focused on creating consistency between historical usages and user experience.

This sensorial capture of the information flows between the interface and modalities via sensorial mappings help to visualize the flow of sensory information during use, as might be experienced by potential users. For example, a digitally augmented flower vase might map light intensity to be proportional to the amount of water in the vase, while light color could contrast aesthetically to the color of the flowers in the vase. This explicit definition of the relationships between the objects, activity, and user perception help to further define the sensory user experience.

We expect that sensorial mappings will take three basic forms. In addition to sensory perception, the following list describes types of intermodal interactions that can exist among the different senses [16, 36]

- *crossmodal mappings*- where information from one modality is re-represented in another modality. For example, LumiTouch maps touch to light.
- *sensory substitutions*- where information from one modality is off-loaded into another modality.
- *illusory effects*- where information alters perception through the pattern-making ability of our mind. For example, for the tactile phenomena, also called the *cutaneous rabbit*, describes the illusion of movement as a result of patterns of stimulation over an area of the skin [15]. Another example is controlling digital shadows across a projected surface to give the illusion that there is a digital wind.

Three examples of sensory design are discussed below to illustrate sensory mappings.

DESIGN EXAMPLE: MUSICBOTTLES

musicBottles [34] is an interface for accessing digital information. The emphasis for the design is the simplicity of accessing music "stored inside the bottles". There is a metaphor of the object as a container, where the user's action of opening the bottle releases the stored music. The shape of the bottles and tops inform the user on how to access information, relying on mankind's historical interactions with bottles as a way to open a wine bottle or release the smell of perfume.

Figure 3. musicBottles are containers for digital information.

When a user approaches the system, she sees the bottles that are near a platform. The bottles can be picked up, and put onto the platform. When the bottle goes near the surface of the platform, the platform alights to guide the user where to place the bottle. The removal of the stopper plays the music associated with the bottle. Feedback in terms of sound and light intensity correspond to the volume of the audio. The user can put sets of bottles on the platform, and experience the musical pieces (Figure 3). Figure 4 depicts the sensorial activity diagram for musicBottles.

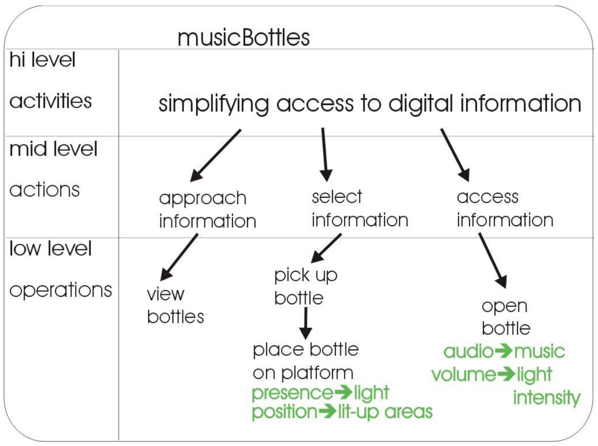

Figure 4. The musicBottles sensorial activity diagram. The sensorial mappings are depicted in green.

DESIGN EXAMPLE: LUMITOUCH

LumiTouch[6] is a system composed of digitally augmented picture frames. The motivation was to bring remote couples closer together by sharing presence and an "always on" connection. The usage scenario was centered on loved ones who work remotely, and designed to support subtle communication as they worked late at night. We envisioned pairs of linked picture frames, to be shared by two remotely located partners (fig 5 shows the concept).

The physical artifact of a picture frame serves as a symbolic link and constant reminder of a particular point in time. This emotionally significant object already exists on a typical office desk, and its higher-level purpose is to serve as an emotional link. We observed that people gaze at and might occasionally pick up the picture of their significant other. Users articulated that they desired to know "Is he/she there? Are they thinking of me?" while considering the other person's picture. This motivation suggested that, by digitally augmenting this artifact, a sensorial mapping could allow these emotional questions to be answered. Figure 6 depicts the sensorial activity diagram.

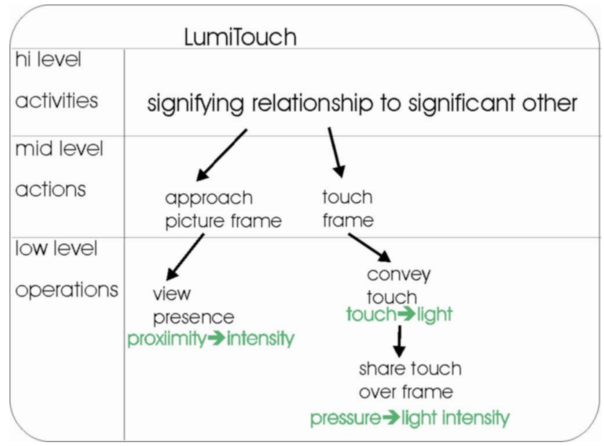

Figure 6. The LumiTouch sensorial activity diagram. There are two different lights to be used, one type for proximity and lights for conveying touch.

We defined two sensory mappings, one for presence, and another for emotional communication. We settled on mapping proximity to light to convey presence and light to touch to signify awareness to the remote person. To give a sense of remote presence, an IR detector sensed the distance between the picture frame and the person in front of it, and mapped that distance to light intensity on the remote frame. The reason for choosing light over other output modalities was based on its ethereal nature, which we felt supported these abstract emotional qualities the picture frames were intended to convey. Touch conveys a personal interaction, and light allows subtlety and ambiguity. The pressure used to touch the object correlates directly with the brightness of the light, while the location of contact on the picture frame determines to the color of the light. Figure 7 shows the sensorial activity diagram with the sensorial augmentation.

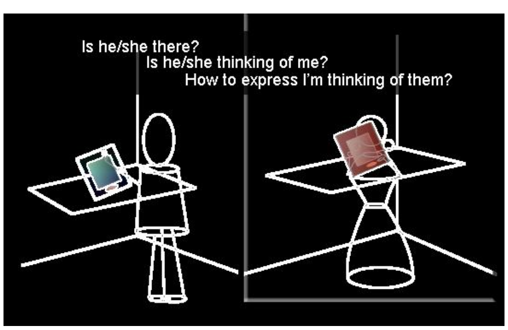

Figure 5. LumiTouch scenario: remote partners communicate presence and goodwill through touch and proximity. The perceived embodiment is a digitally augmented picture frame.

Figure 7. Sensory mapping embodiment for LumiTouch. Then the left user presses, it lights up the other frame. The top left area gives feedback of the color pressed.

DESIGN EXAMPLE: COMTOUCH

ComTouch is a digitally augmented mobile phone concept, where a vibrotactile mapping has been added to allow for a more expressive communication channel [7]. The functional intent of using a mobile phone is to communicate. The sensory augmentation was designed to enhance the expressive capacity between two people on a mobile phone, by the addition of a touch-to-vibration mapping. Figure 8 shows the concept drawing of a mobile phone with extra buttons on the side and back which support this mapping. Figure 9 depicts the touch-to-vibration mapping, while figure 10 shows the sensorial activity diagram for comTouch.

Figure 8. ComTouch adds a tactile communication channel on top of a cellular phone.

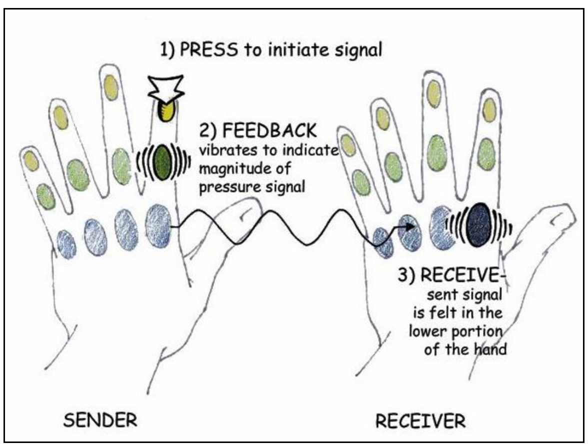

Figure 9. ComTouch touch-to-vibration mapping.

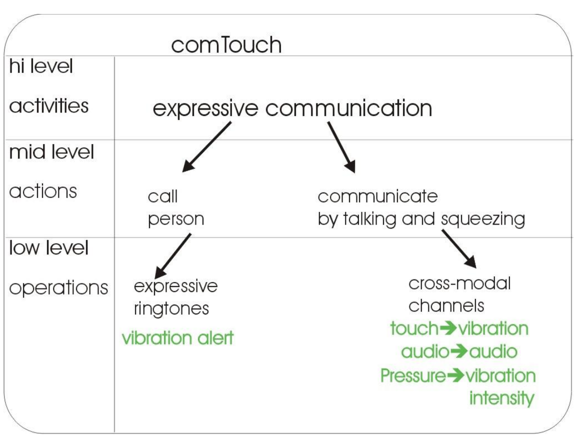

Figure 10. ComTouch sensorial activity diagram.

The design was constrained to the size and power requirements of a handheld object, and the existing usages of mobile communication devices. Special consideration was taken to use the precision grip that we observed people using on current mobile phones. We used pressure sensors under each finger, to allow people a way to squeeze the phone as they talked to each other. The touch pressure under each finger is mapped to vibration intensity. The reason for choosing pressure input was the personal and subtle nature that touch allows, and that the vibration medium allows information to be conveyed in a subtle, private manner. Figure 11 displays the embodiment of the form factor, which were designed to allow users to feel the experience of holding and sending vibrations.

SENSORIAL ACTIVITY THEORY DESIGN CRITERIA

Our focus on sensory interaction makes use of three design criteria to guide sensorial interface design:

1) utilizing the senses (How well does the interface integrate multi-sensory attributes with the higher-level goal of the device?)
2) understanding the usage rituals (How does the user change their actions to interact with the device?)
3) understanding the semantics of physical affordances (When turned off, does the object still convey how it is supposed to be used? Is the object still simple enough to use? Are the planned augmentations subtly integrated into the shape of the object?).

Figure 11. A front and back view of the ComTouch

Utilizing the Senses [Sensorial Mapping]

We have five main senses: vision, audition, touch, taste and smell. Each of our senses is capable of acting on and receiving information from an interface. Defining a sensorial mapping explicitly highlights the flow of information across our senses. By specifying the engagement of our sensory capabilities in the interface, the designer gets closer to the underlying user experience.

Although the digital age has brought about the ability to sense pressure, temperature, and any amount of information, it seems unclear what type of data is appropriate to display. It is now quite easy for interface designers to choose among a variety of mappings for sensory information, mainly in the audio and visual domains. The ergonomic form of the object can inform what type of information should be mapped[13]. When observing the use of a device, it is important to note the higher conceptual reasons why an action is done, the environment in which it is used, and to incorporate any new interactions to be consistent with the known patterns of usage.

Much of our environmental awareness is communicated through the integration of our senses. People often lack awareness of their level of reliance on the integration of their senses in everyday life. To some degree, the sensorial mapping should try to incorporate senses that coincide with the intended aesthetics of the user experience with the objects. For example, a knob might make clicking sounds, depending on whether the user needs to be aware of different states (such as in the igniter on a gas burner) or whether the information flow should be subtle and analog (e.g. frequency knob in a stereo).

Understanding the Rituals [User Actions]

Observing everyday practices is central to designing the experience of sensorial objects. Observational prototyping [5] and ethnography are methods for the study of rituals, allowing researchers to determine how the available "horizon of observation" allows distribution of knowledge in a user's environment, through artifacts, and between humans. People often adapt multiple uses to existing objects, conversely, performing a wide variety of functions with their objects. For example, a pencil is a writing instrument as well as a poking instrument. A pencil can be shared by many people, or used to perform disparate functions for each person. If a sensorial mapping continues to support the known usages of an object, the learning curve of digitally augmented interfaces is lowered[21], and the user will focus on the activity and not the interface.

Many times, the designer of an interface neglects to think about the rich encoding of space in organization, or the relationship of the device to one's body (e.g. arrangements of other objects around a room that are accessible by reaching and pointing). One well known study of the navigation ritual aboard a ship showed the persistent use of old piloting procedures, despite the availability of new technology [21]. The reason for the persistence of these rituals was that *the interactions* themselves represented a system for robust knowledge sharing that new technological systems could not imitate. The ritual of ship navigation allowed people to hand off information and keep abreast of working knowledge. Indeed, it has been reported that technology could not take into account this ad-hoc sharing of information and duty among people [17].

Understanding Affordances [Form and Function]

Understanding affordances means that the shape of the object should inform any new mapping. One part of this clause is determining what objects to digitally augment. The second part of this clause is that designs must leverage the physical information available to the user. If one were to digitally augment a nautilus seashell, perhaps a twisting mechanism, like the kind that exists in a lipstick tube, could be used.

The physical world provides constraints on manipulations, and shapes expectations of common usages. Affordances such as knobs and dials give clues to the usage of the device. When a person presses a button in the elevator, they need to feel a stop in order to realize that they've pressed the button fully.

The set of plausible actions available to the user are based on affordances supported by the object. Simple mappings (e.g. turning the wheel to turn a car a certain direction) seem automatic, and the more they are performed, the better people get at executing these interactions. Hutchins writes about the tools used by a ship's navigator, "A good deal of what needs to be done can be inferred from the structure of the artifacts themselves." An examination of ancient ship navigation tools revealed great examples of form coupled to function. The nomograph allows quick reduction of calculations to a simple gesture. The use of a nomograph provides a quick way to calculate ship speed, by drawing a line across 3 numbers. In contrast, a calculator requires that the user enters digits in serialized manner, while keeping mental track of what data has already been entered.

Detechnologizing is the exercise of considering non-technological methods that inform the technology to be used, removed from any digital enhancements[3]. This perspective highlights the grammar of physical shapes and affordances. What are other non-technical ways to accomplish the same functions? When the power goes out, the shape of the object should still inform the user what actions are available. The point isn't to design technology into the product but to recognize what has to be technical, what can take another form, and make an informed choice based on that. This method relies on determining the object's evolutionary purpose or philosophy, and looking at previously known mediums (e.g. fine arts, environments, social patterns) for embodying similar information. The idea is to transfer familiar design solutions from other disciplines to be re-used in this new interface, and digitize parts of those solutions.

REFLECTIONS ON SENSORIAL INTERFACES

Brief Critique of Example Designs

Sensorialism: Here is a brief evaluation of the sensory design for the three projects described above. In musicBottles, the lighting and color mixing effects are soft transitions, and vary according to the intensity of the audio inside the musicBottles. This audio-visual coincidence draws attention to the musical experience coming out of the bottle. The exhibitionist display of musicBottles can be compared by the silent and ethereal correlation of abstracting touch as light in LumiTouch enhances the emotional significance of the object. LumiTouch uses the expressive range of touch to control light, allowing subtle expression without distracting the remote partner. Even more secretive is the comTouch, where the absence of light and reliance on touch as the sole sensory modality is designed to make the communication more private.

*Rituals:*An assessment of the rituals of our example projects reveals that the sensory mappings alter the rituals to differing degrees. Although opening the bottles is quite intuitive, musicBottles users are required to put the musicBottles on the special platform. Exhibition demonstrators are conditioned to keep the bottles on the lighted platform, so that the bottles remain lit up. The LumiTouch's buttons give visual cue to users on where to touch the LumiTouch. People end up touching the frames more often than they would normally touch their desktop picture frames, to express their emotions. Some users developed an affinity for passive communication (using only the proximity sensor), and some users often expressed only a light touch could be easily overlooked. ComTouch supported the ritual of physical movement during speech and people were seen to squeeze and talk quite naturally. Instead of focusing on the interface, users exhibited audio conversation similar to normal speech. The audio was interspersed with tactile gestures (emphasis, turn-taking and mimicry) which seemed to suggest that the tactile augmentation was easily incorporated by users.. We found it encouraging that new usages could arise from these simple digital augmentations.

Affordances: Finally, a critique of how well our projects match aesthetic form to digital function suggests that consistent sensorial interfaces are a challenge to design. The constraints of reality, it seems, can be just as challenging as designing for the virtual world[23].

The sensual shape of the untethered musicBottles and the illumination from the table succeed in focusing the user on the bottles as an aesthetically pleasing interface. This intense focus of the bottles, where the only affordance available to the user is that the stopper can be pulled, gives a natural indication that the user should pull to activate the experience. One problem with the implementation, however, is that the other manipulations people expect from bottles (such as pouring and shaking) are not supported by the system.

The LumiTouch are unmistakable as picture frames. It seemed the picture frames were a natural choice for supporting intimacy and served well as physical links to remote people [27, 32, 33].Visual cues also help delineate the pressure sensitive areas around the LumiTouch picture frame, informing the user where to squeeze. It takes a few moments before users grasp the mapping between location and color, and a brief explanation of the remote connection is required.

The comTouch phone grip provided a clear affordance on where to grab. However, the design of the comTouch concept was flawed due to the conflicting functions between holding the device and pressing the thumb and lesser finger buttons (see Figure 12). Furthermore, the multitude of visual cues confused users. It would have been clearer to highlight only the pressure sensitive regions, rather than highlighting the remote and local feedback areas.

As the examples illustrate, matching physical form to digital function results in a design tradeoff between usability and revealing functionality to the user. New shape grammars may cause confusion, but changes to existing interfaces may challenge user expectations. For example, when telephones were upgraded from the rotary dial to pushbuttons, people had to relearn the mappings of position to number.

Figure 12. Problem with grip. The user may inadvertently squeeze the buttons while simply holding the phone.

Evaluation of Sensorial Activity Theory

Our process of sensorial activity theory design provides a simple technique for opening up a dialogue about sensorial information flow. We feel that a natural application domain is the mobile telecommunication space. In this domain, there are opportunities for sensorial mappings to combat physical device limitations discussed earlier. For example, observations on the mobile phone usage where an audio-haptic multi-sensory effect was available resulted in better perception of the interface[8]. The small size constraints of a mobile phone provide a challenging application domain, where augmenting the outside embodiment of the interface may improve usability through offloading information to other modalities[7]. The addition of sensorial mappings can potentially create new communication experiences.

Although our method might not be well suited for designing novel forms, we can expand this method to apply to many other areas of HCI and product design. One potentially viable place for sensorial interface design is in mobile devices or gaming. Another area where sensorial mappings can help is in ambient device design, in understanding how to present control sensorial information flow for an ambient system.

Awareness is another HCI domain where we can see sensorial activity theory contributing new perspectives. We were inspired by the traces of presence described by Hill as one way to map usage history to vision [20], and wondered whether could be equally useful aesthetic mappings to other modalities, such as temperature or physical movement. For example, in the design of real-time groupware, explicit mappings of awareness to background noise or shared awareness of screen movement helped remote users collaborate effectively in shared workspaces[19].

Comparison to Other Design Methods

We are not suggesting that sensorial activity method is a replacement for existing design methods. In fact, our method was influenced by many other existing design methodologies[31], which deal with equally important topics, such as context[4], visualization[22], and frameworks[18]. Instead, we view this tool as a way to frame the design discussion around the user's sensory experience.

Designing an interface still requires sketching and storyboarding techniques to describe **experience scenarios**. In sketches, it is common to describe the relation of the user to an action, and the resulting experience. Typically, a UI designer will write "select recipient, push button, send message". A product designer might re-represent this, "user grasps the device, pushes a button at the back of the device, the photo album plays" to describe a digital picture frame product. With sensorial activity theory, the two can discuss whether the pushbutton results in a UI sound or light flash, or discuss the mapping of the button placement for navigation around the shape of the picture frame.

Other design techniques we employ frequently are to consider the **metaphors of use**. Metaphors help users package the properties inherent in the object. For example, the metaphor of a desktop can help users transfer ideas about organizing and selecting files to relationships in the virtual world. Metaphors can fail when the interface neglects certain expectations (such as pouring the bottles), or becomes more complex than the metaphor (such as dealing with nested files structures in a desktop). Metaphors, though greatly simplified in scope for the purpose of explaining the concept, give users a template of how to think about and interact with an object. By drawing analogies to familiar concepts, metaphors guide users to transfer their existing interaction techniques to new interfaces.

Issues surrounding Sensorial Design

The main research questions surrounding sensorial design are concerned with the design of sensorial mappings. Sensorial mappings can be too varied, too ambiguous, or unintuitive. A main issue we have avoided is suggesting that there is a constrained set of solutions for sensorial mappings, or defining what the resolution of the information will be. We feel that ambiguities in describing these design choices are acceptable, and we leave it up to designers to discuss. By creating new mappings, we firmly believe that many new types of interaction can arise.

We do not find it a problem that many mappings are possible or that there may be a combinatorial explosion of sensorial mappings. Furthermore, Sensorial Activity Theory does not intend to limit the range of possible designs to only those that are consistent with the design criteria. We believe firmly that designers should have creative license, even to design against the suggested criteria.

The design language of our familiar objects may break down as modes of use allow people to produce their own artifacts. Indeed, as methods of production and access to digital creation tools become more accessible to designers, we expect that the design language of objects may become diluted. Personal objects might take on many more different shapes, with personalized mappings and affordances. Already we see that there is a growing trend of customization in our culture, where ordinary consumers are expressing their identities by personalizing their devices, clothing, and environments, or mimicking other's expressions on inanimate objects.

We expect a great discussion on how the existing design language of sensorial interfaces may evolve, and how cultures may adapt new technologies overnight. We wonder if the possible mappings will eventually result in mass confusion. "What if I sit down at your phone interface, and I don't know how to call anyone?" Perhaps, like in the picture frame example of symbolizing remote people, device designers will converge on functional shape grammars.

Another concern is possible sensory over-stimulation adding to user annoyance or frustration. If our design criteria are considered seriously, then creating digital-sensory information flow across modalities would allow the designer to explore more seriously the contributions of information presented to each modality. Sensory redundancy can allow for subtlety, as multi-sensory signal changes can allow designers to move information across modalities and between background and foreground. The resulting de-emphasis on any one modality could foster alternative designs of a user's peripheral awareness. We agree, however, that restraint to avoid sensory deluges is necessary.

Finally, to be substantiated is the claim that sensorial interfaces result in better products. Although in popular literature [20], this is implied, it is imperative to assess the influence of a digital augmentation. A designer might have intended the augmentation to blend seamlessly into the user's rituals, but it is usually the case that there is a certain degree of change. In some cases people have come up with new, unexpected usages for an object. Because evaluating existing products is fairly common, we can expect to use techniques that assess product usability and aesthetics, such as observational prototyping, to shed light on evaluating these interfaces[11, 30].

CONCLUSION

We have presented our method of designing *sensorial interfaces*, a type of reality-based interface that leverages the real-world physical cues of existing objects. We have introduced sensorial activity theory, the idea of considering the context of the object's usage, form, and sensory stimulation for designing sensorial experiences. We have presented some examples of sensorial interfaces and appraised the designs using socio-historical contexts (affordances, rituals, and sensory stimulation). Finally, we have discussed the tradeoffs and limitations of concern when designing sensorial interfaces.

We encourage the use of sensorial activity theory to raise awareness of the richness of sensory stimulation possible when designing digitally augmented objects. Our proposed method is intended to open up dialogue on designing sensorial experiences, which can result in better user experience. We hope the ideas presented in this paper help others design and research sensorial objects, and influence cooperative digital and physical aesthetics in product development processes.

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REFERENCES

1. Aarts, E. and Marzano, S. *The new everyday, Views on Ambient Intelligence.* 010 Publishers, Rotterdam, NL 2003.
2. Ackerman, D. A Natural History of the Senses.
3. Angelsleva, J. and Parkes, A. Personal Communication Dec. 13, 2005.
4. Bellotti V, Back M, W. Edwards K, Grinter R.E., Henderson A., Lopes C, Making sense of sensing systems: five questions for designers and researchers. In *Proceedings of the CHI2002*, ACM Press, pp 415-422.
5. Buchenau, M., Fulton, J. 2000. Experience Prototyping. *Symposium on Designing Interactive Systems (DIS'00)*, ACM Press (200), 424-433.
6. Chang, A., Koerner, B., Resner, B., Wang, X. LumiTouch: An Emotional Communication Device. *Extended Abstracts of Conf. on Human Factors in Computing Systems (CHI '02)*, ACM Press(2002), 313-314.
7. Chang, A., O'Modhrain, S., Jacob, R.J.K., Gunther, E., and Ishii, H. comTouch: Design of a Vibrotactile Communication Device. In *Proceedings of Designing Interactive Systems* (DIS '02), ACM Press(2002) 312-320.
8. Chang, A. and O'Sullivan, C. Audio-Haptic Feedback in Mobile Phones. In the *Extended Abstracts of CHI 2005*, ACM Press(2005), 1264 – 1267.
9. Dunne, A, and Raby, E Fields and Thresholds, presented at Doors of Perception Conference (Amsterdam, Netherlands Nov 1994). http://www.mediamatic,nl/Deors/Doors2/DunRab/DunRab-Doers2-E3.html
10. Fishkin, K., Gujar, A., Harrison, B., Moran, T., & Want, R. (2000). Embodied user interfaces for really direct manipulation. *Communications of the ACM*, 43(9). p. 75-80.
11. Frankenberger, E., Badke-Schaub, P. and Birkhofer, H. (editors), 1998, Designers—The Key to Successful Product Development (Berlin: Springer-Verlag).
12. Djajadiningrat, T., Wensveen, S., Frens, J., Overbeek, K. (2004). Tangible products: redressing the balance between appearance and action. Personal and Ubiquitous Computing 8(5), 294-309.
13. Gaver, B.: Provocative awareness. *CSCW 11* (3-4), 2002, 475-493.
14. Gaver, B. Technology affordances, In *Proceedings of the CHI 1991*, ACM Press(1991),79-84.
15. Geldard, F., and Sherrick, C., The cutaneous rabbit: A perceptual illusion, *Science*, *178*, 1972, 178-179.
16. B. Goldstein. *Sensation and Perception (5th Edition)*. Brooks/Cole, New York,1999.
17. Grudin, J. 1994. Groupware and social dynamics: Eight challenges for developers. *Commun.ACM 37, 1* (Jan. 1994), 92–105.
18. Gutwin, C., Greenberg, S. A Descriptive Framework of Workspace Awareness for Real-Time Groupware,

Computer Supported Cooperative Work 11, 3(2002), 411-446

19. Gutwin, C., & Greenberg, S. (1998). Design for individuals, Design for groups: Trade-offs between power and workspace awareness. In *Proceedings of CSCW96 Conference on Computer Supported Cooperative Work*, ACM Press (1998), 207-216.
20. Hill,W., Hollan, J.D., Wroblewski, D., and McCandless, T., Edit wear and read wear, *Proc. of the CHI'92*, ACM Press (1992), 3-9.
21. Hutchins, E. "The Technology of Team Navigation," in *Intellectual Teamwork: Social and Technological Foundations of Cooperative Work*, J. Galegher, R. Kraut, and C. Egido (Eds.), Lawrence Erlbaum Associates, Hillsdale, NJ, 1990. 191-220.
22. Ishii, H., Ratti, C., Piper, B., Wang, Y., Biderman, A., Ben-Joseph, E., Bringing Clay and Sand into Digital Design— Continuous Tangible user Interfaces. In *BT technology journal 22,* 49(2004) 287-299.
23. Jacobs, R. Reality Based Interfaces class, taught in fall at Tufts University, Medford, MA 2005. Class website http://www.cs.tufts.edu/courses/description/COMP/0250-RBI
24. Kaptelinin, V. (1996). "Activity theory: Implications for human-computer interaction." In Nardi, B. A. (Ed.), *Context and consciousness: Activity theory and human-computer interaction,* 103-116. The MIT Press (1996), Massachusetts,USA.
25. Kelly, T. and Littman, J. *The Art of Innovation*. Doubleday, New York, 2000.
26. Kuutti, K., (1996) "Activity Theory as a Potential Framework for Human-Computer Interaction Research." In Nardi, B.A., (Ed) *Context and Consciousness: Activity Theory and Human-Computer Interaction*, MIT (1996), Massachusetts, USA.
27. Landay, J. Digital Simplicity, colloquium talk at the MIT Media Lab, Oct. 20, 2005.
28. McDonagh,D., Hekkert, D. Van Erp, J. and Gyi, D. *Design and Emotion: The Experience of Everyday Things* (Hardcover). p.234-235.
29. Nardi, B. A. (Ed.), *Context and consciousness: Activity theory and human-computer interaction,* The MIT Press (1996), Cambridge, MA: USA.
30. Norman,D.A. 1989. *The Design of Everyday Things*. Currency-Doubleday, New York, 1989.
31. Streitz, N.A., Tandler, P., Müller-Tomfelde, C., Konomi, S. Roomware: Towards the Next Generation of Human-Computer Interaction based on an Integrated Design of Real and Virtual Worlds. In: J. A. Carroll (Ed.): *Human-Computer Interaction in the New Millennium*, Addison Wesley(2001) 553–578.
32. Strong, R., & Gaver, B. Feather, Scent and Shaker: Supporting Simple Intimacy. In *Proceedings of Conference on Computer Supported Cooperative Work (CSCW '96)*, ACM Press(1996), New York, NY, 29-30.
33. Tollmar K., Junestrand S. and Torgny O. Virtually Living Together - Using Multiple-Method Design in the Search for Telematic Emotional Communication. *Proceedings of Designing Interactive Systems (DIS'00)*, ACM Press (2000), 83-91.
34. Ullmer, B., and Ishii, H. Emerging Frameworks for Tangible User Interfaces. *IBM Systems Journal 393, 3*, 2000, 915-931.
35. Wensveen, S., Overbeeke, K. , Djajadiningrat, T. Touch me, hit me and I know how you feel: a design approach to emotionally rich interaction, *Proceedings of the conference on Designing interactive systems: processes, practices, methods, and techniques*, ACM Press(200), 48-52.
36. Woods, A.T., O'Modhrain, S. and Newell, F.N. (2003). Temporal factors in the sharing of cross-modal information. Proceedings of the 2003 EuroHaptics conference. http://www.eurohaptics.vision.ee.ethz.ch/2003/58.pdf