Foundations of Transparency in Tactile Information Design

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Abstract—This paper places contemporary literature on the topic of unimodal single-site display of information using complex tactile signals in the context of progress toward *transparent communication*—placing minimal load on the user's attentional resources. We discuss recent evidence that more is possible with purely haptic display than is commonly believed, as well as procedural developments that support systematic design of transparent tactile information display, and we frame the advances required to realize significant benefits with the technology we have now. Examples used and objectives thus identified focus on establishing effective information representations and outlining efficient tools and processes for perceptually guiding icon design.
Our discussion is inspired by Weiser's vision of *calm technology* based on locatedness and seamless movement between the center and the periphery, and it is organized along the lines of potential utility, form, and learning.

Index Terms—Haptic I/O, human information processing, input devices and strategies, user-centered design.

1 Introduction

We live in a world where our access to information is unprecedented and growing, while human ability to process and absorb it remains static. The use of computation to search, organize, and provide individualized access to this vast space proceeds apace. But too often, the result is interruptions, tiny crowded screens, distracting animations and endless choices [33].

Through both taction and proprioception, the haptic channel has an important role to play in a new generation of *transparent interfaces*, which will convey information as it is needed or desired without overwhelming the user's mental resources. Designing for transparency means considering the user's reality of divided attention and multiple uncoordinated information sources. Displays must convey data abstractions haptically in a way that places little burden on sensory and cognitive resources, and requires a user's attention only when appropriate; but must balance these needs with available display technology. A systematic theory of interaction design, targeted at information display, is needed.

This paper aims to place contemporary literature on the topic of unimodal single-site *tactile* information design in the context of progress toward this ideal. Much of the present discussion applies to information sensed both through taction and proprioception, and to their integration with motor responses; these points will be indicated with the term "haptic." *Taction* is a practical place to enter the larger space of haptic information design: displays must be miniature, portable, and low power, and currently, this is harder to achieve when displaying forces. We focus on *unimodal* rather than multimodally reinforced display of information-rich signals to address the many environments and tasks where multimodal signals are inappropriate or unavailable and to ascertain performance achievable through the haptic sense alone.

Finally, we summarize the foundations that exist for systematic design of transparent tactile information display, and frame the advances required to realize significant benefits in terms of Weiser and Brown's notion of "calm design" [59]. Examples used and objectives thus identified focus on establishing effective *information representations* and efficient *tools and processes for perceptually guiding icon design*.

Because tactile information displays are likely to be most useful in attentionally divided environments, we cannot assume that they will resist the effects of critical workload situations; "stress testing" must be built into the design process. Due to space limits, we can deal with this critical topic only peripherally here.

1.1 How Can Haptics Help, and Why Is It Hard?

Mobile devices, often held or carried in close bodily contact, present the opportunity for signals delivered as tactor waveforms, by a vibrating screen felt through a stylus or by high-frequency excitation of a force-feedback knob, with control over parameters such as frequency content and amplitude. Fig. 1 illustrates the variety of mechanisms constructed for our group's research alone.

The demand for usable tactile signals is clear. Cell phone manufacturers have attempted to move beyond binary vibratory notification of incoming calls to encode more information in tactile signals or to use clicks and whirrs to help navigate through the complex virtual spaces accessed by these handheld windows. But the display capacity of devices on the market is still quite low.

The challenges are threefold: inadequate technology, a difficult operational environment, and unexamined design techniques that do not take the former into account. The

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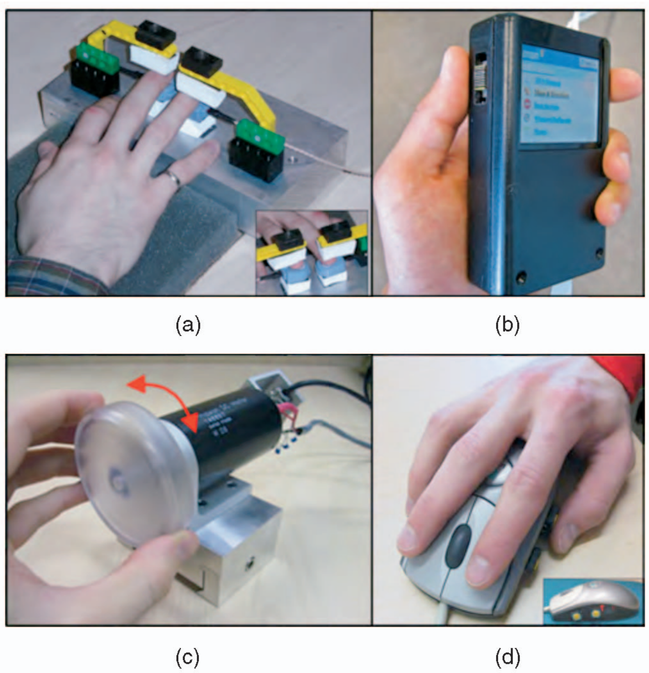


Fig. 1. Examples of research prototypes designed to deliver informative haptic signals, described in (a) [16] and [17], (b) [39] and [44], (c) [41]

technology in most commodity mobile devices has limited expressiveness, capable of binary vibration or a few distinct levels. Richer feedback—more perceivable dimensions, dynamic range, and fine control—impact quantity and clarity of information. Summaries of recent progress, as well as specification of what is needed, can be found in [25], [26], [34], [40], and [42], but for now, the palette is restricted.

Target use environments tend to be complex, unpredictable, disrupted, and multimodal. Whether driving, walking, listening to music, collaborating with others or laboring away in a quiet room on a conventional computer workstation, there are numerous sources of interruptions and parallel threads of activity ready to demand and engage our attention through all our sensory channels. Any additional signals must both compete when needed and not simply add to the cacophony.

Hence, design cannot be ad hoc. Designers need heuristics and evolved user expectations for abstract information transmission. We need tools for quickly generating and perceptually comparing prototype signals and (out of our present scope) methodologies for evaluating candidates in realistic simulations of anticipated environmental stressors.

1.2 Need for a Multifaceted Approach

Any interface design should reflect both specific application contexts and general human capabilities, and this is especially true in haptics where assistance often takes a novel form. These are studied in different ways, e.g., with:

1. *Situated observation.* Qualitative and self-report methods capture user needs, coping mechanisms, and the uptake of the proposed technological interventions in realistic but loosely or uncontrolled situations.
2. *Controlled user studies.* Quantitative examination of specific human abilities are often triggered by questions revealed through the qualitative methods of situated observation.
3. *Tool building.* Practicality demands streamlined mechanisms for creating perceptually and cognitively usable signals and integrating them into applications, such as those that exist for many audio and graphical areas.

Controlled and observational user studies operate under different philosophies. The first are driven by statistically provable hypotheses, and the second by qualitative methods. The combination is powerful. Qualitative and well-simulated contextual research is essential both for framing relevant needs-driven quantitative issues and to highlight practical significance. This paper illustrates how all three techniques can be interweaved.

The remainder is organized around some key questions:

- UTILITY: Where and how will haptic signals be useful?
- FORM: What should the underlying stimuli be, and how should they be created?
- LEARNING: How are icons most easily acquired, and what limits or constraints pertain?

2 UTILITY: WHERE WILL SIGNALS BE USEFUL?

This section lays out our reference points. We begin by examining basic design goals, in search of a standard by which to make decisions and measure progress. A case-study summary then provides an example of how deployed informative haptic signaling might look, be developed, and be evaluated. Finally, we extract heuristics and general possibilities for application design.

2.1 Resource Efficiency versus Calm Design

There are two ways of coming at the question of value potential for haptically communicated information. The most commonly argued is design based on maximization of *resource efficiency.* As we reach the limits of other mental resources (e.g., when vision and audition are saturated or unavailable), touch is available for "offloading." This view is enticing but risky. Sensory perception is just one step in the processing pipeline; downstream constrictions occur in attention, cognition, and response, with Multiple Resource Theory providing one model [60], [20], [48]. If the context is already demanding, another means of grabbing attention is not likely to help overall. There are nonetheless important opportunities for design that adequately consider context, for example in mobile communications. Sometimes touch is simply the most appropriate, seamless, and least disruptive delivery channel.

But is our need to supply *more* information or, rather, to supply it *in a manner* that leaves the user relaxed and in control? Very often, the problem is not insufficient display volume but, rather, the stress and inefficiency associated with too much and the need to continually and explicitly switch contexts in order to process it [33].

Over a decade ago, Weiser and Brown [59] described a "calm technology" as one that "moves easily from the periphery of our attention, to the center, and back," drawing on the premise that our brains have more capacity for peripheral than for central processing. We can attune to more things when they are in the periphery; if something in the periphery is easily moved to the center, we can more easily and *transparently* take control of it. Weiser envisioned interfaces that are "filled with details yet engage our pre-attentive periphery so we are never surprised .... This connection to the world we call "*locatedness*"." There is little evidence of calm technology today outside of human-computer interaction research laboratories.

Locatedness cannot occur without transparency (i.e., requiring only peripheral awareness). Low attentional demand may thus be a clue by which locatedness can be measured and hence designed for. Transparency is *how* the information is displayed, while locatedness is the gist or gestalt awareness that the perception produces.

This brings us back to tactile display. While calming interfaces are clearly holistic and cannot be assembled one modality at a time, we can nevertheless progress by discovering how tactile display (alone) can help us to *locate*, with unintrusive accessible use of the periphery, and by exploring mechanisms for moving seamlessly between the periphery and the center—the possibilities afforded to a user when action is needed.

2.2 Example: Turntaking in Remote Collaboration

An example will ground these goals. To illustrate several principles discussed throughout, we summarize the prototyping and observational evaluation of an iterative user-centered process for icon design and deployment to address a known need (more fully described in [10] and [11]).

Users collaborating remotely using a single-user shared application require a mechanism by which to determine who has cursor control; yet, existing turntaking protocols are impoverished in social cues. In distributed remote collaboration, the primary task generally monopolizes both graphical and vocal/auditory channels. Thus, while information about turntaking mediation can be communicated with graphics and/or sound, this tends to either be intrusive or easily missed as groups grow beyond two or three.

We aimed to channel background information about the task (collaborators' wish to contribute) more appropriately. The use of a task-focused modality ensures that *any* awareness of the turn-request queue has a perceptual and attentional cost; to solve this by conveying only action-demanding requests introduces surprises and forgoes the opportunity for natural and timely passing of control. We hoped to improve *locatedness* by continuously but unintrusively conveying the request queue state via taction, and that an icon set that varied in intrusiveness would enable *seamless movement between the periphery and the center*, driven by request urgency (see also [37] on the value of graded tactile alerts).

Our custom turntaking protocol allowed users to express urgency in a request for control from a collaborator using a custom button on a commodity vibrotactile mouse (Fig. 1c); the status and requests could be communicated via tactile signals or visually. Two-second stimuli were created around gradable metaphors: for the control holder, it is a beating heart to indicate queue length; for the one waiting, it is a tapping foot. Changes of control alluded to the two-frequency auditory signal for computer peripheral insertion/removal—ba-BEEP, BA-beep.

We used four steps in our process: initial icon set design, perceptual refinement, validation of learnability and effectiveness under workload, and observed deployment in a realistic simulation of the actual context. The result of perceptual refinement and stress testing (elaborated below) was that this set of seven icons was learned to 97 percent accuracy in less than 3 minutes and remained identifiable under significant cognitive workload. This implied low perceptual and cognitive effort and suggested that non-attentive processing should be attainable for this small set.

The fourth step was an exploratory observational study that compared tactile, visual, and tactile/visual support for our protocol for four groups of four collaborators. Availability of tactilely communicated state impacted collaboration dynamics favorably, based on metrics such as equitability of time in control and control-turnover rates. Participants overall preferred combined multimodal support and, in particular, preferred tactile support for control changes and visual support for displaying details of the state that could not be displayed tactilely (e.g., identity of a requestor). They did not find the icons intrusive.

Were users more relaxed and in control? In their negotiation, clear utilization by both control holders and requestors of the option of graded-urgency requests suggests their valuation of locatedness (ability to make or be aware of requests that need a "when you're ready" rather than "right now!" response) and/or seamless movement between the periphery and the center (the most salient icons could always capture attention). Was it due to the use of the tactile channel or simply the protocol? These qualities are inextricable: by their sensory nature, the visual and tactile communications of urgency and state manifested differently and provided different utilities. Tactile cues could be in the background, whereas visual cues *had* to interrupt. Thus, users could process tactile cues with less mental effort, but visual cues could provide more information. Multimodal support was therefore valued, in the sense of *different* but complementary information available through the most appropriate channel.

2.3 Benefits, Barriers, and Needs for Deployment

From the foregoing example and others to come, we extract several points:

1. Principled perceptual design of haptic icon sets *can* allow appropriate background processing—with low effort and desired level of attention.
2. Haptic icons *can* provide unintrusive locatedness for a background state and at least part of a mechanism for periphery-center movement.
3. They must also connect the user easily to an action or follow-up, which might be best accomplished by handoff to a process with greater information capacity.
4. We need more direct methods to assess the relative contribution of inherently different communication modalities.

We are not aware of other deployments of *complex* tactile signals that went this far, which limits sweeping conclusions. Luk et al. provide a mobile scenario analysis backed up with perceptual characterization of a novel display (Fig. 1b) to inform appropriate design [39]; Leung et al. obtained similar results for stylus-delivered vibrotactile fixtures and alerts on a handheld tactile display, noting the potential for confusion in alert source when the user is using the stylus for another task [38]. Conversely, there has been situated evaluation of spatially distributed tactile displays for orienting visual attention (e.g., in driving or flying). Spatial displays are out of our scope, but it is fruitful to mine this literature for relevant methodology, particularly with respect to simulating and measuring distractions, e.g., semicontrolled real driving [57] and abstracted simulations [15], [27].

In addition to the need for thorough situational modeling, understanding of mental resources, and signal design, these application opportunities highlight the criticality of appropriate hardware. In the burgeoning mobile application area, there is recent hardware innovation [32], [35], [44], [46]. However, requirements abound: needs for access to delivery sites with adequate tactile sensitivity, for timely or even continuous physical contact, for portable and power-efficient designs, and for rich high-dynamic-range signals [20] are inadequately served by current tactile display technology and interaction paradigms [40], [42].

3 FORM: What Should the Stimuli Be?

Haptic icons are haptic stimuli to which meanings have been associated. The stimuli can be tactile, or proprioceptively sensed. At a general level, we use the terminology of "icons" regardless of depictive/abstracted nature, following common practice for computer graphic symbols (e.g., [1]). The concept of the haptic icon *set* is central; this is even more true than for their graphical or auditory counterparts, due to lower expressiveness. A set must have several properties to be usable. The most critical of these are *stimulus distinguishability*, *icon learnability*, *salience management*, and *recognizability* in realistic conditions.

How do we create such sets? We do not yet have heuristics of sufficient reliability and generality to broadly inform design. A set that works well for one display or application will not necessarily translate to other domains; user bases (e.g., young, elderly, blind, and expert in Morse code) often have different acuity or experience. Satisfying these essential properties currently involves iterative user-centered procedures [40].

In this section, we outline basic representational approaches, summarize progress on icon design tools and procedures in support of *perceptual design*, as well as performance actually achieved using these methods. Finally, we highlight specific needs for further advances.

3.1 Representational Approaches and Implications

Early auditory information design articulated a continuum of directness versus abstraction in stimulus-meaning relationship that, in the terminology of Blattner et al., is bounded by *abstract* (a.k.a. *symbolic* or *nomic*) at one end and *representational* (*iconic*) at the other, with *semiabstract* representations lying in between (Fig. 2) [1], [21]. *Abstract* content provides a largely arbitrary representation of the information, which must be learned or inferred. This encompasses many aspects of written or spoken language

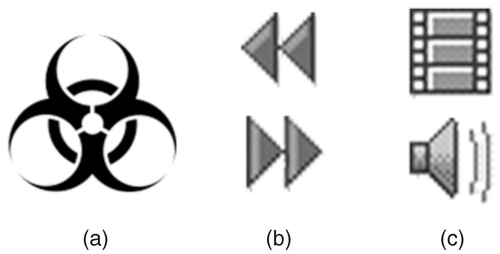


Fig. 2. Graphical representations spanning the abstract/representative continuum. (a) *Abstract:* the biohazard graphic "is entirely designated by convention, and it represents no specific object" [61]. (b) *Semi-abstract:* media control arrows suggest the result of pressing them but in an abstracted way. (c) *Representational:* "movie" and "sound" images depict the media itself.

and culturally dependent graphics. In *representational* relationships, one object depicts another; the former aims for an accurate reconstruction of a specific sensory experience—motion picture films, recorded music, cartoons, the magnifying-glass "search" button on a computer desktop, and force or tactile surgical simulations. In between, mappings capture a relevant possibly metaphorical similarity between the source and the sign without the need for precision or completeness. Possibilities include dimensional metaphor (one dimension describes another), and features that imply a whole. Semiabstract representational structures like Earcons [1] can be efficiently (in a space complexity sense) compounded through combination, inheritance, and transformation.

Learnability. Gaver [21] notes that this abstract-representational continuum is aligned with Hitchins et al.'s concept of *articulatory directness* or the immediate obviousness of the link [31]. Once understood, a mapping with greater articulatory directness should in theory be easier to learn, and for novice or infrequent use, it is a necessity. But directness comes with problems, also summarized in [1]. Less concrete concepts are difficult to render, and even in a richly dimensioned graphical or auditory domain, it is hard to find consistent, simple, but clear portrayals as a set grows. This is the case with the American Sign Language, which is rich with gesture and where signs have been categorized as *transparent*, *translucent*, or *opaque* [36]. As the attempt falters, the user experience moves toward abstract, and learning becomes dominated by perceivable differences between the images themselves, rather than the logic of the relationship. In synthetic haptic display where we might have only a few bits of data display to work with, this transition comes early. Further diffusion of these definitions and their impact on learnability comes from the remarkable human ability to *find or create* meaningful or mnemonic connection where none was specified, as we will see later.

Capacity. Representation may have little impact on the ultimate capacity to learn icons. Our ability to recognize visual symbolic depictions seems inexhaustible: there are 3,000 Chinese ideograms, and a literate person can pick up 50,000 words without analysis in a single language. Essentially, there is no known limit to long-term symbolic memory [12]. Computer Braille maps the English alphabet plus punctuation to 256 tactile images, and experienced Braille readers say that they feel words and not characters,

TABLE 1
Haptic Stimulus Sets (Single-Locus Complex Signal) Available in the Literature

Source	Display Type	Display Dimensions	#Stim (Dur)	Type	Distinguishability Verification	Identification Performance
MacL 03 [41]	VT w/ knob (Maxon RE025)	3 used / found: wave, freq, amp	30 (2s)	n/a	MDS optimization (sorting confirms distinguishability)	n/a
vanE 03 [58]	B&K minishaker (4810)	2 found: intrusive-ness, tempo	59 (15s)	Repres	MDS attribute analysis (distinguish. not verified)	n/a
Cha05,8 [10, 11]	Eccentric mass; whole hand	2: frequency, amplitude	7 (.75s or cyclic)	Repres	MDS optimization, WL tested (1:9, 1x), deployed	95%, w + wo workload
Tang 05 [53]	Force vs VT w/ knob (Max RE025)	1: ord data as frc clicks, ramps, *or* VT	5 (2s)	Repres	ID of ordinal value (1:5, self-paced) under workload	84%/93%/75%; RT 6.0/4.4/3.2s
Brow 05 [5]	Voice coil (EAI C2 Tactor)	2: rhythm, roughness,	9 (n/r)	Semi-abstract	ID of 1 of 2-part meaning (1:3, played 4x)	71% overall; 93%/80%
Luk 06 [39]	Piezo bender array (skin stretch)	3: waveform, amp, speed; dur (dep)	30 (n/r)	n/a	MDS optimization w/ sub-set analysis	n/a
Brow 06 [7]	Inertial mass (TACTAID VBW32)	1: dynamic amplitude change	3 (2s)	Repres	ID of nature of signal (1:3, played 4x)	92-100%
Enri 06 [18]	VT w/ knob (Maxon RE025)	2: waveform, frequency	9 (2s)	Abstract	MDS opt; ID of 1 of 2-part meaning (1:3, sorted)	Overall n/a; 73%/81%
Brow 06 [6]	Voice coil (EAI C2 Tactor)	3: rhythm, rough-ness, location	18 (n/r)	Semi-abstract	ID of 1 of 3-part meaning (1:3 or 1:2, played 4x)	81% overall; 99%/82%/99%
Brow 06 [8]	Eccentric mass; whole hand	2: rhythm, ampli-tude vs. rough	9 (n/r)	Semi-abstract	ID of 2-part meaning (1:9, played 4x)	52% vs 72%
Enri 08 [17]	Inertial mass (TACTAID VBW32)	Not chosen dimensionally	10 (2s)	Abs vs. Semi-abs	ID of 1-part meaning (1:10)	80%; +2 wks, 70.1%
Tern 08 [55]	Piezo touchscreen w/ stylus	3: rhythm, fre-quency, amplitude	84 (2s)	Abstract	MDS optimization	n/a

Type [of representation] is n/a when the stimuli were unlinked. Tang [53] uses force stimuli; the remainder are tactile. Only Chan [11] has been deployed in a realistic setting.

albeit at 1/3 the speed of sighted readers [24]. The *perceptual* acuity required is attainable: in three to four sessions, sighted and inexperienced individuals dramatically reduced dot-pattern discrimination thresholds, approaching the acuity of those blind from birth [22]. Furthermore, associated cognitive structures are plastic: brain imaging studies show a dramatic increase in the cortical representation of the reading finger after two months of learning Braille [3], implying a mechanism for growth in capacity. For tactile displays, we can assume that this limit will lie in the technological ability to accommodate human tactile acuity and learning mechanisms, and not in mental storage space.

How does representation relate to calm design? Low effort and easy physical availability are key to locatedness. However, effort as a function of representational approach is not yet clear. Since learning may eradicate initial differences, it is critical to understand how much learning can be expected in a given application.

3.2 Processes and Heuristics for Icon Design

Design processes. The steps taken to design an icon set depend on the representational approach used, as well as constraints that impact the logical structure—e.g., there is an emerging convention of a 2-second duration for "glancing" use (Table 1). When individual haptic stimuli are created with specific meanings in mind and shaped to convey those meanings (nomic-metaphoric approach), then the steps of stimulus set creation and meaning attachment occur in concert. Ideally, as in the turntaking example, this is followed by perceptual adjustment to ensure set usability (distinguishable and appropriately noticeable) under realistic conditions. This is particularly important when individual stimuli are produced independently, since their behavior as a set is unpredictable. The clarity of the mappings chosen must also be verified.

Icon sets thus guided by metaphorical dimensions (i.e., semiabstract) seem to work well with up to perhaps 10 items (Table 1); but beyond this, practical conflicts mean that systematically spaced stimulus sets and arbitrary linkages are necessary. For example, salience is hard to control, and icons with very different meanings might feel similar [11].

When, conversely, stimulus sets are designed independently of meaning, e.g., to be drawn on for more arbitrary informational relationships (abstract approach), then the process might follow these iterative steps:

1. stimulus set prototyping,
2. stimulus set perceptual optimization (see below),
3. meaning assignment, and
4. testing and further adjustment under realistic conditions.

Simulating realistic conditions. Perceived differences between meaning-matched stimuli can be tested under simulated environmental workload, while the design parameters are further adjusted to achieve relative distinctiveness and salience as needed (e.g., [10] and [53]). In the turntaking application example, we needed to manage the salience of tactile alerts, with some important icons always noticed but less critical ones "washing out" when more urgent tasks were in play [11].

Stimulus design heuristics. Some support for creating stimuli is derived from human performance data, e.g., frequency thresholds, site sensitivity, etc. [20], [56]. But there are essential steps where the designer has little guidance and heuristics would be valuable. For semiabstract icons, the challenge is in finding good sensations to suggest the intended meanings; usually, these sensations are created "from scratch" [40], [42]. What makes a good metaphorical inspiration? How do you handle more abstract concepts? What are ways to minimize salience conflicts or item confusion later on?

Icon matching heuristics. For abstract designs, heuristics will be helpful for the step of icon *matching*—choosing the best fit or the best system of fitting, when choosing items out of a perceptually optimized stimulus set. Adapting ideas from auditory design [1] based on cognitive chunking [43] (based on working memory limits of three to nine items), we can for example use a hierarchical or family-based approach by using a common design parameter for stimuli attached to related meanings [4], [6], [18]. To manage salience, a control dimension whose modulation varies the perceived stimulus intensity could be reserved to create more and less urgent versions of a message that otherwise feels the same (e.g., in the turntaking case, urgency was mapped to beat rate in the heartbeat metaphor [10]).

3.3 Tools for Rapid Stimulus Prototyping

A first step in the icon design/integration cycle described above is the initial creation of haptic stimuli, either as specific elements to be paired with a predetermined set of meanings (as in the turntaking protocol) or as a large pool to be drawn upon for purposes yet to be determined (e.g., [55]). In both cases, it is desirable to rapidly prototype the stimuli themselves to quickly determine how they will feel, alone and relative to each other, and to investigate the expressive abilities of a given haptic display. This process is enhanced in both speed and explorable area by tools that ease signal creation and visualization: for example, providing a variety of mechanisms for creating waveforms (e.g., closed-form equations, sampled data, or graphical sketches) and supporting assembly of complex signals by combination and reuse of basic modules. Examples of such tools, in part inspired by audio and video editing practices, are described in [14] and [52].

3.4 Perceptual Optimization of Stimulus Sets

The next step of icon design is to *perceptually optimize* a set of stimuli. Related but distinct tasks include pairing stimuli with meanings (before or after perceptual optimization) and teaching mappings to users. Whether the intended set contains a few or many members, perceptual optimization's goal is to ensure that stimuli are *distinguishable* from one another and manage *relative* salience within the set. These perceptual goals may be in tension with logical organization schemes aimed at easing memory load, so stimulus clarity and logical organization must be balanced to minimize overall cognitive effort.

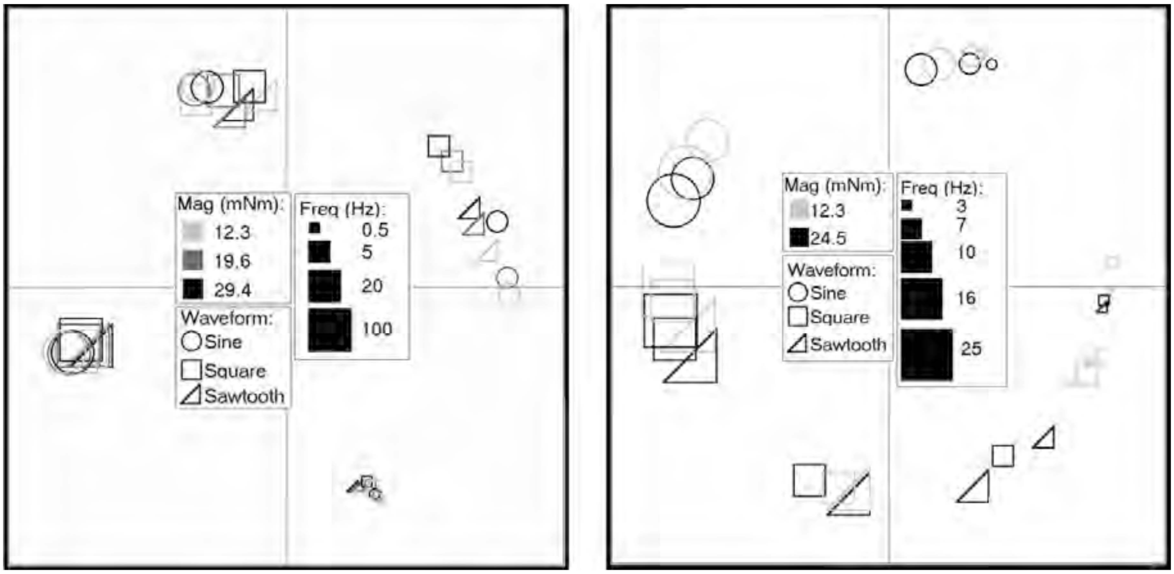
The designer has greatest leverage on this task when able to access the perceptual dimensions by which users naturally organize a collection of stimuli. When the designer modulates stimulus frequency, does the recipient likewise *perceive* a proportionate change along a single dimension or is the transformation more complex? In fact, users have been observed to organize low- and high-frequency ranges as qualitatively different regions with highly nonlinear spacing, i.e., a single design parameter is perceived as two dimensions [39], [41]. Conversely, some design parameters that are influential in isolation are masked in combination with others—e.g., the influence of high-bandwidth carrier frequency can be reduced by lower frequency rhythm modulation [55] (see also [47]).

3.4.1 MDS Tool to Visualize Structure and Optimize Spacing

One approach to revealing users' mental organization of a candidate stimulus set is inspired by auditory perceptual analysis, where Gaver notes the importance of building on how people hear, rather than on acoustic parameters [21]. Multidimensional Scaling (MDS) is a visualization tool that can reveal the underlying structure of data sets [49] and to analyze perception in complex stimulus spaces. In perceptual MDS, the algorithm takes as input a "dissimilarity matrix" containing user-perceived distances between s items (here, haptic stimuli, which may have been created along n design dimensions) and locates them in a euclidean m-dimensional perceptual space such that inter-item distances approximate the degree of dissimilarity described by the input matrix. The algorithm also delivers model "stress," indicating goodness of fit as a function of m: a higher order model may provide a tighter fit (lower stress value) but at the cost of abstraction and/or clarity. Ideally, a knee in the $\mathrm{stress} = f(m)$ curve will suggest the best value for m. We take the m dimensions as the most salient aspects of the set; stimulus coordinates recovered in the scaling locate the objects.

The initial use of MDS to model perception is Grey's analysis of auditory timbre space, delivering a three-dimensional (3D) model of a percept that had long defied characterization [23]. Participants rated pairs of tones, which were synthesized to control factors such as perceptual equalization and tone complexity. In an early use of *haptic* MDS, Hollins et al. tested perception of 17 real tactile surface textures through sorting [30] and derived a 3D solution space; this group has also found "substantial but not complete" agreement in stimulus organization between individuals [29]. More recently, MDS has been used to measure user organization of tactile melodies [58] and complex shapes [19].

Techniques for perceptual MDS deviate primarily in the mechanism by which dissimilarity data is collected from users; this trait also impacts their accuracy. The examples above illustrate two approaches: users can make a large number of *paired comparisons* or, more efficiently, *sort* items into similar groups [49]. Paired comparisons have analytic superiority, giving the finest dissimilarity granularity [45], and would be preferred if people were computers. For data sets beyond 30-50 items, however, user judgments deteriorate due to memory drift and fatigue, and the resulting



(a) (b)

Fig. 3. Two iterations of a 2D (output) MDS map of a haptic stimulus set. (a) Second iteration (36 stimuli). (b) Third iteration (30 stimuli, rearranged by adjusting the three design parameters to achieve a more desirable output spacing). Adapted from [41].

inaccuracy and noise greatly reduces data reliability [2]. Structurally and analytically, cluster sorting and paired comparisons do converge on the same result [45].

The cluster-sorting approach therefore became the core of an iterative icon design tool ([41], tested using the knob in Fig. 1d with results shown in Fig. 3). For set sizes up to $\sim$30, we have found that data from about five users, each contributing a 20-60-minute session, provides enough dissimilarity data for a stable consistent map [10], [41], [45], and thus, a full iteration on a stimulus set of this size requires only 2-5 hours of participant time, depending on the set size. Unclear results arise when a given design parameter is organized inconsistently by different users. This may indicate the need for a more "natural" design parameter or transformation or for a more sophisticated analysis (see below). The resulting map can guide iterative revision of the set until the stimuli are spread out to make best use of the available design space, thus optimizing differentiability over the set. The map also guides choice of the stimuli for application use: for example, those lying together on the map might be given related meanings, facilitating a family-based or hierarchical learning mnemonic [10], [18], [39].

MDS is a useful tool, but we need additional support such as parameterization of interstimulus distance and relative salience. Nor is its data collected in realistic use contexts. Currently, these factors are handled by testing under laborious simulations of varied abstraction (e.g.. [10] and [11]). We need to develop more efficient means for calibration and stress testing. Possibilities include established techniques like Pathfinder [50] and hierarchical cluster analysis [13] (see also [2]) and their modification or combination into iteration-friendly processes.

3.4.2 Unfolding Complex Dimensions

As set size and stimulus expressiveness grows, users' classification behavior becomes more complex yet can remain startlingly consistent across users. For example, Luk et al. asked users to classify 30 unfamiliar stimuli based on three independent design parameters; displayed on a novel skin-stretch device, the sensations did not have any real-world parallel [39], [44]. One organizational axis and three clusters emerged in MDS analysis, but beyond this, little was clear; increasing the dimensionality of the MDS map did not help (Fig. 4a).

It transpired that the requirement for visualizing the entire stimulus set at once was overconstraining the result. When the three unstructured data clouds in the original map were each analyzed separately, they revealed new dimensions that were clear and consistent across individuals (Figs. 4b, 4c, and 4d). Because users were applying these higher order dimensions to the data subset only, they were not characteristic of the entire stimulus set, and the global nature of the MDS solution concealed them. The same subdimension result was obtained whether the MDS map was produced from a submatrix of the original dissimilarity matrix or dissimilarity data collected by sorting just the stimulus subset. This comparison validated a meta-analysis technique of "unfolding" additional data subdimensions by creating localized maps derived from the original data set, i.e., without the need to collect additional user data.

3.4.3 Scaling to Large Sets

"Large" sets of icons—for practical reasons, these will generally be based on tactile stimuli—are of considerable interest, beyond the fascinating academic question of how much abstract information we can absorb through touch. Most notably, networked messaging applications (discreet, eyes-free, person-to-person, or system-to-user applications) could usefully absorb a very large signal space; consider the contemporary use of text messaging. Larger sets also provide a well-characterized and reusable pool from which we can repeatedly source smaller prevalidated sets of stimuli and avoid conflicts between applications when standardization is not achievable.

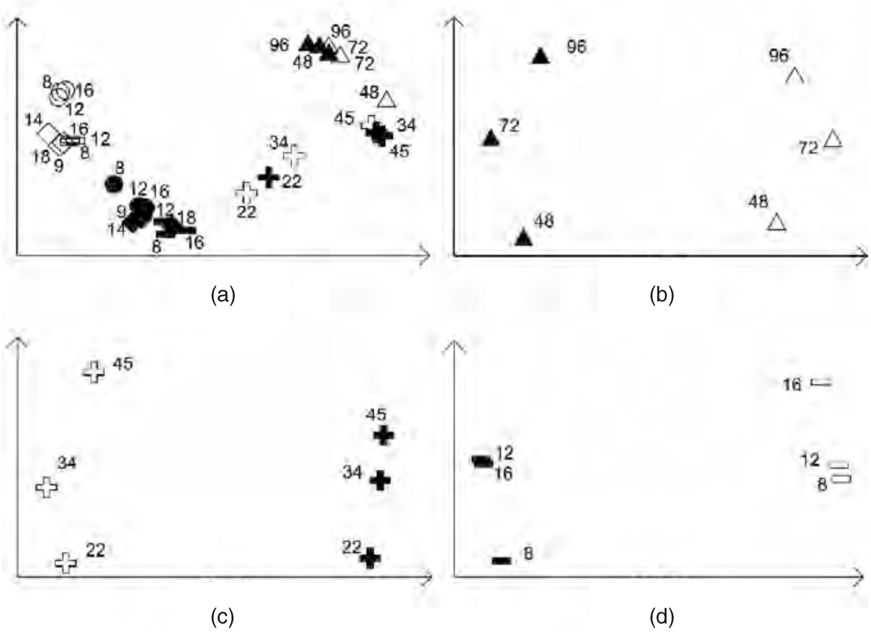


Fig. 4. Unfolding the MDS map to reveal hidden dimensions of complex data. (a) Control MDS map with all 30 stimuli. (b), (c), and (d) Three stimulus subgroups, analyzed separately and each revealing dimensions hidden in (a). Reprinted from [39].

At this point, we do not know how many separate haptic icons (stimuli combined with a meaning) a person can learn and utilize. The studies we are aware of showing reasonably successful identification of haptic icons have used stimulus sets small enough to be learned in a single session (7-18 items, Table 1), and as noted earlier, symbolic memory itself will not be the limit. But to go beyond this, we need larger discernible sets of *stimuli* and heuristics that will facilitate their creation.

Stimulus set size is affected by display hardware, design parameters, and techniques for stimulus creation; the method by which associations will be learned has an impact as well (Section 4). In Table 1, we summarize the hardware and parameters used to create haptic (in most cases, tactile) stimulus sets for informative signaling. Omitting the last row, *stimulus* set sizes of 7-59 have been achieved and substantiated to varying degrees. In increasing order of certainty and ecological validity, distinguishability is inferred from MDS attribute analysis, positively demonstrated through MDS sorting, identity-tested in realistic conditions, or measured after deployment in a realistic application scenario.

The largest sets have been created by varying *rhythm*, a time-varying parameter whose complexity considerably expands the design space but additionally provides linkages to musical and spoken cadences [6], [55], [58]. The latter enables metaphorical association, but it complicates design by introducing another aspect of salience, i.e., familiarity of the rhythm and any affective (emotional) connotation. *This* salience, unlike intensity or rate, tends to be highly individual or cultural and hard to control.

Given the readily available hardware mentioned in Table 1, these numbers represent the easy advances: achieving larger usable sizes requires increasingly systematic design techniques. Ternes et al. created a rhythm-based set of 84 elements, obtained by a thorough rhythm-space analysis for a given device and the use of resulting heuristic design guidelines ([55], last row of Table 1). This set is fully distinguishable by untrained users and is another example of dimensional unfolding. In ongoing work, it is being assessed for learnability over time, tested in the presence of workload.

Perceptual optimization is critical to scalability. The only tool for this of which we are aware, the MDS technique described above, was effective up to 35-50—the number of items comfortably sortable in an hour. Beyond this, sorting becomes overwhelming for a typical person, and the technique fails. To analyze the 84-item set described above, Ternes [54] modified the MDS processing of dissimilarity data to allow the cluster sorts to be performed on overlapping subsets of the entire data set, whereas previously, it was numerically necessary for each participant to sort the entire set together. The key innovation is in sampling the full stimulus set to create subsets connected by a sufficient but minimal number of cross comparisons (a unique subset for each sorter provides the most uniform coverage). The 84-item set was thus divided into 50-element subsets. The result was validated in part by comparing the resulting MDS map with the one obtained by whole-set sorts performed by motivated, experienced participants able to maintain sorting quality. This approach is anticipated to scale up to sets of about 150 before the sampling process becomes overconstrained by the subgroup size limit.

4 LEARNING: HOW CAN ICONS BE ACQUIRED?

Until this point, we have focused on the creation of *stimulus* sets. Now, we address the paired challenges of associating individual stimuli with meanings and supporting users in learning these associations.

As mentioned in Section 3.2, the learning task depends on the overall design approach taken. For representational signals, the meanings and stimuli will have been designed in concert, and now they must be introduced to users. For abstract and semiabstract sets, individual stimuli must now be allocated to the set of target information items. This can be done randomly, as "best fits" by the designer, or with user input. For example, one way to get around the persistent problem of individual differences in "natural" stimulus/meaning associations is to let users choose their own assignments [17].

Several questions will guide future research. Scalability depends on both user capacity and display richness, but given unintrusive opportunities to learn icons over a period of time, user capacity might be increased without impractical degrees of effort for regular-use scenarios. More generally, we need to expand our insights into what makes mappings most *learnable*, *memorable*, and *usable*. The representation-linked issues in Section 3.1 (e.g., articulatory directness versus practical constraints) are a starting point, but they have not been directly compared or scaled; context will play a role.

4.1 Learning Results and Practice in Smaller Sets

What kind of icon-recall performance has been achieved, does it depend upon the design approach, what methods are being used for training, and how will all of this scale?

Identification performance. Referring to those rows of Table 1 that include *recall-tested* icon sets rather than stimuli alone, we see that icons have been identified at rates of 70-100 percent for set sizes of 3-18. The circumstances vary in realism of testing, richness of display hardware, and the type of icons used. Two studies emphasized realism by including simulated workload to compare [53] or test icons [10]. For example, users identified icons in Chan et al.'s metaphor-based seven-item set [10] with 95 percent accuracy under substantial workload.

Most of the remainder employed compound icons created by modulating two to three control dimensions and then assigning meanings separately to each of the dimensions, either arbitrarily or with a metaphorical best match approach. These have all been tested one design dimension at a time. For example, for the largest set in this category, Brown et al. [6] varied rhythm, roughness, and location for 18 stimuli and associated two to three values of various appointment characteristics to each (type, importance, and time until). These were tested by asking participants to identify one appointment characteristic at a time, so correct identification was possible by chance in 1 : 2 or 1 : 3 trials at a time. High single-dimensional rates were found (82-99 percent); the overall rate (all three parameters correct in a single trial) averaged 81 percent. To the extent that such a testing mechanism reflects intended usage, it measures a deliberate feature of the family-based design strategy and illustrates how information content can be increased without cognitive effort, and it also shows a resolution at which multiple dimensions can be perceptually decomposed. However, it sheds less light on unique symbol recognition rates.

None of these studies used "reinforced" icons, in the sense of multiple tactile dimensions used to display identical rather than complementary data. One would expect this practice would lead to even higher performance, if needed, at the cost of a reduced information space.

Design approach. These small- to medium-set studies do not clearly differentiate between icon representations or the use of particular types of perceptual optimization: promising performance is seen with both abstract and semiabstract sets, and all of the sets were verified for differentiability in some manner (e.g., through single-dimension discriminibility, paired comparisons, or set adjustment between icon identification trials).

Learning protocol. In the studies mentioned here, learning support has been fairly simple, generally taking the form of 3-10 minutes of self-guided exposure, with or without a "gatekeeper" check, before continuing to a test phase. Compound icons or intentional metaphorical designs are generally explained to users. There have been no controlled comparisons of learning reinforcement (i.e., providing feedback on success and errors); however, in cases where it was omitted, authors have suggested that its inclusion would have been beneficial (e.g., [11]). With or without reinforcement, accurate recall for at least 1-3 hours of use can be achieved for these small sets by simply exposing users to the icon pairings for a few minutes. Furthermore, accurate recall without use has been observed after a much longer period (Section 4.2).

Transfer effects. Patterns learned in other modalities may facilitate learning of abstract tactile signals. Crossmodal transfer from the auditory domain has been shown both for leveraging "old" knowledge (e.g., tactile melodies [58]) and when auditory signals are newly learned by ear and then tested by touch [28]. Other cases of rhythm facilitating distinctiveness are also likely related to auditory transfer [6], [55]. The major concern with reliance on transfer effects is stimulus/response incompatibility: it is difficult to control prior associations, including emotional ones, which may conflict with new intended meanings.

Scaling. We anticipate that differences resulting from the complex advantages and disadvantages of representation approach and perceptual optimization will emerge with larger sets. A global visualization tool like MDS will become indispensable. Methods to help users learn icons may need to become more sophisticated as learning extends beyond one session and requires greater mental organization, perceptual learning, and persistence. User receptiveness may be sensitive to these factors. To help anticipate this, it is important to understand subjective preferences and mental effort engaged with the smaller sets and to devise user-friendly learning strategies.

4.2 Meaningfulness of Associations

In light of our goal of understanding the respective design advantages of representational and abstract haptic mappings, one recent study requires special attention. It suggests that designers may have less control over which representation the *user* is employing than we think.

Enriquez and MacLean hypothesized that when users can choose the stimuli that will represent specific concepts, their learning and recall will be enhanced, and it is enhanced relative to when arbitrary associations are imposed on them [17]. They tested this idea by comparing the user ability to learn and identify icons for two different 10-icon sets, displayed with the tactor setup in Fig. 1a. Each participant learned two sets, two weeks apart, with meanings corresponding to settings on a vehicle audio (one set) or GPS navigation system (other set). The two-week interval was intended as a "washout" period, i.e., there was no expectation that participants would recall previous associations at the second session. In one set, the experimenter chose stimuli at random from a much larger perceptually optimized candidate set. For the other, the experimenter required participants to choose the 10 matches from a 20-item pool drawn randomly from the same source set. The experiment condition of association type (random versus user chosen) was counterbalanced with the meaning set used. The fact that participants were expected to (and indeed did) use some kind of rationale in match creation implied that they were striving for a representational approach, avoiding randomness. Training lasted ~10-17 minutes.

The study produced three surprising results. Two weeks later, participants recalled 86 percent of the previously learned associations (tested before exposure to the new set) without any intervening reinforcement and without having been told to expect such a test. In contrast to their *actual* performance in this pretest in the second session, immediately before taking it 100 percent of participants reported the number of associations they remembered as zero. Second, there was no statistically significant difference in recall performance between arbitrary and user-chosen association conditions either after the initial learning (first or second session) or at the start of the second session; association persistence was the same. Finally, in follow-up interviews, many participants expressed the impression that icons in the arbitrarily matched set were metaphorically inspired: that is, they had found adequate content in these sets to support that learning strategy.

Two important observations emerge. People have considerable ability to find their own mnemonics for remembering stimulus-meaning relationships, regardless of how the associations are assigned. Furthermore, people are better at learning and retaining associations than they believe they are; this has both positive (untapped potential) and negative (low confidence, at least until this medium becomes more familiar) ramifications, and learning techniques should be devised accordingly. Similar tests on larger sets are required to see how this result scales when stimuli must be more subtly differentiated but balanced with more extensive training.

4.3 Subjective Factors and Locatedness

The observed degree to which people can learn icons without being aware of their learning brings us back to our initial premises of transparency and calm design and to our suggestion that user acceptance will be influenced by *learning methods.* The methods outlined above are an essential part of creating haptic display systems that communicate while conserving attention; but they do not fully capture the users' experience of cognitive effort.

There are established methods for *testing* cognitive demand—for example, measuring tactile signal recognition and distractor performance while a user is subjected to distractions over time periods long enough to simulate realistic levels of stress. This is useful in research as a measure of relative subjective effort associated with the use of a proposed communication system. However, it is not clear that long stressful sessions are the most effective way to learn, either for user acceptance or for movement of data from working to long-term memory [9].

As with other language-learning endeavors, repeated brief exposures may best facilitate both rapid and robust learning. They may also be the key to pinpointing performance ceilings and long-term subjective reactions. Referring again to [3], we anticipate that subjective cognitive effort will initially be high and then diminish with experience, up to a point, and we have repeatedly observed this even in single short sessions. It is therefore important to develop learning methods that minimize the total and individual session durations and that users find them palatable and even enjoyable. Furthermore, users' inaccurately low estimates of their own ability to learn haptic icons suggests that *reinforced learning* will be helpful, in terms of acquiring confidence in this unfamiliar medium.

We anticipate that achievable degrees of transparency and locatedness (background "gestalt" awareness of the system state) are more accurately assessed once a user has achieved some degree of fluency: i.e., subjective cognitive effort should flatten while performance remains high or increases. Future work is required to determine when and if this indeed occurs and how to measure it.

5 Conclusions and Future Directions

The aim of this paper has been to organize our current knowledge on how to attain *transparent* tactile information display, i.e., with low cognitive effort and minimal to zero impact on attentional resources, and to assemble a perspective on where new advances need to occur. Our discussion has been inspired by Weiser's vision of *calm technology* with its concepts of locatedness (our current focus) and seamless movement between the center and the periphery (a topic for future work). We have found constructive themes in the pursuit of the most useful *information representations* and creation of *tools and processes* that support efficient iterative design, by incorporating user data when open-loop design is not possible. Another recurrent thread is the trade-off between what the user needs and what today's hardware can provide.

Our discussion was organized along the lines of potential utility, form, and learning. Following this, we summarize what we know now and what needs to come next.

Utility. The surveyed research shows that well-designed haptic icons do allow appropriate background processing—with low effort and intended level of attention—confirming their candidacy as conduits in calm design. Icons intended to be perceived in the background need to be well integrated with other modalities to support movement from perception to action—from the periphery to the center and back—when their own capabilities for communication or response have been exceeded. Scalability and learnability, topics of future work, will impact appropriate application.

Form and processes. Our analysis suggests that while representational approaches may be initially easier to learn, they do not scale well. It is currently unclear how the early advantage will persist as set sizes and ubiquity grows, as there is little data here. The ultimate capacity is likely indifferent to the representational approach, given examples in other domains; it is presently limited by expressive capability of available displays. More work is needed to understand learning rates.

In terms of process, there are already adequate tool-supported procedures (albeit with room to improve) for rapidly iterating/testing stimuli to form perceptually viable sets. We need heuristics for designing good matches and/or a better understanding of how much this matters as the design approach inevitably becomes more abstract in larger sets.

Learning. All of the results mentioned here need to be examined in the context of longer learning, realistic contexts, and larger sets. As sets grow, learning mechanisms will be more critical in terms of both effectiveness and user willingness, but conversely, as this medium becomes more commonplace we anticipate that tactile skill in some demographics may improve. It is often noted that learning to taste and verbalize subtleties of wine, for example, or to smell fragrances greatly increases awareness and sensitivity to nuances.

Of Braille, Morse code, and wine tasting, what do we keep and what should we discard? *How* haptic iconography is learned will have as much to do with this as *what* is being learned.

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