Designing Haptic and Multimodal Interfaces:  
A Cognitive Scientist’s Perspective

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Abstract: This paper approaches the design of haptic and multimodal interfaces for teleoperation and virtual environments from a cognitive scientist’s viewpoint. It briefly describes key findings from a comprehensive research program on human haptics. It also offers a number of general design principles, derived from these scientific results.

Keywords: Haptic interfaces, human haptics, manual exploration, point-contact haptic interfaces, virtual textures

1 Introduction

As cognitive scientists, we offer a different perspective on the design of haptic and multimodal interfaces for teleoperation and virtual environments. We focus our attention on the human user in the control loop, rather than on either the hardware or the software systems per se. We study how humans sense, perceive, think about and act on worlds that are real or virtual. We have specifically focused our research on “haptics”, a “multimodal” perceptual system that uses both tactile inputs from receptors embedded in skin and kinesthetic inputs from receptors that lie within muscles, tendons and joints. People use the haptic system to perceive and interact with the world of concrete and virtual objects, sometimes on its own, and sometimes in concert with other sensory systems, such as vision and audition.

Relatively little is known scientifically about the sense of touch, compared for example with either vision or audition. For a number of years, therefore, we have been conducting a scientific research program on haptic perception and haptically-guided motor control in humans. In our research, we have addressed what touch does well, and critically important, why. We have been equally educated by determining what touch does poorly, and again, the reasons for such poor performance.

Many of us argue that to develop highly effective sensory interfaces, it is necessary that designers match the capabilities and limitations of the human user to the design characteristics of the hardware and software systems. Such a goal demands complex interactions between computer scientists and engineers, on the one hand, and those who study living systems on the other (e.g., psychophysicists, cognitive scientists, neuroscientists, and ergonomists).

1.1 Contributions to the design of sensory interfaces

Cognitive scientists can serve the field in two complementary ways. First, the basic scientific results they have obtained on how the
human user processes and represents incoming sensory and outgoing motor information can be used to improve the design match between user and interface. Second, cognitive scientists possess a wide variety of scientific “tools” with which to formally evaluate the effectiveness of any new hardware or software system. Scientifically rigorous methodologies permit us to design and conduct experiments with these systems properly. Moreover, formal statistical procedures are available to evaluate the empirical results pertaining to user performance in such experiments.

2 A scientific research program on human haptics

In the remainder of the paper, we will briefly describe several of our research projects on human haptics, and suggest on the basis of each, general recommendations for designing haptic interfaces.

2.1 PROJECT I. The role of extended manual exploration

In our initial examination of the sense of touch, we demonstrated [1] that blindfolded observers are both accurate and fast at identifying common objects by solely by hand. One hundred objects were recognized with almost perfect accuracy, and typically within only a couple of seconds. This highlighted the fact that the haptic system is indeed a highly complex information-processing system.

2.1.1 Brief Summary

In the next study, we chose to investigate the potential contribution of manual exploration to such impressive haptic performance. In Experiment 1, we [2] presented observers with sets of 4 multi-property objects, in sequence. The objects varied in terms of their material properties (e.g., texture, hardness, thermal conductivity, weight), their geometric properties (e.g., weight, shape, size), movable object parts, and in terms of their function, as suggested by object structure. For each set, the blindfolded observers were instructed to manually explore the first object, known as the “standard”, to learn about a designated property, e.g. texture. Next they sequentially examined three “comparison objects”, and selected the one that best matched the standard in terms of the property named. The hand movements were recorded on videotape and subsequently analyzed. Observers demonstrated a high degree of consistency in their manual exploration, performing different highly stereotypical movement patterns, each closely associated with a named property.

These hand movement patterns were designated “Exploratory Procedures”, or “EP”s, for short. Below we describe the 6 EPs that have been most thoroughly investigated (Figure 1). People made a back-and-forth shearing

Figure 1: “Exploratory Procedures” and the object property with which each is most closely associated. (Adapted from and reprinted with permission from Lederman [3] as revised from Lederman & Klatzky, [2]).

motion across the surface (a “Lateral Motion” EP) when told to attend to surface texture. When asked to attend to hardness, however, they varied the force(s) applied normal to the surface (a “Pressure” EP). Thermal properties were typically extracted using a “Static Contact” EP, which involved stationary contact between hand and surface. Weight was usually assessed using
an "Unsupported Holding" EP, in which the object was lifted away from a supporting surface and typically hefted. Observers executed an "Enclosure" EP (or grasp), in which fingers were molded to the contours of the object to obtain information about object volume and coarse shape details. Finally, when precise shape information was necessary, observers chose to execute a "Contour Following" EP, which involved tracing the fingertips along the edges of an object.

The experiment above was subsequently repeated [2], with one change. In Experiment 2, rather than being allowed to freely explore the objects, observers were constrained to perform a designated EP in conjunction with one of the property-matching instructions. Across the entire experiment, observers performed each of the 6 EPS with each of the property-matching instructions. Accuracy and response times were both recorded. For each property-matching instruction, the EPs were ordered in terms of the relative precision, as suggested by accuracy, and in the case of ties, by speed.

2.1.1.1 Relative EP precision. The results are reported in Table 1 in the form of an EP/property weight matrix. The EPs are listed in abbreviated form along the left side; the property-matching instructions are listed along the top, by column. A cell entry of "0" indicates that the designated EP extracted information about the designated property no better than chance (i.e., 33%). A cell entry of "1" indicated that the EP was sufficient, but not the best way to extract information about a given property. A cell entry of "2" indicated that the EP was optimal for extracting the designated property information. Finally, a cell entry of "3" indicated that the designated EP was optimal and necessary for extracting information about the designated property. Notice that the EPs that were optimal and/or necessary were, with few exceptions, the same EPs that people chose to execute when allowed to explore the object freely in Experiment 1. The relative-precision data from Experiment 2 help to account for the associations documented in Experiment 1.

The data from the Lederman & Klatzky experiments [2] also provide information about other performance characteristics of the EPs, namely the “breadth of EP sufficiency” and the mean EP response duration.

a) Property

<table>
<thead>
<tr>
<th></th>
<th>LP</th>
<th>P</th>
<th>SC</th>
<th>UH</th>
<th>E</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hardness</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Temperature</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Weight</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Volume</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Global shape</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Exact shape</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1. a) Relative EP precision, b) Breadth of EP sufficiency and EP response durations. LP = Lateral Motion, P = Pressure, SC = Static Contact, UH = Unsupported Holding, E = enclosure, and CF = Contour Following (adapted and reprinted with permission of the publishers, [4]).

2.1.1.2 Breadth of EP sufficiency. While a given EP is optimal for extracting information about a specific property, it may be sufficient for performing additional property-matching tasks. For each EP, the breadth of EP sufficiency was measured as the sum of all non-zero cells in the designated EP row (Table 1). We see that both Lateral Motion and Pressure are relatively "narrow" EPs, inasmuch as they are only sufficient for extracting information about two properties for which they are not optimal. In contrast, both Enclosure and Contour Following are "broadly" sufficient for extracting information about most properties investigated.

2.1.1.3 Mean EP duration. The mean response duration for each EP measured during the first unconstrained manual exploration experiment is also shown in Table 1b. EPs associated with extracting information about the material properties of objects were notably shorter than
Contour Following, which was used to extract precise geometric details about the objects.

2.1.1.4 EP compatibility. Additional analyses allowed us to evaluate another important EP performance characteristic, EP compatibility. This term refers to whether or not two EPs can be co-executed. The analysis was based on the extent to which values for four EP parameters, which were deemed critical in differentiating EPs, overlapped. The parameters consisted of static vs. dynamic force, direction of force (lateral vs. normal), presence of a workspace constraint (i.e., need for a supporting surface), and the region of object explored (edge, interior surfaces, or both). A detailed analysis is provided in Klatzky & Lederman [4].

2.1.2 Implications for haptic perception. The documented EP performance characteristics have proved to have important consequences for manual exploration, the relative strengths of haptic processing, and the relative salience of different object and surface properties for the haptic system, as opposed to the visual system.

Relative EP precision, breadth of EP sufficiency, and EP response duration collectively predict that observers will execute a highly efficient 2-stage sequence of manual exploration [5]. Stage 1 consists of an initial brief grasp-and-lift sequence (i.e., Enclosure + Unsupported Holding), which is used to quickly obtain coarse information about a large number of object properties. Stage 2, performed when necessary, consists of the execution of one or more EPs that are optimal for obtaining more precise information about a desired object property.

Relative EP precision and EP duration collectively determine the relative salience of two classes of object properties for haptics vs. vision, that is, material and geometric properties. When the property search is not directed by external instructions (e.g., “what is the texture of this object?”) or by knowledge-directed goals (e.g., look for texture, because it is the most diagnostic property for sandpaper), people tend to prefer to search haptically for information about the material properties of objects, as opposed to simultaneously available geometric properties [6, 7]. Given our scientific understanding of the relative EP performance characteristics, we explain this result as being due to the fact that the haptic system can manually extract material properties more efficiently than geometric properties. Conversely, vision is more efficient in its ability to extract geometric, as opposed to material, object properties.

We [8] have also found that breadth of EP sufficiency combines with EP compatibility to reduce the time it takes for people to learn to classify unfamiliar objects that are defined by one property, as opposed to multiple redundant object properties. Take, for example, texture and hardness. When either optimal EP is performed on its own, the EP will make available precise information about the dimension for which each is optimal (i.e., texture for Lateral Motion, and hardness for Pressure). In addition, each EP will make available coarse information about the other property for which it is sufficient, but not optimal (i.e., hardness for Lateral Motion and texture for Pressure). This demonstrates the perceptual effect of EP breadth of sufficiency. However, when the two EPs can be co-executed (i.e., demonstrate EP compatibility), as with Lateral Motion and Pressure, the observer may potentially benefit from the information simultaneously extracted by both EPs. For example, when information about the two dimensions is redundant (e.g., objects are both rough and hard, or smooth and soft), observers use the redundancies to speed object classification.

2.1.3 Some general design principles.

Based on extensive research, only selected aspects of which have been briefly reported in this paper, we propose several general principles for designing haptic interfaces:

1. Haptic interfaces should permit the user to extract object properties using the Exploratory Procedures typically used to obtain information about the properties of real surfaces and objects.

2. The designer should explicitly attempt to maximize the benefits of high breadth of EP sufficiency and EP compatibility.

3. Where possible, material properties should be made accessible to the user via a haptic
interface; in contrast, precise geometric information should be made accessible via a visual interface.

2.2 PROJECT II. What can we learn from brief contact?

Project I dealt with temporally unconstrained manual exploration and its consequences for haptic exploration and for unimodal and multimodal perception. Project II investigated the consequences for haptic perception of markedly constraining contact duration.

2.2.1 Brief Summary. We were interested in whether properties of surfaces and objects were differentially accessible for further processing following only a very brief (i.e., about 200 ms) “haptic glance” [9, 10].

Across trials, participants were presented with haptic displays that contacted varying numbers of fingertips. They were told to decide as quickly and as accurately as possible whether or not a designated target (e.g., a rough patch) was present among varying numbers of distractor patches (e.g., all similarly smooth). The target was only present on half the trials.

Across experiments, subjects were presented with pairs of stimuli that widely varied along a single material dimension (e.g., rough vs. smooth, hard vs. soft, warm vs. cool) or along some geometric dimension (e.g., right vs. left position of a raised element relative to a central indentation, right vs. left planar orientation of a raised bar, and right vs. left orientation of a 3D ramp). We also considered binary dimensions pertaining to whether or not an edge was present. The haptic search functions shown in Figure 2 plot mean response time as a function of the number of items in the haptic display, for both target-present and target-absent trials. The functions are fit with linear equations. The value of the slope indicates the amount of additional time (in ms) required to process each additional item in the display. Flat functions indicate that the display may be processed in parallel across both hands. Non-zero functions suggest that an additional processing load is required for each additional item.

The top function represents the haptic search for a rough target embedded amongst varying numbers of smooth distractor items. Clearly the search for roughness is processed relatively quickly, and in parallel. This generally proved to be the case for material-property searches. (Thermal search functions were also relatively flat, although the searches took somewhat longer, presumably because of the time required for heat exchange between finger and surface.) In striking contrast, the slopes describing haptic search functions for geometric properties proved to be considerably greater. The range of slopes documented across experiments is represented by the top and bottom graphs in Figure 2.

Based on the relative magnitudes of the slopes of the haptic search functions, we concluded that information about material properties and about the presence/absence of edges is available relatively earlier than that concerning geometric properties.

Figure 2: Mean response times as a function of the number of items in the haptic display: a) Rough target among smooth distractors; b) Right relative-position target among left relative-position distractors. (Reprinted with permission [11])
2.2.2 Some general design principles. Based on the reported work, we suggest the following general principles:

4. When the human operator must be signaled quickly, or when coded inputs to the hand may prove useful to display, selection of material properties and edge information are strongly recommended.

2.3 PROJECT III. Haptic interfaces: Should spatially distributed fingertip forces be displayed?

In PROJECT III, we specifically considered whether there was a role in haptic interfaces for tactile feedback displayed to the fingertip. Many early haptic interfaces served power, as opposed to precision, functions in motor tasks. Net forces were delivered to the wrist or forearm. However, some of the most exciting application domains today require higher-precision coordination for pointing, grasping and manipulation tasks, which are typically performed with the fingertips. We know from both the clinical-rehabilitation and the neurophysiology fields that deprived of cutaneous inputs to the fingertips, people will drop objects [12], apply too much force [13], and can damage their hands using dangerous tools, such as a knife [14].

We wondered specifically whether the spatially distributed fingertip forces normally available during haptic perception and action might play a critical role in the use of effective haptic interfaces. To date, technological challenges have limited the development of array force sensors and stimulators. We thought it important to scientifically evaluate the extent to which there was a need for array force technologies in recent application domains, such as minimally invasive surgery, remote surgery and medical diagnosis, rapid prototyping, and space repair.

2.3.2 Brief summary. We [10] therefore psychophysically assessed tactile sensitivity and haptic perception in a battery of tasks when spatially distributed fingertip force patterns were either available or not. To eliminate the spatially distributed inputs, we produced molded, rigid fiberglass sheaths. On half the trials, observers wore a form-fitting sheath on the volar (palmar) surface of their thumb, index or middle finger. The sheath was held firmly in place by a lightweight, latex “finger” or “thumb” piece, cut from standard surgical gloves. In control trials, the spatially distributed forces were available to the observer, who wore the same surgical fingertip (without the sheath), to equate the friction conditions.

The sensory tasks included force thresholds, tactile spatial acuity (the minimum gap between two contact points that is perceived as separate points), and vibrotactile thresholds across the full range of frequencies to which the skin is sensitive. The perceptual tasks included estimation of roughness magnitude and roughness discrimination (“which is rougher?”), perception of the 2D orientation of a raised bar, and finally the threshold for detecting the presence of a simulated lump in simulated tissue. The tasks and their impact on performance are listed in Table 2.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Impact on performance</th>
</tr>
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<tbody>
<tr>
<td><strong>Sensory:</strong></td>
<td></td>
</tr>
<tr>
<td>Force thresholds</td>
<td>74% decline in threshold</td>
</tr>
<tr>
<td>Spatial resolution (2 pt. touch threshold)</td>
<td>543% decline in threshold</td>
</tr>
<tr>
<td>Vibrotactile thresholds</td>
<td>no significant effect</td>
</tr>
<tr>
<td><strong>Perceptual:</strong></td>
<td></td>
</tr>
<tr>
<td>Roughness estimation (slope)</td>
<td>32% decline in slope</td>
</tr>
<tr>
<td>Which is rougher? one-step pairs</td>
<td>18% decline in accuracy</td>
</tr>
<tr>
<td>&gt; one-step pairs</td>
<td>&lt;4% decline in accuracy</td>
</tr>
<tr>
<td>2-D bar orientation</td>
<td>chance-level matching accuracy</td>
</tr>
<tr>
<td>estimated information transfer (max = 2.58 bits)</td>
<td></td>
</tr>
<tr>
<td>glove-only = 1.54 bits</td>
<td></td>
</tr>
<tr>
<td>sheath + glove = 0.03 bits</td>
<td></td>
</tr>
<tr>
<td>Detection of 3D mass via palpation</td>
<td>191% decline in confidence rating</td>
</tr>
<tr>
<td></td>
<td>44% increase in size of mass detected at 75% accuracy</td>
</tr>
</tbody>
</table>
Table 2. Impact on performance of eliminating spatially distributed forces to the fingertip (revised and reprinted with permission of the publisher [10]).

The results show considerable performance impairments for all but the texture-perception tasks, for which there were only modest deficits, and for vibrotactile thresholds, which were unaffected (presumably because of the conduct of vibrations through the rigid sheaths).

2.3.2 Some general design principles. Based on the results obtained in PROJECT III, we propose the following general design principles:

5. There would appear to be strong benefits in presenting spatially distributed force feedback to the fingertips

6. There is therefore a need to develop complex array-force technologies, especially since current haptic interfaces typically involve point contact (e.g., SensAble’s PHANToM)

7. Using vibration-based cues may prove to be a viable way of creating virtual textures.

2.4 PROJECT IV. Feeling objects and surfaces remotely with a rigid probe

People perform many tasks remotely by means of intermediate tools. Project IV is an ongoing project that investigates how people perceive and identify objects and surfaces remotely via a rigid probe. Here we will briefly consider some of our research to date on perceiving roughness and identifying common objects with rigid probes, as well as some consequences for designing haptic interfaces. The probes were rigid, stick-like styluses, with spherical tips. The shape of the tip was selected so that the probe could serve as a simple but elegant model for point-contact haptic interfaces.

2.4.1 Brief Summary

Perceiving surface roughness. We are currently conducting a broad research project aimed at developing a psychophysical model of roughness perception via a rigid probe. The surfaces consist of spatially jittered (angularly and radially) raised-dot patterns.

To date, we have been isolating a small set of critical psychophysical parameters that most strongly influence vibration-based roughness perception. These fall into two major sets: 1) probe/surface geometry, and 2) the manual exploration process. Where relevant, we have also compared the results to those obtained with the bare finger.

With respect to the plate parameters, we have found that whether bare finger or rigid probe is used, perceived roughness magnitude is strongly influenced by interelement spacing. However, the shape of the psychophysical roughness function -- perceived roughness magnitude plotted as a function of interelement spacing on log scales -- is best described by a quadratic equation (see e.g., Fig. 3). This contrasts with published bare-finger data, which have been linear over the range within which subjects are willing to say they perceive

Figure 3. Perceived roughness magnitude as a function of interelement spacing for three probe forces (revised and reprinted with permission of the publisher [16]).

With respect to probe characteristics, we have documented consistent effects of probe-tip roughness.
2.4.3 Some general design principles. Based on the results obtained in PROJECT IV, we propose the following general design principles:

8 Given the absence of perfect roughness constancy, designers must address how to stabilize the user's percept. For example, should forces and speeds be sensed, so that the perceptual changes could be nullified by the software? Alternately, could/should the user be sufficiently trained to maintain exploration parameters constant?

9 Designing virtual textures must be model-based. Detailed psychophysics is therefore required.

10. Point-contact haptic interfaces will likely severely constrain the haptic perception and identification of objects.

3 General Conclusions

In the current paper, we have briefly described selected aspects of a broad research program on human haptics. The results we have obtained not only contribute to fundamental theories of human haptics, but they offer a number of general design principles to those who design haptic interfaces for teleoperation and virtual environments. And finally, the cognitive approach, together with its scientific methodologies and statistical procedures, is valuable when applied to multimodal sensory interfaces that include other sensory systems (e.g., vision, audition).

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References


