Tactual Displays for Wearable Computing

Hong Z. Tan and Alex Pentland

Vision and Modeling Group, MIT Media Laboratory, Cambridge, MA, USA

Abstract: This paper provides a general overview of tactual displays (i.e., devices that communicate to a user through the sense of touch) and issues concerning the development of such displays for wearable computing. A wearable tactile directional display is presented. It takes advantage of a sensory phenomenon called 'sensory saltation' and simulates directional lines and simple geometric patterns dynamically. Initial results indicate that this information is intuitive and easy to interpret even for first-time users, and interpretations are highly consistent among observers. Several applications of this tactile directional display for wearable computing are proposed.

Introduction

A major challenge in building practical wearable computer systems is the development of displays. Much effort has been devoted to visual displays that are light-weight and high-resolution (e.g., the PrivateEyeÅ). Such efforts are warranted since visual displays are still the dominant output devices used for most computing systems. Recently, auditory displays are becoming the norm of multimedia systems in addition to visual displays. This paper is intended as an introduction to displays that communicate to humans through the sense of touch (i.e., tactual displays). Although such systems have been traditionally studied in the area of sensory substitution (i.e., tactile displays for people with visual or auditory impairments; see [1] for a review), recent advances in the area of virtual environments and teleoperation systems have made it possible to explore the use of tactual devices as general human-machine interfaces [2]. The advent of wearable computing systems presents new opportunities and challenges for tactual interfaces. The essential role of any display is information transmission. The potential to receive information tactually is well illustrated by some natural (i.e., non-device related) methods of tactual speech communication. Particularly noteworthy is the so-called Tadoma method that is employed by some individuals who are both deaf and blind. In Tadoma, one places a hand on the face and neck of a talker and monitors a variety of actions associated with speech production. Previous research has documented the remarkable abilities of experienced Tadoma users [3]; these individuals can understand everyday speech at very high levels, allowing rich two-way conversation with both familiar and novel talkers. This Tadoma method is a living proof that the human tactual sensory system is capable of high information throughput when properly engaged and adequately trained. In the general area of human-computer interfaces, however, the tactual sense is still underutilised compared with vision and audition.

The goal of our work is to extend the work on tactual displays in the areas of sensory substitution and virtual environments to the area of human-computer interfaces. Our current work focuses on the transmission of directional and simple geometric information on a user's back. Such information is salient, intuitive and always presented in the local coordinates of the user's body. It has the potential to greatly enhance existing visual/auditory interfaces in situations where visual/auditory channels are heavily loaded or where visual/auditory information is obscure. This paper provides a general background for tactual displays by highlighting a few tactual communication systems and human-machine interfaces that not only show promise in laboratory studies but also prove to be useful for a group of people sharing common interests and/or impairments. The issues concerning the development of tactual displays for wearable computing are then discussed. Finally, an example of a tactile display for wearable computing, the tactile directional display, is given to illustrate the key features that are essential for a successful wearable tactile display.

A Brief Review of Tactual Interfaces

The human tactual sense is generally regarded as made up of two subsystems: the tactile and

Personal Technologies (1997) 1:225-230

kinesthetic senses. Tactile (or cutaneous) sense refers to the awareness of stimulation to the body surfaces. Kinesthetic sense refers to the awareness of limb positions, movements and muscle tensions. The term haptics refers to manipulation as well as perception through the tactual sense. Most displays developed for sensory substitution are tactile communication systems. Most haptic interfaces used in teleoperation and virtual environment systems are force-reflective devices, and are therefore primarily kinesthetic displays. There are obvious exceptions. For example, the 'OMAR' system [4] uses stiffness as a cue to help the deaf understand speech; and researchers at the Harvard Robotics Laboratory [5] investigated the use of vibrotactile feedback to enhance the sense of reality in a virtual environment simulation.

Most tactual communication systems have been developed based on two major principles: pictorial or frequency-to-place transformation. Devices for the blind tend to adopt the pictorial approach; i.e., direct translation of spatial-temporal visual information to the skin. Thus, pictures and letters can be represented by the spatial stimulation patterns of tactile stimulator arrays. Examples of such systems are the Optacon (OPtical-to-TActile CONversion [6]), the TVSS (Tactile Vision Substitution System [7]), and the Kinotact (KINesthetic, Optical and TACTile display [8]). The Optacon (Telesensory Corp, Mountain View, CA) consists of a small hand-held camera with an array of photocells (6 columns wide by 24 rows high), and a corresponding tactile display made up with a 6-by-24 array of pins measuring 1.1 by 2.7 cm (see Fig. 1). Whenever a photocell detects a 'black' spot on a sheet of paper, the corresponding pin vibrates. Thus, the pin array reproduces the image the camera 'sees' as a 'black-and-white' pattern. Reading speed varies from 10 to 100 wpm depending on the individual and the amount of training and experience, with a typical rate of about 50 wpm [9]. Devices for the deaf are usually based on the cochlea model of speech, i.e., positional encoding of frequency information. With this model, the acoustic signal of speech is sent through several bandpass filters. The outputs of the filters are rectified and used to modulate the amplitudes of a corresponding array of vibrators. Examples of such systems range from the 'Felix' system developed by Dr. Nobert Wiener in the early 50's at the Research Laboratory of Electronics at MIT (see Fig. 2) to the modern day portable version of Tactaid VII (Audiological Engineering Corp., Somerville, MA; see Fig. 3). Research has shown that sentence perception accuracy increases from 0 to 20% for users of Tactaid VII with a typical increase of around 10% [10].

Whereas tactile communication systems developed for sensory substitution tend to focus solely on transmitting speech information, haptic

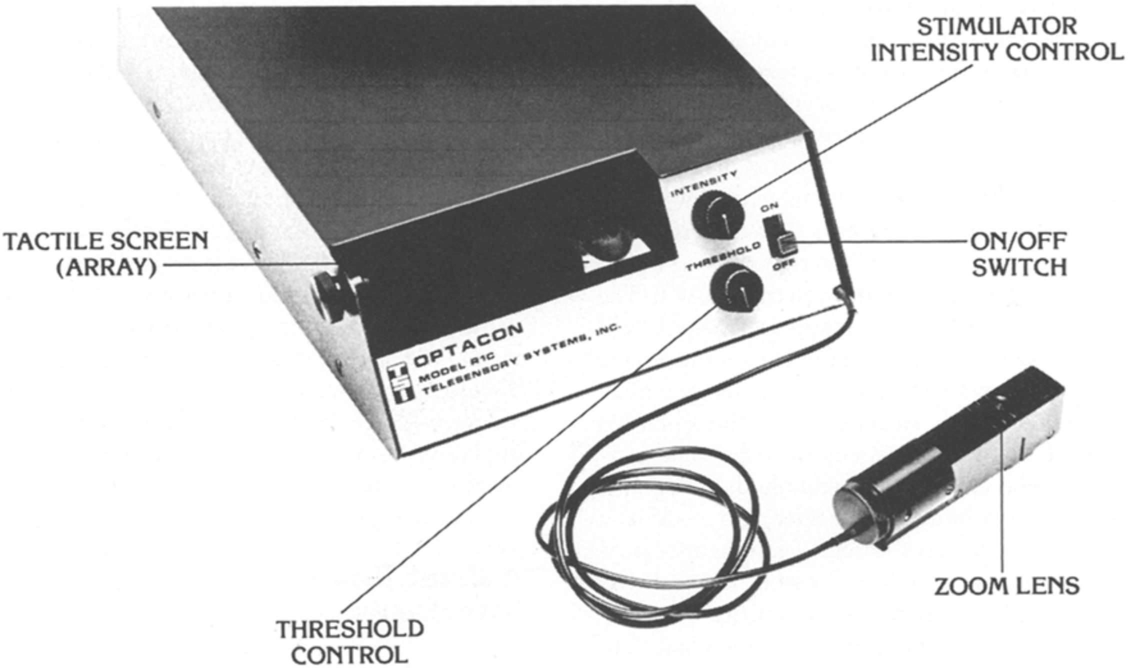

Fig. 1. The Optacon.

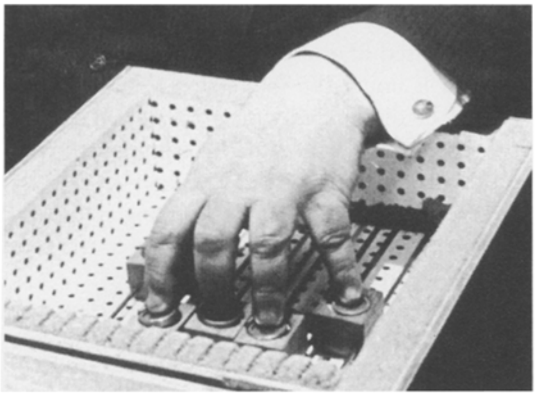

Fig. 2. The 'FELIX' system (from archives of the Research Lab of Electronics at MIT).

interfaces developed for virtual environment simulation or teleoperator systems are mostly force-reflective devices. These devices monitor the position of a contact point (such as the tip of a joystick or a stylus) and deliver a force based on the penetration of this point into a virtual object. The user of such a device experiences virtual objects through force information. An early work in this field was conducted by Margaret Minsky at the MIT Media Lab who simulated texture with a force-reflective joystick [11]. The PHANToMÅ (SensAble Technologies Inc., Cambridge, MA) and the ImpulseEngineÅ (Immersion Corp., San Jose, CA) are commercially-available force-reflective devices that have been widely used in teleoperation and virtual environment applications. Force displays enhance a user's performance (e.g., increased speed and higher accuracy), but results are highly task-dependent [12].

Considerations for Wearable Tactual Displays

The challenges to the development of tactual displays in general are two-folded. On the one hand, an understanding of the human tactual sensory system (often referred to as the somatosensory system) enables us to associate physical stimulation parameters with well-defined percepts. On the other hand, advances in technologies make it possible for us to design apparatus that can deliver desired stimulation patterns. The development of wearable tactual displays presents additional challenges and opportunities.

First of all, a wearable display has to be light-weight. This requirement makes a force-reflective tactual display an unlikely candidate for a wearable computer. Force displays are driven by motors and require a force ground. State-of-the-art devices such as the PHANToM and the ImpulseEngine are typically desk-top devices. Wearable force displays, such as the exoskeleton system developed by EXOS Inc. for NASA astronauts, requires the user to carry the weight of the structure and absorb the excessive force at body sites strapped to the device. Studies recommend that such devices be worn for no more than an hour or two due to user fatigue [14]. Vibrotactile displays use vibrator arrays that are light-weight and can be easily powered electronically. They are good candidates for wearable tactual displays given the state of current technology.

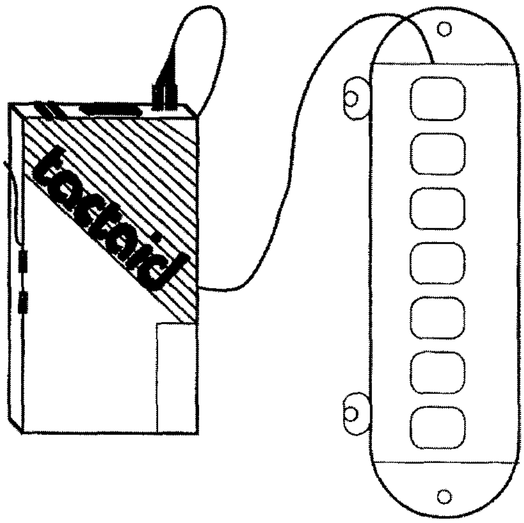

Fig. 3. The TactaidVII with its processor and the seven-vibrator array (from [13]).

Secondly, tactual displays are relatively new compared to visual and auditory ones, and the somatosensory system is usually engaged in conveying nonverbal signals. To begin with, it is best to develop tactual displays that serve as supplementary displays in wearable computers. Information such as text and graphics is still best displayed by devices such as the PrivateEye (unless, of course, that the user is visually impaired). Tactual displays are effective in conveying information in an intuitive and attention-grabbing way. For example, a little tap on the shoulder is much more effective in calling the user's attention than a text string of 'so-and-so is standing right behind you.' Increased pressure on the user's back can signal something approaching the user from behind. With careful design, it is possible to introduce tactual stimulation devices as novel informational displays that require little training on the user's part.

For users of wearable computers with visual and/or auditory impairments, tactual displays can be used to display information that is otherwise displayed visually or auditorily. The additional computational power provided by the wearable computer will greatly enhance the capabilities of currently available adaptive technologies.

A Tactile Directional Display

In an attempt to develop a light-weight tactual wearable display that can be effectively used with little training, a tactile directional display has been developed at the MIT Media Lab. The display, also called the 'rabbit' display, takes advantage of a perceptual illusion called the 'cutaneous rabbit', or more formally sensory saltation, discovered by Dr. Frank Geldard and his colleagues at the Cutaneous Communication Laboratory at Princeton University in the early seventies [15]. Our 'rabbit' display is designed to stimulate the back of a user, as this is an area that is rarely engaged by any other human-computer interfaces. It provides vivid directional cues to even the first-time observers. Preliminary results also indicate that it can be used to present simple geometric patterns.

The sensory saltation phenomenon

In a typical set-up for eliciting the 'rabbit', three mechanical stimulators are placed with equal distance on the forearm. Three brief pulses are delivered to the first stimulator closest to the wrist, followed by three more at the middle stimulator, followed by another three at the stimulator farthest from the wrist. Instead of feeling the successive taps localised at the three stimulator sites, the observer is under the impression that the pulses seem to be distributed with more or less uniform spacing from the site of the first stimulator to that of the third. The sensation is characteristically discrete as if a tiny rabbit was hopping up the arm from wrist to elbow (see Fig. 4), hence the term 'cutaneous rabbit'.

Dr Cholewiak, who participated in the original studies of the sensory saltation phenomenon at the Cutaneous Communication Laboratory at Princeton University, is studying the phenomenon in an effort to develop displays for spatial orientation for aviation [Cholewiak, personal communication, 1996] [16]. In an illuminating diagram, Dr. Cholewiak illustrated the sensation versus the actual stimulation pattern (reproduced here with modification in Fig. 5). One important feature of the cutaneous 'rabbit' is its ability to simulate higher spatial resolution than the actual spacing of stimulators, yet mimic the sensation produced by a veridical set of stimulators with the same higher-density spacing [17, 18].

The 'rabbit' display

Our 'rabbit' display consists of a 3-by-3 vibrator array with an equal inter-stimulator spacing of roughly 8 cm (see Fig. 6). An initial protocol was implemented on the back of a seat. The stimulators are based on flat magnetic speakers (FDK Corp., Tokyo, Japan) with modifications to lower its resonant-frequency region and to increase the gain [Franklin, President of Audiological Engineering Corp., personal communication, 1996]. Audio

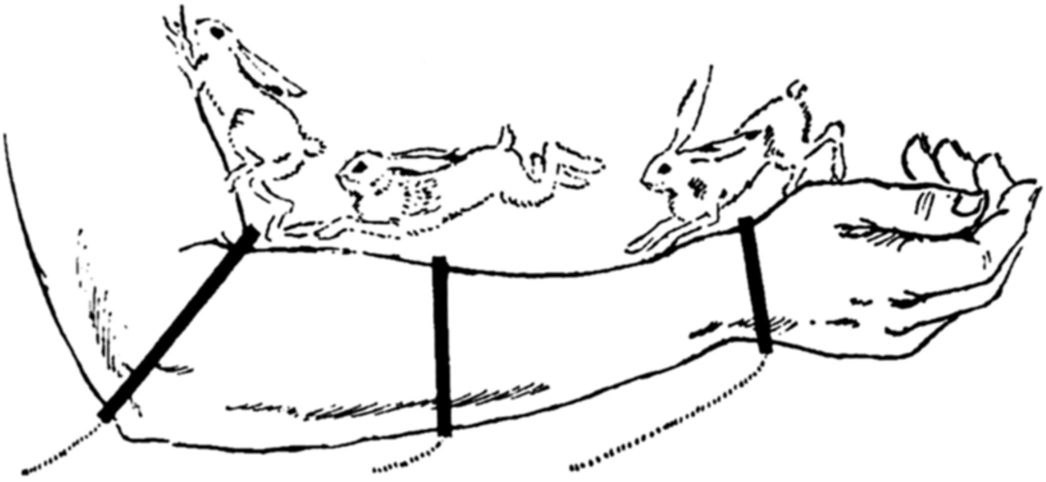

Fig. 4. A Norwegian cartoonist's illustration of sensory saltation [15].

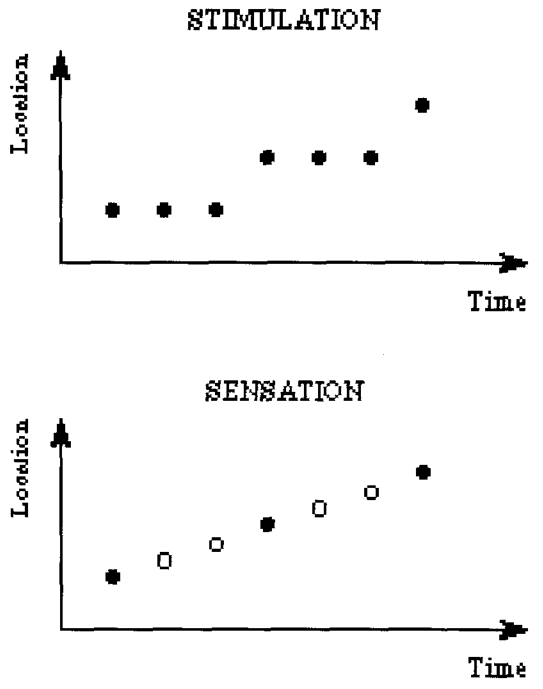

Fig. 5. An illustration of sensation vs. stimulation pattern for sensory saltation. Open circles indicate perceived pulses at phantom locations between stimulators.

power amplifiers based on LM383 (National Semiconductor Corp.) are used to drive the modified speakers. Stimulation frequency is kept between 200-250 Hz as humans are most sensitive to stimulation around this frequency range.

Studies of the sensory saltation phenomenon usually employ a linear array of stimulators that induces sensations such as the length or straightness of a line [3–5]. As far as we know, our 'rabbit' display is one of the first few two-dimensional stimulation arrays that has been constructed to explore the cutaneous rabbit. Initial tests have already shown some interesting new results.

The sensation

At an informal test, about a dozen people were asked to try out the 'rabbit' display. The observers were not aware of the sensory saltation phenomenon. One pattern consisted of three pulses sent to stimulator #8 (see Fig. 6), followed by three pulses sent to #5, and followed by another three sent to #2. Most observers commented on a sensation of 'something crawling up the spine.' When asked how many pulses were felt, most gave an answer between 6 and 8 and indicated a perception of pulses in-between stimulator locations. This is quite consistent with the classical definition of the sensory saltation phenomenon. In a two-dimensional pattern, three pulses of each were sent sequentially to stimulators in the order of #1, #2, #3, #6, #9, #8, #7 and #4. Instead of feeling a square, most observers reported that they felt a circular pattern. This was an interesting finding and its interpretation awaits further investigation of the sensory saltation phenomenon, especially in the case of a two-dimensional stimulator array.

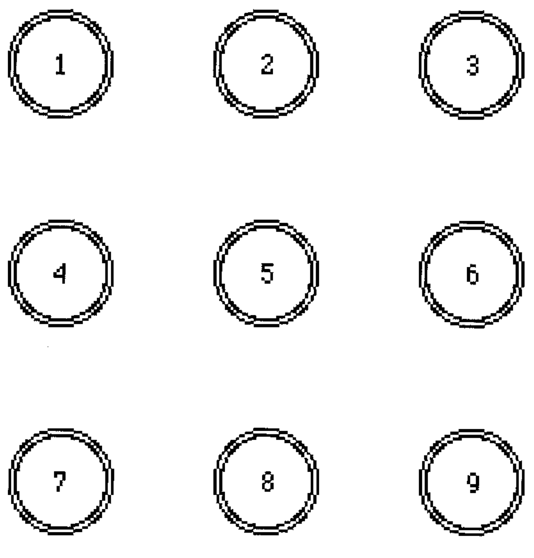

Fig. 6. Layout of the two-dimensional 'rabbit' display.

Summary

This paper has presented a general review of tactual displays. In addition, a description of a tactile directional display designed for wearable computing has been given. The two-dimensional 'rabbit' display has many features that make it an attractive candidate for displaying directional and simple geometric patterns to a user of wearable computers. Its light weight permits it to be sewn into a piece of clothing (e.g., a vest) and worn by the user all the time. It uses the back of the user as the stimulation site and doesn't compete with other sensory channels that are normally engaged during daily activities including computer work. It elicits vivid movement sensation (up, down, left, right, upward or downward along a line of 45∞ or – 45∞ incline). Because it takes advantage of the sensory saltation phenomenon to induce directional sensation instead of 'printing' a pattern statically, it doesn't suffer from sensory adaptation (i.e., the sensation wears off after a period of time, such as the awareness of one's own clothing). The directional cues are intuitive and relative to the user's own body coordinate, thus, requiring no additional coordinate transformation. Although the stimulators are sparsely spaced, the user's perceptual illusion fills the gap in-between and, thus, produces a mental image whose spatial resolution can be manipulated by the number of pulses sent to individual stimulators. The fact that a circular pattern can be perceived suggests that other patterns might be 'drawn' as well.

In an implementation of driving simulation, a vest-based wearable version of our two-dimensional 'rabbit' display is worn by the driver. It maps information about the surrounding traffic condition onto the back of the driver and delivers warning and guidance signals for navigation. This system demonstrates the feasibility and effectiveness of wearable tactile displays. Application of such a display for the blind is self-evident. With a global positioning system (GPS), the 'rabbit' display can be used to help the blind navigate through unfamiliar spaces using a map accessible through the wearable computer. It has also been reported that many aeroplane accidents are due to pilot's loss of spatial orientation during complicated manoeuvres. Thus, a pilot vest that is always there to indicate 'up' has the potential of saving lives [Cholewiak, personal communication, 1996]. One can also imagine using such a display to direct the traffic during a public gathering such as a conference. Most conference attendees are unfamiliar with the layout of a new conference space. It is conceivable that a user can enter the name of a room or the title of a talk and let the wearable tactile display guide the way to the meeting room. The possibilities of displaying geometric patterns and using them to encode useful information is still very much a research topic at this time.

Acknowledgements

This work has been funded by the Things That Think Consortium at the MIT Media Laboratory. The authors wish to thank Ifung Lu and Pietro Russo for their assistance with the tactile directional display.

References

1. Geldard FA (Ed.). Cutaneous Communication Systems and Devices, The Psychonomic Society, Inc., 1973.
2. Durlach NI and Mavor AS (Eds). Virtual Reality: Scientific and Technological Challenges. National Academy Press, Washington, D.C., 1994.
3. Reed CM, Rabinowitz WM, Durlach NI, Braida LD, Conway-Fithian S and Schultz MC. Research on the Tadoma method of speech communication, Journal of the Acoustical Society of America, 1985; 77(1): 247–257.
4. Eberhardt SP, Bernstein LE, Barac-Cikoja D, Coulter DC and Jordan J. Inducing dynamic haptic perception by the hand: system description and some results, Proceedings of ASME Dynamic Systems and Control, 1994; DSC-55(1): 345–351.
5. Wellman P and Howe RD. Towards realistic vibrotactile display in virtual environments, Proceedings of the ASME Dynamic Systems and Control Division, 1995; DSC-57(2): 713–718.
6. Linvill JG and Bliss JC. A direct translation reading aid for the blind, Proceedings of the Institute of Electrical and Electronics Engineers, 1966; 54: 40–51.
7. Bach-y-Rita P. Brain Mechanisms in Sensory Substitution, Academic Press, New York, 1972.
8. Craig JC. Pictorial and abstract cutaneous displays, In F. Geldard (Ed.), Cutaneous Communication Systems and Devices, 1973; 78–83.
9. Craig JC and Sherrick CE. Dynamic tactile displays, In W. Shiff and E. Foulke (Eds.), Tactual Perception: A Sourcebook, Cambridge University Press, 1982; (6).
10. Reed CM and Delhorne LA. Current results of field study of adult users of tactile aids, Seminars in Hearing, 1995; 16(4): 305–315.
11. Minsky M, Ouh-young M, Steele O, Frederick P, Brooks J and Behensky M. Feeling and seeing: Issues in force display, Computer Graphics (ACM), 1990; 24(2): 235–243.
12. Burdea GC. Force and touch feedback for virtual reality, John Wiley & Sons, Inc., New York, 1996; (9).
13. Weisenberger JM and Percy ME. Use of the Tactaid II and Tactaid VII with children, The Volta Review, 1994; 96(5): 41–57.
14. Tan HZ, Srinivasan MA, Eberman B and Cheng B. Human factors for the design of force-reflecting haptic interfaces, Proceedings of the ASME Dynamic Systems and Control Division, 1994; DSC-55(1): 353–359.
15. Geldard FA. Sensory Saltation: Metastability in the Perceptual World, Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1975.
16. Cholewiak RW, Sherrick CE and Collins A. Studies of saltation, in Princeton Cutaneous Research Project, Princeton University, Department of Psychology, 1996; 62.
17. Cholewiak RW. Exploring the conditions that generate a good vibrotactile line, presented at the Psychonomic Society Meetings, Los Angeles, CA, 1995.
18. Collins AA. Presentation at the Tactile Research Group Meeting of the Psychonomic Society Meetings, Oct. 31, 1996.

Correspondence and offprint requests to: Hong Z. Tan, Vision and Modeling Group, The Media Laboratory, Massachusetts Institute of Technology, Room E15-383, 20 Ames Street, Cambridge, MA 02139, USA. Email: {hongtan, sandy}@media.mit.edu