Touch

In User Interface Navigation

David V. Keyson

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Keyson, David Victor

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David Victor Keyson.

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1

Introduction

Though few may doubt the intrinsic value of touch perception in everyday life, one is hard pressed to find examples in modern technology where human-machine communication has utilized the tactile and kinesthetic senses as additional channels of information flow. What little touch feedback did exist in early analog technologies through mechanical mechanisms such as knobs and dials has been largely replaced by digital electronics and visual displays. Human-computer interfaces have also shifted, from purely textual to graphical and spatial representations of information. These changes have led to increasing amounts of visually presented information and thus higher demands on the human visual systems.

In considering how touch information can be applied to the user interface, towards reducing demands on the visual system, empirically-based knowledge on human touch perception as well as novel interaction concepts and technologies are required.

1.1 Background

The lack of auditory and touch information in human-computer interaction may be largely attributed to the emergence of the graphical user interface as the de facto-standard platform for supporting human-computer communication. Graphical concepts such as windows, the mouse and icons date back to the Xerox Star of the early seventies. Even the universally accepted mouse, which utilizes human motor skills, exploits primarily visual feedback. This is in contrast to the sense of touch feedback in grasping real objects in everyday life. In short, to be successful, new human interface technologies, utilizing more than the visual sense alone, will not only have to demonstrate performance gains but will also have to be integrated with existing graphical user interface styles in a compatible and consistent manner.

In thinking about applying lessons from touch interaction in everyday life to human-computer interaction, the aspect of navigation emerges as a central area. A sense of navigation, knowing where you came from, where you are and where and how you can go to a point, is critical in working with any human-computer interface that utilizes spatial layouts of information and controls. In everyday life, visually impaired people use their sense of hearing and touch as well as internal spatial representations to navigate through complex spaces. Though less apparent, sighted individuals also use touch perception in navigation. For example, consider the act of skiing, which requires constant judgement of ground texture and judgement of force information to gauge movements, or driving a car, where being able to feel road conditions is critical to control. In a virtual context, touch information can be presented as force fields which are designed to assist navigation. For example, the sense of being pulled by the hand, following a path, hitting a wall, climbing a hill, falling in a hole, or feeling a texture, can be used to guide user movements and act as a source for additional qualitative-spatial information.

Given that the current research is concerned with assisting the sighted user, instances where visual attention is heavily loaded or where the user could be engaged in two or more simultaneous tasks will be considered. In fact, navigation in everyday life occurs typically while we are doing something else and frequently involves more than one modality. For example, think of reaching for a cup of coffee while engaged in a conversation with almost no shift in eye contact and attention. Closer to human-computer interaction is “touch typing”, which implies memory and recall of keyboard button positions and the use of tactile feedback with minimal visual peripheral information.

1.2 Plan of the chapter

After a description of the main research question and goals, the terminology used throughout this dissertation will be explained. A brief phenomenological review of touch perception and an overview of the subsequent chapters will then

be presented. Given the range of studies, relevant literature pertaining to each area of investigation will be presented within the chapters.

1.3 Research question and goals

The general questions underlying this dissertation were: (1) how can tactual information be applied in the user interface to improve cursor-based movement performance, (2) can internal spatial representations, including distance and orientation, be formed in the absence of visual feedback, and (3) can touch information be used to enable navigation to be performed as a concurrent rather than sequential task?

Several objectives were developed to address the research questions, namely: (a) to contribute to scientific knowledge pertaining to relevant human perceptual and motor capabilities in touch interaction, (b) to develop a range of touch navigational-fields that reflect "real world" physical variables, (c) to create design methods and tools for the rapid construction and evaluation of user interfaces with touch fields (d) to apply and test theories in experimental and applied settings, and (e) to develop new input devices with touch feedback. Each of these goals can be placed along a continuum, from acquiring knowledge on human perception to developing new technologies and applications. Particular emphasis was placed on conducting empirical studies across a broad range of topics, given the lack of basic research pertaining to touch perception using force feedback and experimental work on touch in human-computer navigation.

1.4 Terminology

Few people engaged in daily activities realize that their touch perception is based on two fundamentally different perceptual mechanisms being the cutaneous and kinesthetic senses. These two senses work closely together, especially when touch through movement is involved (Loomis and Lederman, 1986). Viewed functionally, the cutaneous senses provide awareness of stimulation of the outer surface of the body by means of receptors within the skin and the associated nervous systems. Cutaneous sensations are triggered by three main groups of receptors: mechanoreceptors (sensitive to skin stretch and vibration), thermoreceptors (sensitive to temperature changes) and nociceptors (sensitive to pain) with at least 15 morphological and functional distinctions (Iggo, 1982). The kinesthetic sense provides the observer with an awareness of static and dynamic body posture on the basis of (1) afferent information originating within the muscles, joints and skin and (2) efference copy, which is the correlate of muscle efference available to the higher brain centres (Von Holst, 1954). A detailed description of the motor and the touch senses can be found in Keele (1986) and Loomis and Lederman (1986), respectively.

Though often used in a broad context, tactile perception refers to perception mediated solely by variations in cutaneous stimulation while the observer's

posture remains constant. Where movement is involved, the term haptic perception is used, whereby both the cutaneous sensitivity and kinesthesia convey information about distal objects and events. Tactual perception has been employed in literature as a general term to refer inclusively to all perception mediated by cutaneous sensibility and/or kinesthesia (Loomis and Lederman, 1986). Thus within this dissertation an explicit distinction in usage is made between the terms tactual and tactile.

1.5 Phenomenology of touch

Historically, touch was considered to be a very important sense (Berkeley, 1709). Sensations of extension and resistance obtained via touch were regarded as critical in developing the concept of external objects (Brown, 1838). “If priority of sensation alone were to be regarded, the sense of touch might deserve to be considered in the first place; as it must have been exercised long before birth, and is probably the very feeling with which sentient life begins” (Brown, 1838). Aristotle and the Stoic philosophers held that touch mediates every type of sense perception, even vision (Siegel, 1970); invisible particles bombard various surfaces of the body to convey smell, taste, and sound. Katz (1925) was recognized by Gibson (1962) for considering phenomena in active (haptic) touch. The historical prominence of touch is also evident in the way touch-related words have been extended to other modalities, as in “sharp tastes,” “dull sounds,” and “soft colours.” Rarely does the reverse occur; we never speak of “loud or fragrant touches” (Williams, 1976).

The phenomena of externalization of experience in spite of subsidiary awareness is central in considering the potential for virtual tactual displays to transparently communicate “everyday tactile experiences”. Katz (cited in Krueger, 1982) observed that frequently when the skin is touched the perceptual experience is of an object external to the perceptual boundary of the body. For example, when one probes a surface using a stylus held in the hand, one’s awareness is not of the vibrations felt in the hand, but of the surface being explored. Similarly, when one stirs a viscous fluid, one has the experience of fluid at the end of the stirring rod rather than of sensations per se in the fingers, joints, and muscles. Katz observed that both the touch and the visual senses vary in the degree to which the resulting percepts are experienced as part of the self (“phenomenally subjective”) or external to the self (“phenomenally objective”). Vision was considered the most object-sided sense, since most visual experiences are referred to as perceptual space beyond the body itself. Interoceptive senses such as hunger, thirst and pain were regarded at the other extreme as “sensations” within the phenomenal body. The sense of touch was considered to be intermediate between vision and interoceptive senses in terms of how often perceptual experiences are referred to either the subjective or objective pole¹. Katz observed that the objective pole dominates for the moving body part and

the subjective pole for the stationary part. This can be observed by moving one fingertip over another. By combining vision and touch, the “externalization” of tactual experience becomes especially compelling (Krueger, 1970), presumably because vision, which is the more object-sided of the two senses, dominates over touch. For example, when one touches an object with a probe while viewing the tip of the probe, one “feels” the probe making contact almost as if it were one’s fingertip (Loomis and Lederman, 1986).

Despite the wealth of early phenomenological detail on touch perception, relatively modest progress in the understanding of the touch senses has been achieved since Katz (Taylor, Lederman, and Gibson, 1973). This may be partially attributed to lack of off-the-shelf technologies for conducting touch research, as may also be the case for studies on taste and smell perception. Studies have been largely limited to cutaneous perception using vibro-tactile arrays such as an Optacon (optical-to-tactile converter). However, the use of force feedback devices in telerobotics and virtual reality has renewed interest in the study of tactual perception and in the context of multisensory interaction (e.g. Durlach and Mavor, 1995).

In some ways human experiences relating to tactual perception can be extended using force feedback displays. For example, climbing up a hill is associated with an increase in muscular effort while descent requires a braking effort. This experience will be the same regardless of the direction in which the hill is approached and descended. Virtually, this experience can be simulated by a circular area where unidirectional forces are applied from the centre of the area such that more effort is required to reach than leave the centre. Assuming a hand-controlled device is used, lifting the hand off the device would cause a movement similar to falling. What is actually occurring in this example is a perceptual translation of force information into height information based on associations with common experience. For a ball-based device controlled by motors, this translation process was observed to occur rapidly with no or minimal external interference (Section 7.1).

1.6 Overview of chapters

In Chapter 2 a classification of technologies for kinesthetic and tactile feedback in human computer interaction is presented, including a description of the technologies developed within the course of the current research work. A rapid prototyping tool for creating and evaluating experimental interfaces will then be described, including informal trials of navigational touch models. Chapter 3 deals with the directional sensitivity of the hand and fingerpad, as input channels for directional cues and the discrimination of trackball-produced forces as a key mechanism underlying the discrimination of tactile forms. In Chapter 4 perform-

¹In German vision and hearing are categorized as far senses (Fernesinne) while touch and smell are grouped as near senses (Nähesinne).

ance gains using tactile feedback and dynamic cursor gain in target acquisition will be considered. Attentional aspects in responding to kinesthetic directional cues while performing a visually demanded task will be considered in Chapter 5. Chapter 6 covers work on the internal spatial representation of simple tactually presented forms, as examined through a mental rotation task and the estimation of felt path lengths, including the influence of friction during movement. Lastly, conclusions and future directions for research will be described in Chapter 7. Particular emphasis will be given to touch feedback in navigation from a multi-modal perspective.

2

Force Feedback Technologies and Design Concepts

In recent years a number of new force feedback and tactile technologies have been introduced by companies involved in the design of VR (virtual reality) systems. Despite the technology push, research work relating to the use of touch in human-computer interaction has lagged far behind. This may be partially due to the emphasis on force feedback technologies for VR applications, which typically involves grasping and manipulating objects in space, as contrasted to the use of touch in more explorative and movement based tasks such as navigation.

After a review of current force feedback and tactile technologies, including those developed in the course of the present research, the importance of software and design tools in modelling and creating tactual interfaces will be discussed. The design tool TacTool which was developed to support the current research will be described¹. The tool enables rapid prototyping of tactual navigational interfaces and modelling of new touch fields.

¹ Keyson (1994), Keyson and Tang (1995)

2.1 Touch technologies for human-computer interaction

Broadly speaking, touch and force feedback systems can be classified as: (1) ground-based platforms, including hand controllers such as a trackball, joystick, or mouse, (2) body-based, exoskeletons devices which fit over and move with the limbs or fingers of the user and (3) tactile displays for fine cutaneous contact.

2.2 Ground-based controllers

Ground-based controllers typically offer between one and six degrees of movement or freedom (DOF) and are affixed to the ground or a work surface. Such devices are particularly well suited for engaging touch objects while moving through a felt space. In simulating the tactual sensation of pushing and pulling an object, the force equilibrium of the user-to-object interaction requires that the device be attached somewhere. This is in contrast to simulating the effect of squeezing, exploring or manipulating an object in virtual space where equal and opposite forces may be imposed at multiple regions of contact. In such cases the touch interface need not be mechanically grounded.

Most ground-based tactual feedback technologies provide force feedback for movements while using the hand and arm as contrasted to the fingers. For example, Akamatsu has developed a mouse-like device with force feedback using electromagnets mounted under the mouse, which moves on a metal plate and a solenoid pin under the finger for kinesthetic feedback (Akamatsu, MacKenzie, & Hasbrouq, 1995). Hand-arm operated tactual feedback devices involve two major drawbacks. First, higher levels of force feedback are required for operating hand-arm systems as compared to finger controlled devices, due to the higher force output potential of the hand and arm. For example, in the mouse developed by Akamatsu touch fields can hardly be felt at relatively faster movement control rates. The force feedback, produced by small electromagnets under the mouse, is not sufficient to overcome the inertia in hand-arm movements (based on personal observation). Secondly, the high tactile sensitivity in the fingerpads for interpreting touch signals combined with the potential for fine finger-based movement control, supported by force feedback, is not fully utilized. However, a primarily-finger and partially-wrist based controlled device such as a trackball with force feedback lacks in proprioceptive-spatial feedback from arm and hand positions as compared with mouse devices.

In Appendix B a table showing a number of ground-based controllers is presented along with key technology aspects. These technologies can be grouped into two main categories, passive and active technologies. Passive device can sense the amount of force exerted by the user, while active devices produce force feedback. Many of the early devices were built for research; however, in recent years virtual reality companies have begun to market ground-based systems (e.g. Immersion Corp., Cybernet Systems & EXOS Inc.) Given

the rapid pace which new force feedback technologies are being introduced, the Internet serves as a good information point for new devices.

2.2.1 IPO force feedback devices

The IPO ground-based force feedback technologies are mainly motor-based devices with one to three degrees of movement freedom (DOF). The one-DOF devices are rotary dials utilizing either motor- or electromagnetic-based force feedback. The two-DOF devices are trackballs devices. Force feedback is created in a two-dimensional x and y plane, using two motors positioned along the ball axes. The three-DOF device is a trackball similar to the two-DOF unit. The two-DOF ball-motor unit can be moved in the z coordinate (i.e., up and down) with force feedback.

Rotary dials

Rotary dials and other analog controls were in the past commonly used in professional (e.g. oscilloscopes) and consumer equipment (e.g. early car radios). In recent years many traditional dials and knobs in professional and consumer equipment have been replaced by push-buttons, which enable multi-functional control and thus require less space. The key advantage of a rotary dial with tactual feedback is that the felt characteristics of the dial can be dynamically changed depending upon the application. Thus multiple functions can be distinguished using a single dial. For example, a demonstration was built at IPO (by Haakma at IPO) using a single rotary knob with motor force feedback to control a radio. Radio stations and signal strength were felt as notches, the current balance setting was felt as a single notch, and volume was felt as a rotational spring force. In this manner the user could feel and change the current dial function without looking at a visual display, while the force feedback assisted in locating pre-sets and radio stations. During the course of the present research, work was conducted with Philips Research Labs in Eindhoven, which led to the design of a low-power, low-cost, force feedback dial using electromagnets rather than motor forces. An electromagnetic field was created around the motor shaft of a dial with optical position sensors and a digital potentiometer. A prototype device was built for the Electron Microscope of Philips Electron Optics. While working in the dark, operators can feel whether they are in a fine or coarse focus mode, via the distance in degrees between each software-generated tactual notch. For most applications the simple electromagnetic rotary dial may be sufficient. End-stops and notches can be felt by distance and intensity, though feedforward or force fields which are greater than the total force exerted by the user (e.g. a spring force) are not possible.

Mechanical structure of 2-DOF Trackball

The IPO trackball with 2-DOF was used throughout the experiments described in this dissertation as a motor input and tactual output device. The basic mechanical design of the original IPO trackball (Engel, Haakma & Itegem; Philips patent, 1990) is depicted below in Figure 1. The ball rests on a single ball-bearing ring. At the end of each motor is an optical position sensor, with a resolution of 1060 dots per revolution, and a rubber-rimmed wheel which presses against the ball. Opposite each motor driven wheel, is a free-rolling support wheel. The orthogonal position of the motors against the ball creates a two-dimensional force plane as described in Appendix A.

Figure 1. Mechanical construction of the force feedback trackball.

Electronic hardware of 2-DOF trackball

The electronic hardware of the trackball is depicted schematically in Figure 2. The central control unit is a personal computer (PC). Two I/O cards, a digital-analog converter (DAC) and an analog-digital converter (ADC) enable communication between the PC and trackball. The torques produced by the motors depend on the voltages applied to the motors. Two independent power amplifiers produce the voltages for the x and y motors. The derived voltage setting is based on a set point value. The set point value is a two-element vector variable and is interpreted by the DAC converter. The amplifier cards were modified for the present research to provide constant forces, independent of ball rotation speeds.

To support the current research, several modifications were also made to the design of the original IPO trackball with assistance from the IPO workshop. Two additional wheels, with optical position sensors, were placed opposite the x and y motor shafts to ensure fine movement control and monitoring of ball position independent of motor shaft positions. Other modifications included a double bearing under the ball to reduce friction and improve smoothness of rolling. Tension screws were added to control for wheel contact forces on the ball. A contact switch was also mounted under the bearing system to enable object selection by pressing down on the ball (Figure 3).

Figure 2. Hardware configuration of the 2-DOF force feedback trackball.

Miniature Trackball with Force Feedback

During the course of the current research a low-cost version of the 2-DOF trackball was developed, together with Philips Research Labs and New Business Creation, as an early commercial prototype. Small motors from a CD-ROM player for PCs were placed along the x-axis and y-axis of a Logitech trackball. Control hardware similar to that of the full-size trackball was used, except that the power was supplied by the PC. Future versions will include ADC and DAC circuits within the trackball unit and will connect to a standard Serial port. Users will thus require no special hardware.

Figure 3. Modified trackball with force feedback.

The 3-DOF trackball

The IPO 3-DOF trackball was developed in the latter course of the current research (Keyson, 1995) as a device for exploring navigation in 3-D visual spaces with 3-D force feedback. For example, the perception of depth as a function of ball height and applied force could be studied. As depicted in Figure 4, the mechanical assembly around the ball is similar to the 2-D trackball described above. The entire x and y motor structure, including the ball, is mounted on a vertically hinged spring-counter weighted metal plate which is controlled by an additional motor and optical position sensor unit. The x and y motors are positioned below the ball axis to maximize the ball height and thus finger contact surface area. The users can rest his/her wrist on the Plexiglas surface while moving the ball in the x, y and z directions. To support future research on the influence of larger ball sizes on tactual perception, the distance between the motor wheels and the ball can be adjusted to accommodate ball sizes from 56-mm to 120-mm diam. As depicted in the close-up view in Figure 4, a variable ceramic-based force sensor is positioned under the ball to enable switching between vertical (z) direction and x and y directions.

Figure 4. The 3-DOF Trackball with force feedback.

After the control PC has been booted up, the ball is positioned fully upwards. To move downwards or upwards (i.e. z-direction) the user pushes on the ball with a force level above a pre-set threshold value (e.g. 0.5N). At this point the ball tends to float upwards and follows the hand in the vertical direction. When the user stops moving in the z direction for a preset interval (e.g. 500 msec) the ball locks at the current height. The trackball can then be moved in the x and y directions with 2-DOF force feedback. After a 500-msec delay, the force sensor under the ball, for interpreting user intent to switch to movement in the z direction, is activated. This delay period prevents unintended selection of a z position. In theory, force feedback at various levels of z movement could be given by the third motor; this would create a sense of steps as one moves downwards and would simplify selection of a given z position. The motor control program has yet to be fully expanded to realize this potential. The basic control hardware of the 3-DOF trackball is identical to the 2-DOF trackball with the addition of a third motor and the variable force sensor.

3-DOF Trackball Pilot Study

A pilot study was conducted to evaluate the control method for the 3-DOF track-

ball, with 12 paid adults with little to no computer experience and a mean age of 31. A mock-up of Microsoft Windows 3.1 was created under DOS. Six to three windows, each appearing as an empty MS Windows shell, with a letter label (A-F) in the title bar, were aligned on top of each other. The active window appeared at the top of the stack. To reach a target window, users pressed down on the trackball from within the active window which caused the brake force for trackball movement in the z direction to be released. Users then navigated through the stack in depth by lightly lifting their hand or by pressing downwards on the ball. To select the target window users were instructed to briefly refrain from movement in the z-direction. The ball locked in the z-direction after a minimal period (500 msec) of no up or down control movement. The selected window was then immediately placed at the top of the stack and the ball returned to the fully raised position to reflect the new position of the activated window. This method of window selection required no window “thrashing” (i.e. changing the size or selecting and moving windows) to reach an underlying window. In the control condition the ball was locked in the fully upward position and users manipulated the windows using a selection button mounted on the Plexiglas to select and resize or move windows. The cursor position was controlled by user movement of the trackball in the x and y directions. Preliminary results indicated that, despite the absence of force feedback in the vertical directions, or, simply put, the feeling of steps when encountering a window level, the subjects preferred the 3-D windows control over windows-like manipulation and were able to locate window levels at a faster rate. A formal study in the future should include force feedback in the z direction (thus reducing visual load) as well as comparisons with key-board alternatives (e.g. Alt-Tab) and mouse-based devices which feature a rolling dial for switching between windows. To support further research using the 3-DOF trackball, many of the navigational touch fields contained in the design tool TacTool (described later in this chapter) could be expanded to include a physical height dimension.

2.3 Body-based controllers

Body-based force feedback exoskeletal devices are characterized by the fact that they are designed to fit over and move with the user’s limbs or fingers. Because they are formed to and move with the arms and hands they monitor and stimulate, they have the advantage of the widest range of unrestricted user motion. As position-measuring systems, exoskeletal devices such as the VPL DataGlove and DataSuit are relatively inexpensive, in terms of VR technologies, and are comfortable to use (Durlach & Mavor, 1995). However, providing high-quality force feedback with such devices that is commensurate with the human resolution is currently not possible. Further work in the area of actuator size minimization and control bandwidth is needed (Durlach & Mavor, 1995). Despite the limited tactual quality of exoskeletal devices, work can be found utilizing the

devices across a broad range of applications. For example, Bongers (1994) experimented with the use of small strands of nickel titanium alloy (Tactors, Mondo-tronics) to create a sense of touch feedback in playing a string-based synthesizer. The Tactors, which produced a pulsating effect while energized, were mounted in gloves. A review of exoskeletal devices and design issues, including both human factors and technology, can be found in Shimoga (1992).

2.4 Tactile displays

Over the past decade tactile display systems have been largely developed for conveying visual and auditory information to deaf and blind individuals (Bachy-Rita, 1982; Reed et al., 1982). Formats for tactile stimulators include: miniature solenoids or tiny strands of heat sensitive metal which can drive a small pin against the skin when energized (e.g., TiNi Alloy Company's Muscle Wire devices), piezoelectric buzzers/voice coils (vibro-tactile) and pneumatic air-bladders which aim to provide contact feedback on inflation (e.g. the Teletact II device). Tactual arrays with moving or vibrating pins are commonly used in research involving the visually impaired. The Optacon (optical-to-tactile converter), marketed by Telesensory Systems, and the Bagej Corporation tactile stimulator belong to this class. Similar to the Optacon, a matrix of 64 piezoceramic reed benders for presenting complex spatiotemporal patterns to steeply contoured skin surfaces was developed by Cholewiak and Sherrick (1981). A highly complex array of miniature solenoids was developed by Weber, which enabled the display and manipulation of MS Window icons (Weber, Kochanek, Homatas, 1993). Several devices have been developed in research to measure tactile acuity including moving brushes, water jets, and a trackball-driven point (see Section 3.1.3). Adam, Keyson and Paas (1996) combined an array of contact switches with voice coils to study vibro-tactile reaction times between fingers on one and two hands.

More recently, research into tactile systems for the control of remote manipulation arms, which can convey information on texture and slip, has led to new technologies. A number of techniques are used to convey touch contact information. Shape-changing displays are used to convey the local shape of contact by controlling the deformation of forces distributed on the skin. This has been accomplished by an array of stimulators actuated by DC solenoids (Fisken-Gibson et al., 1987), shape memory alloys such as nickel titanium which assumes different forms at different temperatures (TiNi, 1990) and compressed air. The use of a continuous surface actuated by an electrorheological fluid has been proposed by Monkman (1992).

2.5 Software and design issues for tactual displays

Tognazzini (1992) stated about four years ago "we will undoubtedly see commercially available force feedback devices added to visual interfaces, letting

users directly feel as well as see the objects on the display...consider feeling the cell walls as you slip from cell to cell in your 1995 spreadsheet application". While such hardware is now available to some degree (Appendix B), application software and design tools are lacking. This situation may be attributed to several factors. First, new interaction styles may be considered too risky given the large investment in visually-based applications. Secondly, like force feedback hardware, software has been developed for VR applications within the context of teleoperation and controlling of autonomous robots. For example, the PHANTOM interface developed in the MIT Artificial Intelligence Laboratory has been used to tactually display the forces of contact of a stylus held in the user's hand with a variety of static and dynamic virtual objects in synchrony with visual images of objects and their motion (Durlach and Mavor, 1995). Some exceptions to software development for VR-based devices can be found. For example, EXOS Inc. is marketing a power joystick with software that builds on the Windows 95 Application Program Interfaces (APIs) for joysticks². Third, those few researchers who have been working on non-VR applications for tactual feedback, such as systems for the visually impaired, have focused mainly on building new hardware rather than on cognitive issues.

In considering the design of software and tools for touch navigational interfaces, the modelling of individual tactual fields and their physical properties, as well as a flexible simulation environment, are necessary. While individual fields can be considered in terms of a desired effect on movement behaviour, a navigational test environment is needed to consider issues such as spatial layout between tactual objects and interactions. Additionally, the test environment should support the integration of multi-sensory feedback for navigation. Given that areas can be explored through touch beyond a visible screen region, the area in which objects are placed and interacted with, should be a seamless or virtual space. In the following section a tool which embodies both the modelling of tactual fields and the environment in which they act will be described. The tool also served as a database for fields developed in the course of this research.

2.6 TacTool: a rapid prototyping tool for multisensory interfaces

2.6.1 Introduction

Recent advances in auditory and tactual display technologies for human-computer interaction have created new opportunities for enriching visual interfaces. Given the complexity of multi-modal interaction, development techniques are needed which can support the rapid prototyping and assessment of new designs. Rapid prototyping theory and methods, in support of user interface design, have been developed largely over the past decade with the availability of software

²Note: Microsoft recently announced the acquisition of EXOS Inc.

tools (Keyson and Parsons, 1990).

While some researchers have sought to demonstrate that tactual information can be programmed into an existing graphical user interface (e.g. Ramstein and Hayward, 1994), such methods leave little room for exploring new paradigms of human-computer interaction. When tactual features are hard-coded into an interface, the user and designer are left with few options for customizing the “feel” in the “look and feel” of a system. In this section, a flexible and object-oriented approach to designing interfaces with tactual feedback will be presented. Tactual feedback can be treated as a cursor-sensitive or a workspace-related attribute with object characteristics similar to working with a screen background graphic and one or more foreground graphics.

Of central interest in the current design approach is the study of user interface navigation, whereby tactual information is used to guide the user while enhancing his/her sense of spatialization. For example, by feeling a path on the screen towards a felt “trash can” object, the user can simply dump a document while viewing the contents of the next file. The user’s movement is thus guided without a substantial cost to visual attention. The perception of available space could be increased for example by providing a directional pulling force at the edge of a window. In this sense, the potential for tactual feedback in an interface may be greater in systems which permit navigation in a virtual space in contrast to within a window region, as the user can feel what he/she cannot see.

The potential for tactual feedback in navigation may be more evident in systems which consider navigation as a parallel rather than a sequential activity (Keyson, 1994). In particular, simple control movements should be possible without interrupting attention. Think of picking up a cup of coffee while engaged in a conversation. Once you know where the cup is, you can feel where it is and pick it up without disturbing your conversation. Thus, investigations into the potential of tactual feedback, as related to user interface navigation, should include applications in which basic motor navigational movements can be separated from visually or otherwise demanding tasks.

2.6.2 TacTool Concept

The TacTool design environment was developed to serve as a database for storing and retrieving individual tactual fields and groups of tactual objects which can be stored as tactual navigational models. Tactual objects with iconic representations are referred to herein as TouchConsTM³. TouchConsTM can be grouped and nested, using direct manipulation, to create new complex fields. TacTool, written in C++, is a stand-alone application that can also be ported to other applications. In “edit mode”, the user selects and applies tactual fields from a visually displayed tool box. In “run mode” the tactual fields can be felt. Field names such as “hill”, “path”, “hole”, and “wave” are used, given their

³Note: TouchConsTM is a trademark (Philips Research, Author: Keyson, 1994)

associations with everyday tactual sensations. While a field such as a “hole” is not felt in the sense that the input device moves up or down, one can image a hole, as more force, mediated through the input device, is required to leave than to approach the centre of the “hole”. The sensation of texture as mediated by force information was studied by Minsky, Ouh-young, Steele, Brooks and Behensky (1990). Subjects were able to sort virtual sandpaper by texture on the basis of force information.

All user-editable parameters for tactual fields are directly manipulated and displayed using visual representations. The physical area in which a tactual field can be felt is defined by pointing and stretching an object’s visual outline. In “run mode” the visual representations of each object can be hidden. Parameters such as force information are displayed in a pop-up window. For example, to change the texture of an object, the user can directly manipulate a visually displayed sign wave, using a trackball to control force amplitude (height of “bumps”) and frequency (spacing between “bumps”). To support studies in virtual space, TacTool utilizes a seamless workspace equivalent in size to a 3 by 3 screen monitor area. The user can thus follow a felt path and move beyond the limits of a single viewable screen.

2.6.3 Tactual Device Description

The TacTool design environment is supported by the IPO trackballs with force feedback described in the previous section. The current fields in TacTool utilize trackball force feedback in the x and y directions.

2.6.4 Classification of TouchCons™

The TacTool navigational TouchCons™ can be classified in terms of type of feedback, either active or passive, and region felt, either locally relative to cursor position or globally related to the workspace. Active feedback implies movement of the ball independent of hand force, while passive feedback is felt as force feedback during user movement. For example, the “hole” field as described below could be considered as a local-passive field, while a pulling force towards the centre of a workspace (essentially a large hole) would be global-passive. A tactual directional cue, given as a system-driven ball movement in a specific direction, would be classified as a local-active field. A global-active field would be a screen-wide vibrating field.

2.6.5 Design of an interface with TouchCons™

The following two examples illustrate how TouchCons™ are built in terms of ball forces, displayed as objects, and edited using direct manipulation within the TacTool environment. The “hole” field will be explained, followed by the “path” field.

The “hole” object

Each object in TacTool has an unique force structure which defines the tactual nature of the field. The “hole” object, when encountered by the cursor, exhibits a directional pulling-force towards the field centre. The “hole” area is circular and is visually displayed as a circle. The “hole” force⁴ is derived from the following formulas:

$$Force = \sin(r \times \pi / (radius)) \times depth \times C$$

where $\pi (= 3.14....)$ and C are constants, and

$$radius = \sqrt{(X - X_{pos})^2 + (Y - Y_{pos})^2}$$

where X_{pos} and Y_{pos} are initial cursor positions (centre of a circle). X and Y are reference positions in relation to the “hole” edge.

The “depth” variable is used to determine the intensity of the “hole” forces. As can be seen in the equations above, the “hole” force field is dependent upon the radius of the hole, such that the smaller the radius, the greater the forces are towards the centre of the “hole”.

The variable ‘ r ’ is the absolute distance between the current cursor position and the centre of the “hole” field. As this distance becomes shorter, the forces become weaker, such that the forces towards the centre of circle approach zero as the “hole” centre is approached. The force map for a hole is depicted in Figure 5.

Figure 5. “hole” force map

Defining the “hole”

In the following section a step-by-step description for defining a “hole” object is given.

(1) Selecting the “hole” from the TacTool tool box

The first step in defining an object such as the hole is selecting the object’s vis-

⁴A “hill” object is created, in which the cursor is pushed away from the object centre by a negative sine function.

ual representation from the TacTool tool box, as depicted in Figure 6. At this point the visual appearance of the cursor changes to reflect the current design object.

(2) Position the "hole"

Once the object is selected, it can be placed by positioning the cursor within the 3 by 3 screen monitor region (Figure 7). The screen automatically scrolls when the cursor approaches the edge of a given screen. A button on the trackball or the ball is pressed down to confirm the centre position of the "hole".

Figure 6. selecting the "hole".

3) Define the "hole" area and force depth

Once the position has been selected, moving the trackball in the x (horizontal) direction increases the radius of the visually-displayed tactual "hole", while the depth (i.e. the force towards the "hole" centre) can be set by moving the trackball in the y (forwards & backwards) direction (Figures 8a & 8b). As illustrated in Figure 8b, the depth information is displayed in a pop-up window.

Figure 7. defining the object position

Figure 8a. "hole" area

Figure 8b. "hole" depth

The "path" object

The "path" object is explained as a second example will now be explained, The "path" force is similar to the "hole" with the difference that horizontal-only forces are directed from both sides of the path middle line (Figure 9a). The one-way directional forces are lowest towards the middle-line (Figure 9b). The 'path' field is based on the "hole" force formula. The force map is rectangular rather than circular, as defined in the equations below.

$$Force = \sin(l \times \pi/d) \times pathdepth \times C$$

where $\pi (= 3.14....)$ and C are constants, and

$$d = \sqrt{(X - X_{pos})^2 + (Y - Y_{pos})^2}$$

where 'Path depth' is the force factor (user-variable). Variable l is the absolute distance between the current cursor position and the middle-line of the path.

Variable d , path inner-border width, is the distance from the path edge to the path middle line. A wider inner-border width creates the feeling of being held along the centre of the path (Figure 9b). X_{pos} and Y_{pos} are middle-line positions. X and Y are the distances to the nearest path edge.

Figure 9a. direction of force vectors

Figure 9b. path force field

Defining the “path”

(1) Selecting the “path” from the tool box
As in the “hole” example, the cursor shows a path form once the “path” icon has been selected.

Figure 10a. Status feedback

(2) Position the “path”

As described above, the user clicks on a point in the workspace and moves the cursor to stretch the path’s visual-outline representation according to the desired direction and length (Figures 10a & 10b).

Figure 10b. Sizing a Path

(3) Define the “path” width, force depth and inner-border width

Once the user has confirmed the path position, length and direction by pressing the trackball button, a pop-up window is displayed (Figures 11a & 11b). The path width is set by moving the trackball in the x direction. At this point the path is redrawn with the middle line displayed (Figure 12a). A pop-up window then appears with a graphic for the path. The path depth is defined by moving the ball in the y direction; moving it in the x direction changes the inner-border width. Beneath the graphic, the numerical values for the path depth and inner-width are displayed (Figure 12b).

Figure 11a. Set width

Figure 11b. Status feedback

Figure 12a. Redrawing the path

Figure 12b. Status feedback

2.6.6 Sample Scenario Using Navigational TouchCons™

The model below (Figure 13) illustrates a scenario in which the user is confronted with a group of tactual fields which act as a series of movement guidance cues. The fields and their spatial relations are treated as a single model which can be retrieved as a file. When exploring the three possible directions from point B, the user feels a rough path with a wall at the end, a smooth course, and a third rough-path which contains a large hole along the way. Moving along the smooth path, the user drops an anchor at point D to create a reference mark for embarking on further exploration. The reference point now acts as a magnet. The user continues along the smooth path and is alerted to information which is highlighted as a bump.

Figure 13. Suggested Path

Figure 14. Relationship of TacTool to research

2.6.7 Classification of TouchCons™

As depicted in Figure 15, TouchCons™ can be classified by the region in which they act (i.e. cursor- or screen-dependent) and by the type of feedback which they emit. Active ball motion or feedforward implies that ball motion can be used to signal the user, for example a vibration as a contextual cue could be given or a linear movement as a directional cue. TouchCons™ can include agent-like intelligence. For example, a tactual path could become increasingly smoother over repeated usage, or a “hole” could become deeper (i.e. stronger pulling forces from the centre).

Feedback Spatial Region	Active	Passive
Cursor-Specific	<ul style="list-style-type: none"> - Vibrating object - Directional cue at a location 	<ul style="list-style-type: none"> - Bumps - Walls - Holes - Sense of path wear (after repeated use) - Retraction towards target - Repulsion from target
Screen-Wide	<ul style="list-style-type: none"> - Window with a gravity level - Ball led movement course - Vibrating screen region 	<ul style="list-style-type: none"> - Friction or resistance - Inertia in initial movement - Ball rolling characteristics (e.g. ball weight) - Gravity level within a region

Figure 15. Classification of TouchCons

2.6.8 TacTool in Research

As shown in Figure 14, the design of tactual forces in TacTool is guided by fundamental and applied research findings pertaining to tactual perception. Individual TouchCons™ can be studied and optimized within an experimental context before being integrated and tested within a model or application. For example, research was conducted to examine the degree to which subjects could accurately discriminate the orientation and force of a tactual directional stimulus (Keyson & Houtsma, 1995). The “hint” TouchCons™ described earlier was subsequently designed. In short, given the amount of available research pertaining to tactual perception as related to dynamic tactual displays and interactive applications with tactual feedback, both fundamental and applied research is needed. The approaches should support each other.

2.6.9 TacTool as a demonstration tool

TacTool was adapted to support the miniature force feedback trackball (Section 2.2.1) for use by Philips New Business Creation (NBC) as a demonstration tool. A windows-compatible version of TacTool is currently being developed at IPO to enable screen-based demonstrations for MS Windows applications.

2.6.10 Future Directions

TacTool is currently being expanded, to include, MIDI (Musical Instrument Digital Interface) programmable auditory objects which are linked to files, object based event-handlers for managing cursor position and presentation times for multimodal objects, and a 3-D information viewer which is based on a carousel presentation of pictures or views that can be rotated by the trackball. These features will enable multimodal navigational concepts to be tested while simulating new interaction concepts for multimedia systems. A number of future

additions to the TacTool prototyping environment are foreseen. For example, while cursor entry into “start” and “end” object fields are currently used to set and display the results of a movement timer, a record movement function could enable the recording and playback of actual user movements within a given model. Additionally, the TacTool prototyping environment could be enhanced to support 3-D navigation using the IPO 3-D trackball with force feedback (Section 2.2.1). Lastly, the TacTool environment has recently been ported to ACD-3D (animation creation design tool kit) which is shareware featuring a virtual space with walls and rooms, similar to the Doooms game. Users can move between visual objects in a simulated 3-D space while feeling the TacTool objects. For example, the walls are automatically coded with force feedback. Future experiments relating to navigation in a rich visual space, supported by tactual and auditory fields, could be conducted using this environment. The use of textures or pulling forces in areas which are explored for the first time could be for example considered. Such cues could enable the user to find his or her way back to a certain point.

3

Discrimination of Tactual Directional Cues and Forces

This chapter begins with a discussion of studies on the directional discrimination of a moving tactile point stimulus over the fingerpad and kinesthetically perceived ball-movement direction using the hand. Knowledge of the human capacity to determine a felt direction of motion is considered as a first step in understanding the degree to which tactual directional cues in the human interface could be used in place of or in addition to visual cues. In Chapter 5, where dual task performance will be examined, movement replication accuracy and reaction time in using tactual and visual cues while performing a concurrent task is considered. In the latter half of this chapter experiments on the discrimination of trackball-produced forces will be presented. In designing and evaluating tactual fields and technologies for navigation support, knowledge of the degree to which tactual forces can be discriminated is critical. The degree to which factors such as physical force magnitude and displacement as well as user movement velocity and orientation may influence discrimination between forces will be considered.

3.1 Directional sensitivity to a tactile point moving across the fingerpad

3.1.1 Introduction

Although little research has been reported on the thresholds for tactile directional discrimination of a moving point across the skin, several studies have examined tactile and haptic perception of orientation for static stimuli. In particular, the degree to which deviations can be detected from referent or standard vertical, horizontal and diagonal orientations has been considered. However, a clear understanding of directional sensitivity to a single point contactor, as opposed to sensitivity to a static linear contactor array is lacking. Furthermore, it is not clear how directional discrimination at opposite ends of the principal meridians may vary, given skin stretch by a single point. Thus the present study had two major objectives: (1) to estimate the degree to which subjects can discriminate the angle of a point contact moving across the right index finger¹, and (2) to determine how threshold levels vary with stimulus orientations in relation to a fixed finger position.

Studies of non-moving tactile and haptic line orientation perception suggest that an oblique effect (Appelle, 1972) occurs in the haptic and tactile modalities, whereby the discrimination of stimuli presented along or straight across the finger axis (i.e. in a vertical or a horizontal orientation, respectively) is superior to performance with stimuli in oblique orientations. Lechelt, Eliuk and Tanne (1976) and Lechelt and Verenka (1980) first reported similar spatial asymmetries in the haptic modality as well as in visual/haptic cross-modal judgments of stimulus orientations. Lechelt (1988) examined the tactile discrimination threshold for stimulus orientation discrepancy from standard or referent vertical, horizontal and diagonal reference orientations. The stimuli were vibrating linear displays presented to the pad of the right index finger via an Optacon (optical-to-tactile converter). The Optacon converted optical line images into a 6 x 24 tactile array using piezoelectric bimorph reeds vibrating at 230 Hz. Results indicated that deviations of 2.5° and 5°, respectively, could be discriminated at the 75%-correct level from horizontal and vertical standards, whereas 15° deviations were required for right and left diagonals. Using the same device and an adaptive staircase method (Levitt, 1971), Schneider, Hughes, Epstein, and Bachy-Rita (1986) also observed an oblique effect and, at the 71%-correct level, found thresholds as low as 7°.

Spatial asymmetries in discrimination thresholds for tactile orientation have been attributed to both neurophysiological and experiential factors (Appelle, 1972). For example, Lechelt (1988) considered the uneven distribution of sensory units in the index finger to be a sensory-neurophysiological explanation for the better discrimination of horizontal orientations while the

¹Based on Keyson and Houtsma, 1995

increased number of Rapid-Adapting (RA) and Slow-Adapting Type1 (SA1) cutaneous receptors in the distal direction (Johansson & Vallbo, 1976) comprised a sensory-neural explanation for the better discrimination of vertical orientations.

Lechelt (1988) also considered common experience and awareness of the principal meridians as factors possibly contributing to tactile spatial asymmetry. Such experiential factors were also examined by Appelle and Countryman (1986), who found that the oblique effect could be significantly reduced for haptic stimuli when subjects were not verbally informed of the test orientations. Given that both the experiential and neurophysiological factors contribute to the asymmetrical spatial perception of static lines, one might expect directional discrimination of point motion in the vertical and horizontal directions to be superior to that of movements along an oblique axis.

In considering directional discrimination of moving tactile stimuli, attentional factors may play a role, in particular when more than one stimulus at a time is presented. Gardner and Palmer (1990) found direction-sensitive neurons in the primary (SI) cortex of monkeys, suggesting that direction of movement may be registered in a relatively automatic fashion (i.e. without focused attention). However, a recent study by Evans and Craig (1991) suggests that the spotlight theory of attention (Posner, 1980) can be applied to the skin, although the spotlight is considerably broader than that of the visual system. Selective attention to a moving stimulus, given a simultaneous movement in an incompatible direction, depends to a high degree on the spatial separation between the two stimuli. Results of Evans and Craig's (1991) study indicate that incompatible non-target movement at an adjacent finger interfered with the subjects' ability to judge direction of movement at a target location, but this was not the case when an incompatible movement was presented to the corresponding finger of the contralateral hand. In addition to spatial separation, the temporal interval between two moving stimuli can affect selective attention. In a recent study by Craig and Evans (1995), the temporal interval between a moving target and non-target stimulus, both on the fingerpad, was shown to contribute to errors in directional judgments. In particular when the stimulus onset asynchronies were reduced from 500 to 50 msec, with either target or non-target presented first, the percentage correct of trials in terms of determining direction of movement was significantly reduced. However, in conditions which two different directional stimuli were given, both requiring the same response, the decrease in performance at 52 ms did not occur. Craig and Evans (1995) suggest that response competition may be a major factor in temporal masking.

The velocity and skin site of a moving stimulus have also been shown to influence directional discrimination. The capacity of four neurologically healthy young adults to distinguish opposing directions of cutaneous motion along the upper limbs was considered by Essick, Bredehoeft, McLaughlin and Szaniszlo (1991). Using a constant-velocity brush, with a traverse length of 0.33 cm, they

found optimal directional sensitivity on the index finger pad to occur at a velocity of 1.5 to 9.4 cm/sec, with a mean of 5.4 cm/sec across all four subjects. To obtain the finger pad sensitivity levels measured by d' along the forearm, the stimulus had to traverse a distance approximately six times longer, and, in addition, the velocity of stimulus motion at which direction sensitivity was highest increased systematically, to 18.57 cm/sec, as the test site was shifted from fingerpad to proximal forearm. Using the same type of device, similar effects on directional discrimination thresholds, with respect to contact site, were also found by Dreyer, Hollins, and Whitsel (1978), although the optimal velocity range (3 to 25 cm/sec) was the same for arm and wrist. Effects of changes in line length on orientation change thresholds were also found by Schneider et al. (1986), who found that subjects were more easily able to discriminate the direction of lines presented by an Optacon on the left index finger that utilized the full length, as opposed to half the length of the display. However, while only 2% of the variation in thresholds was attributed to absolute line length, 28% was attributed to trials in which a short line was compared with a long line, or vice versa. The velocity of a stimulus has also been shown to affect perception of straightness. As observed by Langford, Hall, and Monty (1973), the accuracy of perception of a straight line formed by a point moving across the volar surface of the forearm or straight track of stimulation increased as the stimulus velocity increased to about 16 cm/sec.

A limited amount of research has been conducted to consider possible effects of gender and handedness on the perception of tactile direction. In their study using an electromechanical stimulator, consisting of three steel rods, Varney and Benton (1975) asked their subjects to judge the direction of stimulation, which was either vertical, horizontal or along either 45° diagonal. A main effect for handedness was found ($p < 0.02$), whereby 66% of the right-handed subjects showed superior accuracy of recognition in the left hand, while 56% of the left-handed subjects showed superior accuracy of recognition in the right hand.

Knowledge about the discrimination of a moving tactile stimulus may be used to examine how tactile navigational cues can be communicated to help guide a user through a complex information display. The findings can be further used in the construction of interactive multimodal interfaces, as well as in the development of dynamic tactile input devices. The fingerpad is ideally suited as a point of interface for tactile communication, given the degree of fine motion control that can be exercised, as well as the fine spatial resolution owing to the high spatial density of mechanoreceptors.

3.1.2 Experiment

An experiment was conducted to measure the ability of subjects to discriminate between directions of a point contact moving across the fingerpad. While it appears that the skin of the fingerpad is sensitive to the difference between forward and backward motion, this experiment was an attempt to clarify (1) to

what degree the cutaneous afferents can discriminate directions of motion across a range of orientations for a given contactor size and movement; (2) whether threshold levels are uniform across orientations; and (3) whether angle discrimination for a moving tactile point differs from the tactile discrimination of orientation for a vibrating line contactor. Additionally, pilot experiments were conducted to consider issues concerning the influence of velocity and temporal masking in the directional discrimination of a moving point stimulus.

3.1.3 Method

Subjects

To avoid possible handedness effects (Varney & Benton, 1975) in the perception of moving tactile stimuli, familial right-handed volunteer subjects from IPO were used in the experiment. All of the subjects indicated a strong-to-moderate right-handedness according to the criteria used by Varney and Benton (1975). With participation based upon availability, fourteen male subjects with normal or corrected-to-normal vision took part. They ranged in age from 21 to 54, with a mean age of 30. With the exception of two subjects, none of the subjects had felt the tactile stimuli prior to the experiment.

Apparatus

The IPO force feedback trackball with ball-independent position sensors (see Section 2.2.1) was used to generate a moving point stimulus. To support the current experiment two modifications were made to the trackball: (1) a hard-plastic round standard-size braille point, with a diameter of 0.8 mm, a height of 1 mm, and a flat top, was fixed to the ball's surface and (2) the original plexiglas surface with a ball-sized opening was replaced by a 4-mm thick plexiglas sheet with a 14-mm diameter hole, such that the point on the ball could be felt in the centre of the fingerpad. The surface around the hole was bevelled to accommodate the finger. The entire apparatus was placed inside a cardboard box to conceal possible visual cues of movement direction. The motors did not emit any audible noise. A heating lamp was used to maintain the surface temperature of the device at 30° C. The control software held deviations from the intended movement path, caused by skin friction, to within 1.5°. Each subject rested his hand in a flat position, perpendicular to the front edge of the trackball, on the plexiglas surface with the right index finger placed over the hole. Subjects were seated alone in a quiet room.

Procedure

In each trial, two successive stimuli were presented in a V pattern on the pad of the right index finger, each stimulus consisting of a forward and backward movement from the vertex (Figure 1). On the basis of the results from the initial

pilot tests described below, each single movement was 3.25 mm long and ran for 79 msec, at a velocity of 4.1 cm/sec. One leg of the V pattern was in a reference direction, while the other, a comparison leg, moved at an angle from the reference direction. The order of stimulus presentation was random, with an equal distribution of reference-first or comparison-first stimulus trials. A 0.5-sec pause was set between reference and comparison movements, and a 1.5-s pause between trials. After each trial, the subjects reported the direction of motion formed by the random order of the two stimuli as being either clockwise or counterclockwise. The left cursor key was used to indicate a counterclockwise direction of motion, and the right key indicated a clockwise motion. Both keys were labelled with a clock-like diagram and an arrow pointing in the appropriate direction. For example, if a reference stimulus at 0° was given, followed by a comparison stimulus at 150° (Figure 1), the correct response would be selection of the clockwise key. In the reversed-stimuli order, selection of the counterclockwise key would be the correct response. As described below, two correct responses in a row led to a one-step decrease in the angle between the reference and comparison stimuli. An incorrect response led to a one-step increase in the angle. A correct response followed by an incorrect response was counted as a staircase reversal, as was an incorrect response followed by two correct responses. When the subject reached 20 staircase reversals, a new measurement was begun from either the clockwise or the counterclockwise side of a reference orientation, for a total of 16 staircases per subject.

Correct judgment of the motion formed by the two stimuli was thus dependent upon discrimination between the reference and comparison stimuli. The orientation under investigation was not readily apparent, thus limiting biases that were due to experiential factors such as those examined by Appelle and Countryman (1986). On a trial-by-trial basis, a low beep tone was given for an incorrect response and a high tone was given for a correct response.

A two-down, one-up adaptive-staircase method (Levitt, 1971) was applied to estimate the 70.7%-correct response threshold for eight reference orientations (90° , 45° , 0° , 315° , 270° , 225° , 180° and 135°). Using a two-interval, two-alternative forced-choice (2I2AFC) procedure, the angle between the reference and the comparison legs was either increased or decreased, depending on the subjects' response. The following three rules for the two-down, one-up decision criteria were used: (1) every pair of two consecutive correct responses causes a one-step decrease in the angle; (2) the angle is increased whenever an incorrect response is given; and (3) after 20 reversals, the staircase run is terminated and the threshold is computed as the median value of the last 14 reversals.

Most subjects required about 80 trials to reach the 20 reversals. The initial angle difference between the reference and comparison stimuli was 30° , with a step size of 9° for the first 3 reversals, followed by 6° for the next 3 reversals, and 3° for the last 14 reversals. The first 6 reversals, with larger step sizes, were omitted from the calculation, as they were intended to allow the user to adjust to

the experimental procedure prior to actual measurement. As depicted in Figure 1, both the clockwise and counterclockwise sides of the eight reference orientations were evaluated, for a total of 16 staircases per subject. For each staircase, one reference orientation, selected at random, was tested.

Figure 1. Top view of test orientations in relation to index finger of right hand. The four lines drawn on the finger indicate the directions of the point felt under the finger. In this example, the reference orientation is 0°. The comparison movement (Lines 1 and 2) and the reference orientation (Lines 3 and 4) were presented in random order, on a trial-by-trial basis. Two correct responses in a row led to a decrease in the angle between the reference and comparison stimuli. An incorrect response led to an increase in the angle.

The subjects were asked to complete one practice staircase before beginning the experiment. They then completed two staircases per session, with two sessions per day, spread over four days. On average, a staircase took 5 min to complete. The staircases for each subject were plotted and saved for later analysis. The percentage of correct judgments for the clockwise and counterclockwise stimuli, at each test orientation, was recorded for later analysis of potential response biases.

3.1.4 Pilot Tests

A series of pilot tests, using 4 subjects, was conducted to optimize the surface height, the diameter of the finger rest hole, the ball displacement, the ball velocity and the maximum available force level to maintain movement speed, given friction between ball point and finger. Adjustments were made to enable the ball point to maintain contact that could just be perceived along the index pad with

minimum skin friction. The finger-hole size was selected to accommodate a wide range of finger sizes, while still being small enough to act as a surrounding reference edge. A maximum-available force level on the ball of 1.5 newton enabled a constant movement speed of the contact point with the finger in position.

Two additional pilot tests were conducted on the basis of initial feedback from journal reviewers who suggested that directional discrimination thresholds could be lower with a stimulus velocity higher than 4.1 cm/sec, and that the persistent sensory impression from the first line could alter the perception of orientation of the second. Using the procedure described above, two groups of 8 right-handed males were assigned to one of two pilot tests. One test, referred to as Pilot A, was conducted to consider the effects of ball velocity on discrimination of direction of motion, while a second test, Pilot B, was performed to consider the delay interval between the comparison and reference stimuli, or interstimulus interval (ISI), as a factor that could reduce any temporal masking effects. In Pilot A, four ball velocities (0.5, 1.5, 4.1 and 7.2 cm/sec) were used, with an ISI of 500 msec. In Pilot B, four ISIs were used (50, 500, 1000 and 2000 msec), with the ball velocity fixed at 4.1 cm/sec. In both tests, one of the eight possible orientations was selected at random, with either clockwise or counter-clockwise deviations. Over a two-day period, two staircases per treatment condition were run for a total of eight staircases per subject.

The results of the pilot experiments were analysed using a preplanned Multiple Analysis of Variance (MANOVA) for repeated measures (also known as multiple regression for repeated measures). In repeated measures designs in situations in which assumptions for a traditional analysis are violated, a multivariate analysis is generally accepted as a preferred approach over univariate ANOVA. An example of such a situation is one in which there is a time factor in which observations made close together are likely to be more highly correlated than observations separated by longer time intervals (Pedhazur, 1982 & Poor, 1973).

Results of MANOVA indicated main effects for changes in stimulus velocity (Pilot A) [$F(3,5) = 6.22, p < .01$] and ISI (Pilot B) [$F(3,5) = 5.51, p < .01$] on the mean directional-change threshold. A contrast of means analysis indicated that optimum velocity, in terms of discrimination of direction for a moving point, may not be a single value, but rather a wide range of values from 1.5 to 4.1 cm/sec (Table 1). While the low end of this range is lower than the mean optimum velocity for discrimination of a forward versus backward movement found by Essick, et al. (1991), one of the four subjects in Essick's study obtained optimum discrimination at 1.5 cm/sec. The results of Pilot B confirmed Craig and Evans's (1995) findings regarding the effects of a 50-msec ISI compared with a 500-msec ISI in the discrimination of sequential moving stimuli on the index finger. There was no sign of a persistent sensory impression from the first line which could have altered the perception of orientation of the second line. Thresholds did not significantly differ as the ISI was increased from 500 to

2,000 msec (Table 2). In short, the pilot tests confirmed the initial settings for a stimulus velocity of 4.1 cm/sec and an ISI of 500ms.

Table 1
Pilot A: Mean thresholds for Velocity
(With Standard Deviations) and MANOVA Contrast
of Means Analysis

Velocity (cm/sec)	Threshold		<i>F</i> -Score of Contrast ^a	<i>df</i>
	M	SD		
7.2	21.63	7.37	24.46**	1,7
4.1	14.03	4.92		
1.5	14.51	5.13	0.34	1,7
0.5	17.86	6.14	10.17*	1,7

^aContrast with mean at 4.1 cm/sec.

* $p < .05$. ** $p < .01$

Table 2
Pilot B: Mean thresholds (With Standard Deviations) for
Interstimulus Interval (ISI, in Milliseconds) and
MANOVA Contrast of Means Analysis

ISI	Threshold		<i>F</i> -Score of Contrast ^a	<i>df</i>
	M	SD		
2,000	15.32	6.36	1.12	1,7
1,000	14.88	6.77	0.84	
500	13.63	5.42		1,7
50	25.01	9.91	22.44*	1,7

^aContrast with mean at 500-msec ISI.

* $p < .01$

3.1.5 Results

Examination of individual data plots did not show any apparent dependence of directional change threshold on reference orientation. When the mean of the median-based estimates across the subjects was plotted for each orientation, however, discrimination thresholds with regard to the finger axis were found to be fairly uniform, except for thresholds at 180°.

The calculated threshold for all orientations other than 180° varied between approximately 12.9° and 15.6°, whereas the threshold for 180° was about 10.6°, with both clockwise and counterclockwise deviations being lower in comparison with measurements from the other orientations (Table 3). The results of a MANOVA for repeated measures indicated no significant differences between thresholds for clockwise and counterclockwise deviations across the eight reference orientations. The data from the clockwise and counterclockwise sides of each orientation were subsequently pooled to determine a single

threshold estimate for each reference orientation.

Table 3
Mean Directional Discrimination Thresholds (With Standard Deviations) for Clockwise and Counterclockwise Deviations from Test Orientations

Test Orientation	Clockwise		Counterclockwise	
	M	SD	M	SD
90°	16.85	7.59	12.51	6.30
45°	13.27	5.48	13.87	4.18
0°	15.35	8.11	13.88	8.83
315°	13.65	4.56	12.15	7.14
270°	14.08	5.46	17.08	5.73
225°	16.76	7.66	13.76	7.17
180°	11.13	5.48	10.03	4.69
135°	16.76	8.91	14.88	8.30

A preplanned MANOVA contrast of individual means across orientations (O'Brien & Kaiser, 1985), treating the thresholds for clockwise and counterclockwise deviations from each orientation as a repeated variable, was conducted to compare discrimination thresholds at 180° with those of the other seven orientations. The contrast showed that angle discrimination at 180° was significantly different from that at all of the orientations except 45° and 315° (Table 4).

Table 4
MANOVA contrasts of means for clockwise and counterclockwise mean discrimination thresholds at each reference orientation by the mean of thresholds at 180°

Orientation by 180°	df	F ¹	Mean Difference ^a
90°	1,13	8.79**	4.10°
45°	1,13	3.44	2.99°
0°	1,13	8.19*	2.56°
315°	1,13	1.93	2.32°
270°	1,13	11.28**	5.0°
225°	1,13	4.79*	4.68°
135°	1,13	5.15*	4.44°

^aDifference based on 10.58°; mean of the clockwise and counterclockwise discrimination thresholds at 180°. * $p < 0.05$ ** $p < .01$

No bias was observed in the response to clockwise or counterclockwise stimuli. As expected, the percentage of correct trials at threshold level as defined by the 2I2AFC procedure for both stimuli was about 71%, with 71.48% correct for clockwise deviations and 71.41% correct for counterclockwise deviations.

3.1.6 Discussion

The possibility that our measured directional change thresholds are based entirely on perceived displacement cues cannot be excluded a priori. Had the subjects responded to spatial shifts in the endpoints of the reference- and comparison-movement legs (Figure 1), in contrast to perceived changes in orientation, the predicted minimal discriminable angle would have been about 27° ($2 \arcsin(.75/3.25) = 26.68^\circ$), given that each stimulus leg had a length of 3.25mm, and that the fingertip has a 1.5-mm error of localization (Sherrick & Cholewiak, 1986). This appears unlikely, given that the average directional change threshold for the eight major orientations was found to be approximately 14° . However, point localization has been observed to be as low as 0.17 mm (Loomis, 1979). In an earlier study by Loomis and Collins (1978), using a 1.8-mm-diam water-jet stimulus, excursions 0.1 mm to the left or right from a reference point were detected correctly 75% of the time. Given the relationship between point localization and slight movement, as well as the observed effects of stimulus velocity on discrimination thresholds, further research is needed to determine the degree to which end-point information with little or no motion, in contrast to constant motion, is used to discriminate the direction of a moving tactile stimulus. Lastly, using variable line lengths as a technique to control for displacement cues appears to have limitations, as observed in the study by Schneider et al. (1986). The introduction of length changes increased a lowest observed orientation change threshold from 7° to 25° .

In comparing observed directional-discrimination thresholds for a moving point with those obtained by Schneider et al. (1986), where the lowest threshold was 7° , the apparently higher thresholds obtained in the current study may be due to differences in the minimum step size used within the adaptive-staircase method (Levitt, 1971). While the lowest step size in the current study was 3° , the lowest measurable angle in Schneider et al. (1986) was 7° , at a reference orientation of 146° . Since some subjects in the current study were able to detect changes in direction as low as 3.12° , at a test orientation of 180° , a step size of three was chosen. The larger step size in Schneider et al. (1986) may have reduced the number of trials reaching threshold, thus limiting adaptation to threshold, in addition to reducing the difficulty of discriminating the reference from the comparison stimulus on a trial-by-trial basis. Using the same device, Lechelt (1988) estimated the orientation change thresholds for left and right diagonals to be 15° .

Apparently, Lechelt's (1988) finding of an oblique effect for apparent vibrating lines does not fully apply to the discrimination of direction for a moving point, given that only a partial oblique effect was found for one of the vertical orientations (180°) that was superior to other orientations. The nature of the tactile stimuli, as well as the method used in eliciting responses, may explain why, in general, no oblique effect was found. A moving-point contactor causes the skin to be pulled in the direction of movement, which is not the case with

linear vibro-tactile contactors, where a static spatial presentation is given. The subjects in Lechelt's study were asked to report which set of two lines (i.e. the first or the second) had an orientation that was not the standard orientation for that condition. The subjects may have been more able to map the tactile stimuli to a familiar spatial model or pattern than subjects in the current study, who were required to report whether the lines of motion changed in a clockwise or counterclockwise direction. In the present study, the reference orientation under investigation was not intuitively obvious.

Lechelt (1988) attributed the lower thresholds for discrimination of deviations from the horizontal orientations, compared with those for vertical and diagonal orientations, to the increased number of SA1 and RA receptors in the distal direction of the index finger (Johansson & Vallbo, 1976). Increased homogeneity of receptors in the horizontal direction was considered to provide a sensory-neural advantage in the horizontal direction. Such an advantage does not appear to be a factor in the perception of point-contactor movement.

In addition to the spatial distribution of cutaneous afferents in the fingerpad, the stretching of the skin may be a key factor in directional discrimination of point-contactor movement. In particular, the observed pattern of discrimination thresholds, by orientation, may reflect stretch characteristics of the skin of the index fingerpad. The three cutaneous afferents - RAs, Pacinian Corpuscles (PCs) and SAs - are triggered in the initial stretch of fingerpad skin, but only the SAs appear to have a significant directional bias in their responses (Westling & Johansson, 1987; Srinivasan, Whitehouse & LaMotte, 1990). Though the mechanism by which the direction of skin stretch is perceived is not clear, Srinivasan et al. (1990) suggest, as one possible explanation, that directional sensitivity of SA neurons may be due to the way fibers innervate specific skin locations. The example given is that the skin in front of a leading edge of a contact area is subjected to parallel compression, whereas the skin behind the contactor area (including the point at which it is anchored to the fingernail) is subjected to tension.

In a classic monograph by Katz (1925, cited by Krueger, 1982), the relationship between felt friction and movement was discussed. Katz noted that surface hardness-softness, as well as elasticity, is revealed by up-down movement vertical to the material, whereas roughness-smoothness is revealed by lateral movement across the material. In one study, Katz found that the hardness of a pencil was more readily recognized by writing downstrokes than upstrokes. As noted by Krueger, the fingerpads produce different types of forces on inward and outward thrusts. When pushed outwards, more resistance is encountered by the fingers, and they move in a jerkier fashion because they tend to dig into the surface.

As a factor of direction of skin stretch, the differences in apparent friction could be due to the fact that the skin is anchored at the fingernail but not at the distal interphalangeal joint. Because of this difference, orientation change

thresholds may tend to be lower at 180°, since tension in the skin can differ significantly where it joins the nail, while one would expect no significant difference in opposite horizontal and diagonal orientations. While the skin near the nail was stretched at 0°, in the second and fourth V-pattern movements, the apparent friction was masked by initial forward compression of the skin.

While the observed pattern of orientation change thresholds appears to reflect stretch characteristics of the index fingerpad skin, the influence of velocity and temporal factors (Craig and Evans, 1995; Essick et al., 1991) on directional sensitivity thresholds suggests that, in addition to neural activity associated with skin stretch, spatiotemporal factors play a key role in the discrimination of direction of movement. Essick (1992) attributes more neural activity to spatiotemporal factors than skin stretch on the basis of the fact that a reduction in the capacity to recognize the direction of stimulus objects (i.e. directional cutaneous kinesthesia) can accompany peripheral nerve injury whereas directional dermatokiestheia (i.e. the capacity to appreciate direction of skin stretch) is known to be a less sensitive indicator of neural injury (Essick). Also noted by Essick is unpublished work by Rath and Essick, in which directional sensitivity (i.e. discrimination of forward vs. backward movement), measured using a vibrating tactile array, was similar to that measured with a servo-controlled brush, as long as the same velocities of motion were delivered and the same chord of skin was traversed. While the encoding of directional information based on movement or on static presentation appears to be similar, one cannot readily assume that skin stretch plays little or no role in directional discrimination of a moving point. As observed in the present study, thresholds appear to reflect the skin stretch characteristics of the fingerpad. In short, it seems reasonable to hypothesize that information about the direction of stimulus motion is made available by the sequential activation of mechanoreceptors, as well as by simpler mechanisms which do not require spatiotemporal integration.

In concluding, our results suggest near-uniform discrimination threshold across all orientations with the exception of 180°. This is despite the differences between individual responses, which may have been due to the way the shearing force interacted with the formation of papillary ridges (fingerprints). Overall, orientation-change thresholds for the moving stimuli appeared to be higher than those reported by Lechelt (1988) for non-oblique lines felt along a fixed vibrating line. The oblique effect which they found was generally not apparent in our data.

Future research is aimed at measuring how subjects can replicate the tactile motion, using the tactile display as the response-input device. The results of such work should be used to guide the design of future tactile displays for man-machine communication, in particular where there is a need to indicate direction of movement.

3.2 Directional sensitivity to kinesthetically perceived ball movements

A small study was conducted to estimate the degree to which users can kinesthetically perceive a direction of ball movement. While the previous study indicated that tactile directional cues can be efficiently discriminated using the fingerpad, an estimation of directional discrimination of movement using the hand was sought as current devices such as the trackball with force feedback are hand-based rather than finger-based input devices.

3.2.1 Method

Twelve male staff and students of IPO with a mean age of 32 volunteered for the experiment. Using the staircase method described in the previous experiment, reference and comparison stimuli were presented as two separate legs of linear movement which formed an angle. A 500 ms pause occurred after each leg. The subjects were instructed to determine whether the resulting angle of ball movement was in the clockwise or counterclockwise direction. The angle was judged by letting three fingers (middle and adjacent) lightly rest on the ball while letting the fingers be pulled along the two-leg path. The reference leg was presented as a ball movement in one of eight possible orientations, whereas the comparison leg moved the ball at an angle from the reference leg. The angle was based upon the results of the current trial within the staircase as in the finger experiment. For example, at a test orientation of 90° if the reference orientation was presented first followed by a comparison movement at 96° , the correct response would have been clockwise, had the comparison movement been presented first followed by the reference orientation the correct response would have been counterclockwise, since the ball ended up moving upwards or towards 12 o'clock. Thus, correct judgement was dependent upon being able to determine the angular shift in movement between the reference and comparison stimuli.

3.2.2 Results and Discussion

Unlike for the tactically perceived direction of a moving point on the fingerpad, no significant difference in directional discrimination thresholds across orientations was found for the kinesthetically perceived stimuli (Table 5). Though some degree of skin stretching may have occurred as the ball pulled the finger along the two-leg path, directional discrimination was uniform across the orientations, suggesting that kinesthetic information was more dominant than tactile information. The kinesthetic directional discrimination thresholds were also lower than those observed for the point moving over the fingerpad.

Table 5

Mean Directional Discrimination Thresholds (With Standard Deviations) for Clockwise and Counterclockwise Deviations from Test Orientations

Test Orientation	Clockwise		Counterclockwise	
	M	SD	M	SD
90°	8.45	5.74	9.39	4.69
45°	8.44	4.42	9.71	4.14
0°	9.71	6.19	9.79	6.09
315°	9.89	3.41	9.57	3.94
270°	8.90	3.69	8.36	4.31
225°	9.19	4.43	9.26	5.06
180°	9.13	5.24	9.03	4.69
135°	8.42	3.77	9.58	4.55

3.3 Force discrimination and tactual distance

The ability to discriminate a change in force magnitude is central to the development of tactual form features and in the design of efficient force feedback devices. In the current section, the just noticeable differences (JND's) from a range of reference forces will be considered as well as possible influencing factors such as force displacement, direction, and user movement speed. Additionally, the effect of movement displacement on JND's was considered. The method used in measuring the trackball-produced forces is described in Appendix A.

3.3.1 Introduction

Force JND's can be considered in relation to Weber's law, whereby perceived changes from a given reference force are assumed to be relative to the magnitude of the reference force itself. JND's would thus be expected to increase linearly with an increase in the physical force level.

Weber's law

If I represents stimulus intensity, then: (1)

$$\frac{\Delta I}{I} = \kappa$$

where ΔI is the smallest discriminable change in stimulus intensity. The constant κ is Weber's fraction.

A curvilinear relationship between JND's and physical stimulation was proposed by Fechner, whereby psychological magnitude (R) is equal to a constant (κ) multiplied by the logarithm of the intensity of the physical stimulus ($R = \kappa \log I$). According to Steven's power law R , measured by subjective scaling of stimulus intensity, is equal to a constant multiplied by the physical intensity

of the stimulus which has been raised to the n th power ($R = \kappa I^n$) (Stevens, 1975).

Weber's law has been shown to hold across a given range of stimulus intensity levels in a number of weight and force perception studies. The range is delimited by a cross-over effect, such that the constant κ varies outside the range. For example, Ross and Brodie (1987) estimated the JND's in swinging weights from side to side (mass condition). While a significant difference in JND percents was found between the 50g and 200g conditions, no shift was observed between a 200g and a 400g condition, indicating that the cross-over point occurred below 200g (or 2N). Holway and Hurvich (1937) also obtained a cross-over point of 200g for lifting weights. Rees and Coopeland (1960) found that Weber's law held in both weight and mass conditions from 1000g to 7000g.

In considering manual discrimination of force using active finger motion, whereby two plates were grasped between the thumb and forefinger and squeezed together, Pang, Tan and Durlach (1991) found a relatively constant JND of 7% in the 2.5 to 10.0N range. The JND also remained constant over a range of displacement conditions and observed velocities. Generally, the JND for contact force has been observed to be 5-15 percent of the reference force value over a wide range of contact conditions through motor action (Durlach & Mavor, 1995).

An experiment was conducted to consider the JND's for trackball-produced forces as a function of force level, displacement and movement velocity. JND's were estimated in the range of 0.85N to 1.1N, which was the range in which tactual forms were being created. Given the findings of Pang et al., JND's were expected to remain constant across the force range, assuming the 0.85N reference force level was above a possible crossover point.

3.3.2 Method

Subjects

To avoid possible handedness effects (Varney & Benton, 1975), only self-reported right-handed subjects were chosen. Six male and six female subjects with normal or corrected to normal vision volunteered for the study. The subjects were graduate students and IPO employees, ranging in age from 21 to 35, with an average age of 26. None of the subjects had participated in previous experiments involving the estimation of trackball forces.

Apparatus

The IPO trackball with force feedback described in chapter two was connected to a 486/33MHz PC and a 14" VGA monitor.

Procedure

The experiment consisted of nine conditions (3 reference force levels of 0.88N, 0.99N and 1.10N) X 3 movement displacements, 20°, 40°, and 60° or approximately, 10mm, 20mm, and 30mm). Using a repeated-measures design, each subject completed a condition as a block in a random order, in three blocks, over three days. A practice block selected at random was presented to each subject before he or she began the actual experiment. A block consisted of 20 staircase reversals (about 75 trials per run). Each reversal was defined as a change in the staircase direction (i.e. either an increase or a decrease in the comparison stimulus). Each block took about 8 to 10 minutes to complete. A five-minute break was given between blocks. The subjects were seated alone in quiet room with a computer screen in front of them. A keyboard was positioned on the left-hand side of the monitor and the trackball on the right-side. A platform was placed in front of the trackball, at the same height as the device, to enable the subjects to rest their arm during the experiment. Using a two-alternative forced choice method (2AFC), reference and comparison forces were presented in a random order per staircase trial. The reference force was fixed according to one of the three force levels, while the comparison force had the magnitude of the reference force plus a particular level, depending on the trial within a staircase. The force stimulus was presented at 180°, which was directly opposite to the specified direction of trackball movement (0°) and remained constant until the required movement displacement was reached.

The subjects were instructed to place the middle finger just below the top of the ball and just above the ball's surface before the trial began. In this position the subjects could, as instructed, rotate the ball straight at 0° over the required displacement without releasing the finger. A 80ms 900-Hz beep was given to indicate the start of movement. Either the reference or a comparison force was then presented on a random basis. Once the subject had moved the required distance, a second higher beep tone (1300Hz, 80ms) was given. The subjects were instructed to release the ball upon hearing the signal and to reposition their finger for the next stimulus. The subjects performed a second movement after a delay of one second indicated by two beeps (80ms, 900Hz with a delay of 70ms). Two higher beeps were signalled to mark the end of the trial (80ms at 1300Hz, separated by same delay). Subjects then gave their response by pressing the "1" key to indicate that the first counter-force felt weaker, or the "2" key to indicate that the second counter-force felt weaker. The instructions appeared on the monitor after each trial. Either the word "Right" or "Wrong" appeared on the screen as feedback. The next trial was presented 0.5s after the judgement had been made.

Force stimulus

The force stimulus as a function of the distance for one movement is illustrated in Figure 2. The force was increased linearly between d_0 and d_1 over the first

five degrees to avoid the subjective feeling of a click at the beginning of a movement. The stimulus force level was reached at point d1. The force level remained constant until the required displacement was reached (d2). At this point, the subject was prompted by the beep tone to lift the finger. The force remained constant for an extra 300ms, which prevented a click being felt within the displacement condition. This is shown in Figure 2 as the time between the distances d2 and d3 (d2 and d3 could be equal if the ball did not move during the 300ms). The 300ms was long enough for the subjects to lift their finger from the ball without feeling the force stop and short enough to be over before they put their finger back.

Figure 2. Force stimulus during one movement.

Method of JND estimation

A two-down, one-up adaptive-staircase method (Levitt, 1971) was applied to estimate the 70.7%-correct response thresholds for each of the nine conditions. The following three rules for the two-down, one-up decision criteria were used: (1) every pair of two consecutive correct responses causes a one-step decrease in the comparison force; (2) the force is increased whenever an incorrect response is given; and (3) after 20 reversals, the staircase run is terminated. On the basis of pilot results three different step sizes were used to increase and decrease the comparison force. A large step size was used to allow the subjects to adjust to the task, a medium step size enabled rapid convergence while a smaller stepsize provided fine measurement of JND's. For the first four reversals a stepsize of 8% from the reference force level was used, followed by 4% and then 2% for the ninth and remaining reversals.

An example of a typical staircase run is shown in Figure 3. The trials have been plotted along the horizontal axis and the force along the vertical axis. The horizontal axis is at the level of the reference force (0.8N). The plus and minus symbols follow the level of the comparison force as a function of the trial number. Two consecutive correct responses (indicated by a plus) resulted in a decrease in the comparison force by a particular step size. Every incorrect answer (incorrect by a minus) resulted in an increase in the comparison force.

Figure 3. Sample staircase run.

A score for each staircase was derived by taking the mean of the maximum and minimum values, according to the limit method (Wetherhill and Levitt, 1965), in the 2% step size trial range. The point of convergence at the 70.7% correct level for a given condition was then based on the mean of the staircase scores. The JND for a given condition was calculated as the percentage of the difference between the reference force and the point of convergence (F_{mean}), being the Weber fraction expressed as a percentage (Equation 2).

$$\text{JND [\%]} = \frac{F_{\text{mean}} - F_{\text{reference}}}{F_{\text{reference}}} \times 100\%$$

Weber's fraction expressed as a percentage. (2)

3.3.3 Results

The JND's in percents are given in Table 6 per movement displacement condition and reference force magnitude. Results of MANOVA (multivariate analysis) indicated no significant main effect for the three reference force conditions on JND's (Figure 4). As depicted in Figure 4, no trend was observed for JND's as a function of one or more force reference levels. Similarly no significant difference between the three displacement conditions or an interaction with reference force levels was found.

Table 6
Just Noticeable Differences (JND's) in Percents as a Function of Force and Displacement

Force (N)	Movement Displacement							
	20°		40°		60°		Mean	
	JND%	SD	JND%	SD	JND%	SD	JND%	SD
0.88	12.0	4.4	12.7	8.4	12.8	5.7	12.5	6.2
0.99	14.9	7.6	10.2	4.6	14.2	5.4	13.1	6.2
1.10	14.5	4.1	11.9	6.0	13.0	6.5	13.1	5.6
Mean	13.7	5.6	11.6	6.4	13.3	5.8

Figure 4. JND's as a function of movement displacement in degrees and force reference level.

The mean movement velocities for the reference and comparison trials per subject, averaged over all blocks, using the last 12 reversals of each staircase, are shown in Table 7. With the exception of those of two subjects (numbers 2 and 10), the results showed that the subjects generally tended to rotate the ball at a preferred velocity in judging the force levels across conditions. Additionally, the mean JND's across the blocks per mean movement time were plotted for each subject along a best fitting regression line. As can be seen in Figure 5, the JND's correlated significantly with the mean subject movement speeds ($r = 0.86$, $F(1,10) = 27.488$, $p < 0.0001$).

Table 7
Mean Movement Velocities of Individual Subjects in Reference
and Comparison Trials

Subject Number	Force Stimulus			
	Reference		Comparison	
	Velocity [mm/ sec]	SD	Velocity [mm/ sec]	SD
1	62.3	9.7	61.5	9.5
2	142.7	62.8	137.3	66.6
3	32.0	4.8	30.8	5.1
4	26.9	9.6	26.0	9.4
5	17.3	5.9	16.4	6.2
6	84.0	19.7	80.6	20.0
7	24.2	8.6	22.8	8.7
8	52.2	17.1	48.2	18.5
9	37.2	7.0	37.0	6.5
10	94.0	66.0	89.3	68.0
11	15.9	6.7	14.7	6.7
12	29.1	9.4	27.2	9.8

Figure 5. JND (in percentage) as a function of movement speed per subject

3.3.4 Discussion

Though Weber's law held for the range of reference forces (i.e. 0.88 to 1.1N) the observed JND's were not much greater than the range in forces considered. The maximum difference between the reference forces was 0.22N, which is 25% of the smallest reference force (0.88N), whereas the JND at 0.88N was approximately 13%. Roughly, a subject could just distinguish 0.88N from 0.99N (the physical difference is 13%). At a reference force level of 0.99N, with about the

same JND, a force of 1.11N could also just be distinguished. The lack of a significant effect for reference force level on force JND's was similar to the findings of Pang, Tan and Durlach (1991). The observed relation between the JND's and the subjects' movement velocity was not found by Pang et al. (1991). This may be attributed to the difference in tasks and free limb movement. In considering the observed relationship between JND's and individual movement speeds, adaptive or dynamic force fields sensitive to user movement speed could be of benefit in maintaining a constant feel across users.

3.4 Follow-up experiment on force discrimination

3.4.1 Introduction

On the basis of the constant trend in JND's observed in the previous study, a follow-up experiment was conducted to determine the point at which a cross-over effect may occur. Given the natural friction in the trackball (0.42N) and the fact that motor forces (feedforward) could be used to further reduce this level, reference forces below 0.88N were considered. As an additional factor, movement orientation was examined in light of the increased directional sensitivity in the finger pad to proximal movements (Section 1).

3.4.2 Method

The staircase method described in the previous experiment was used. The experiment consisted of eight experimental conditions completed as blocks in a random order, over three days, with 16 staircase reversals required per condition (about 50 trials). Additionally, one block chosen at random was given as a practice session to acquaint the subjects with the task. Twelve right-handed male subjects, with a mean age of 26, volunteered for the experiment. None of the subjects had participated in the previous experiments. As can be seen in Table 8, the experimental blocks were designed to consider the effects of lower reference forces on JND's (conditions 1-4, with 0.19N, 0.42N, 0.65N and 0.88N), a partial replication of the movement displacement factor (conditions 4 and 5, using 40 and 20 degrees) and movement direction, being either 0, 90, 180, or 270 degrees (conditions 3, 8, 7, and 6, respectively). To reduce the number of trials in each staircase series, larger step sizes were used than increased in the previous experiment. This was done to limit fatigue effects over repeated trials, which had been reported by two of the subjects in the previous experiment. The stepsize was 16% of the reference force for the first three reversals, followed by 8% for the next three and 4% for the remaining 10 reversals

Table 8
Reference Forces Levels, Amplitudes, and Orientations in Eight Experimental Conditions

Block	Conditions			
	Reference Force (newtons)	Initial Threshold (newtons)	Amplitude (degrees)	Direction [degrees]
1	0.19	0.26	40	0
2	0.42	0.57	40	0
3	0.65	0.88	40	0
4	0.88	1.19	40	0
5	0.88	1.19	20	0
6	0.65	0.88	40	270
7	0.65	0.88	40	180
8	0.65	0.88	40	90

3.4.3 Results

The values of the JND's as a function of the force level are given in Table 9. Within the four reference force level conditions a significant effect for force magnitude was found on JND's ($F(3,9)=4.78$; $p<.03$). As can be seen in Figure 6 this effect can be largely attributed to the observed mean JND's at the 0.19N force reference level as compared to 0.42 ($F(1,11)=10.59$; $p<.008$). No significant difference was found between 0.42N and the higher reference force levels.

As in the previous study, no significant difference in JND's was found between the displacement conditions of 40° and 20° at a movement orientation of 0° and a reference force level of 0.88N. The mean JND's were 13.9% and 11.4%, respectively. No significant difference was observed for movement direction (Table 10).

Table 9
JND's (percentages) as a function of reference forces

Reference Force (New- ton)	JND	SD
0.19	29.8	11.8
0.42	18.0	9.1
0.65	15.8	5.3

Table 10
JND's (percentages) as a function of direction

Direction [degrees]	JND	SD
0	15.8	5.3
270	14.8	6.7
180	12.8	4.8
90	12.8	4.1

Figure 6: JND for force discrimination as a function of the reference force

3.4.4 Discussion

The cross-over point of which JND's are no longer a constant fraction of the reference force for trackball-produced forces appears to occur just below 0.44N. On the basis of the JND's observed in the current and previous studies, the degree to which a reference force needs to be increased to obtain a distinguishable force 70.7% of the time is shown in Figure 7. For example, at the 0.42 reference level the JND was 18%, corresponding to a 0.076N difference in threshold.

Figure 7. The degree to which a force must be increased to ensure a distinguishable force 70.7% of the time.

The plotted dots represent the observed JND's. The lack of influence of movement orientation on JND's, despite the observed directional sensitivity of the fingerpad reported earlier, suggests that kinesthetic rather than mainly cutaneous perception may be critical in force discrimination. In the follow-up study on the finger, no directional sensitivity was found in the hand in discriminating kinesthetically perceived movement orientations. On a subjective level, the results of a follow-up questionnaire indicated that the 0.19N force level was perceived as a natural, light friction force, indicating that feedforward could be effectively used to reduce felt friction.

The data obtained in the current study indicate that forces below 0.500N could be used in building force fields, in contrast to higher forces, which could cause fatigue. Additionally, the results of both force discrimination studies were used to guide the development of the low-powered trackball described in Chapter 2. The CD-ROM motors produce forces in excess of 0.700N on the ball, which are more than sufficient in terms of reaching a JND level equivalent to that of the larger trackball, though the full range of forces perceivable is smaller. Whether this is or is not a critical factor will depend on the type of force field. For example, a texture field built from a constant force displayed at alternating pixels would feel qualitatively equivalent on both devices. The sensation of a "hole" (Chapter 2) would feel qualitatively richer on the larger trackball. Lastly, on the basis of the JND data, the actual bit rate for sending force-level information to the small trackball was also reduced, from eight to five bytes, which saved on hardware costs.

4

Dynamic Cursor Gain and Tactual Feedback Over Targets

In this chapter the influence of tactual feedback over a target in the user interface will be contrasted to the use of dynamic-cursor gain in the capture of user movements¹. The two types of target feedback simulate a cursor catching effect using tactual and visual techniques, respectively. Performance is contrasted with a control condition in which visual-only feedback is given. Additionally, the influence of a tactual non-target along the movement path towards a target will be considered.

¹Based on Keyson (1996)

4.1 Introduction

Recently, several authors have compared cursor positioning times and errors using combined tactual-visual feedback and visual-only feedback in the target region (e.g. Akamatsu, Sato & MacKenzie, 1994; Goossens, 1992). Tactual feedback is defined as a force transmitted through the input device as the user passes over a target area, while visual feedback is commonly provided by highlighting the selected target or through a change in background and foreground colours.

In the above-mentioned studies, using a mouse or trackball with force feedback, movement times were observed to be shorter when combined tactual-visual feedback rather than visual-only feedback was used. For example, Akamatsu et al. (1994) observed a 143-ms reduction in mean total response times taken to complete a series of target acquisition tasks using a mouse with force feedback, compared to the same situation without force feedback. At least three factors may contribute to improvements in total target acquisition times (i.e. from beginning an acquisition movement to selection of target) given tactual feedback over the target area: (1) reaction times for a single tactual stimulus are shorter than those for visual or auditory cues (Jordan, 1972), which leads to faster responses when the cursor enters the target area; (2) tactual feedback is physically applied to the input device, thus reducing final positioning times, while requiring minimal interpretation; (3) users may be taking advantage of the knowledge that the system will 'catch' the cursor and this may lead to faster movement behaviours. Such a 'catching effect' over the target area is felt as the ball of the trackball is pulled towards the centre of the target, while leaving the target area requires the user to exert a force greater than the pulling force. The benefits of a catching effect may partially explain why users exhibit an eight percent lower movement time, from start point to target border, given the presence versus absence of tactual feedback, as observed in a recent, unpublished IPO study.

While the first two factors described above are attributes of tactual interaction, the third relates to the device and display interaction, which may not necessarily be modality-dependent. Thus, some of the gains observed with tactual feedback may be obtained by means of a non-tactual cursor-catching effect. One way of bringing such an effect about is by changing the gain ratio over the target area so that longer movements of the input device are required to reach the target centre than to it. The amount of movement that occurs over a displayed target area (D) in response to a unit amount of movement on the control device (C) is commonly referred to as the D/C gain. This relationship is indicated by the following expression:

$$D/C \text{ gain} = \frac{\text{display output}}{\text{control input}} \quad (1)$$

As is evident from the above equation, gain can be changed by altering the dis-

play output, the control input or both, assuming the task does not require either the display cursor or the control device to be moved a specified distance. However, in most target acquisition tasks the target is displayed at a fixed distance, so a change in gain can only be achieved by altering the control input. A low gain means that more movement of the input device is required to shift the cursor a specified distance.

4.2 Determining components of gain

In considering movement from a given starting-point to the centre of a target, D/C gain can be characterized by four components (Arnaut & Greenstein, 1990). A distinction can be made between display amplitude: the visual distance from a starting position to a target border; and display target width: the displayed size of a target. Similarly, a distinction can be drawn between control amplitude, the distance the control device is moved from its starting position to a position that places the display cursor at the target border; and control target width: the distance the control device is moved to shift the cursor within the target area. In this manner two gain levels can be derived, one for outside-target movements and the other for within-target movements, namely:

$$\text{Outside-targets gain} = \frac{\text{display amplitude (cursor to target visual distance)}}{\text{control amplitude (cursor to target linear control distance)}} \quad (2)$$

$$\text{Within-target gain} = \frac{\text{display target width (visual width of target)}}{\text{control target width (linear control distance across target)}} \quad (3)$$

Buck (1980) found that changes in control target width rather than D/C gain affected movement times and accuracy rates in a target-alignment task. Buck's findings call into question the findings in other studies which consider D/C gain as a single measure for optimizing the control-display movement relationship (e.g. Arnaut & Greenstein, 1990; Gibbs, 1962; Hammerton, 1962; Jenkins & Connor, 1949).

By changing the control target width and display target width the movement time required by users to move a cursor over a target area is altered. According to Fitts' law (Fitts, 1954; Keele, 1986), the difficulty in acquiring a target, as measured in movement time, decreases as the target width increases, assuming the target distance is a constant. This is summarized in the following equation:

$$\text{Movement time} = a + b \log_2 \left(\frac{2C}{T} \right), \quad (4)$$

where a and b are empirically determined constants, C is the control amplitude

and T is the control target width. The quantity $\log_2\left(\frac{2C}{T}\right)$ is referred to as the index of difficulty of the movement. Fitts' law predicts a total movement time for a discrete movement task in which the control and the display are integral rather than separate, for example, moving the hand or arm different distances to targets of varying sizes. In this case the control and display amplitudes of the task are identical, as are the control and display target widths. However, in conditions where the control is separate from the display target width, one could imagine that a control target width that is larger than the display target width would lead to longer movement times, simply because of the greater movement time required to enter and leave the target region. This could give rise to a confounding effect in assessing capture performance. To limit this potential problem, the movement effort required to reach the centre of the target can be increased above the outside-target gain level, while the total effort required to leave the target centre can be decreased, so that the total effort required to move towards and away from the centre of the target would be equivalent to that of the outside-target gain level. This type of cursor gain will be referred to henceforth as dynamic-cursor gain. In short, changes in the cursor gain can be used to create a cursor-catching effect such that more user movement effort is required to reach than to leave the target centre, without increasing the total amount of operator movement effort required to enter and leave the target. The total gain in the dynamic-cursor gain condition is thus equivalent to the outside-target gain level. Fitts' measure of target difficulty relationship $\log_2\left(\frac{2C}{T}\right)$ is thus not affected.

An experiment was conducted to study the extent to which a cursor-catching feedback using dynamic-cursor gain can reduce target acquisition times in relation to visual-only and combined tactual-visual feedback. Dynamic-cursor gain was applied across a range of outside-target gain levels to consider possible interactions between the two variables. Secondly, movement performance was considered with and without the addition of a non-target along the target acquisition path.

4.3 Method

Apparatus

The IPO trackball with force feedback with ball-independent position sensors described in Section 2.2.1, connected to a 486 PC with a 21" Philips Brilliance 2110 monitor, was used to generate the tactual feedback.

Subjects

Sixteen subjects with normal or correct-to-normal vision, working at IPO, volunteered for the experiment. The subjects ranged in age from 21 to 35 years, with a mean of 24. To control for handedness effects (Varney & Benton, 1975) only right-handed subjects were chosen.

Procedure

To investigate the effects of dynamic gain, in contrast to combined tactual-visual and visual-only feedback, four target feedback conditions were created, namely, (1) visual-only, (2) combined tactual-visual, (3) visual-only with dynamic-cursor gain and (4) combined tactual-visual with dynamic-cursor gain. Each of the four target feedback conditions was tested under three outside-target gain levels and with or without the presence of a non-target along the target path. Each subject thus completed a total of 24 blocks (four feedback conditions X three outside-target gains X presence or absence of non-target) with 40 trials per block. On a trial-by-trial basis the target difficulty level² was randomly set by changing the visual display. One of three target diameters, 9.6, 14.4 or 28.8 mm, was selected at a distance of either 60 or 120 mm from the centre of the screen.

The target appeared as a light-grey filled circle (6.25% black) with a one-pixel solid white outline. The non-target was presented as a light-grey ring, with a one-pixel white outline, around the displayed target. The ring diameter was randomly set at either 60 or 120 mm, with the width of the grey area equal to the target diameter. In the combined tactual-visual feedback condition, a 'hole' force field (see Section 2.6.5) was presented over the target area with a maximum pulling force of 225 mN exerted on the trackball at the outer edge of the target (forces were measured independent of hand forces), and diminishing to 0 mN at the target centre. The non-target in the tactual feedback condition contained many small overlapping 'hole' shapes to limit unintentional redirection of a subject's movements. The outside-target gain levels were set at either 1.5, 1.04 or 0.74 mm of movement per 1 mm of trackball movement.

Method for creating Dynamic-cursor Gain

Dynamic-cursor gain in the visual-only and combined tactual-visual feedback conditions was produced by halving the outside-target gain for movements towards the target centre and by increasing the gain by 50% for movements away from the centre. Thus, more movement of the trackball was required to approach than to leave the centre of the target.

Experimental Variables

The experiment was divided into four sessions with a five-minute break between blocks. The subjects were instructed to move the 3-mm square pointer which appeared in the middle of the screen as accurately and fast as possible to within the target region, and then press the button mounted on the lower left-hand cor-

²Using the same variables as Fitts' law, a slightly modified formula (MacKenzie, 1992; Shannon & Weaver, 1949) was used to calculate the index of target difficulty (ID), with $ID = \log_2(A/W) + 1$. The target amplitude is given by A and the target width by W.

ner of the trackball device surface. Each trial began with a random delay, from 250 to 1250 ms, to limit the occurrence of rhythmic movements. The target then appeared at one of eight possible orientations, in increments of 45 degrees, from 0 to 315 degrees. The following objective measures were recorded for each trial:

- Total response time: the time from which the pointer was moved for more than 3.0 cm until the trackball button was pressed to indicate target selection.
- Movement time: the difference between the time at which the pointer was moved for more than 3.0 cm and the time at which the pointer entered the target for the final time.
- Error count: an error was recorded if the subject pressed the trackball button while the pointer was outside the target region.

A series of pilot tests using four subjects was conducted to optimize the gain and dynamic-cursor gain levels so that the subjects would report a wide range of subjectively perceived pointer speeds. The target conditions were based on the maximum and minimum displayable target sizes, given the requirement that the smallest target could still be felt as a 'hole' field in the combined tactual-visual condition.

4.4 Results

The results of the 40 trials per block indicated that the performance in the first trial across all the blocks showed no correlation with the remaining trials. Given that the subjects were unaware of the feedback condition when beginning a new block, the first trial was omitted from the data analysis. The data obtained in the trials in which the trackball button was pressed while the pointer was outside the target area were used only in the analysis of errors. Unrealistic scores across all objective variables were defined as those which were three times greater than the mean. These scores were not included in the analysis.

Mean Response Times

Mean response times were lower in the two (with and without dynamic gain) tactual target feedback conditions (mean = 819 ms) than in the visual-only condition (mean = 931 ms) and visual with dynamic-cursor gain feedback (mean = 897 ms) [$F(1,15) = 89.07$, $p = 0.0001$]. The response times in the visual-dynamic gain were 34 ms lower than in the visual-only condition by [$F(1,15) = 9.47$, $p < 0.01$]. No significant change was observed when dynamic-cursor gain was present in the combined tactual-visual feedback condition (mean = 808 ms) [$F(1,15) = 0.71$, $p = 0.41$]. The effect of feedback condition was constant across the outside-target gain levels (Figure 1). In general, the subjects performed best at the lowest outside-target gain level; three of the sixteen subjects achieved lower total response times at higher gains. The percentage of errors decreased from 4.5% in the visual-only condition and visual with dynamic-cursor gain to

1.8% for the two tactual feedback conditions.

Mean Movement Times

The movement time measure, which excluded reaction times, indicated a trend similar to that observed in the total response time measure. Movement times were lowest in both tactual feedback conditions (combined mean = 487 ms), while the presence of dynamic-cursor gain feedback significantly reduced movement times in the visual-only condition from 554 ms to 538 ms (Figure 2) [$F(1,15) = 4.61$, $p < 0.05$]. No interaction was found between the three outside-target gain levels and the dynamic-cursor gain feedback [$F(2,14) = 0.03$, $p = 0.9681$], indicating that the effect of dynamic gain was constant across movement conditions.

Presence of a non-target

With the presence of a non-target along the target path, total response times were not affected in the visual-only and the visual with dynamic gain conditions [$F(1,15) = 0.16$, $p = 0.6984$], while response times in the tactual conditions increased significantly, from 813 ms to 870 ms [$F(1,15) = 9.49$, $p = 0.008$].

Figure 1. Mean response times for target feedback condition by outside-target gain values.

Figure 2. Mean movement times per target feedback condition.

4.5 Discussion

The results of the current experiment indicate that force feedback may provide a stronger sense of a catching field than a displacement cue. The subjects may have consequently moved faster between target positions, having had a stronger sense of certainty in the combined tactual-visual condition than in the visual-with-dynamic-cursor gain condition. The lower response times in the presence of tactual feedback appear to be due mainly to a change in the users' behaviour rather than simply shorter reaction times for a tactual stimulus. By subtracting the 'total response time' measure from the 'movement time' measure, simple reaction times are obtained, or the time taken to press the space bar when the pointer enters the screen region. The difference in simple reaction times between the visual-only and combined tactual-visual feedback conditions (5 ms) indicates that the decrease in total response times under the tactual condition can be largely attributed to shorter movement times.

In considering movement performance using dynamic-cursor gain feedback in contrast to visual-only feedback, it may be noted that, while total response times were 34 ms shorter in the dynamic-cursor gain condition, actual reaction times were 22 ms longer. Perhaps movement performance with dynamic-cursor gain feedback could be further improved using compatible vis-

ual feedback. For example, the pointer size could change as the gain within the target area changes.

Results obtained in the tasks in which a non-target appeared on the target path indicated that the benefits of tactual feedback, in contrast to the non-tactual target feedback conditions, decreased as the user encountered the tactual non-target along the target path. The potential for various forms of non-tactual target feedback, such as dynamic gain, may be greater under such circumstances. Clearly, the results indicate that tactual feedback should not simply be added to existing visual interfaces where the user may encounter a series of tactual non-targets before reaching the final target.

4.6 Conclusion

In considering the design of visual interfaces where movement in the display is coupled to movement of a device controller, target-acquisition performance may be improved by separating D/C gain into two components, namely an outside-target and a within-target dynamic gain. There appears to be no interaction between the two types of gain, suggesting that improvement in movement performance may be achieved by adding dynamic-cursor gain feedback to existing graphical interfaces. Such a modification would involve no additional hardware costs. Further research is needed to determine the subjective appeal of dynamic-cursor gain feedback as well as the design of compatible visual feedback.

While research demonstrates a potential for tactual feedback in the user interface in terms of movement performance, techniques are needed which can assist in the prediction of user movements such that tactual feedback in non-targets along a trajectory can be deactivated. Secondly, a new look at interface design is warranted: menu layouts should be positioned to take advantage of the human capacity to remember spatial positions. For example, a pie menu instead of a list menu may reduce the problem of tactual interference caused by non-targets while facilitating target acquisition through recall of item position and tactual feedback. Effective layouts of screen objects with tactual feedback may increase the degree to which the user can perform a visually-based task such as reading, while performing a movement-based task such as dropping a closed file on a felt 'trash can' object.

5

Compatibility of Visual and Tactual Directional Cues

In Chapter 3 the directional discrimination of tactile and kinesthetic information was considered. The current chapter describes the results of a study on the use of visual-only, kinesthetic-only and combined visual-kinesthetic directional information to instruct a user to move in a particular direction while performing a visually-demanding task¹. In a single task condition, subjects were instructed to rotate a trackball in an indicated direction. In a dual task scenario, a visual search task was performed concurrently with the movement task. The benefits of multisensory input, in terms of performing two or more concurrent tasks, are discussed under multiple resource sharing theory.

¹Based on Keyson (submitted)

5.1 Introduction

While human-computer interaction has shifted from purely textual to graphical and spatial representations of information, direct manipulation of data has imposed new demands on the human visual system with little relief. In a discussion of input devices for human-computer interaction, Buxton (1986) states that "if a physical anthropologist unearthed a modern-day computer store, a likely picture of human physiology would be a human with a well-developed eye, a long right arm, a short left arm, uniform-length fingers and a "low-fi" ear". Using only vision to perform navigational movements in a spatial environment may lead to costly shifts in visual attention, as awareness is moved away from the task at hand and into the workspace in search of movement guidance. To reduce the load on the human visual system in user interface navigation, novel means and devices for human-computer interaction are needed. For example, the use of audio information in spatial feedback was examined by Cohen and Ludwig (1991) who developed "filtears", i.e. non-distracting audio directional cues. They applied methods of gesture recognition and spatial sound to guide the user through a multi-channel conference system.

Two relatively unexplored modalities in user interface navigation for sighted users are the tactile and kinesthetic senses. A kinesthetically felt movement, presented by an input device, can be used to create a sensation similar to being led by the hand through an unknown space. Such a cue can be displayed upon request by the user or can be pre-programmed, depending on the task. On the assumption that the user can be led in a given direction, tactile paths and end-points or "holes" and "hills" can be created to further guide the user to a designated or user-requested location (Section 2.6.4). Directional cues could also be communicated while the user is performing a movement in the user interface.

The aim of the present study is to examine the effectiveness of kinesthetic-only and combined visual-kinesthetic directional cue as compared with a visual-only directional cue, in terms of movement time, accuracy and response rate, using a motor-assisted trackball (Section 2.2.1). On the assumption that a non-visual cue may be most effective under conditions in which the user is engaged in a visually demanding task, performance is also considered in the presence of a concurrent visual search task. The kinesthetic cue is a linear ball movement produced by the motors attached to the trackball, the visual cue is presented as a moving dot on a linear path. The subject follows the cued direction by replicating the direction of movement indicated by one or both of the tactile and visual directional cues.

Research on the use of tactile and kinesthetic feedback in the user interface has focused on qualitative aspects of tactile feedback (Minski, Ouh-Young, Steele, Brooks, and Behensky, 1990) as well as on quantitative aspects relating to speed and accuracy of movement. Studies of the latter category, have typi-

cally examined performance in simple target-acquisition tasks. For example, Akamatsu, MacKenzie, and Hasbroucq (1995) compared visual, tactile and auditory feedback in target selection performance. The time to complete a trial once the cursor had entered the target region was found to be 61 ms shorter with tactile than with visual feedback. Auditory feedback was only slightly better than visual feedback, and combined (auditory, visual, and tactile) feedback worked as well as tactile alone. Akamatsu et al. (1995) noted that the slight performance gains with touch feedback over the target region might have been greater had the subjects been engaged on a visually demanding task, such as using the other hand to tick a box with a pencil while performing the target-acquisition task.

Although movement-based actions in human-computer navigation appear to be conducted typically as a sequence between tasks rather than concurrently, this may be done to avoid inherent visual interactions as opposed to limitations of human central processing. The ability to divide attention efficiently between two simultaneous tasks depends on the compatibility between the stimuli (S) and response mechanisms (R) associated with each task. In contrasting visual and auditory directional cues, Greenwald (1972) demonstrated that subjects could efficiently say the word "left" or "right" while hearing it and at the same time move a switch in response to a visual arrow pointing either left or right. Error rates and reaction times were higher when the subjects had to respond motorically to a verbal stimulus and verbally to a visual cue. The effect of an incompatible stimulus-response relationship, in which the motor response is counter to the stimulus, has also been demonstrated using reaction time data in several modalities. Fitts and Seeger (1953) demonstrated S-R compatibility with visual stimuli, Broadbent and Gregory (1965) with tactile stimuli, and Simon, Hinrichs, and Craft (1970) with auditory stimuli. In the current study the kinesthetic cue is considered to be highly compatible with the movement task as translation from a visual to a motor space was not required.

The notion of S-R compatibility was further expanded by Wickens, Sandry, and Vidulich (1983) to account for a motor (response) task combined with a cognitive (perceptual) task, which is of particular relevance to the current study in view of the assumption that a kinesthetic or combined visual-kinesthetic cue will increase the availability of visual attentional resources. The role of central processing (C) in S-R compatibility is accounted for under the term S-C-R compatibility, as described in the Multiple Resource model by Wickens et al. 1983, based on Kahneman (1973), Navon and Gopher (1979) and Norman and Bobrow (1975). According to the model, the limited human processing resources for which tasks compete are defined by three relatively simple dichotomous dimensions: (a) by input and output modalities (auditory and visual), (b) by stages of information processing (early versus late) and by codes of processing (verbal/spatial). Two tasks sharing common resource demands will be time-shared less efficiently than two tasks with non-overlapping demands. Perceptual

and cognitive processes draw from a common resource, separate from those underlying response processes. Hence, increased perceptual competition will disrupt a task whose primary demands are cognitive more than it will disrupt a task whose demands are motor. Correspondingly, the increase in response competition will most harm a motor task such as tracking. Furthermore, the task that will derive the greatest benefit from time-sharing efficiency is presumed to be the one that is emphasized the most.

Wickens et al. (1983) considered the effects of resource competition and S-C-R compatibility by combining navigational motor-movements with a cognitive task. In one experiment cross-modality input and output combinations were considered, among other factors. Subjects time-shared a (spatial) one-dimensional compensatory tracking-task with a (verbal) character-search task. The character search task was performed using four input/output combinations (auditory-speech, visual-speech, auditory-manual, and visual-manual). Wickens et al. found that the search task, being a cognitive task, was disrupted by common inputs (i.e. auditory input with speech output as compared with visual input with speech output), whereas the tracking task was disrupted by common outputs (two-button right-hand manual response to the search task while tracking with the joystick in the left hand). In a second experiment, the competition for spatial and verbal resources was examined using a simulated flight task. Best performance in terms of RTs on the search task and tracking error occurred when the spatial task (target acquisition) was displayed visually and responded to manually and when the verbal task was displayed auditorily and responded to with speech.

While the Multiple Resource model by Wickens et al. 1983 is central to the current study, several limitations in the theory have been noted. As stated by Eberts and Posey (1990), (1) mental models and task consistency may play a greater role in central processing than the static representation code of a task, (2) the model accounts for purely spatial or verbal tasks not for a mixture of representation codes within a given task, and (3) there is no provision for the representation code of a task on the verbal/spatial continuum to change with time as a result of learning.

In relation to the current study, (1) the resource sharing model by Wickens et al. does not include the combination of a kinesthetic input coupled to a manual response spatial task, (2) spatial tasks (and possibly verbal tasks) could be performed using two or more modalities for input (and possibly output) and (3) the notion of stages of information-processing assumes that perception is followed by action, although in a dual-task scenario the user could be involved in both stages simultaneously.

Given that the dual-task in the current study combines a more verbal (character search) task with a spatial-movement task (following a directional cue) benefits of S-C-R compatibility were expected, except in the case of the visual cue task, in which perceptual competition under a common input modality (i.e.

visual) occurs. In particular, costs in the visual-cue dual-task condition were expected generally to appear in the RT measure instead of the movement data, seeing how there was no response competition which could have effected motor performance.

A factor which was expected to influence movement accuracy was the "oblique effect" (Appelle, 1972), whereby judgement of the diagonal orientations is known to be reproduced less reliably than horizontal or vertical orientations in the haptic and visual modalities (Lechelt and Verenka, 1980). Both experiential, depending upon awareness of stimulus orientation, and neurophysiological factors may contribute to an oblique effect (Section 3.1.6). Benefits of potential S-R compatibility in terms of movement accuracy were thus expected to be most pronounced in diagonal orientations using the combination of a kinesthetic input and motor output.

5.2 Method

Twelve right-handed IPO staff members with normal or corrected-to-normal vision, comprising six males and six females with an average age of 31, volunteered for the experiment. The modified version of the IPO trackball with force feedback (Section 2.2.1) was used to produce the kinesthetic cues using motor forces which caused the ball to move independently as contrasted to feeling force feedback during user-based ball movement. The trackball also served as the input device for recording user movement responses to the directional cues. When kinesthetic information was presented, the entire apparatus was placed inside a cardboard box to conceal any visual cues. A Dell 433/M computer connected to a Philips Brilliance 1410 14-inch monitor was used to control the trackball and visual display. All data were collected and recorded by the PC transparently to the subject.

A repeated-measures design was used with 6 conditions (three directional cue modalities X single or dual task condition). The three directional cue modality were visual-only, kinesthetic-only, and combined visual-kinesthetic. Within each condition, 24 cue orientations were randomly presented four times, for a total of 96 trials per cue condition. To limit order effects, half of the subjects completed the single-task conditions first and the other half completed the dual-task conditions first. Furthermore, male and female subjects were distributed equally on a random basis across the six possible cue orders. The subjects completed two conditions per daily session. Each block of 96 trials was divided into two units of 48 trials, separated by 5-minute rest periods. The subjects completed 20 practice trials prior to each condition.

In the three single-task conditions, the subjects moved in response to either a visual-only, a kinesthetic-only or a combined kinesthetic-visual directional cue by moving the trackball in the cued direction; in the three dual-task conditions, the subjects performed exactly the same tasks with the addition of a concurrent

visual-search task. The kinesthetic-only and visual-only directional cues were both displayed for one second over a distance of two cm, at a constant rate of two-cm/sec., in one of 24 orientations ranging from 0 to 345 degrees, in steps of 15 degrees. Each orientation was randomly presented four times for a total of 96 trials per condition.

The visual directional indicator appeared as two 0.3-cm-diameter dots, with one fixed at the centre of the screen, as a fixation point, and the other moving linearly outwards before disappearing. The visual angle of the directional indicator, based on full extent, was approximately 5.72 degrees. The kinesthetic-only cue was presented as a linear ball movement using the same rate of movement as the visual-only cue. The subjects were instructed to follow the movement by lightly resting three fingers on the ball and then replicate the direction of movement, as accurately as possible, after the ball had stopped moving or the visual directional cue had disappeared. No mention of replicating the rate of the cue movement was made. A brake force was applied to the ball to prevent movement prior to completion of the kinesthetic and visual directional cue display. The subject then had to move the ball a distance of two cm until a brake force was felt. Once the subject had moved the ball the required distance, a 750 ms pause occurred, in which only the fixation point was displayed and between one and three beeps were heard, the number of beeps depending upon the movement accuracy. Three beeps were presented if the calculated regression angle of movement from the cued path was less than three degrees, two beeps meant a movement error of between 3 and 10 degrees and one an error of more than 10 degrees in moving the required 2 cm distance. The subjects' scores, based upon the accumulated number of beeps in the current condition and personal best for the previous single-task conditions, were then displayed in the upper-right-hand corner of the display for one second. A 1300-ms blank-screen pause occurred before the next cue was displayed. Movement accuracy was recorded by calculating the total spatial deviation area from the cued path in trackball pixel units of 0.04 mm. Response time was recorded as the time from when the directional cue was fully displayed (i.e., when the ball stopped moving and/or the moving dot disappeared) until the start of user movement. User movement time was recorded as the time from when the user first moved the ball until the required distance was reached.

Under the dual-task conditions the subjects had to search for a target letter (P, X, E, K, T, S, Z or D) in a rapidly changing character display while responding to either the visual-only, kinesthetic-only or combined directional cues described above. The target character was randomly changed every 48 trials. After 48 trials, the subject was presented with a screen indicating which character to search for and a nine-second count-down display to indicate the beginning of the trial. The characters (2.3-cm by 1.7-cm block form) were randomly presented in a circular area at a rate of one character every 100 ms, with the centre of the characters within two-cm from the centre of the screen. The visual angle

of the character display was 5.52 degrees, for an average viewing distance of 40 cm. The kinesthetic and visual directional cues appeared one second after the start of the character display. The visual directional cue, at a visual angle of 5.72 degrees was presented within the same visual area as the characters which appeared around the cue (Figure 1). The subjects were instructed to divide their attention equally between the two tasks.

Figure 1. Visual directional cue in relation to character search display.

To ensure that the subject would perform the character-search task while viewing and responding to the directional cue, the target character was presented 25% of the time during the one second duration of the directional cue and 25% of the time within one second after the cue had been given. In the remaining 50% of the trials no target was present. Pilot data indicated that movements were typically completed within 1.5 seconds after the cue had been given. The subjects were instructed to move the trackball in the indicated direction while searching for the target letter. Random characters were continuously displayed until the subject moved the trackball. Once the subject had moved the trackball the required distance, he or she was prompted to indicate whether the target character had appeared. Using the trackball, the subject pointed to either a “yes” or a “no” box. The two boxes (each 2.5 cm high by 8 cm wide) were displayed along the centre vertical of the screen with the “yes” box appearing two cm above the “no” box. The cumulative score in the current condition and the personal best from the other dual-task conditions were displayed in the upper right corner of the display. The current search character in actual size and font was displayed in the upper left corner of the display. The selected box was highlighted and the entire screen froze for four seconds followed by a one-second black screen before the next trial. A correct response was followed by the awarding of the points gained in the movement task. No points were awarded if the subject made an incorrect decision in the search task. The number of hits and false alarms in deciding whether the target character had appeared was recorded

by the PC.

Two small follow-up experiments, two days apart, were conducted one week after the full experiment. Ten of the original 12 subjects participated; the other two were unavailable. The first experiment was conducted to determine the baseline correct response rate for the visual-search task only. The experiment was identical to the dual-task experiment, except that but the directional cue was omitted. The subjects completed 96 trials with a five-minute break after 48 trials. One point was awarded for a correct response. The second follow-up experiment was designed to examine the relationship between the timing of the directional cue timing and user movement times, depending on cue modality. In a balanced order, the subjects performed the single task as described above, completing trials under either the visual-only or kinesthetic-only cue conditions first. The cue was displayed for 800 msec instead of one second, at a constant rate of 2.5 cm/sec.

5.3 Results

For statistical analysis the response time data, movement accuracy and user movement time data from the 24 cued directions was grouped into three groups of cue orientation, from the user's perspective: horizontal (i.e., left and right), vertical (i.e., up and down visually and forward and back kinesthetically) and diagonal. The results from the response time data, the spatial integral for total deviation area from cued path and user movement times in response to the directional cues were analysed by multivariate analysis of variance (MANOVA) with repeated measures.

5.3.1 Response time

As expected, within the dual task response times in following the directional cues were longer in the visual-only cue condition due to the presence of a visual search task, whereas no difference was found between response times in the single task (Figure 2). The results of MANOVA indicated a main effect for cue modality on response times [$F(5,7) = 4.9$; $p < .05$]. This can be largely attributed to a significant difference between the single and dual task response times [$F(1,11) = 9.2$; $p < .01$]. While no significant difference between tasks was found for response times in the kinesthetic-only and combined cue conditions, response times between tasks under the visual-only cue condition were significantly different [$F(1,11) = 9.3$; $p < .01$]. For all orientations combined, the results of a contrast of means within the dual-task indicated that response times were significantly longer in the case of the visual-only cue (mean=756 ms, sd=454) than in the case of the kinesthetic-only cue (mean=364 ms, sd=264) [$F(1,11) = 7.80$; $p < .01$] and the combined cue (mean=413, sd=318) [$F(1,11) = 5.0$; $p < .05$] (Figure 2, right plot). There was no significant main effect for cue orientation, nor was there an interaction between cue modality condition and cue orientation

on response times.

Figure 2. Mean response times per cue condition and orientation in single-task (left-panel) and dual-task conditions (right-panel).

5.3.2 Movement accuracy

Significant main effects were found for cue modality and orientation on movement accuracy [$F(5,7) = 7.57$; $p < .01$] and [$F(2,10) = 87.46$; $p < .0001$], respectively. Additionally, an interaction between cue condition and orientation on movement accuracy occurred [$F(2,10) = 205.17$; $p < .005$]. As described below, within the single- and dual-task, movement accuracy tended to be the same or higher when the combined visual-kinesthetic cue was followed as compared with the visual-only or kinesthetic-only cue. The gains for combined cue were most evident in the diagonal orientations (Figure 3). No significant main effect for task condition on movement accuracy was found, though an interaction between tasks for the combined cue, in the horizontal orientations, was found (Figure 3) [$F(1,11) = 4.8$; $p < .05$].

Figure 3. Spatial deviation from cue by cue condition and orientation in single-task (left) and dual-task (right) conditions.

5.3.3 Movement accuracy - single task

Results of MANOVA indicated significant effects for cue modality on user movement accuracy [$F(2,10) = 15.48$; $p < .001$]. Additionally, significant effects for cue orientation on movement accuracy were found [$F(2,10) = 167.89$; $p < .0001$]. A significant interaction between cue condition and orientation on movement accuracy was also found [$F(4,8) = 4.80$; $p < .05$]. Further analysis using a contrast of means (Figure 3, left plot) indicated that movement accuracy in the vertical orientations with the visual-only cue was higher than with the kinesthetic-only cue [$F(1,11) = 10.68$; $p < .01$], while no significant difference was found between the visual-only and the combined cue. In the horizontally cued orientations the combined visual-kinesthetic cue tended to significantly improve movement accuracy over either the visual-only or the kinesthetic-only cue alone [$F(1,11) = 6.44$; $p < .05$] and [$F(1,11) = 6.07$; $p < .05$], respectively. A similar advantage of the combined cue over the visual-only or kinesthetic-only cue alone was found for diagonally cued orientations [$F(1,11) = 4.80$; $p < .05$] and [$F(1,11) = 5.33$; $p < .05$], respectively.

5.3.4 Movement accuracy - dual-task

Within the dual-task condition significant effects were again found for cue modality condition and orientation on user movement accuracy [$F(2,10) = 4.42$; $p < .05$] [$F(2,10) = 39.62$; $p < .0001$], respectively. A significant interaction between cue modality condition and cue orientation on movement accuracy was

observed [$F(4,8) = 10.00$; $p < .001$] (Figure 3, right plot). Accuracy in following the combined cue in the horizontal and vertical directions did not differ significantly over the visual-only or kinesthetic-only cue alone. Movement accuracy in following the combined cue was however higher than when the visual-only and kinesthetic-only cues were followed in the diagonal directions, respectively [$F(1,11) = 16.74$; $p < .001$] and [$F(1,11) = 6.15$; $p < .05$].

5.3.5 User movement time

Significant main effects for cue modality and orientation on user movement times were found [$F(5,7) = 5.18$; $p < .05$] and [$F(2,10) = 7.33$; $p < .01$], respectively. As described below, movement times were generally shorter in the visual-only cue condition and in the horizontal orientation within the dual-task (Figure 4). No significant interaction between cue condition and cue orientation on user movement times was found. While no significant main effect was found for task on user movement time, an interaction between the horizontal cue orientations and task occurred [$F(1,11) = 4.7$; $p < .05$].

Figure 4. Mean user movement times per cue condition and orientation in single-task (left) and dual-task (right) conditions.

5.3.6 User movement time - single-task

No significant effects for cue orientation or an interaction with cue modality condition on user movement time was found. User movement times in response to the visual-only cue, across all orientations, were lower than with the kinesthetic-only [$F(1,11) = 15.81$; $p < .001$] and combined cues [$F(1,11) = 8.20$; $p < .01$] (Figure 4, left plot). No significant difference in user movement times

was found between the combined and tactile cue conditions.

5.3.7 User movement time - dual-task

Results of the analysis of user movement times in response to the directional cue indicated a significant effect for cue orientation on movement time, which did not appear in the single task [$F(2,10) = 11.71$; $p < .001$]. User movement times in the vertical direction were significantly longer than movement times in the horizontal and diagonal orientations [$F(1,11) = 17.54$; $p < .001$] and [$F(1,11) = 5.85$; $p < .05$], respectively. Horizontal movement times were significantly lower than diagonal times [$F(1,11) = 24.84$; $p < .0001$]. No significant interaction in user movement times was found between orientation and cue condition. As in the single task, movement times in response to the visual-only cue, across orientations, were lower than the kinesthetic-only cue [$F(1,11) = 4.66$; $p < .05$] and combined cue [$F(1,11) = 5.15$; $p < .05$]. No significant difference was found between the combined and kinesthetic-only cues on user movement times. The slight dip in the vertical orientation for movement times in response to the kinesthetic-only cue compared with the combined cue, which appears in the plot of Figure 4 (right side), is not significant ($p < .53$).

5.3.8 Follow-up experiment using faster cue

A univariate F test was conducted to compare the mean times for the kinesthetic-only and visual-only cue conditions in the follow-up experiment with the single-task results. Given the higher kinesthetic cue movement rate in the follow-up study, the mean user movement time (for all orientations combined) was 862 (sd=210), which was significantly lower than the mean movement time in the single task (mean=1209 ms, sd=246) [$F(1,9) = 6.38$; $p < .05$]. In the visual-only cue conditions, no significant difference was found between the single-task and follow-up results.

5.3.9 Visual search task

Performance in the visual search task remained almost constant across all three cue conditions in terms of hit and false alarm rates (FA), namely visual-only [$p(\text{hit})=0.84$, $p(\text{FA})=0.05$, $d'=2.64$] kinesthetic-only [$p(\text{hit})=0.84$, $p(\text{FA})=.04$, $d'=2.74$] and combined [$p(\text{hit})=0.81$, $p(\text{FA})=.05$, $d'=2.52$]. The results of the follow-up experiment, in which the visual-search task was presented without the movement task, were [$p(\text{hit})=0.91$, $p(\text{FA})=.02$, $d'=3.39$]. In both studies, the subjects reported no difficulties in indicating their responses.

5.4 Discussion

The results of the study indicated two main trends. First, user movements in response to the combined cue were generally more accurate compared to when

the kinesthetic-only or visual-only cue was followed. In particular, the combined cue tended to improve movement accuracy in comparison with the kinesthetic-only cue in the vertical and horizontal orientations and with the visual-only cue in the diagonal orientations. Secondly, the movement response time data indicated the effects of perceptual competition under one modality. Response times were longer when subjects followed the visual-only directional cue while searching for the target character, in comparison to when the kinesthetic-only or combined cue was presented.

Movement accuracy

Both experiential and physiological factors, as underlying aspects of S-R compatibility, may help explain why movement accuracy in response to the combined cue was higher than the kinesthetic-only cue or visual-only cue alone for vertical / horizontal and diagonal movements, respectively.

The higher accuracy for diagonally cued movements using the combination of a kinesthetic-only input and motor output, compared with visual input and motor output, could be attributed to S-R compatibility. In using the kinesthetic-only and the combined directional cues a translation of a visual plane to the motor space was not required². As expected the effects of a compatible cue and response relationship were most evident in the diagonal orientations due to the oblique effect, whereby judgement of diagonal orientations tends to be less accurate than vertical and horizontal orientations (Lechelt and Verenka, 1980). Both experiential, depending upon awareness of stimulus orientation, and neuro-physiological factors may contribute to the oblique effect (Section 3.1.6).

Anatomical factors could also help explain why replication of movements in the diagonally cued orientations and partially in the horizontal orientation was more accurate using the combined cue instead of the visual-only cue. However, one must first assume that the kinesthetic component in the combined cue influenced user movements. This would appear to be the case given the similarity in user movement times between the kinesthetic-only and combined cues.³ The follow-up experiment, in which a faster cue rate was used, further indicated the influence of a kinesthetic cue on overall movement patterns as seen in the tendency of subjects to replicate the faster cue movement rate in the kinesthetic-only but not in the visual-only condition.

For certain orientations, the kinesthetic cue may have reduced the natural tendency to move in a curvilinear path while using a trackball. In unpublished studies on using the trackball to perform free movements in target acquisition tasks, curvilinear traces have been observed. In particular, curvilinear patterns

²The ability of subjects to form internal representations of object orientations in the absence of visual information is further considered in Section 6.2.

³Note that subjects were instructed to move in the direction of the cue, with no mention of replication of the cue movement rate.

are most pronounced in the horizontal and diagonal orientations, where movement of the wrist as distinct from abductive movements (increasing the joint angles involved) and adductive movements (decreasing the joint angles involved) of the fingers for vertical movements occur. Research on handwriting has attributed curvilinear wrist movements to the fact that the wrist can only rotate. While most studies on human trajectory formation stress that humans (and animals) use straight trajectories, closer examination, as observed in handwriting studies, shows that there are always some deviations from perfectly straight trajectories which is related to the basically curvilinear displacements of separate joints (Van Galen, Van Doorn, and Schomaker, 1990). In the current experiment the subjects must have been using some additional degree of freedom to produce more or less straight trajectories while relying on wrist movements to replicate the horizontally and diagonally cued orientations. Vertical (i.e., forward and back) movement of the trackball, in which finger movements were dominant, may have provided a much better opportunity to realize the natural tendency to move along a straight path. Thus from an anatomical perspective, the kinesthetic cue may have had no effect on vertical movements but may have assisted in the planning of linear horizontal and diagonal movements, as evidenced in the replication of cue movement time, in addition to cue direction.

In short, given that the subjects replicated the entire kinesthetic movement as distinct from performing a free movement between two points, accuracy may have been improved in the non-vertical orientations. This appears to have partially held in the case of the combined cue, where user movement times were influenced by the presence of kinesthetic cue information. In the dual task, movement-accuracy gains using the combined cue in the horizontal orientations were less pronounced than in the single task (Figure 3). The reduced movement accuracy gain in following the combined-horizontal cue in the dual task, as compared with the single task, may be related to the fact that horizontal movement times were shorter in the dual-task (Figure 4, right plot).

Perceptual competition

The second main trend in the data is the evidence of perceptual competition under one modality, given a visual directional cue and a visually demanding (search) task. The longer response times under the visual-only cue condition, in the visual search task, could be attributed to lower S-C-R compatibility. The observed cost of perceptual competition under one modality may be related to attentional factors instead of eye movement times in scanning between the visual-directional cue and target letter. Had eye movements been used to spot the target character while performing the navigation task, the target character would most likely have been missed more frequently in the visual-only cue condition than in the kinesthetic-only cue condition. The time required to plan an eye movement is about 250 ms (Matlin and Foley, 1992), which is longer than the 100 ms per character display rate used. The response times associated with the

visual directional cue might have been even longer had the visual search information been displayed outside the visual area of the cue, thus requiring timely eye movements.

While the response time data for the directional cues reflected perceptual competition under the visual-only cue condition, results obtained in the character search task, as an additional measure of cognitive performance, indicated perceptual competition independent of cue modality. Performance across all cue conditions for the search task was lower than when the search task was presented as a single task in the follow-up experiment. In the dual-task condition, subjects may have paid more attention to spotting the target character than to responding as soon as possible to the directional cue, with the consequence that this trade-off was more pronounced in the visual-only cue response times. On a conscious level, the nature of the reward system used in the game-like feedback may have influenced the amount of attentional effort devoted to the visual search task. At least one beep was heard regardless of movement accuracy, however the receipt of points based on the number of beeps was contingent upon making a correct decision in the visual-search task. As noted earlier, the task that will yield the greatest benefits of time-sharing efficiency is presumed to be the one that is emphasized the most (Wickens et al., 1983).

Interactions between visual search and movement task

User movement times at different orientations were apparently influenced by the presence of the visual search task. In particular, horizontal movements in the dual-task, across all cue modalities, were faster, followed by diagonal and then vertical movements (Figure 4). The interaction between movement time and orientation could be linked to visual search processes. In plotting successive eye fixations in a character-string search task, Van Nes, Juola, and Moonen (1987) identified two basic search strategies. The “readers” tended to search horizontally for text strings, while “hoppers” searched using a partly random strategy. Though the current task consisted of single Latin characters, a verbal search process may have been evoked, benefiting eye-hand movement coordination, which may have been more compatible for horizontally cued movements and somewhat less so for diagonal cues than for vertically cued movements. Further research is needed to determine possible interactions between concurrent verbal-perceptual and motor tasks. The present research demonstrates that the two tasks may occur concurrently rather than as “stages of information” processing. More specifically, perceptual-motor interaction should be considered under conditions involving eye-hand coordination.

5.5 Conclusion

The fact that the response times in the dual-task condition using the combined visual-kinesthetic cue were as short as the kinesthetic-only cue suggests that the

most effective information available from the senses at any given time is utilized, especially when one of the senses is heavily loaded. Furthermore, results of the movement accuracy data suggest that combined sensory information can enhance certain movements compared to when only one sense is used.

Comparison of the response time results of the single-task conditions with those of the dual-task conditions reveals the importance of studying novel means of navigation in situations where the human visual system is likely to be heavily loaded. In short, the potential gains for additional tactile and kinesthetic navigational information may be more apparent under conditions in which the human potential for multimodal interaction can be realized. While previous studies on S-C-R compatibility under dual-task constraints have been based predominantly on tracking and visual search common to aircraft control, the emergence of multimedia and new input devices for human-computer interaction has created opportunities for expanding existing theories on resource sharing. To reduce the increasing demands on the human visual system new means for multimodal navigation should be considered.

6

Internal Representation of Tactual Distance and Orientation

The degree to which spatial relations between objects can be formed in the absence of visual feedback is central to the spatial design of tactual fields. For example, consider a user travelling along a felt path with no visual feedback and reaching a felt intersection, the decision as to which direction to travel in will depend upon the user's ability to position himself or herself with respect to the path or vice versa. While moving along felt paths, distances could also be perceived which could imply a physical or semantic relationship between objects placed on the path. Two studies were conducted into these two areas of tactual spatial perception. In the first study, estimates of felt and visually perceived path length were examined. Additionally, the influence of a virtual path friction on distance judgements was examined¹. In the second study, a mental rotation task was used to examine the ability of subjects to perceive and process tactual orientational information from simple path-like forms².

¹Based on Keyson (submitted)

²Based on Keyson and Solso (submitted)

6.1 Estimation of virtually felt and seen distance

Experiments on perceived and felt length were conducted as early as 1886 by Jastrow (Jastrow, 1886). In the late 1950s studies on distance estimation using the method of direct estimation of magnitude appeared. Subjective estimates were recorded by asking the subject to verbally estimate the distance (e.g. Stevens and Galanter, 1957) or by using a physical scale. For example, Ronco (1963) examined extent of arm movement by having a blindfolded subject grasp a slider and move his arm until it touched a peg. Using this method visual and felt judgements of length were generally found to be linearly related to physical length.

Teghtsoonian and Teghtsoonian (1965) considered visual and kinesthetic distance perception of eight rods, ranging in length from 1.7 to 83.82 cm, by having subjects assign a number to the perceived length. In the visual condition the rods were placed on a table for judgement, in the kinesthetic condition the subjects were blindfolded and placed one index finger at each end of the rod. In regressing actual length on estimated length a slope of 1.007 for the visual judgement was found and 0.983 for the kinesthetic condition. The product-moment correlation coefficient between log visual and log kinesthetic judgements was 0.946. Stanley (1966) partially replicated Teghtsoonian and Teghtsoonian's (1965) study and removed the cutaneous aspect (i.e., feeling the end of the rods). The resulting slope for the kinesthetic condition was 0.94 in contrast to 1.05 for the haptic condition (i.e. with feeling of rod ends). Stanley (1966) concluded that at smaller distances touch enabled a more accurate estimate than pure kinesthesia. As distance increased, touch information became redundant for accurate estimation of lengths. In a later study by Teghtsoonian and Teghtsoonian (1970), in which subjects estimated the lengths of blocks held between the fingers, visual input was found to be preemptive when combined with kinesthetic information.

More recently, movement dynamics during wielding of an object, in the absence of visual feedback, have been shown to contribute to linear estimates of length (Solomon and Turvey, 1988 & 1989). The observed relations between perceived and actual reaching distances for rods wielded about the wrist were attributed to the principal moment of inertia in a hand-rod system about the axis of rotation.

The current study is concerned with estimating felt horizontal path distances using the IPO 2-D trackball with force feedback (described in Chapter 2). In navigating through a virtual environment, the perceived distance between objects can be based on touch information rather than requiring visual space on a screen. In particular, creating a visual plane for objects located at a distance of more than one screen apart, or in virtual space, may require extensive graphics. Tactually perceived distances could be used to establish physical, functional, and semantic proximity between user interface objects. For example a waste-

basket object may be felt to be farther away from the other objects on a desktop to prevent accidental deletion of files, or, in an information system, the amount of movement and direction required to reach the category “leaves” may be about the same as that to reach “trees”.

In judging tactual path distance through a device such as the trackball with force feedback (Section 2.2.1), the kinesthetically felt ends and haptic distance are sequentially perceived before an image of the total distance can be formed. This contrasts with the studies mentioned above, in which the entire length of an object was felt as a holistic image between fingers or hands or the object in its entirety was wielded. Using the trackball is perhaps more similar to perceiving distances by tracing the hand over a fixed surface. Both the actual number of ball revolutions required to move between felt end-points, as a measure of spatial-temporal extent, and estimation of muscular effort based on the force required to move the ball may influence path distance estimation. Unlike visual space, where distances are perceived as a function of the retinal angle, in tactual perception distances can be imagined which bear no linear relationship to a euclidean space. In considering spatial-temporal factors in tactual distance perception, Lederman, Klatzky, and Barber (1985) found that subjects using one finger increasingly overestimated the euclidean distance of a felt pathway as the length of the explored pathway was increased.

An experiment was conducted to consider the relationship between virtually perceived tactual path distances and actual physical lengths. The modality of perception was considered (i.e. visual, tactual or both) as well as the influence of a constant simulated-friction force on the path.

6.1.1 Method

Twenty-four paid, 12 male, 12 female, subjects with normal or corrected-to-normal vision, and a mean age of 31 participated in the experiment. Using a repeated measures design, they completed each of the path conditions (visual, tactual, combined visual-tactual and tactual with force) as a block in random order. Within each condition eight path lengths (1.6, 2.5, 4, 6.3, 10, 15.8, 25.1 and 39.8 cm) were presented 8 times each in a random order. Five practice trials were conducted prior to each block. The lengths were chosen to approximate the distances used by Teghtsoonian and Teghtsoonian (1965) and Stanley (1966). The maximum distance was limited due to the monitor dimensions. In the visual condition each path was displayed as a four-pixel-wide solid white horizontal line on a 42 cm-wide monitor. The monitor was positioned symmetrically with respect to the centre of the subject's body and at eye level. The viewing distance was approximately 1.7 m. The trackball was placed directly in front of the subject, on the table and in line with the centre of the screen. At 180 degrees behind the subject and at a distance of 0.5 m a linear 1.5-meter-long metal bar with a slider was horizontally placed against a window, into the experimenter's room, at chest level. The side of the bar facing the one-way mirror was marked by

units of 1 mm. The window was also completely covered with black paper, except for the area where the bar was positioned. On a trial-by-trial basis the path was generated by computer and displayed on the monitor in the observation room. The subjects were instructed to match the perceived distance, when ready, such that the distance from the far right side of the bar to the inside-right edge of the slider corresponded to the estimated path length. When they were ready, the subjects turned around on a rotating stool and moved the slider on the bar to give their judgement. The experimenter recorded the slider position and pressed a button which signalled a beep tone, instructing the subject to move the slider back to the far-right position on the metal bar. The next path was then displayed. The subjects were monitored by camera throughout the experiment.

In the tactual condition, the subjects were blindfolded and felt a tactual path mediated by the trackball (described in Chapter 2). The path lengths were the same as the visual lengths. To delimit the path length, a constant brake force of 1.7 N was applied at the path end-points. To prevent deviations from the horizontal path in the vertical directions, the tension of the y-axis support wheel against the trackball was increased, allowing only one degree of movement in the ball. Using the force measurement device described in Chapter 2, the friction in the trackball mechanism was measured at 0.2N. The subjects were allowed to move freely back and forth between end-points before making a judgement using the metal bar and slider. In the combined visual-tactual condition the subjects were instructed to move the ball between felt end-points and view the displayed path before making a judgement as in the other conditions. In the tactual condition with force, a constant force of 1.17 Newton, measured independent of the hand (see Appendix A on method), was applied in the direction opposite to the user's movement while movement of the ball was detected. The resulting unidirectional-force was felt as constant friction on the ball. A view of the hand on the trackball was monitored and recorded on video.

6.1.2 Results

The log mean distance judgements for each path length are given below in Table 1. In the visual, tactual, and combined visual-tactual conditions, judgements were generally overestimated for shorter physical lengths and underestimated for longer lengths. In the tactual with force condition shorter path distances were generally over estimated while longer distances were underestimated. The mean differences between estimated and physical lengths were calculated for each path modality condition. Results of a MANOVA on the resulting distribution indicated a main effect for modality condition [$F(3,21) = 18.46; p < .0001$]. In contrasting mean tactual difference estimates, significant differences were found between visual [$F(1,23) = 16.19; p < .001$] and visual-tactual [$F(1,23) = 22.12; p < .0001$] values. The tactual-force condition mean difference estimates were significantly different than the tactual values [$F(1,23) = 25.22; p < .0001$]. No significant difference was found between the visual and visual-tactual mean dif-

ference distributions. No significant differences between means were found due to the order of the presentation conditions. The product-moment correlation coefficient between log visual and log kinesthetic judgements was 0.979 ($p<.0001$).

Table 1
Mean judgements (cm) per path length and modality of presentation. Standard deviations are given in parentheses.

Path Modality	Path Length							
	1.6	2.5	4	6.3	10	15.8	25.1	39.8
Visual	2.03 (0.50)	2.70 (0.67)	4.38 (0.90)	6.28 (1.29)	9.46 (1.82)	13.55 (2.25)	20.89 (4.03)	33.89 (5.68)
Visual-Tactual	2.01 (0.47)	2.76 (0.61)	4.44 (0.97)	6.38 (1.34)	9.26 (1.85)	13.72 (2.65)	21.71 (4.02)	34.40 (6.64)
Tactual	1.93 (0.56)	2.72 (0.60)	3.73 (0.76)	5.83 (1.04)	8.23 (1.86)	12.86 (3.24)	19.02 (5.09)	29.87 (8.13)
Tactual & force	2.38 (0.72)	3.59 (0.91)	5.61 (2.33)	7.13 (3.76)	9.36 (5.03)	13.50 (5.22)	23.67 (6.67)	33.71 (8.0)

Using the method of averages (Lewis, 1960) linear functions were obtained for log geometric mean distance estimates (Y) against log physical length (X) for each path modality condition. The respective functions are shown in Figure 1. In all conditions r^2 (i.e. the proportion of variance accounted for in the regression equation) was highly significant ($p< 0.0001$; $df=1,206$). The standard error for the obtained slopes ranged from 0.2 (visual) to 0.3 (tactual with force).

A review of the video material indicated that all subjects tended to explore the tactual paths by moving the trackball back and forth, two to three times, between path endpoints. One subject was observed to count partial ball rotations by repositioning his hands between movements.

Figure 1. Log geometric mean distance estimates plotted against log physical length.

6.1.3 Discussion

The high correlation between tactual and visual estimates as well as tactual and physical lengths suggests that spatial relations between user interface objects could be accurately communicated by non-visual means³. While larger distances were slightly underestimated in the tactual condition, the same effect was found in the visual condition. This effect can also be found in classical studies on felt and seen length using methods of direct estimation of magnitude (e.g. Stanley, 1966). The results of the tactual condition with force suggests that a virtual friction force on a path could be used to increase the perceived distance between closely located non-visual objects, without requiring more trackball movement.

While the use of force represents one way of virtually increasing tactual estimates of distance between objects, other methods could include the use of texture or spatial deviation from a euclidean path. For example, Thorndyke (1981) investigated visual map clutter as a source of distortion in subjects' estimates of distance and found that estimates increased as a linear function of the number of intervening points. Similar effects could be studied in tactual perception of distance by placing felt objects along a felt path. In investigating effects of texture on tactually perceived length, Corsini and Pick (1969) found that fine-

³Note: In the case of the current study only one subject was observed to use the strategy of actually counting ball rotations to judge path distances.

texture stimuli were perceived as longer than coarse-textured stimuli. A curved rather than straight tactual path may also lead to longer estimates of distance as more movement of the trackball would be required to reach a given point, similar to Lederman's et al. (1985) finding that blind-folded observers increasingly overestimated the length of a euclidean line as the explored pathway increased. The advantage of using curved paths rather than simply requiring more movement of the trackball to reach a given point is that the control-display movement ratio can be kept constant. In a sense using non-euclidean tactual paths in this manner creates a subjective space, that can only be felt.

The current study demonstrated the ability of observers to form internal spatial representations of tactually perceived path distances and to directly map those representations to a one-to-one physical scale. In the following section the ability of subjects to perceive and process tactual orientational information of simple path-like forms will be considered through a mental rotation task.

6.2 Mental rotation of kinesthetically perceived stimuli

Since the seminal experiments by Shepard and his associates (Shepard, 1975, Shepard & Metzler, and Cooper & Shepard 1973, and Metzler & Shepard 1971), cognitive psychologists have vigorously probed the topic of the spatial manipulation of perceived objects. In the first of a series of experiments and theoretical papers, Shepard and Metzler (1971) presented subjects with pairs of two-dimensional illustrations of three-dimensional objects. Their task was to determine whether the two figures "matched", except for rotation. Null pairs contained mirror images of one of the images. The results of this experiment revealed that the time it took for subjects to determine if the figures "matched" was linearly related to the degrees of rotation. These studies, and others, have generally dealt with internal representations of geometric forms as measured by reaction time data and have generated numerous research papers in which a wide assortment of related features have been investigated, ranging from studies of population differences (e.g., gender) to orientation of stimuli (e.g. surface rotation vs. depth rotation) and presentation mode of stimuli (e.g., tactually presented stimuli), to mention but a few of the various experimental approaches to the problem. In addition to providing useful data about the way visual information is processed, the mental rotation paradigm is sufficiently versatile to provide interesting information on the way stimuli from a variety of sensory modes are processed. In this section yet another unique means of presenting stimuli will be described, which addresses the fundamental question as to how tactual orientational information is stored and processed, in relation to similar visual stimuli.

A perennial issue in the cognitive psychology which is central to the design of multisensory spatial information in human-computer workspaces has been: are experiences resulting from one sensory mode cognitively isomorphic with experiences acquired by another mode? Data presented by Shepard and his

colleagues suggest that subjects "rotate" a three-dimensional visual object, presumably, by means of a complicated series of neuro-cognitive processes, that requires time, which is entirely consistent with the physical disparity between two geometric objects. While it is logical to infer that these operations are undertaken by different parts of the cerebral cortex, until recently that inference had not been observed directly. Internal representations have typically been studied by means of cross-modal transfer. And, in the case of geometric analysis (as in the instance of three-dimensional figures), the research varies in intention, as some researchers are interested in the investigation of cross-modal similarities for the purpose of discovering universal information-processing traits (e.g. Solso, Mearns, & Oppy, 1990). Specifically, in the investigation of cross-modal similarities in mental rotation, O'Connor and Hermelin (1975) examined tactually presented stimuli and found that the relationship between mental rotation of visual objects, as in the original work of Shepard and Metzler, did not hold for tactual experiments in which stimuli were touched. Others have extended the mental rotation paradigm using tactual stimuli with mixed results. Dellantonio and Spagnolo (1990) found that in the case of tactual shapes, subjects showed no rotation effects when two successive rotated shapes were presented, but did yield linear results when a single stimulus was presented and the subjects were to decide whether the rotated stimulus was the "same" or a "reversed" image. Yet other studies have concentrated on the effects of blindness and mental rotation of tactual stimuli (see Marmor & Zaback, 1976 and Röder, Rösler, Heil, & Hennighausen, 1993). Such inconsistent results might suggest that mental rotation, a robust phenomenon in visual experiments, is not a central system for the analysis of information and that the linear results of tactual experiments (when obtained) might be the result of mediated activity in which tactually sensed stimuli are transformed into visual codes and then mentally rotated.

Thus far, data regarding the generality of mental rotation have been somewhat limited to tactically presented stimuli due, partly, to methodological limitations. However, two areas of research have recently extended the available data; one involving single-cell recording of the cortex of non-human animals, especially the motor cortex, and the other, involving the motoric presentation of geometric forms as reported in this paper. Relevant studies of the motor cortex by Montcastle, Lynch, Georgopolous, Sakata, and Aeuna (1975) and more recently by Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989 and Georgopoulos, Taira, & Masato, (1993), in which brain activity in the motor cortex was directly observed while a simian subject performed a mental rotation task. Georgopoulos et. al. (1993) measured neural activity in the motor cortex of rhesus monkeys which were trained to move a handle 90° counterclockwise from a reference location indicated by a light. During the few milliseconds before the response the animal anticipated the movement and it was possible to measure minute electrical activity in the monkeys motor cortex which, when enhanced by computer graphics, showed individual cells have directional preferences. The

activity level of cells in the motor cortex was found to depend on angle formed between the direction of movement and the cell's preferred direction (i.e., the highest cell activity level for a movement in a particular direction). The results of the studies by Georgopolous and his associates thereby suggest that the motor cortex serves as a centre of brain activity which is connected with "mental rotation". No reaction time data are available on kinesthetically presented stimuli which have been tested using the mental rotation paradigm.

In the present study we examine mental rotation of stimuli presented motorically. In many of the above examples and experiments motor responses are important yet, the reaction time literature is mute on the question of mental rotation and motor stimuli. In the present study this issue is addressed by presenting kinesthetically perceived stimuli under controlled conditions within a reaction time paradigm for mental rotation.

6.2.1 Method

Subjects

Fourteen (7 male, 7 female) familial right-handed volunteer subjects from IPO with normal or corrected-to-normal vision took part in the experiment. All of the subjects indicated a strong-to-moderate right-handedness according to the criteria used by Varney and Benton (1975). They ranged in age from 21 to 48, with a mean age of 30.

Apparatus

A modified version of the IPO trackball with ball-independent position sensors (see Section 2.2.1) was used to generate the kinesthetic stimulus. The subject's index finger was guided along a predefined pattern by a hard-plastic round point, with a diameter of 0.8 mm and a height of 1 mm., affixed to the ball surface.

Each subject rested his or her right wrist on the Plexiglas surface, perpendicular to the front edge of the trackball. The right index finger was placed on top of the ball point. The entire apparatus was placed inside a cardboard box to conceal any visual cues of finger movement direction. The motors did not emit any audible noise. The subjects were seated alone in a quiet room and were monitored remotely. Reaction times and judgements were recorded by a 486/66Mhz PC, which was also used to control the trackball.

Stimuli

The stimuli consisted of an inverted "L"-like pattern and its mirror image. The pattern was drawn by the trackball point in three equal line segments with two segments forming the vertical line in the "L" and one forming the base line. Each single segment was 8 mm long and ran for 200 msec, at a constant velocity

of 4 cm/sec. A 200 ms pause was given between each line segment. Two patterns were presented in succession with a 3000-msec pause between them. The first pattern, as a reference, was always presented at 0 degrees in normal form. The second pattern was presented at one of 8 orientations: 0, 45, 90, 135, 180, 225, 270 or 315 degrees, rotated in clockwise direction, in either normal or reflected form.

Procedure

Two successive patterns were presented on each trial. The subjects were instructed to determine, as quickly as they could without making errors, whether the second pattern was normal or reflected in relation to the first image and to press a key labelled "normal" with the left index finger or a second key labelled "reflected" with the left middle finger. Reaction time was recorded as the time from when the second pattern was fully presented until the subject pressed one of the response keys. The subjects were instructed to lightly rest their right index fingers on the ball point to allow their fingers to be guided along the pattern.

To prevent masking effects while the ball point was being repositioned to the centre point after the first pattern had been presented, a beep tone was given. The subjects were instructed to lift his/her finger briefly (about 1 second) when the beep tone was heard. Once the subject had entered his/her response, feedback was given for a correct or incorrect decision. A correct judgment was signalled by a 392 Hz beep tone for 125 msec, followed by a 30-msec pause and then a second tone at 493 Hz with the same duration. An incorrect response was signalled using the same time intervals but at lower frequencies, 92Hz followed by 193 Hz. A 5-sec. inter-trial delay occurred before the next pair of pattern presentations. This was indicated by a computer display with seconds remaining positioned in the direct view of the subjects.

Prior to the actual experiment, the subjects completed 16 practice trials to familiarise themselves with the experimental task. Following this initial training period each subject completed two sessions, one per day, for a total of 128 trials. The 64 trials per session consisted of 8 trials per each of the 8 orientations. At each orientation, half of the trials had a reflected second image, the other half had a normal image. Within each session all possible conditions were presented in a random order. The subjects completed 16 trials at a time, followed by a three-minute break. On average, each block of 16 trials took approximately four minutes and 15 seconds. In total, the data consisted of 1792 observations.

6.2.2 Results

The mean reaction times to indicate whether the second pattern was "normal" are given in Table 2. A preplanned MANOVA across orientations, treating each session as a repeated variable, indicated that the effects of stimulus orientation [$F(7,7) = 8.92, p < .005$] and session [$F(1,13) = 11.37, p < .005$] were signifi-

cant. No significant interaction was found between session and stimulus orientation [$F(7,7) = 3.11, p < .08$]. A contrast of means indicated that reaction times at 45° were significantly lower than at 315° across both sessions, respectively [$F(1,13) = 6.81, p < .005$] and [$F(1,13) = 5.74, p < .005$]. In order to test the hypothesis that mental rotation of tactual images is a function of stimulus orientation, mean reaction times were regressed on orientation. Results of a linear regression analysis by least-squares, using test orientations 0 to 180° (with both sessions combined) indicated that 41 percent of the proportion of reaction time variance (R-squared) was accounted for by stimulus orientations [$F(1,138) = 48.56, p < .0001$] and 43 percent of the reaction time variance accounted for orientations 180° to 360° [$F(1,138) = 54.81, p < .0001$]. Data at 360° were derived from results at 0° degrees. The slope of the least squares line relating rotations to reaction time was 0.03 for both 0° to 180° (and 180° to 360° orientations (Figure 2). The percent of response errors in terms of indicating whether the second pattern was either normal or reflected was less than 3%.

Table 2
Mean Reaction Times in Seconds (with Standard Deviations) for Mental Rotation
Task per Test Orientation in Session 1 and Session 2

Test Orientation	Session 1		Session 2	
	M	SD	M	SD
0°	0.626	0.153	0.394	0.085
45°	0.587	0.240	0.409	0.127
90°	0.830	0.291	0.544	0.129
135°	1.032	0.316	0.747	0.240
180°	1.216	0.329	0.90	0.402
225°	0.958	0.321	0.743	0.260
270°	0.764	0.425	0.666	0.182
315°	0.815	0.369	0.427	0.093

Figure 2. Reaction time means and least squares fits of the means for 0 to 180 (Figure 1) and 180 to 360 degrees (Figure 2) as a function of angular separation between stimuli. (Slopes are given in units of sec / degree. The 95% confidence limits about each mean are based on the *t* distribution.

6.2.3 DISCUSSION

Estimates of the speed of mental rotation based on the slope suggest approximately 333 degrees per second (Figure 2); the rate of mental rotation is almost identical to the results obtained by Cooper and Shepard for a similar visual stimuli, in which the observed rate of rotation was about 362 degrees per second (for 0° to 180°). The intercept in the current study was about 0.5 as compared to 0.55 in the Cooper and Shepard study. In the Shepard and Metzler study, using three-dimensional complex forms, reaction time data from the mental rotation task indicated a higher intercept and a slower rotation time (about 60 degrees per second). The disparity between Shepard and Metzler's results and the current data may be due to the fact their data was collected on complex forms and in 3-D space. As for the similarity between the results reported in this paper and the results obtained by Cooper and Shepard, in both experiments simple forms were used, viz. two feature forms (e.g. "7") and letters (e.g. "R"), respectively. Given the similarity in reaction times as a function of tactual or visual orientation for two feature forms, it would appear that the mental rotation of simple forms, whether visually or motorically presented, yields very similar reaction time data, which, of course, does not mean that these data reveal the same internal neurological processes, but it may suggest a central mechanism for the transformation of rotated objects-whether visual or motor.

The notion of a neuro-cognitive centre for the transformation of visual or kinesthetic rotational information processing is supported by the work of Georgopoulos and his colleagues (1993) described earlier, in so far as individual cells in the monkey's motor cortex, were found to shown signs of directional preferences in a motor task similar mental rotation (i.e. a reaching task). However, such experimentation has yet to be extended to visual and kinesthetic stimuli.

A central mechanism for the transformation of rotated objects can also be considered in terms of a sensorimotor system which is organized on the basis of a hierarchy of central sensorimotor programs (e.g. Brooks, 1986 and Georgopoulos, 1991). Abbreviated, the theory states that the sensorimotor system does not work in a one-to-one fashion in controlling individual muscles, as in moving a lever to the right or left, but that the system is organized in such a way that functional patterns of muscle activity are produced much in the same way as some memory functions are hierarchically structured. The relevance of this theory to the present research is that many sensory experiences, for example, visual patterns, may be stored in a sensory-motor system as a progenitor for action. The fact that primates and perhaps other animals are capable of mental rotation of visual stimuli may be due to an anticipated action on the organisms' part involving motor performance. The existence of hierarchical coordinative motor planning structures is further supported by the linearity of the observed reaction times slopes, which was also the case for similar visual stimuli (e.g., Cooper and Shepard, 1973). The more the observed pattern deviates from the represented structure (i.e. the memorized one) the more transformations, or plans for transformation have to make. This may well be linear in time, resulting in the observed linearity. The alternative view to mental rotation proposed by Hinton and Parsons (1981), whereby subjects search first for a frame of reference that matches the object, rather than mentally rotate the object, is also considered to be a continuous process. Time is needed to find the internal frame of reference, which is found by "testing" the coordinative structure. More time is required to impose a nonvertical frame of reference and to represent a stimulus relative to this frame.

The notion of a sensory-motor system as a progenitor for action suggests that the locus of mental rotation is centred in the motor cortex and part of the central sensorimotor program, involved in action, not thought. Neurological studies of the motor cortex and cerebellum, both of which play central roles in processing motor actions, may be a likely site for the localization of this process. This notion is based on the assumption that mental rotation may be a natural process, in which humans and other animals receive and interpret signals from the visual world as a precursor to actions, many of which are executed kinesthetically. This notion is consistent with motor prototype theory as expressed by Solso (1989), in which motor actions, such as those expressed in dance, are governed by the development of subordinate mental structures, or schemes. It is possible that all mental rotation of visually presented stimuli may have a motor component which is a preparatory stage to action. The similarity of kinesthetic and visually judgements for perceived distances (Section 6.1), may also be attributed to subordinate mental structures, or schemes.

Further evidence for the relationship between imaged and motor activation may be found in recent studies of brain activity as measured by PET investigations. In one study by Anderson et al. (1994) regional cerebral blood flow acti-

vation was measured during reflexive saccades to random targets and in remembered saccades to locations of recent targets. The results indicated that during remembered saccades there was an activation of the posterial parietal cortex and frontal eye fields, as one might expect with visually related recall but, in addition, an activation of the supplementary motor area and related motoric regions. The co-activation of remembered visual locations and motor activation in these experiments based on saccadic activity suggest a well organized relationship between these areas and functions which, along with the data presented in the present study, lend support for the notion that motor cognition may be involved in a wide range of cognitive and visual processes including mental rotation.

In short, the notion of a central mechanism for the transformation of rotated objects-be they visual or motor implies that the spatial perception of simple path-like forms may not be a visually-mediated activity in which tactually sensed stimuli are transformed into visual codes and then mentally rotated. The similarity in mental rotation times for visual and tactual forms, suggests that tactual and visual paths, containing orientational information, could be efficiently utilized, side-by-side or as combined tactual-visual fields, in a user interface.

7

General Conclusions and Future Directions

In considering the use of touch in user interface navigation, the empirical studies in this dissertation demonstrated the potentials for touch in several areas including, improved performance in target acquisition, the formation of internal spatial representations similar to vision, and enabling user interface navigation to be performed as a concurrent rather than sequential task. In support of the studies, several touch navigational fields were developed including, directional cues, “hole” forms for capturing the cursor and tactual paths. These fields and others such as, “walls”, “hills” and textures were built into the TacTool rapid prototyping environment as design objects.

In examining relations between touch and visual perception, further insight into visual performance was gained. For example, observations on the effects of tactual feedback over a target led to the idea of dynamic cursor gain, which was shown to improve visual target acquisition performance. A common thread throughout the studies was the degree of compatibility between the touch and the visual senses, which indicates that visual and touch information can be effectively combined or interchanged within the user interface. Future work towards designing compact force-feedback devices and the development of concepts for managing multimodal feedback in the user interface is foreseen.

7.1 General findings

The stage for the current research was set in Chapter 1. An emphasis was placed on developing tactual-navigational concepts that could be compatibly integrated into existing visually-oriented user interfaces. In Chapter 2 force feedback technologies were discussed within a classification framework, including those developed in the course of the current research and those for future studies, such as the 3-D trackball with force feedback. The need for multimodal design tools and interface concepts which can match the pace of hardware development was stressed. The rapid prototyping tool, TacTool, for the design and evaluation of integrated and individual tactual-navigational fields was described.

The results of work discussed in Chapter 3 provided insight into the degree to which users can be expected to discriminate tactual directional cues in the finger and hand. The average directional change threshold for a moving point over the fingerpad was found to be approximately 14° , except at an orientation of 180° , where it was 10.6° . Using a similar method, the mean directional discrimination for ball movements, detected kinesthetically by the hand, was found to be uniform, at about 9° . Chapter 4 provided insight into the behavioural implications for movements towards objects with a visual or tactual "cursor catching" effect in relation to no such effect. The visual "catching effect", using dynamic cursor gain, as well as tactual feedback over the target were shown to reduce reaction times while speeding up movements towards the target. The tactual feedback condition led to the highest performance levels. The importance of tactual interface design was emphasized by the costs in target acquisition performance when encountering a non-target field with tactual feedback. Chapter 5 extended the discussion in Chapter 3 by considering movement performance in response to directional cues. The combined visual-kinesthetic cue produced response times equal to those of the kinesthetic cue and equivalent or greater movement accuracy across all orientations. Lower response time gains using kinesthetic cue information, in comparison with those obtained using visual-only cues, within a dual-task scenario, indicated that tactual directional information could be efficiently utilized while performing a concurrent visually-demanding task. The need to build upon existing models of human resource sharing theory while taking into account new human-machine interaction technologies was stressed. Finally, Chapter 6 demonstrated the remarkable similarity in tactually perceived path distances, as felt through the force feedback trackball, in comparison with visual perception. Furthermore, the work on mental rotation, as a means for investigating internal spatial representation, suggested a congruence between visual and kinesthetic modalities in the mental manipulation of simple forms.

In considering the total integration of findings, one can begin to consider how directional cues, felt navigational objects and their spatial layout can be applied to build tactual navigational models where movement efficiency and

extraction of spatially-based information are key criteria. The work on dual-tasking (Chapter 5) suggests that tactual navigational spaces could be accessed while performing a visually-demanding task. Preliminary evaluations of navigational spaces, constructed in TacTool (Section 2.6), utilizing multiple tactual fields including tactual targets, paths and directional cues suggests that limited amounts of visual-spatial information can be effectively combined with tactual information. For example, subjects were able to utilize dots in a circle formation, with each dot serving as a marker for a tactual path, to rapidly locate and move along a “bumpy” as compared to “smooth” tactual path. In moving between visual markers subjects travelled along tactual paths with a blank screen, in this sense distance judgments could be influenced using non-euclidean trails. These investigations also showed that users can rapidly (i.e., within one or two encounters) associate virtual tactual fields with “everyday touch sensations”.

A common trend observed throughout the experiments was that tactual information can be integrated in a compatible manner with visual information. Compatibility depends not only upon human perceptual and cognitive factors, such as resource sharing, but also upon the spatial and contextual design of information displays as well as on the efficiency of input and output displays. For example, the design of interface objects with auditory and visually linked information should take into account faster movement and reaction times when tactual feedback over a target is given. From a technological perspective, input devices are needed which can optimize fine motor capabilities, supported by nominal levels of force feedback. Finger-controlled input devices with force feedback could be considered here.

While the current research focused on the use of tactual navigational information within visual displays, the use of auditory information (e.g. Poll, 1996), including speech and non-speech feedback, will begin to play an increasingly greater role in future user interfaces given recent advances in the area of integrated multimedia systems and network technologies, including data-compression techniques for transferring real-time sound and low-cost hardware. In short, the ultimate success of touch-based technologies in consumer as well as professional systems will depend upon an integrated approach towards designing and applying tactual feedback within a multimodal context. A provisional model for considering multisensory navigational cues in multimedia will be presented in the next section.

7.2 Multisensory navigation in multimedia

Like graphical user interfaces, current multimedia systems tend to rely primarily on the visual channel in performing navigational tasks, despite the availability of auditory information. Navigation thus requires the user’s full visual attention and is performed as a sequential activity. While a common assumption

in multimedia systems is that temporal coordination of multiple media such as speech, video, text or graphics can provide presentations that are more effective than those afforded by a single medium (Goodman, 1993), the “de-synchronization” of sensory information relating to different media may actually be of benefit to navigation. Consider here the experimental findings of Chapter 5, which indicated that tactual directional cues could be efficiently followed while performing a visual search task. More generally, in everyday interaction, we utilize multisensory navigational cues to build a spatial awareness of objects and their locations. For example, the awareness of some objects and events in our environment, at a given time, stems from spatial auditory cues. Though somewhat more subtle, spatial tactual cues provide a sense of object location in our immediate environment as we feel and grasp objects while doing something else. The tactual-spatial domain of the visually impaired is even greater. For example, consider the spatial representation of a building in the absence of visual experience.

The decision to present a set of object-based navigational cues in the interface could be controlled by an application using an adaptive navigation management system with access to a database of multimedia objects, a user model, and a set of decision rules based on resource sharing theory (Figure 1). The goal of such a system is to enable the user to perform navigational tasks while doing something else, or more broadly, multitasking through multimodal interaction. Furthermore, multimodal feedback can also be used to assist users with particular physical limitations, for example, elderly users with low visual acuity or limited motor control¹. Multimodal spatial-navigational cues are linked to a database of multimedia objects. The decision as to which combination of modality cues to present is determined by a cue management system on the basis of the task at hand and resource sharing rules. Such a management system may also fit well into future database systems which will utilize virtual reality (Khoshafian and Baker, 1996). Within the course of the current research, an early attempt at building a system for handling multisensory navigational cues was built into a car-system prototype for controlling traffic messages, a CD player and a radio. Given the visual task of driving, auditory objects in a database (i.e., auditory sources from CD-tracks, traffic messages and radio stations) were linked to tactual and speech navigational cues. Tactual and auditory information (speech messages and sources) were distributed along a spatial model. Moving the trackball in the x-direction changed the volume level, which could be heard and felt as a spring force from the current preset value. Once the ball was moved forward (i.e., at 0°) the volume level was set. From within the forward position, the ball could be moved left or right, source presets (e.g. CD tracks) could then be felt as small “hills” (section 2.6) and heard. To switch between the radio, CD player and traffic messages, the user activated a switch by pressing the ball downwards. The user model took into account the user’s level of familiarity with the system

¹See Keyson (1995) for further discussion.

by detecting hesitation in performing control movements. When the user demonstrated difficulty in navigating between functions, speech feedback was given in addition to the tactual feedback just above the current volume setting.

In terms of assisting movements through multimodal feedback, as in the above case, gesture recognition should also be considered within the scope of multimodal interaction. For example, force feedback over a spatially-located menu option could be applied if the system recognizes the control action. This could enable users to perform control actions without relying on visual feedback.

In short, the ultimate success of touch-based technologies in consumer - as well as professional systems will depend upon an integrated approach towards designing and applying tactual feedback within a multimodal interaction context. While the current work focused on navigational issues, touch could also be combined with other modalities to provide contextual information such as object texture. Besides in movement-based tasks, multisensory information could be provided at any time to indicate a change in system or application state.

Figure 1. Management of multisensory navigational cues in multimedia.

Lastly, the multifaceted research approach adopted in the current dissertation indicated the feasibility of conducting parallel empirical investigations, from which results are then used to refine the attributes of a simulation tool. This approach may be especially useful in relatively new areas of human perception and technology, where fundamental work is lacking and there is a need to evaluate results within an applied context.

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Summary

The current research seeks to explore new concepts and technologies for using touch feedback to facilitate navigation in user interfaces with spatial layouts, while considering relevant human perceptual and motor capabilities. In support of this, a number of controlled studies and applied investigations were conducted, including issues of compatibility between the visual and touch modalities.

The study begins with a review of the touch and motor senses for one-hand interaction followed by a classification of current technologies with touch feedback for human-computer interaction. New devices developed in the course of the current research are then described, including a modified version of the IPO trackball with 2-D input, a trackball with 3-D input and force feedback and lower-energy systems. Experiments on the directional sensitivity of the hand and fingerpad, as input channels for interpreting tactual directional cues, indicated relatively uniform thresholds which were attributed to the nature of the tactile-fingerpad stimuli and kinesthetic-hand stimuli. An observed lower threshold in the distal-to-proximal direction over the fingerpad was thought to be due to stretch of the skin at the tip of the finger nail, to which one may be particularly sensitive. To consider motor and cognitive aspects in using directional cues, a study was conducted where visual, kinesthetic and combined visual-kinesthetic cues were considered in a single and dual task condition which involved a visual search task. The combined visual-kinesthetic cue produced response times equal to those of the kinesthetic cue and equivalent or greater movement accuracy across all orientations. Results of experiments on the discrimination of trackball produced forces, as the underlying mechanism for discriminating tactual forms, indicated that the just noticeable difference for forces was approximately 15 percent with force direction and degree of ball rotation having minimal to no influence on discrimination levels. The potential gain of a felt hole-shaped form over a visual target was compared with no-tactual feedback and the use of dynamic cursor gain in target acquisition. Results indicated that target acquisition performance was generally higher in the tactual feedback condition, followed by cursor gain feedback, in comparison with no-cursor gain feedback.

To consider the internal spatial representation of simple tactual forms such as a path in a given direction, a study was conducted to consider whether mental

rotation, as a means for investigating internal spatial representation, occurs for kinesthetically presented forms in the absence of visual feedback. Reaction times increased as a linear function of angular dependency between stimuli, suggesting a congruence between visual and kinesthetic modalities in the formation of internal representations for simple forms. A study on perception of tactual and visual path length also indicated a high degree of similarity in representations.

In general the studies indicated that touch feedback can be integrated in a compatible manner with visual displays and that navigational gains are greatest under conditions where the user is engaged in one or more visually demanding tasks. The present research also led to the development of a rapid prototyping design and evaluation tool for interfaces with touch-navigational fields. The tool demonstrated the feasibility of designing touch fields without requiring programming. Finally, several prototype applications and devices were developed including dynamic-tactual rotary controls for an electron microscope, a 3-D windows navigation model with 3-D force feedback, an animated game with felt rooms and a car-systems demonstration with speech and tactual feedback for controlling multiple auditory sources.

Samenvatting

Het onderhavige onderzoek is gericht op de bestudering van nieuwe concepten en technieken voor het gebruik van terugkoppeling via de tastzin bij de navigatie door gebruiker interfaces met een ruimtelijke vormgegeven layout, rekening houdend met de relevante perceptuele en motorische vermogens van de mens. Om dit onderzoek te staven, is een aantal gecontroleerde experimenten en toegepaste onderzoeken uitgevoerd, onder meer op het gebied van de compatibiliteit tussen visuele en tactuele modaliteiten.

Het onderzoek begint met een bespreking van de tactiele en motorische vermogens voor eenhandige interactie, gevolgd door een classificatie van bestaande technieken met terugkoppeling via de tastzin voor de interactie tussen mens en computer. Daarna volgt een beschrijving van de nieuwe apparaten die in de loop van het onderzoek ontwikkeld zijn, zoals een aangepaste versie van de IPO-trackball met tweedimensionale invoer, een trackball met driedimensionale invoer en krachtterugkoppeling en andere energiearme systemen. Experimenten met de richtinggevoeligheid van de hand en de vingertop als invoerkanalen voor richtingsaanwijzingen duiden op relatief uniforme drempels. Deze worden toegeschreven aan de aard van de tactiele vingertopstimuli en de kinesthetische handstimuli. Een waargenomen lagere drempel in distale richting van de vingertop wordt toegeschreven aan rek van de huid bij de top van de vingernagel, waarvoor men bijzonder gevoelig kan zijn. Om inzicht te krijgen in motorische en cognitieve aspecten bij het gebruik van richtingsaanwijzingen, is onderzoek gedaan naar visuele, kinesthetische en gecombineerde visueel-kinesthetische aanwijzingen in situaties waarbij sprake was van een enkelvoudige taak en van een dubbele taak, waaronder een visuele zoektaak. Dit onderzoek heeft aangetoond dat de gecombineerde visueel-kinesthetische aanwijzing reactietijden oplevert die gelijk zijn aan die van de kinesthetische aanwijzing alleen en dat de gecombineerde aanwijzing in alle richtingen een gelijke of grotere bewegingsnauwkeurigheid oplevert. Uit experimenten met de waarneming van door trackball voortgebrachte krachten als onderliggend mechanisme voor de waarneming van tactuele vormen, is gebleken dat het nog net waarneembare verschil voor krachten ongeveer 15 procent bedraagt, waarbij de waarnemingsniveaus nauwelijks of niet beïnvloed worden door de richting van de krachten en de rotatiehoek van de bal. De potentiële voordelen van een voelbaar kuilvormig doel ten opzichte van een visueel doel zijn vergeleken met terugkoppeling

die niet via de tastzin plaatsvindt en het gebruik van dynamische variatie in de visuele presentatie van de cursorbesturing bij doelacquisitie. De resultaten hebben aangetoond dat de doelacquisitie in het algemeen beter is bij terugkoppeling via de tastzin, gevolgd door terugkoppeling via variatie in de visuele presentatie van de cursorbesturing, in vergelijking met geen terugkoppeling via variatie in de visuele presentatie van de cursorbesturing.

Om inzicht te krijgen in de mentale ruimtelijke voorstelling van simpele tactuele vormen, zoals een baan in een gegeven richting, is onderzocht of voor kinesthetisch gepresenteerde vormen bij afwezigheid van visuele terugkoppeling mentale rotatie optreedt als middel om de mentale ruimtelijke voorstelling te onderzoeken. Gebleken is dat de reactietijden toenemen als lineaire functie van de hoekafhankelijkheid tussen stimuli, wat lijkt te wijzen op een gelijkvormigheid tussen visuele en kinesthetische modaliteiten bij de vorming van mentale voorstellingen van simpele vormen. Een studie naar de perceptie van tactuele en visuele baanlengte heeft eveneens een hoge mate van gelijkvormigheid in voorstellingen aangetoond.

Uit dit onderzoek is gebleken dat terugkoppeling via de tastzin op een compatibele manier gecombineerd kan worden met visuele displays en dat de voordelen voor de besturing het grootst zijn wanneer de gebruiker met één of meer visueel veeleisende taken bezig is. Het onderhavige onderzoek heeft tevens geleid tot de ontwikkeling van een snel prototypisch ontwerp- en evaluatiegereedschap voor interfaces met tactiele-besturingsvelden. Het gereedschap heeft aangetoond dat het mogelijk is om interfaces met tactiele velden te ontwerpen zonder gebruik te maken van programmeren. Bovendien zijn diverse prototypische applicaties en apparaten ontwikkeld, zoals dynamisch-tactiele draaiknoppen voor een elektronenmicroscop, een driedimensionaal vensterbesturingsmodel met driedimensionale model voor het selecteren van computer windows, een animatiespel met 'voelruimten', en een demonstratie met terugkoppeling via spraak en tastzin voor de besturing van diverse geluidsbronnen in de auto.

Appendix A

Measurement of trackball-produced forces

In this appendix the technique used for the physical measurement of the trackball produced forces is described. The trackball-produced forces were measured independent of the hand in the x, y and diagonal directions. A slightly lower force was expected in the diagonal directions for a given motor current due to increased wheel friction, in contrast to a horizontal or vertical movement, where one motor wheel rolled in same direction as the ball.

The forces produced by the trackball can be seen as a vector;

$$|\vec{F}| = \sqrt{F_x^2 + F_y^2} = F$$

a resultant force based upon x and y motor forces can be described as:

$$\alpha = \arctan \frac{F_y}{F_x}$$

A representation of the force measurement device in relation to the ball is shown in Figure 1. A small hole was made in a spare trackball having the same mass and dimensions as the actual ball. Depending on the force magnitude, either a Correx 10-100 gram force-meter, (resolution 2 grams) or a correx 50-500 gram pressure-meter (resolution 10 grams) was mounted above the ball using a metal frame with two rotating joints. The force-meter could be positioned for all directions of movement while enabling the rotation of the force meter rather than the ball. Forces were measured by allowing the meter to rotate until an equilibrium in force between ball force and internal meter tension was

reached. A 90-degree angle was thus maintained between the force meter pin and ball hole.

Figure 1. Measurement of ball forces.

To ensure the software scale for setting motor currents (i.e. set point) was linear with actual physical forces, a number of set point levels were plotted against actual trackball produced forces (Figure 2). The results indicated a small increase (about 5 grams) for trackball movements in the diagonal directions (Table 1). A highly linear relationship was found between the digital set point and physical force values ($r=0.99$).

Figure. 2 Force (grams) as a function of motor current (set point) to trackball physical force.

Table 1
Trackball-Produced Forces per Orientation Across Set Point Values

Set Point (digital)	Force [gram]							
	Force Direction [degrees]							
	0	45	90	135	180	225	270	315
0	46	52	44	50	46	50	44	54
200	66	72	66	70	64	68	66	72
400	86	92	86	92	82	92	88	94
600	105	115	105	110	110	115	110	120
800	130	135	130	135	135	140	130	140
1000	160	170	160	170	165	170	155	170
1200	190	195	190	200	195	200	190	195

Appendix B

Table of ground-based ForceFeedback Devices

Device Type	Key Features	Reference
Joysticks with force feedback	motor-based feedback 2-DOF	Adelstein and Rosen (1992), Ouhyoung et al., (1995), Immersion Corp.
Mini-joystick	force-reflecting 2-DOF	Shmult and Jebens, 1993
Joystick with 3-DOF force feedback	servo-motor-based	Minsky et al., (1990) and Cybernet Systems
Force sensitive joystick	passive system, not force reflecting	Measurement Systems Inc.
Mouse with tactile and force feedback	electromagnetic field under mouse and solenoids in buttons	Akamatsu, MacKenzie, and Hasbroucq (1995)
3-D Mouse with force feedback	10 degree extension on mouse button with force feedback	Microsoft Corp. Patent #0591960A2
Pressure-sensitive mouse	air pressure sensor in mouse detects pressing force on mouse	Yamaha Corporation Patent #0653725A2

Device Type	Key Features	Reference
Feelmouse	works like normal mouse with force-sensitive, variable-height button	Penz and Tscheligi, Vienna UI Group, Institute of Statistics and Computer Science, University of Vienna
Mouse with tactile buttons	four mouse buttons with vibro-tactile actuators	Gobel, Luczak, Springer, Hedicke, Rotting (1995)
Touch-sensitive tablet	x,y position sensed as well as contact pressure, no force feedback	Lee, Buxton, and Smith (1985)
Miniature control rod with force feedback	rod placed on keyboard and in mouse-selection buttons	IBM European patent application #0607580A1
Force feedback stylus	3 to 4-DOF pen-shaped devices for simulating surgical and other fine-movement tasks	Immersion Corp and Exos Inc.
Remote force-reflecting manipulator arms	6 to 7-DOF motor-based force feedback	Early model Brooks et al. (1990) Several labs in the US, Japan and Canada, (see Durlach & Mavor, 1995)
Pantograph	2-DOF plus button, 2 motors 10N force	
Tensed-string-based devices	tetrahedrons with shaft encoders and torque motors 3-DOF using 4 motors	Atkinson et al., (1977) and Ishii and Sato (1994)
Yoke with force feedback	2-DOF	Cybernet Systems

Device Type	Key Features	Reference
Grasping mouse	sliding mouse- like device with force feed-back grabbing mechanism and pin actuators over fingertips	Akamatsu (1995)
Remote force reflecting manipulator arms	4 to 7-DOF motor based force feed-back system	Early model Brooks et al, (1990) Several labs in the US, Japan and Canada, (see Durlach & Mavor, 1995 for review)
PHANToM Haptic Interface	3- DOF motor driven thimble interface	SensAble Devices, Inc. Inventor: K. Salisbury, MIT Artificial Intelligence Lab.
Finger force feedback device	Attaches to 6-DOF handcontroller, fingers and thumb are placed in small stirrups	Cybernet Systems
Slider with force feedback IPO Rotary dial	1-DOF Dial with digital POT, motor feed-back and feedforward, 1-DOF	Immersion Corp. Chapter 2 of this dissertation
NatLab-IPO Rotary dial with electromagnetic feedback	Low-energy, dial with digital POT, electromagnetic feedback, no feedforward, 1-DOF	Chapter 2 of this dissertation
Desktop steering wheel with force feedback IPO 2-D Trackball	1-DOF	Cybernet Systems
	2-DOF with force sensing and feedback, also small version	see Chapter 2 Invention by Engel, Haakma and van Itegem Philips patent # PHN 13.522

Device Type	Key Features	Reference
IPO 3-D Trackball	3-DOF with force sensing and feedback	see Chapter 2. Invention by D. Keyson Philips patent # PHN 15.232

Curriculum Vitae

April 4, 1962	Born in Redwood City, California.
1980	Graduated Gunn High School, Palo Alto, California.
1985	B.A. Political and General Social Sciences, Tel Aviv University, Israel.
1985-1986	High School Teacher in Israel.
1987	M.S.c. Ergonomics, Loughborough University of Technology, England.
1987-1988	Human Factors Engineer and Technical Writer, Tadiran Telecommunications, Peta Tiqva, Israel.
1988-1992	Human Factors Engineer, Xerox Corporation, El Segundo, California.
1992 to Present	Researcher, Institute for Perception Research, Eindhoven, The Netherlands.

Stellingen
behorende bij het proefschrift
Touch in User Interface Navigation
van D.V. Keyson

I

In everyday interaction people use their sense of touch, hearing and vision concurrently to form a spatial awareness of objects in the environment. This potential is largely neglected in current human-computer interaction where nearly all feedback is visual.

II

“The ear tends to be lazy, craves the familiar, and is shocked by the unexpected. The eye tends to be impatient, craves the novel and is bored by repetition” (W.H. Auden, “Hic et Ille,” *The Dyer’s Hand* (1962). In thinking about applying a sense of touch to the user interface, the hand lacks patience, craves the familiar and is shocked by the unexpected.

III

Most touch displays feel like glass.

IV

Proactive design of user interfaces, including new functionality for networked media systems, cannot be conducted without collaborative tools and work styles.

V

Everyday expressions such as, “hands-on experience”, “get the feel of it”, “feel the rhythm”, “touchy”, “have a feeling for”, “show one’s hand”, “with clean hands”, “with a heavy hand”, “handy”, “hold on”, “the look and feel”, “get a grip/handle on it” and “get the hang of it” reflect the closeness of touch in interaction with our immediate environment.

VI

In the future more wars will be fought within than between states.

VII

International bodies will increasingly attempt to influence domestic policies.

VIII

“A theorist without practice is a tree without fruit; and a devotee without learning is a house without an entrance” (SA’DI, *Gulistan*, 1258). Correspondingly, user interface design is about combining theory and application-oriented knowledge.