"No Restrictions"

ACTIVE AND PASSIVE HAPTIC EXPLORATION OF TWO- AND THREE-DIMENSIONAL STIMULI

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ABSTRACT

Experiments were conducted in three broad areas: 1. haptic exploration of raised line drawings, 2. active versus passive exploration of virtual objects using a Phantom force feedback device, and 3. visual and tactile perception of two-dimensional displays. In addition, Experiment 1 was conducted to ensure that the sounds made by one of the devices used – the Tactile Display System (TDS) – did not provide any assistance to subjects attempting to identify the stimuli.

1. In Experiment 2, passive haptic perception of raised line drawings was studied in terms of four components (a) kinaesthesis, (b) shear forces from relative movement between the skin and a surface, (c) cutaneous input from the presence of a raised line, and (d) the pressure against the sides of the finger exerted by the TDS. It was found that exploration strategies involving kinaesthesis generally resulted in a greater number of correct identifications in the shortest time. Conditions with "minimal" information, such as the shear forces produced when a plain surface is moved underneath a stationary fingertip, resulted in lower levels of performance that were nevertheless quite remarkable. In Experiment 3, the TDS allowed a subject to freely explore a stimulus with one finger, and those movements caused a rotated version of the stimulus to move under the contralateral finger. The stimuli of each pair (i.e., normal and rotated forms) had different meanings (e.g., d and p). Most subjects did not detect that one stimulus was the rotation of the other. The letter or number named by the subject identified the finger to which the subject was attending, and this was influenced more by the presence or absence of a raised line than by whether the finger was moving.

2. The passive exploration of simple, two-dimensional pictures with the Phantom resulted in superior performance compared with active exploration (Experiment 4), consistent with research previously conducted using the TDS. However, active superiority was evident when simple three-dimensional geometric shapes (e.g., sphere or cone) were explored with the Phantom. Active superiority was found whether the active-passive comparison was delayed (Experiment 5, in which the active subject's exploration was recorded and later used to guide the passive counterpart), or the matching was done in real time (Experiment 6, in which two Phantoms were electronically yoked). Results were interpreted in terms of cognitive rather than sensory burdens associated with active and passive exploration.

3. In Experiment 7, subjects were guided around two-dimensional letters using the Phantom and a pre-recorded movement pattern, which was also plotted on a screen in two visual conditions: a 1 cm segment of line moved around the screen, following the movement path (an analogy to moving a 1 cm hole in an opaque surface over a line that represented the

movement path); or the 1 cm segment remained in the centre of the screen and seemed to "dance" (analogous to moving the stimulus behind a stationary 1 cm hole in an opaque surface). In Experiment 8, the TDS was used for two haptic conditions: moving a fingertip and moving the stimulus underneath a stationary fingertip (haptic equivalents to a moving and stationary hole respectively). Haptic performance was equivalent to that found with vision in terms of response time. The moving window/moving finger conditions were superior to the stationary window/stationary finger conditions.

Some conclusions were that the haptic system can interpret displays with minimal information, active touch seems to be superior for exploration of three dimensional objects, and touch in general compares favourably with vision if tasks are matched. Results will be useful in guiding the design of haptic virtual environments, and relevant to applications of telepresence, robotics, sensory aids, and simulations.

SIGNED STATEMENT

I hereby certify that, unless explicitly indicated, none of the material contained in this thesis has been submitted for the award of any other degree or diploma in any university or other institution. To the best of my knowledge, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

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Mark Symmons

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1. INTRODUCTION

The sense of touch is ubiquitous. It is involved in everything we do. In fact, as our bodies are literally covered in touch receptors and our joints and muscles are monitored by nerve endings it is difficult to consciously suppress the sense of touch in the same way that we can close our eyes to "turn off" vision and block our ears to dull our hearing. Even when we are asleep a prod can produce a response, whether we wake or not.

A critical difference between touch and the other senses centres on the method of interaction with the environment. Each of the other senses can be considered to be somewhat passive in that they "wait" for stimuli to impinge upon their receptors; for example, sounds have to reach our ears and reflected light has to enter our eyes before any sensation can be registered. However, touch is purposive. We do receive touch stimuli in a variety of forms as they impinge upon a range of receptors, but generally we seek out stimulation with that most specialised of exploration tools – the hand; we reach out to make contact with objects of interest or desire.

Unlike the other senses, touch arises from a variety of stimuli. In very simple terms, hearing is the result of sound pressure waves acting on the ear drum and sight is a consequence of light impinging on the retina. The different elements of touch will be considered in further detail later, but briefly they include pressure and vibration from contact between the skin and a surface, movement of hairs on the skin due to a puff of wind, knowledge of where limbs and other body parts are in space, feedback from muscles during movement of any part of the body, and the detection of temperature and pain.

In this thesis three facets of touch are examined – the role of kinaesthetic and cutaneous cues in haptic exploration, the importance of voluntary control when seeking out touch information, and how touch compares with vision in a matched task. After defining some basic touch concepts and providing a brief and selective history of research in this field, the remainder of this chapter presents an introduction to each of the three avenues to be explored. Later chapters will then separately address the three issues identified, followed by a general discussion to bring these disparate areas together in a more integrated fashion. Each "issue chapter" contains a dedicated literature review, the method and results of two or three experiments, and a brief discussion of those results.

1.1 Touch definitions and concepts

In the scientific literature the term "haptics" is often used instead of, and regularly interchangeably with, touch. An Oxford Dictionary definition of haptics says that it arises from the Greek word haptilos meaning "able to touch", and that it "pertains to the sense of touch". Another word often appearing in the literature is "tactile", which the Concise Oxford Dictionary defines as "of, perceived by, connected with, the sense of touch". Additionally, others use the term "cutaneous" to include sensations that arise from objects directly contacting the skin, such as pressure.

Many scientific journal articles on the subject start out by defining terms such as "haptics", according it a more specific meaning than can be found in the dictionary; though these definitions are not always consistent. In this thesis, touch and haptics will be treated as having the same meaning and will be used interchangeably.

In general terms, touch would most often be considered to relate to sensations on the skin. Stimuli creating those sensations would include pointed objects and pressure against the skin. However, touch sensations can arise from a much greater variety of stimuli. Buss (2004) provides a reasonable list of the sensations involved in the sense of touch: "The haptic sense is understood to comprise tactile (pressure, temperature, roughness and vibration) and kinaesthetic information (proprioception, torques and forces)" (p. iii). However, Buss' list does not include the sensation that arises from the movement of hairs due to air (or something else) flowing over them.

The terms proprioception and kinaesthesis are often used interchangeably and definitions differ, in part because there is still some question in the literature as to the relative importance of kinaesthesis versus proprioception and the role of each in particular types of movement. For the purposes of this thesis kinaesthesis and proprioception need not be considered separately, and so taken together they relate to movement and position of limbs and body parts in space.

1.2 The importance of touch

An issue that continues to crop up in reviews and overviews of touch research is the lack of importance afforded this seemingly lower-rung sense. One of the earliest to lament the relegation of touch to a secondary sensory system was Katz in the seminal work De Aufbau de Tastwelt (The World of Touch). In the Editor's Introduction to the translated version of Katz's 1925 work, Krueger (1989) says that "by showing how wondrous are the abilities of touch and how rich the tactual stimulus can be in specifying objects, surfaces, substances, and events [Katz] hoped to regain for touch its former prominence, if not its predominance" (p. 2).

Other, more recent examples decrying the low value placed on touch by sensory researchers include Craig and Rollman (1999): "Workers in somesthesis have often complained of the difficulty of conveying to others the importance of the sense of touch and position" (p. 306), and Klatzky and Lederman (2003): "As a topic of psychological research, touch has received far less attention than vision has". The lower value attached to touch research (at least until recently anyway – see later for a description of the increasing sophistication of haptics-related technology) probably reflects a lack of respect for the sense in the general population:

> *In everyday life we attach great value to vision and hearing for the roles they play in making us aware of our surroundings, roles impressed by their temporary occlusion (e.g., blindfolding) and by the knowledge that either can be lost permanently. With the sense of touch it is a different matter, for without the examples of temporary occlusion and permanent loss we tend to underestimate the role of touch in our perception of the world*
>
> (Loomis & Lederman, 1986, pp. 31-2)

There are several possible reasons why vision and hearing in particular could have been accorded a greater prominence than touch. Loomis and Lederman (1986) noted that it is unusual to lose the sense of touch in the same way that people can be blind or deaf, although it can happen. So, there has not been the same impetus to construct devices as substitutes for touch, or any particular element of it. The cochlear implant enables some individuals who have been deaf to hear again, depending upon the reasons for their deafness, and research is well underway to construct a "bionic eye" – an implant that may one day successfully replace an inoperative retina. Katz (Krueger, 1989) pointed out that even at the most basic level of technology, there was nothing equivalent to a magnifying glass or microscope to improve one's touch (or, for that matter the equivalent of a stethoscope, in the case of audition). Almost 80 years later this is still true.

Compared to touch, each of the other senses has a relatively compact and localised sensory organ – the eyes for vision, ears (and inner ears) for audition, and so on. This may make the research task simpler, both for research involving humans and animal experimentation, particularly for sensory substitution work. While most purposive touching is done with the hands, all of the skin, hairs on the skin, receptors in the joints and muscles, and receptors embedded more deeply in the viscera can be regarded as part of the touch organ. An adult's skin surface area alone comes to around two square metres (Quilliam, 1978). But there is a lack of certainty as to the functions of each of the touch receptor types.

Loomis and Lederman (1986) suggested that we do not value our sense of touch because we can become deaf or blind but not "touchless". Those who *are* deaf and/or blind particularly learn to value their sense of touch and can better appreciate its potential. Much touch-related research has focused on the options for replacing or substituting for lost vision and hearing. Such efforts range from measures that require no technological intervention, such as the Tadoma method, through low and medium technology, such as the white cane and Braille, to solutions that are more technology-intensive, such as the Optacon and variants of the Tactile Vision Substitution System (TVSS).

The Tadoma method allows those who are deaf and blind to communicate by placing their hand(s) on a speaker's face while they are talking. The "listener's" fingers are strategically located in order to detect information-carrying aspects such as the movement of the jaw and nearby facial muscles, air flow out of the mouth and nose, and vibration in the throat (Chomsky, 1986). Practised users of this method can approach comprehension and accuracies at near normal rates (Reed, Rabinowitz, Durlach, Braida, Conway-Fithian & Schultz, 1985).

Both the Optacon (see Craig, 1980 for a description) and the TVSS (see Bach-y-Rita, 1970) provide stimulation to the skin surface via an array of vibrators – for a fingertip in the case of the Optacon and for the back or stomach in the case of the TVSS. The pattern displayed by the vibrators is the output of a camera. Movement of the camera, or the scene being targeted, creates the impression of movement across the array of vibrators. Indeed, the TVSS works better when the user is able to move the camera (White, Saunders, Scadden, Bach-y-Rita & Collins, 1970, Bach-y-Rita, 1967). According to Collins (1977), after just a few hours of experience with a visual prosthesis based on the TVSS, users reported tactile patterns perceived as three-dimensional "visual" images. This device was a miniature television camera mounted on a pair of glasses and a flexible stimulator array worn over a 650 cm^2 area of the abdomen. Furthermore, the congenitally blind have been able to experience concepts such as perspective, shadow, size constancy and shape distortion as a function of viewpoint (Bach-y-Rita, Tyler & Kaczmarek, 2003).

The sense of touch seems to have taken a back seat in sensory systems research. However, an argument could be mounted to suggest that touch and all that it encompasses is actually the most important sense, or at the very least *as* important as vision and audition. Touch can operate with little dependence on vision or hearing, as evidenced by the use of touch as a substitute for either or both of these senses, but neither of these sensory modalities are very effective without touch. For example, kinaesthetic feedback from the muscles is involved in the precise movements of the eyes and reshaping of the lenses to ensure that we can see a coherent binocular scene in a clearly.

Both vision and hearing are passive senses in that the receptors must "wait" for energy to impinge upon them. Touch, however, and particularly the hands, can be used to seek out stimulation – exploring unseen surfaces and unheard vibrations. Indeed a barely seen object or a sound heard from behind remains a matter of uncertainty unless we move towards the object or turn to face the source of the sound – both of which require haptics (most particularly kinaesthesis and proprioception) for successful execution.

Touch can also be considered to be both a proximal and a distal sense. Proximal stimulation occurs when there is contact between the skin and the surface being explored, while distal stimulation arises when there is no such physical contact between the source of the stimulation and the receptors. An example of a proximal touch stimulus is the pressure of an object against the skin. Distal stimuli include radiant heat from a nearby hot body, and a rush of wind across the hair on the arms as something large passes close by. However, vision and audition are both distal senses only – depending respectively on reflected light from a surface and sound pressure waves from an object. Proximal contact between the eye and a physical object can result in a visual sensation, such as seeing an explosion of bright light after being poked in the eye, but this is not a normal or useful visual perception. As further evidence of the pervasiveness of touch, such an event would be accompanied by the touch sensations of pressure, kinaesthesis if the eyeball is moved, and of course pain. We cannot attend to receptor states in vision and audition in the way that we can with touch. For example, we can attend to the warmth on our skin that comes from a nearby fire – a touch receptor stimulation and so a proximal sensation, or we can consider the fire itself as the source of the warmth – a distal source of information.

Although the terms "distal" and "proximal" refer to sensations, they are also used when discussing perception. While we can pay attention to a sensation or what is happening at the receptor site, most of our touch experiences are distal, provided that there is an object to which the sensation can be attributed. Our tactile percepts are more likely to be proximal when they are not readily attributable to outside sources[1]. When a mosquito has bitten, the percept is proximal, but if it is caught in the act of biting, the percept is close, but distal in the sense that it is externalised. Gibson (1966) called these concepts the objective and subjective poles of experience. He suggested that the reader press against the edge of a table: "Within limits, you can concentrate either on the edge of the table, say, or on the dent it makes in *you*" (p. 99) – the objective and subjective poles respectively. Some would go

[1] An instance where it is less clear whether proximal or distal attributions are involved is when we touch our own body. If we touch our nose with our finger are we perceiving one or both proximally and distally, one of these, or neither?

further and argue that attributes of objects not touching the skin at all may be distally perceived.

> *We sometimes touch a thing to find out about the thing itself but at other times the information we get is about things much removed from the contacted surface. For instance, notice what is delivered to the hands of someone riding a bicycle...the roughness of the road, firmness of tyres, tightness of steering, and even slippage of the hand grips. These features of the haptic environment are distal to the skin's surface and are perceived to be so. As air conveys information about distal sound sources, the bicycle in our example transmits information about vibratory sources several steps removed from the perceiver.*
>
> (Kennedy, Richardson & Magee, 1980, pp. 301-303)

Both Katz (Krueger, 1989) and Gibson (1962) identified the hand as a special element in the sense of touch, Katz suggesting that it was equivalent to the eye or ear as a primary touch sense organ. This is a reflection not just of the sensitivity of the hands and the fingers, a function of the presence of, and spacing between, touch receptor cells, but of the purposive nature of touch. As a sensory organ, the hand can be moulded to suit a particular surface or modified to control the amount of stimulation required. For example, an object can be encircled with the hand, or rotated so that other surfaces can be touched or seen.

Evidence for the evolution of the hand as a functional sensory unit arises from applying sensation to it in an unusual manner. For example, when two adjacent fingers are crossed and they touch a small object, the sensation is often of touching two objects (Benedetti, 1988). This effect is commonly known as Aristotle's illusion. The tactile information seems to be processed as though the areas of skin were not displaced from their normal position, or the crossed fingers were not crossed. So, the hand functions as an integrated unit rather than the integration of information of the various hand subunits (i.e., the individual fingers, the palm, etc). However, there is flexibility in the system. Benedetti (1991) found that maintaining the fingers in a crossed state for up to six months stopped the illusion from occurring, so that a single rather than a double rod was detected whether the fingers were crossed or uncrossed. Vision must have "re-educated" touch it seems. However, Benedetti (1998) did not test the illusion with and without vision and so it is not known whether the illusion would diminish without visual input.

For both vision and audition the transduced energy from a small number of cell types needs to be integrated, such as occurs for rods and cones in vision, and hair cells in audition. There is a greater range of touch receptor types. While they are used for different purposes, such as the coding of temperature, vibration, and pressure, their outputs are seemingly effortlessly integrated to form a unitary haptic percept. This suggests that the haptic senses are at least as complex or evolved as the senses of vision and hearing and perhaps more so.

Some recognition of the importance of the sense of touch can be seen in the relatively recent impetus in the field of robotics (Sherrick, 1985). Robots provide a number of advantages over the human operator, including strength, speed, and precise repetition. There are also benefits related to relieving humans of hazardous or boring activities. Accordingly, there is a push to automate many processes. In order to increase the sophistication of robotic devices and expand their repertoire of potential uses, they require a machine version of the human sense of touch. To pick up a variety of shapes, weights or sizes, robots need to be able to intelligently adapt their grasp, the pressure of their grip, and the force of their heft. Humans use a number of different touch receptor types to accomplish these tasks (and more) with apparent ease, but designing robots to accomplish these tasks has proved difficult.

For many current robotics applications the robot operates under its own programming, which may or may not be sophisticated enough to allow for adaptive learning or response – there are no humans in the loop. For a number of reasons human operators may wish to operate through robotic (or synthetic) effectors – to become part of the loop. In some instances humans *must* be part of the loop for perceived safety and trust in the system, even though robotic applications exist that may be superior to human operators. For example, many passenger aeroplanes are capable of flying and landing themselves under computer control. However, it is likely to be some time before human passengers will comfortably travel on any vehicle without a human operator at the helm who can "step in" in the computer system fails.

Humans can be part of the loop but operate or supervise the robotic effector through the burgeoning related fields of teleoperation and telepresence. In teleoperation a human controls a robotic device at a remote location. This is particularly valuable when environments are dangerous (such as bomb defusal and disposal scenarios), inaccessible (such as deep sea exploration and underwater oil well maintenance), or of the wrong scale for direct human intervention (such as manipulation and exploration at the molecular level). Teleoperation is not always successful. For example, Richardson, Wuillemin and Symmons (2004) discuss the teleoperation of a rock breaking device for mining applications. For reasons related to safety, efficiency and economics it would be advantageous to automate this task. However, practised human operators always outperform automated machines, quickly determining the best way to pick up a rock, the most likely clean cleavage point and the manipulation of the broken pieces. The efficient human performance of this task can be "poetry in motion". However, providing remote controls for a human to operate a robotic rock breaker does not approach the efficiency of the worker actually sitting in the driver's seat. In fact equipment is often damaged, reportedly because operators can no longer tell when tolerances are being breached or margins for error exceeded. What is missing is "the feel" of the machine, the environment, and the rocks. Even with high fidelity stereo audio and binocular vision for depth cues, the current evidence is that remote operator performance is not equivalent to the worker physically driving the machine. The feedback still missing relates to touch. It is likely that for an experienced operator the rock breaker has become an extension of their own effectors, in much the same way as a road can be felt "through" a bicycle.

Telepresence relates to the realism of the information conveyed to a teleoperator:

> *Telemanipulation is defined as the extension of human sensing and manipulation capabilities by coupling it to remote artificial sensors and actuators...Telepresence means that the operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way that the operator feels physically present at the remote site.*
>
> (Stassen & Smets, 1997, p 364)

> *Telepresence is achieved if the human operator of a technical system is provided with the impression of actually being present in a remote environment. Teleaction emphasises the aspect that the operator is not only present passively but also able to interact actively with the remote environment*
>
> (Bus, 2004, p. iii)

Currently, teleoperators can be provided with quite high fidelity feedback of their actions and the impact of their actions on the environment through vision and audition using commercially-available devices, but haptic feedback systems are still in an early stage of development (Kammermeier, Kron, Hoogen & Schmidt, 2004).

When telepresence has not been fully achieved, such that vision and audition are realistic but the haptic sense is not reproduced, the operator can suffer "virtual reality sickness" or "cybersickness" (Stanney, Mourant & Kennedy, 1998). Feelings ranging from discomfort through nausea to vomiting can be experienced because cues between the senses do not properly match. The author is familiar with the signs and symptoms of this illness appearing during the use of a sophisticated driving simulator – both as an experimenter and as a participant in road safety research. The negative experiences generally arise when the visual and auditory feedback indicate that the car (a real car body, fitted out in showroom condition) is accelerating, decelerating or turning. While some haptic cues are available through a motion platform on which the car is mounted, they are not sufficient to match the sensations expected to accompany the visual and auditory information, and cybersickness occurs. The body does not experience the forces expected with acceleration or deceleration, or the tilt from turning a corner. The severity of cybersickness is quite variable, depending on the situation, such as the degree of mismatch between cues, and the individual.

Burdea and Coiffet (2003) claim that in 1965 Sutherland, a pioneer in commercial virtual reality systems, was one of the first to recognise the importance of haptics in virtual reality. However, the first sensing glove was not released to the market until 1992. There is an impetus to further improve the haptic feedback qualities of commercially available virtual reality and teleoperator systems. Stanney, et al. (1998) provide a number of examples from the literature where haptic feedback in virtual environments enhanced performance. Enhancement occurs even when haptic feedback might not at first seem particularly relevant to the problem at hand. For example, chemists' problem-solving abilities improved for synthetic molecular modelling problems when haptic feedback was incorporated (Brooks, Ouh-Young, Batter & Kirkpatrick, 1990, cited in Stanney et al.). If this haptic feedback was of high fidelity, performance may improve further.

Despite the recent renewed interest in haptics, or perhaps because of it, there is a lack of coherence in research effort. In a comment reminiscent of those attributed to Katz (Krueger, 1989) and Craig and Rollman (1999), Stassen and Smets (1997) express amazement in their realisation that "researchers in the fields of man-machine systems, human-computer interaction, and the rehabilitation of severely bodily disabled persons are not aware of each other's research activities; often they work on the same problems almost independently" (p. 372). They point out that this is not helped by the fact that each field has its own vocabulary, methods, approaches, and journals.

1.3 Breaking touch down into its constituent components

Touch is a complex sense in that it encompasses a variety of components that often have different specialised receptors. For example, kinaesthesis is related to muscle use and so primarily provides information about movement of the body. Vibration arises from contact between a surface and the skin with the presence of relative movement. In most instances the haptic perception of some object or event involves the spatial and temporal integration of multiple aspects of touch. In order to achieve telepresence it is assumed that each of the constituent touch components needs to be supplied in such a way that they can be integrated.

In theory it should be possible to provide the hand with all of the elements of haptics in a passive virtual system. Actuators exist that will present vibration, pressure, temperature, kinaesthesis, and so on (Kammermeier, et al., 2004). However, combining these devices into a single useable unit along with sensors to give feedback and control mechanisms is currently not possible (Brewster, 2001; Kammermeier, et al.); and when this feat is accomplished the next challenge will be to provide the whole hand, each finger and thumb independently, the palm, and so on, with adequate input and feedback opportunities. At present, devices commercially available tend to accommodate only one aspect of the haptic sense. For example, the Phantom is basically a hand-held stylus that provides force-feedback as a cue to exploring virtual three-dimensional objects (see Chapter 2 and www.sensable.com for more detailed descriptions). As there is no contact between the hand and the (virtual) object to be explored, the principle touch components are kinaesthesis and proprioception (although there is pressure at the fingerpads from gripping the stylus, and this is not a negligible sensation). The Optacon and TVSS provide vibration as the stimulus. However, more "natural" devices designed specifically for use by the blind offer more haptic aspects. For example, both Braille and the white cane use kinaesthesis (and proprioception) as well as vibration (and pressure).

Devices that will provide as much of the "natural" touch experience as possible in a bid to achieve true telepresence are in various stages of development. One of the most sophisticated devices, or at least most thorough in terms of the haptic components included, is described by Kammermeier, et al. (2004). The user receives kinaesthetic feedback through an exoskeleton that fits over a hand (a Cybergrasp supplied by Immersion Inc.; see www.immersion.com). Wires exert force on the phalanges of the fingers by pulling on the relevant elements of the exoskeleton. In response to "contact" with the solid surfaces of a virtual object, the device stops the fingers from closing any further. It can also pull the fingers open. It cannot, however, provide force to close the hand or clench the fingers, and no exoskeletal device seems to possess this feature. This means that the pliability of the grasped object cannot be simulated at the fingers.

Another limitation is that the finger sensing and control are monodirectional – only abduction at the finger joints can be manipulated. While this does not mean that the fingers cannot be moved sideways, it does mean that that this movement can not yet be sensed and relayed to the teleoperated device. A Peltier tile underneath the fingertip supplies warmth or cold, and a small DC motor underneath the Peltier tile applies vibration to the fingertip. Presumably the forces acting to stop the finger would result in pressure stimulation to the fingertip as well. So far the device provides all of these sensations to just one finger (see Figure 1.1). According to Kammermeier, et al., testing with novice users demonstrated the system to be intuitively easy to use, with the haptic stimuli being fused into holistic sensations.

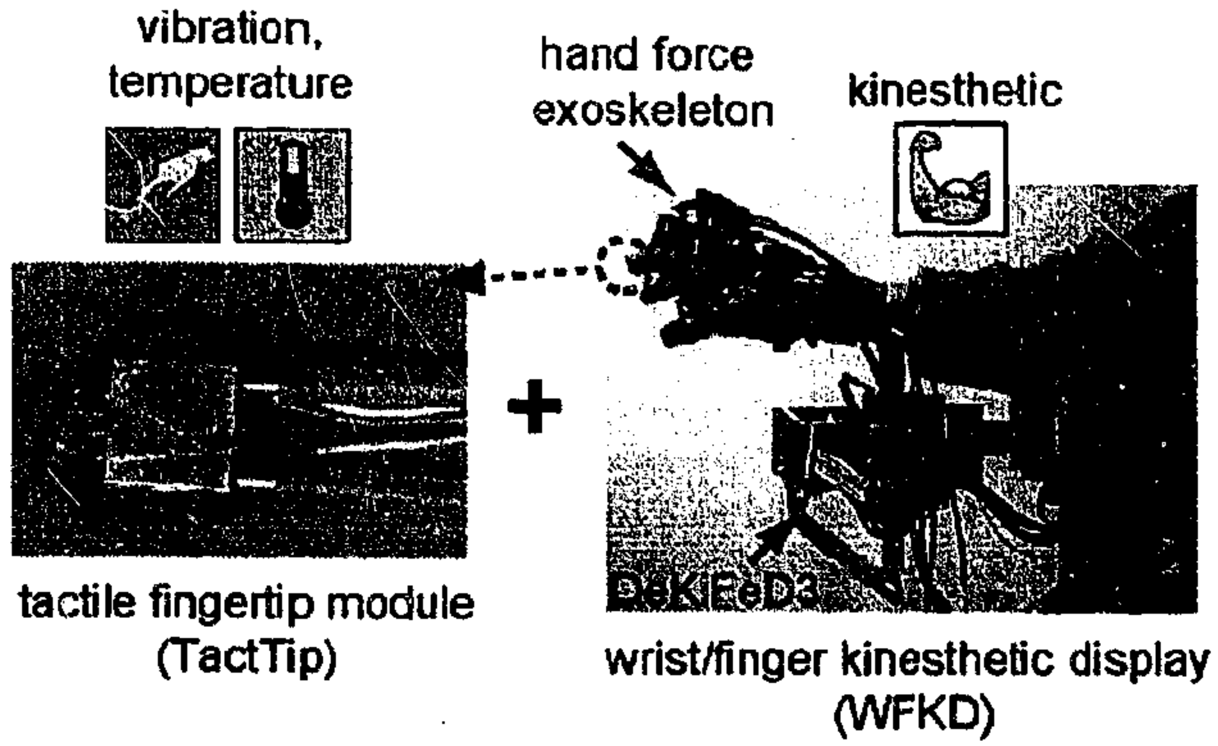

Figure 1-1. Haptic feedback device providing vibration, temperature and kinaesthesis for virtual objects (from Kammermeier, et al., 2004).

There would seem to be technical difficulties in including and combining all of the haptic components experienced in real touch. A relevant question is whether it is *necessary* to provide all of the components. Given that not all components can be provided, are there particular combinations that work better than others, and which components are critical? The experiments reported in Chapter 3 are designed to address some aspects of these questions.

1.4 Active versus passive touch

Both Katz (Krueger, 1989) and Gibson (1962) emphasized the purposive nature of touch – particularly that of the hands. Humans tend to seek out information and the hand is well suited to this task. This seeking of stimulation was termed "active touch" by Gibson, with its opposite being passive touch – applying stimulation to a non-exploring hand. Gibson suggested that the passive mode of touch was "unnatural". It might be argued that when passive, touch is operating, it functions in a similar way to vision and hearing which, as described earlier, operate as passive receivers of information because the relevant receptors cannot be brought into contact with the source of visual or auditory information. Yet when touch is passive it seems less likely to be responsible for distal perception than when it is active. It should be noted that touch most often requires contact between the skin and a surface of interest in order to pick up any significant information about objects. Although passive, vision and audition can operate more remotely, as reflected light and sounds emanating from an object generally do so in all directions and can carry a reasonable distance. The energies relevant to touch are not the same.

Gibson (1962) tested his active-passive distinction by allowing subjects to freely explore cookie cutter shapes in the active condition, while passive subjects held their upturned palm stationary and a cookie cutter was pressed into it. Active touch was superior. However, performance in passive touch was significantly better than chance. This suggests that Gibson's passive touch may not have been as "unnatural" as he suggested.

Others have compared active and passive touch for two-dimensional stimuli. Symmons, Richardson and Wuillemin (2004) reviewed 33 studies involving 73 separate comparisons. There was considerable variety in the experimental methods and results were not consistent. Sometimes active touch was superior, sometimes passive was better, and on other occasions there was no difference between the conditions (see Chapter 4 for more detail). There was also variety in the definitions of active and passive touch.

The definitions used for active and passive touch seem to depend on the reason for doing the research. For example, in many skills training applications a coach or teacher will hold the student's arm or hand and perform the skill to be learned – such as a tennis backhand shot. The coach expects that guiding the student in this manner will produce faster or better learning than modelling the skill for the student and allowing them to try to emulate the actions. In the guided-action situation the student would be classed as passive, while in the modelled-skill scenario the student could be considered to be active. This active-passive distinction is not consistent with that used by Gibson (1962); for example, the passive condition involves movement of the touch instrument – the hand. Being guided in such a manner is not as unusual or unnatural as Gibson's passive condition in which an object is pressed against the skin and held there. Experimentally comparing moving oneself (active mode) with being guided through those movements (passive mode) has a practical significance and an application. Chapter 4 includes an examination of the active-passive issue for exploration in three dimensions.

1.5 Vision versus touch

Vision is considered to be a more important sense than touch. One of the reasons for this is that vision is often found to dominate touch. A study concerning "sensory capture" pits the senses against each other with ambiguous or conflicting stimuli. Sometimes subjects are aware that there is a mismatch and at other times they are naïve, but they are typically required to provide a response that can be interpreted as demonstrating capture or dominance. There may be perfectly plausible alternate responses, but the one offered by the participant indicates which sense was primarily used. Most often, vision tends to dominate,

or capture, touch, and the other senses too. Chapter 5 provides some examples of this research.

There is no doubt that vision *is* more important for some tasks. For example, vision can provide an appraisal of an entire spatial environment more quickly than touch, which is often constrained by having to contact many surfaces sequentially. Vision is superior in most tasks requiring an analysis of space larger than a "handful", and even then a better appraisal will be afforded by vision, unless important information is hidden at the back of the object. Touch, on the other hand, is more likely to be superior for fine texture analysis. For example, carpenters tend to slide their fingers over a sanded surface to check for irregularities that they cannot detect using their eyes. When comparing the senses it may be important to "fairly" match the sensory modes. This is not always easy.

There are applications of research in which senses are compared. For example, in the pursuit of true telepresence a large amount of information needs to be provided to the operator. However, this information may not need to be in its "natural" form. Information usually perceived visually may be channelled to the haptic sense with a resultant improvement in the feeling of immersion. Such considerations are also important for augmented reality scenarios. In augmented reality there is real time video, with a virtual overlay providing additional information not readily or simultaneously available in the real world. For example, the inner workings of an apparatus can be presented as an overlay to an output on a video monitor. The operator can choose the best way to access a particular internal component as they can see where this component is in relation to others and to external access hatches. The advantages in fields such as bomb defusal and laparoscopic surgery are obvious. Knowledge of which sense to use for augmented components is critical, not just for immersion purposes but for ergonomic principles and problems related to sensory overload.

In Chapter 5 there is a comparison of vision and touch on a spatiotemporal task where the former is restricted to receiving the spatial information at the same rate as touch. Vision's usual spatial advantage due to being able to take in a whole scene at once is tempered by being obliged to acquire spatial information in the same way touch does – sequentially rather than simultaneously.

In summary, the aim of the research described in the following chapters is to help show how the haptic senses work exquisitely to integrate not only the multiple inputs within this rich sense itself, but those from other senses too.

2. DETAILED MATERIALS & APPARATUS

Some of the research reported in this thesis required devices and computer programs specifically designed for these experiments. Rather than repeat details in each chapter, they are described here and then referred to as necessary. This chapter also includes a test of whether auditory cues could represent a confounding variable in some of the experiments.

2.1 The Tactile Display System (TDS)

Symmons, Richardson and Wuillemin (2004) reviewed 33 studies involving 73 comparisons of active and passive haptic exploration of two-dimensional stimuli. Of those comparisons, 42 indicated that active touch was superior, 11 suggested passive to be better, and 20 resulted in no performance differences between the two conditions. However, it was suggested that many of these studies were not truly comparing active and passive touch, or at least were not using a "fair" comparison. For example, Heller (1980) traced a pattern onto the palm of a participant as the passive task for comparison with free voluntary movement of the participant's finger in the active condition. These tasks differed with respect to variables other than active and passive conditions. For example, differences included type of voluntary control, nature of movement of the participant's skin in relation to the stimulus, differing sensitivities of skin areas, different rates of movement, and presence or absence of physical contact with the experimenter. Accordingly, it is difficult to determine which variable or combination of variables was likely to be responsible for any performance differences. "Only in those cases in which performance is essentially the same in the two conditions is anything definitive learned." (Loomis & Lederman, 1984, p. 10).

Symmons et al. (2004) suggested that of the 36 active-passive comparisons identified, 18 (within 33 studies), involved matching of the active and passive tasks sufficient to achieve at least some control over potentially confounding variables. For example, Loo, Hall, McCloskey and Rowe (1983) splinted the wrist and finger joints of their active and passive participants and suspended their forearms in a sling hung from the ceiling. Participants were only allowed one "lap" of the stimulus and were not allowed to retrace. An experimenter guided the passive participant's finger by holding and dragging the splints, trying to move at a rate that was the "average" of the active movement. Bairstow and Laszlo (1978) also suspended participant's arms in a sling and allowed only one circuit of the stimulus. They also manually attempted to match movement speed between the active and passive participants. Magee and Kennedy's (1980) active-passive comparison included similar restrictions on exploration. They more accurately matched the passive participant's speed of movement with that of the active explorer by using a digitising tablet to map the active participant's exploration. Despite the control present in these studies, a potential confounding variable in each was the presence or absence of physical contact between an experimenter and the passive participant. This contact was necessary to guide the passive participant's finger around the stimuli in an attempt to match the movements of the active subject.

There are two aspects to consider in relation to contact between experimenter and participants. The first has to do with the fact that active participants did not require such contact, and passive subjects did. This provides the potential for several confounds that may or may not be identifiable. One such possibility is the well-known experimenter effect in which influence may be exerted by the experimenter and picked up by the subject quite unconsciously (Rosenthall, 1963, cited in Gravetter & Wallnau, 1996).The second concerns known affects of touching. For example, Fisher, Rytting and Heslin (1976) had librarians surreptitiously touch some patrons while returning their library card. Those who had been touched later reported more positive evaluations of the librarian than did those who had not been touched. A similar effect has been noted in a more positive impression of a hospital stay after briefly being touched by a nurse (Whitcher & Fisher, 1979). Gueguen (2003) reviewed a number of studies in which touching someone produced a positive effect. For example, shoppers were be more likely to taste or test products being demonstrated in a store and the sales rate increased if the demonstrator touched the consumer (Smith, Gier & Willis, 1982; Hornik, 1992, both cited in Gueguen). Touching a student twice on the arm during an interview lead to an improvement in later performance compared to students not touched (Stewart & Lupfer, 1987, cited in Gueguen). Gueguen found that briefly touching a student during class led to an increased rate of volunteering to work on the blackboard at the front of the class.

Richardson, Wuillemin and Mackintosh (1981) matched the movements of the passive participant to that of the active counterpart by physically yoking them together. Each had their hand strapped to a platform that could move in two dimensions. The passive participant's finger therefore did not require guidance by an experimenter, and so no physical contact between the passive participant and the experimenter was necessary. In theory, Richardson et al.'s device could have been used without restrictions on the number of laps or retracing, but they only reported results for a maze task and did not mention whether retracing movements were made. A potential concern with this task, however, is that even though the passive participant was asked to relax, the active explorer had to overcome the inertia inherent in dragging and pushing the passive subject's finger around the stimulus. If the passive participant thought they knew what the stimulus was and had an expectation of

the likely next movement direction, they may have unintentionally applied additional resistance to the active explorer's movement in an unexpected direction.

Taking advantage of new technologies, Jansson (1998) used an Optacon. To use this device a fingertip is placed on an array of pins that vibrate in a pattern that a camera "sees" when passed over contrasting lines (see Craig, 1980 for a description). Jansson mounted the Optacon on a platform that could move in two dimensions. As the active subject moved the Optacon to explore, rows or columns of pins in the Optacon's finger display vibrated to indicate the line that would have been under the user's fingertip had the stimulus been real. The position of the Optacon was recorded and stepper motors were used to play back the movements. While this device deals with many of the criticisms of previous active-passive research, at the time of writing, active and passive performance has not been compared by Jansson. In addition, when using an Optacon the explorer's finger does not actually contact the surface being explored – only the vibrating pins are felt. Therefore, there are no shearing forces on the skin.

A new device was built to more adequately match active and passive tactile perception tasks for exploration in two dimensions. The Tactile Display System (TDS) is a self-contained desk-top unit (see Figure 2.1). The active subject places their index finger into a plastic finger holder consisting of a concave cradle, against which the upper side of the finger rests. Two curved, spring-loaded jaws apply pressure to the sides of the second phalange of the finger, gripping it firmly but without discomfort (see Figures 2.2 and 2.3). The finger can be slipped in and out of the holder or moved up and down until the subject can comfortably feel the surface to be explored.

In the active mode the blindfolded participant was free to investigate the stimulus. In theory, any kind of tangible material or relief pattern could be mounted on the exploration surface, so long as it will fit into a 12 cm x 12 cm square. For example, the raised line drawing was replaced with a Peltier tile to examine tactile temperature perception in active and passive conditions (VanDoorn, Richardson, Wuillemin & Symmons, in press). However, most of the research reported here involved raised line drawings, prepared by engraving a special plastic sheet with a point, such as a ball point pen, to produce a relief pattern. Figure 2.4 shows a participant exploring a raised line picture of a Christmas tree.

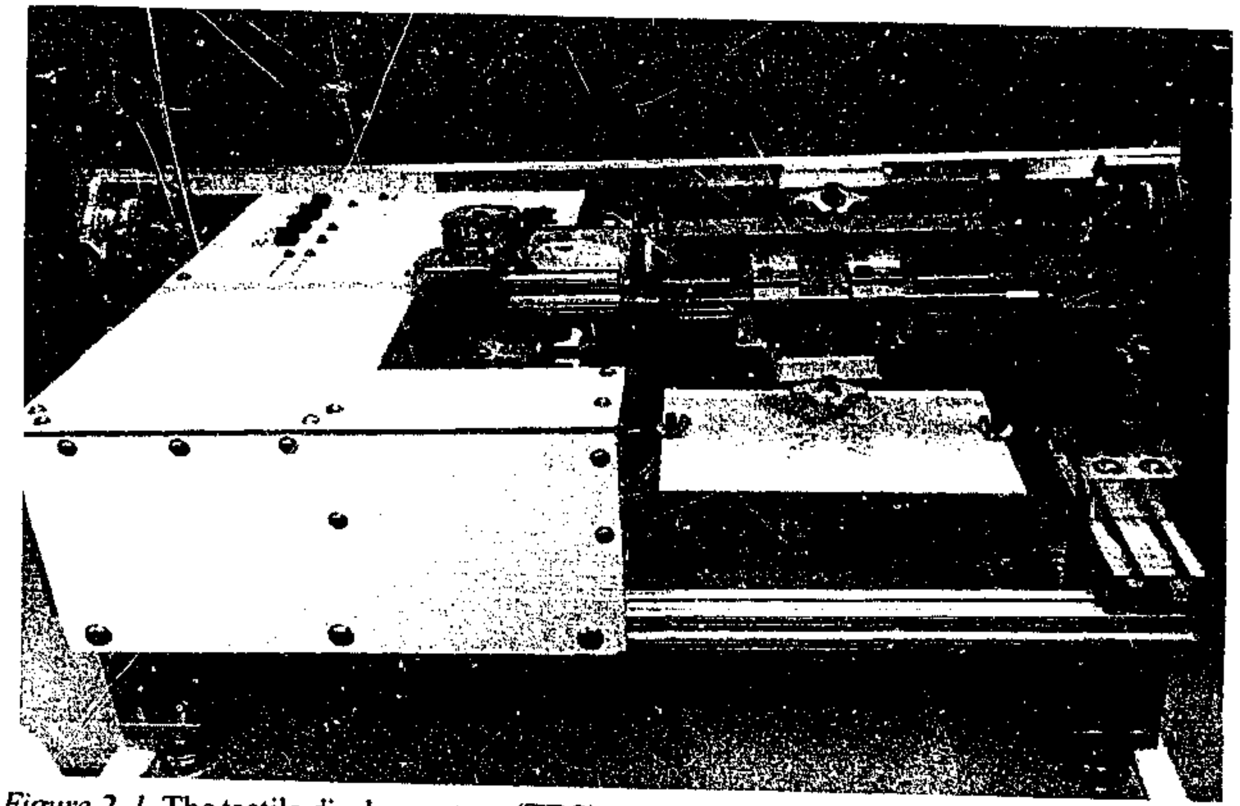

Figure 2-1. The tactile display system (TDS).

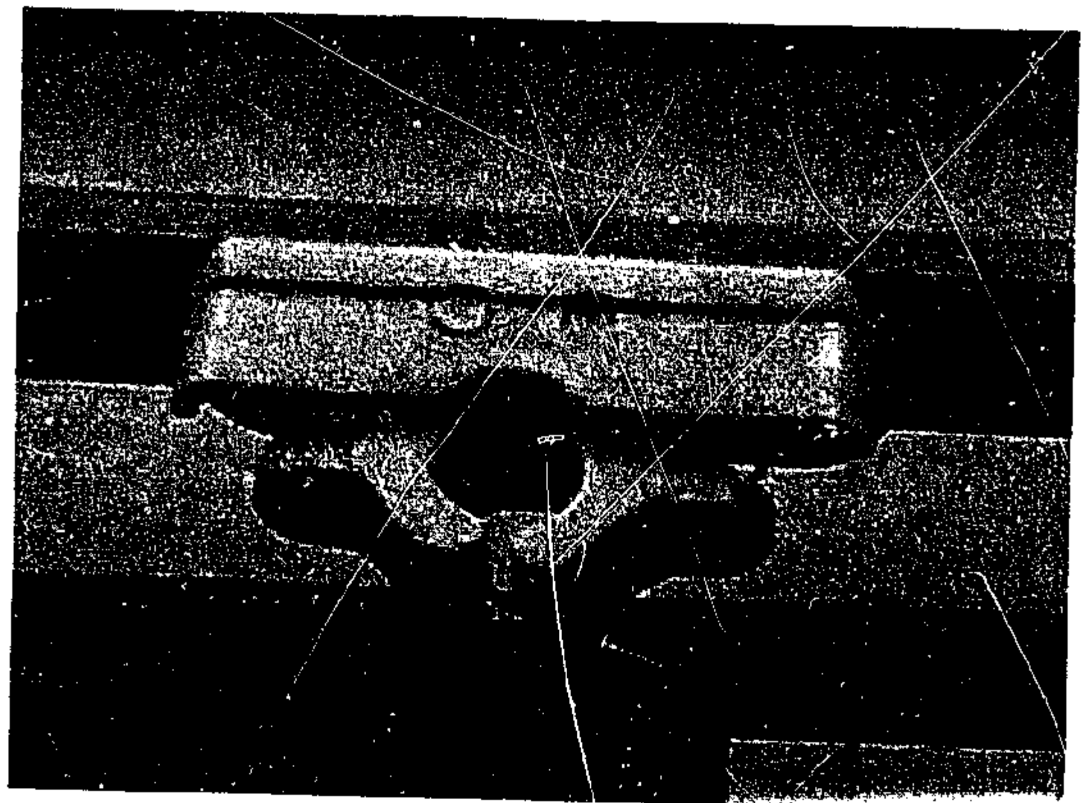

Figure 2-2. Close-up of the spring-loaded finger holder.

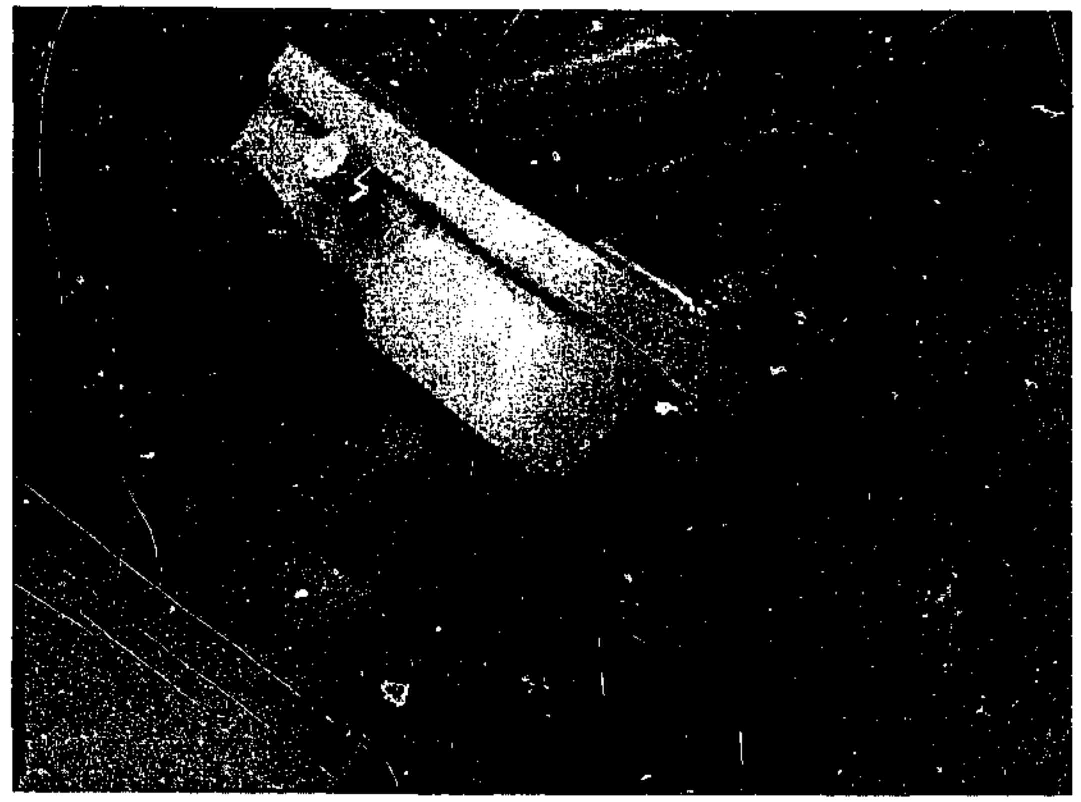

Figure 2-3. Close-up of a finger in the finger holder.

As demonstrated in Figure 2.4, the finger-holder is mounted on a carriage that can travel on the x-axis (at right angles to the participant). This carriage and the tracks it runs along are in turn mounted on a set of rods that allow movement along the y-axis – towards and away from the participant. Precision-ground, low resistance, ball races allow free, almost frictionless movement of the subject's finger in any direction in the x–y horizontal plane.

The exploration pattern followed by the active subject while they explore the raised line drawing is electronically logged using two optical encoders (one each for the x- and y-axes) to track the direction and speed of movement. The pattern of movement is stored in the device's memory, where it remains until overwritten by the next pattern. A passive subject subsequently places their finger into the finger holder and the device guides them over the same pattern, matching for the speed and direction of movements originally made by the active subject.

Two stepper motors (see Figure 2.5) are connected to gears and belts that drive the finger holder in the x-y plane when a passive subject is to be guided. To reduce friction and inertia to a negligible level these motors are disengaged while the active subject is exploring.

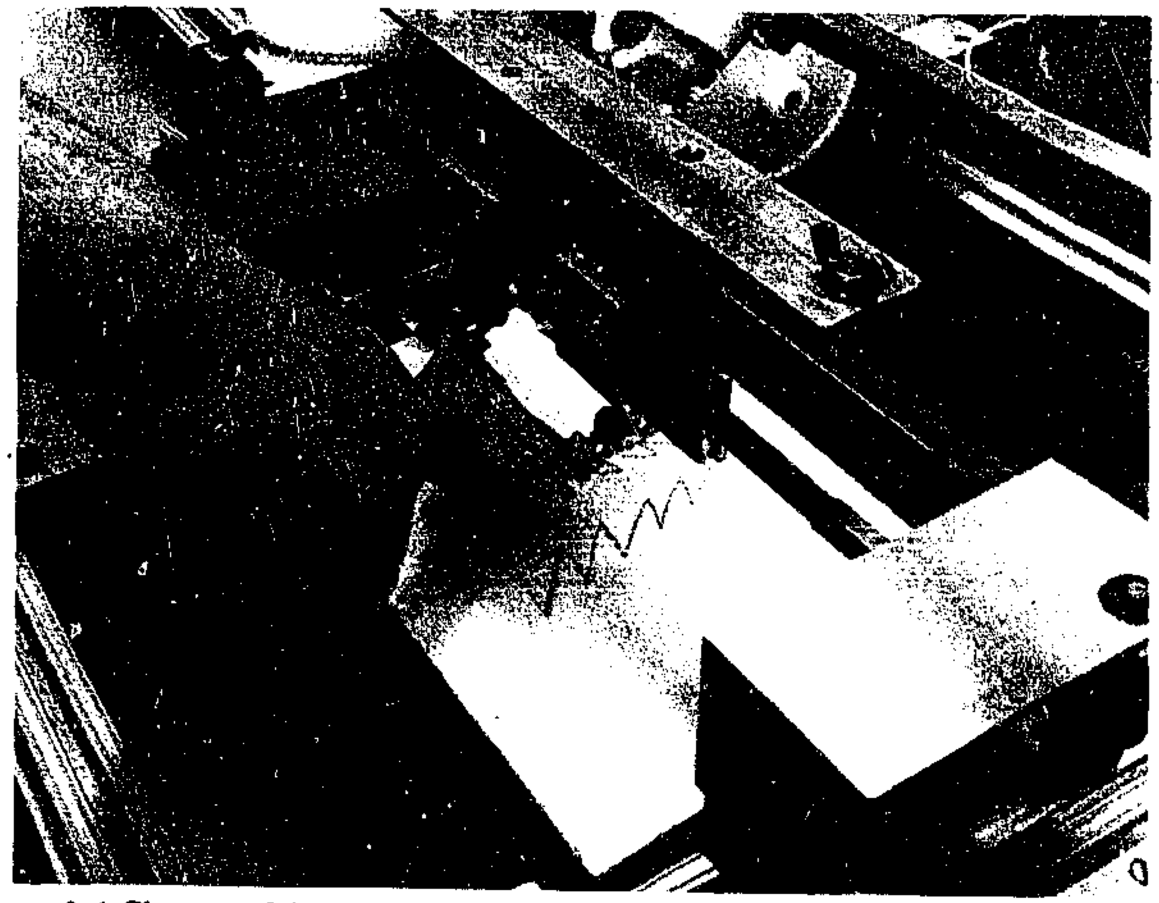

Figure 2-4. Close-up of the exploration using the TDS.

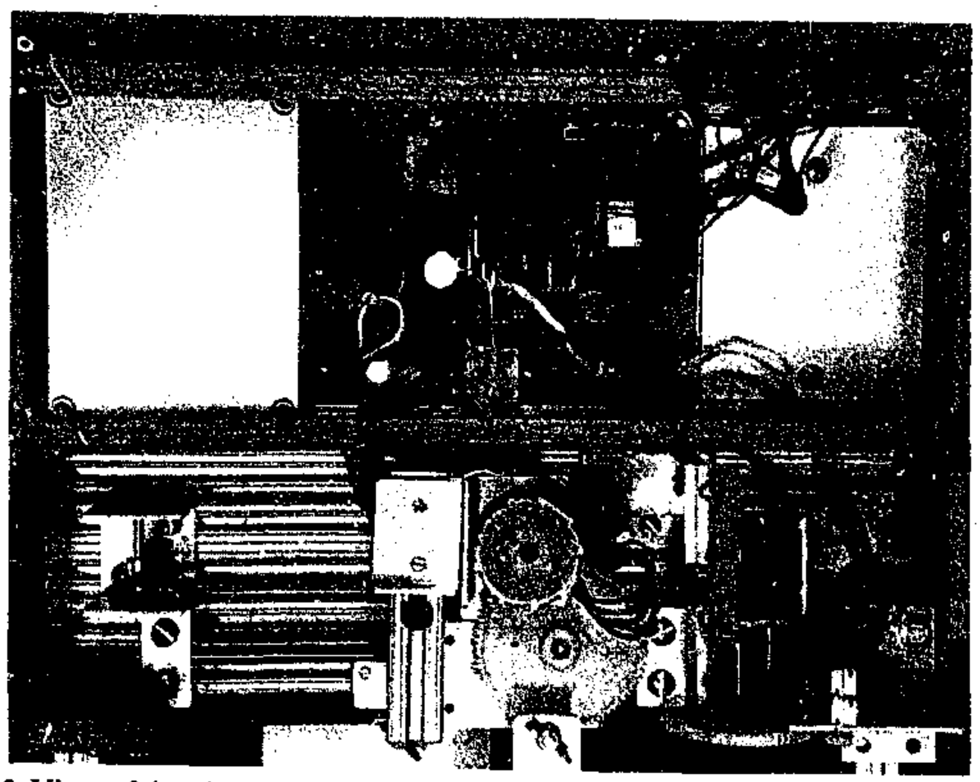

Figure 2-5. View of the electronics and the two stepper motors.

The device can also hold the passive subject's finger stationary while a raised line drawing is moved underneath their fingertip to recreate the cutaneous experience of the active subject with kinaesthetic and proprioceptive cues removed. Alternatively, a passive subject can be guided through the movements made by an active subject while the finger tip

is in contact with a surface with no raised line (thus eliminating the line information but leaving shearing forces on the skin and movement cues intact), or the surface can be removed completely, leaving only movement cues since there is not contact at the fingertip. These conditions allow a comparison of the relative contributions made by haptic components to the perceptual process (see Chapter 3). They also address the difficulty Jansson (1998) noted in separating the components of haptics in order to determine the relative importance of kinaesthetic and cutaneous information: "[there is a] lack of equipment able to simulate all aspects [of haptics] together and separately" (p.27).

The TDS operates by separating the distance travelled by the active participant into discrete steps of 0.1524 mm. While recording a pattern the device measures the time interval of each step expressed in increments of 0.2 ms, and the direction of the step. During replay, to achieve a smoother motion, each step duration is halved and two steps are taken in the required time. The maximum speed possible is 10 cm/s and the device has a memory capacity of 128 Kbytes per direction of movement. This is sufficient for several minutes of continuous movement recording.

The control panel includes record and stop buttons to store the movement pattern, a playback button for the passive condition, and another for moving the pattern under the passive subject's stationary finger while held in the upper grip (see Figure 2.6). If the position of the playback does not match the expected position according to the stored pattern (for example, if the passive subject overly resists the device or their finger or fingernail catches on something) the device halts and the "position error" warning light is illuminated. While the system is capable of storing only one exploration pattern at a time, any pattern can be downloaded to a computer or a new pattern uploaded via an RS232 serial link. As the pattern is digitally encoded the data can be accessed and transformed, displayed by a relatively simple computer program, and shown on a monitor, or printed.

The special feature of the TDS is that it allows matching the experience of the active and passive subjects for all factors except for the presence or absence of volitional motor control. This is consistent with Loomis and Lederman's (1986) criterion that the active participant should have total control while the passive has none. It is also compatible with Gibson's (1962) assertion that active touch involves actively seeking stimulation while passive touch is restricted to simply receiving it.

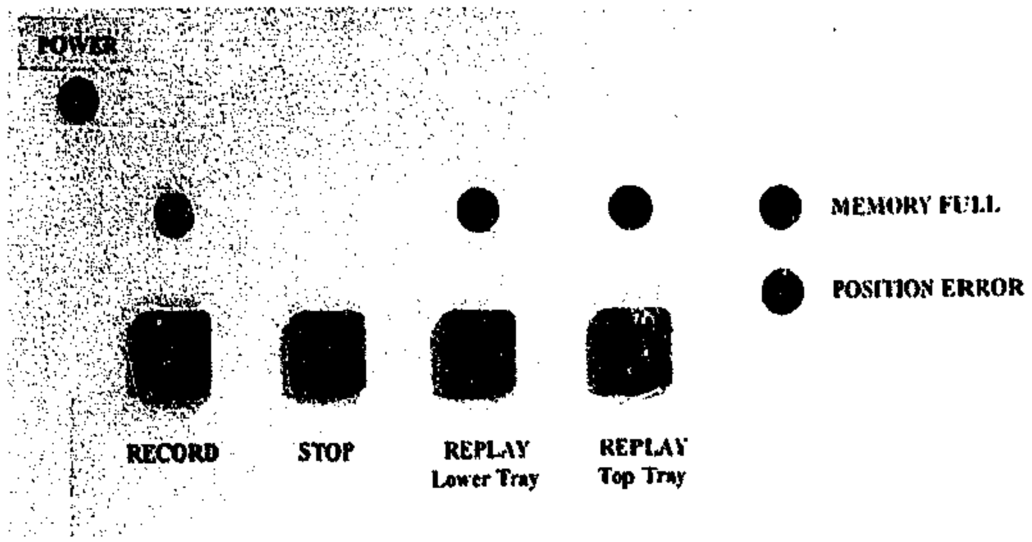

Figure 2-6. Close-up of the TDS control panel.

2.1.1 Ecological validity of the TDS

A criticism that could be levelled at the TDS (and other active-passive research) is the seemingly "unnatural" mode of exploration – using a single finger to explore. Symmons and Richardson (2000) tested whether this from of exploration was in fact unnatural.. To familiarise them with the medium, participants were exposed to raised line paper with a picture of a square. Care was taken not to provide any cues or suggestions as to how such a stimulus should be explored. Participants were then blindfolded and, in turn, three relatively simple raised line drawings (the outline of a Christmas tree, a smiling face and the word "key" in capital letters) of around 10 cm along their longest axis were clamped to the surface of a table in front of them. They were asked to identify the pictures depicted as quickly and accurately as possible. Participants' strategies were recorded by a video camera for later analysis.

Each of the eleven participants used just one index finger to explore the raised line pictures for more than 50% of the time, although only three participants used a single index finger exclusively. Other exploratory strategies were evident but did not seem to dominate. For example, individuals sometimes made a full-palm sweep of the stimulus at the beginning, or used one index finger for exploration but placed the index finger of the other hand on the drawing as some sort of place marker or anchor, although it was not demonstrated that participants were using the second finger as a reference point. When both index fingers were used for exploration they were never moving at the same time – one was always held still while the other explored. Figure 2.7 shows a subject using a single finger to explore the raised line picture of a Christmas tree, and resting their other hand near, but not on, the stimulus. When multiple fingers on the same hand were used they were rarely used independently. In only four of the total of 33 explorations (12% of occasions) were multiple

fingers used to investigate different parts of the pattern simultaneously – but not for the whole time. Generally, multiple fingers were kept together. It is not clear whether this was for comfort or to create some sort of extra-wide finger.

In 28 of the 33 trials the stimulus was correctly identified. This 85% hit rate was remarkable since the stimuli were from an essentially infinite set. No hint, prompting or feedback was provided. There may have been a practice effect due to familiarity of the medium or elaboration of exploration strategies. However, as there was no evidence that participants' exploration strategies improved, practice effects were not evident (the stimuli had been presented in a counterbalanced order as a precautionary measure).

Figure 2-7. Spontaneous exploration of a raised line picture using just one finger.

It was noted that no participant ever began at one point in the drawing and progressed through to the end, but all employed at least some retracing. Each participant also tended to dwell on parts of the drawing and would sometimes only briefly attend to what might be particularly important aspects of the picture (such as intersections). But there was no consistency across subjects with regard to where and how much time was spent. There seemed to be idiosyncratic variations between individuals in the way they explored these raised line pictures. This kind of variety during exploration has been noted by others, e.g. Gibson (1962): "The movements do not ever seem to be the same, but they are not aimless" (p. 481).

If ecological validity is sought, it would seem that choice of movement direction and velocity of exploration should be minimally restrained to allow for the wide range of individual differences in exploration strategies. The TDS allows this freedom and contrasts with previous devices and methods that have restricted subjects to a single lap of the drawing with no retracing (e.g., Magee & Kennedy, 1980).

2.1.2 *Experiment 1: TDS auditory cues*

When operating in any of the passive-guidance modes, the stepper motors of the TDS can be heard as they move the passive participant's finger around the display. The purpose of Experiment 1 was to investigate the possibility that the noise made by the TDS when it is guiding a participant or moving a stimulus under a participant's stationary finger can aid the participant in their task of identifying the stimulus.

The accuracy of participant's responses in attempting to identify a set of raised-line letter stimuli based on the sound produced by the TDS was compared to chance performance. The responses were recorded in a confusion matrix to examine the possibility that some useful information was obtained despite an error.

Method

Participants

Nine blindfolded adult volunteers from the Gippsland Campus of Monash University were exposed to the sounds of the TDS as it traced out a series of stimuli.

Materials

Raised line drawings of capital letters were chosen to include letters that could be grouped into one or more of the following categories: letters that involved diagonals, that included circular elements, that contained intersections, that could be completely explored without retracing, and letters that required backtracking.

A B G K M Q R X Z

Figure 2-8. Stimuli used in Experiment 1.

All of the raised line drawing stimuli used were approximately 7.5-10 cm along their longest axis. They were prepared by drawing with a ball-point pen on a special plastic sheet resting on a rubber mat. This method produces well-defined raised-lines (Kennedy, 1993). The stimulus was then mounted onto a sheet of particle board or perspex, ready for use with the TDS.

These raised line drawing stimuli were approximately 7.5-10 cm along their longest axis and mounted onto a sheet of particle board or perspex, ready for use with the TDS.

Procedure

Each participant placed a finger in the upper of the two finger-holders on the TDS (see Figures 2.1 and 2.4), so that the finger was not moved and was not in contact with any surface. This ensured consistency between the conditions experienced by participants in this control study and those in later experiments in terms of the distance between the participant's ears and the stepper motors, finger positioning, and subject's posture and orientation while standing at the TDS.

While the participant's finger was held stationary, the TDS was activated so that, for each subject, the sounds made during the passive-guided presentations of three capital letters could be heard. Each pattern lasted for 30 seconds. The movement patterns were prepared earlier by the experimenter continuously tracing over the raised line drawings of the letters. Participants were asked to name the letter presented as soon as they thought they knew what it was. They were also asked to choose a number from 1 to 5 to indicate their level of confidence in their decision, with 1 denoting very little confidence through to 5 meaning very confident.

Results & Discussion

Overall, two letters out of the total of 27 presented were correctly identified, a 7% accuracy rate. This response rate is not significantly different to that expected by chance[1] (z=1.94; p>0.05).

Interestingly, no participant volunteered a response before the 30 second exploratory period was over – each had to be prompted for an answer. Such hesitation was probably indicative of the difficulty of the task. Accordingly, latency to correct response was discarded as a useful source of data.

Of the nine participants, only two correctly identified any of the stimuli, and each of them identified only one of their three stimuli. One of these participants correctly identified their third stimulus as a "G", and the other correctly named their second stimulus – a "B". One participant refused to guess at any of their stimuli, insisting that they were receiving no usable information. No particular pattern arose from the comparison of stimulus and responses within a confusion matrix (Figure 2.9).

[1] For each trial the probability of guessing correctly is 1 in 26. For 27 trials the overall chance response rate is 1.04

Stim / Resp	A	B	G	K	M	Q	R	X	Z	Total
A										0
B	1	1							1	3
C						1				1
E	1			1	1					3
G		1	1							2
H				1						1
K									1	1
L										0
M							1			1
O			1		1					2
P						1				1
Q										0
R		1								1
S					1	1		1	1	4
T				1						1
W				1			1	1		3
X										0
Z										0
No resp	1		1					1		3

Figure 2-9. Number of responses provided for each stimulus presented by the TDS. Shaded cells indicate congruence between stimulus and response.

With respect to the confidence scores, the average confidence level was 1.8 (on a scale of 1 to 5). Only one participant nominated a confidence greater than 3 (they chose 4), although their response was incorrect anyway. For the two correctly identified letters, the confidence score was 3.

It would seem that sounds made by the TDS stepper motors provide no useful cues for identifying stimuli. As the noises are not particularly loud or annoying (in fact, they are not significantly louder than the sound of carriage movement in the active condition), it is unlikely that they act to either detract from or improve the passive explorer's performance.

2.2 The Phantom

The Phantom is a commercially available device produced by Sensable Systems. It was used in more than one of the studies reported in this thesis and so a brief description is included here.

The Phantom is advertised as a haptic device with six degrees of freedom. It is essentially a probe with articulations at three points (see Figure 2.10). Virtual objects can be designed using specialised software and "touched" with the probe. When the probe is in contact with a virtual surface motors provide force-feedback to produce the impression of touching the surface, similar to the experience of a blind person exploring the world with a

cane. The joint closest to the main body of the device contains motors that provide force-feedback in the vertical and horizontal planes (up and down, and side to side relative to the user, respectively). A motorised second joint provides force-feedback in a depth plane (towards and away from the user). Further technical details about the Phantom can be found on Sensable Systems' website (www.sensable.com).

The force-feedback motors can also be programmed to drive rather than simply stop movement as directed by contact with the virtual surface. The Phantom can then be used to guide a passive user in three-dimensional virtual space. This programming was done in-house to facilitate some of the research reported in this thesis.

Figure 2-10. The Phantom (reproduced from the Sensable website).

2.3 In-house programming

A number of principal computer programs were required to conduct some of the experiments reported in this thesis. They are described together in this chapter and referred to where relevant.

2.3.1 Phantom Explorer

The Phantom Explorer computer program was written in C++ in conjunction with the Ghost Software Development Kit (a C++ object-oriented toolkit) supplied by Sensable Systems. Using this program, three-dimensional objects can be created with any combination of the basic shapes of a cube, sphere, cone and cylinder. The basic shapes are customisable in terms of their dimensions and can be melded and meshed together to theoretically create any object in virtual space. The resultant external (and internal) surfaces of the three-dimensional object can then be felt with the Phantom.

The Phantom Explorer can also convert graphics files in Targa (*.tga) format into virtual drawings (i.e., two-dimensional representations) that can be felt with the Phantom. Any paint or draw program can be used to initially create the Targa file. When the file is converted it becomes a wall in the Phantom's world space (as a graphics file is, by definition, two-dimensional). Either side of the wall can be explored. On one side of the wall the picture is made up of raised lines and on the other side there are engraved channels (i.e., the obverse of the raised lines). One of the purposes of this feature was to allow testing of shape identification using the Phantom, instead of drawings on raised line paper as used with the TDS.

Using a hotkey, the Phantom Explorer can turn off the haptic force-feedback, allowing the probe to pass through surfaces. For example, haptics can be deactivated to allow the user to enter a three-dimensional object and turned back on again so that the inside surface of an object can be explored. Another hotkey can be used to activate a gravity point at the centre of the nearest object. The Phantom, and therefore the user, is then drawn towards this point until stopped by the object's surface (unless the haptics hotkey is pressed). Movement across the surface is still possible. This feature enables an object to be found easily and quickly when vision is not allowed and stops the user "flying off" the surface.

Finally, and most importantly for the current research, the Phantom Explorer program can be used to record the active movements of an explorer as they investigate a virtual object or surface with the Phantom. The program can then use this stored pattern to drive the Phantom and guide another participant over the same movement pathways, matching for position and speed in three dimensions. This feature can be used to make a comparison of active versus passive touch in three dimensions (see Chapter 4), providing an equivalent to the principal function of the TDS, but in three-dimensions.

2.3.2 *Haptics-to-Vision Translation Program*

Movement patterns resulting from the active exploration of stimuli using either the TDS or the Phantom can be recorded and stored as individual digital files. The Haptics-to-Vision Translation Program (HVTP) was written to produce visual analogues of these active haptic movement pathways. A movement pathway is plotted on a monitor to show the position and speed of the fingertip in the case of the TDS or the stylus (or probe) in the case of the Phantom. The stimulus that was explored (whether it was a raised line drawing or a

virtual three-dimensional shape) was not shown visually, only where the individual had moved while exploring the object is visible (although it is expected that the programming will be modified to also allow the stimulus to be shown in future studies).

The purpose of this program was to allow a comparison between vision and touch in exploring stimuli such that vision is supplied with information in the same way that touch receives it when exploring with a fingertip or probe – as a one centimetre (or thereabouts) segment of the pattern at any one point in time.

The HVTP also has a number of customisable options for viewing the movement path that can be related to the haptic experience of creating it. For instance, the size of the segment can be altered – the haptic equivalent would be to have more or less skin surface (e.g., a smaller or larger fingerpad) in contact with the surface being explored. Additionally, the movement path "history" as the segment of line traces out the movement path can be left illuminated – an analogue to haptic exploration with perfect memory.

In each of the HVTP applications thus far described, the visual line or segment appears to advance around the screen in concert with the way a fingertip or probe moved. Another method of providing the haptic sense with information is to keep the skin surface (e.g., the fingertip) still and move the surface to be explored underneath it. This mode of haptic exploration has often been used as the passive experience in comparisons of active and passive touch. For example, Loo et al. (1983) clamped participant's hands to keep them stationary and moved a raised line drawing under an extended fingertip. As described earlier, the TDS can also provide the haptic condition in which a raised line drawing is moved underneath a stationary fingertip, where the position and speed of movement is precisely matched for the condition in which an active explorer was able to freely move around the drawing, including retracing. The HTVP provides a visual analogue of this experience, where the segment of line seems to "dance" in the centre of the screen; however the boundary of this area is never visible.

The HTVP programming was done using C++ with the OpenGL and GLUT libraries.

2.3.3 *Phantom Yoking*

The Phantom Explorer program can be used to record the movement patterns of an active explorer and then use this information to guide a passive participant over the same path, matching for position and speed of movement. Essentially the active and passive explorers are yoked, but not in real time. An additional stand-alone program was written to yoke two Phantom devices in real time. The movement of an active (or master) explorer is directly translated into force-feedback at a second, slave Phantom. The program allowed for a cube, sphere, cylinder or a cone to be explored. No visual feedback was available, just the haptic sensation via force-feedback.

The Phantom Yoking program was written with C++, using elements of the Ghost SDK supplied by Sensable Systems. The position of the master Phantom is calculated and the slave Phantom is driven to match that position. The greater the distance between the current positions of the two Phantoms, the greater the forces that are used to draw the slave Phantom to the same position.

3. THE COMPONENTS OF TOUCH

The haptic sense is generally considered to be comprised of kinaesthesis and touch. Kinaesthesis arises from movement and touch generally relates to sensations that arise from interactions between the skin and the environment, usually involving physical contact. The term proprioception is often used interchangeably with kinaesthesis, and for the purposes of this thesis will be included as an element of kinaesthesis. The terms tactile and cutaneous are often used interchangeably with touch as a skin sensation, and for the purposes of this thesis all three terms will be taken to have the same meaning. However, these categories could be further partitioned to include information arising from the shearing forces that occur with relative movement between an explorer's skin surface and the surface being explored.

Shearing forces between the skin and the surface being explored are critical when texture is the focus, such as when a carpenter runs a hand over a sanded surface to judge how smooth it is. Shoppers like to stroke garments when purchasing clothing made of materials such as silk, and so it is likely that shearing information is involved when a consumer says that a fabric "feels nice". However, there are also instances where it may seem that this shearing information would be mostly irrelevant, such as the "empty" spaces between Braille words. In both of these examples there are other haptic components involved simultaneously, including kinaesthesis accompanying movement of an arm. There is utility in determining the importance of each of the "components" that make up the haptic experience (Jansson, 1998; Goldberg & Bajcsy, 1984). Some of the questions that could be addressed include which of the constituents are critical; which components are additive and in what combinations does redundancy occur. The answers to such questions would be useful in applications such as telesurgery, virtual reality interfaces, and sensory substitution. For example, if one of the components is mostly redundant for a particular task then it might be ignored when designing a particular device.

For the purposes of this research, the haptic sense has been partitioned into three principal components. The first, kinaesthesis (K) is the information that arises from movement, such as that of a finger, hand, arm and so on. The second component is found when feeling something with a texture or relief different from that of the surrounding area, such as when running a fingertip over a raised line or Braille dots. For brevity, this component will be called "line" (L). Finally, shearing forces (S) are felt when there is relative movement between the skin and a surface, deforming the skin as a consequence of friction. All three components involve movement of either the haptic receptors or the stimulus surface, but not all need necessarily involve contact between the subject and the stimulus.

No reports were found in which researchers had deliberately separated the haptic sense into this many components. However, a number of studies have included conditions with some degree of separation, and these generally involve a comparison of active and passive touch. They can be reanalysed to estimate the likely outcome of such a separation. In order to ensure that active versus passive exploration itself is not a confounding factor, only those studies in which the components are separated within an active mode or separated within a passive mode are included. Additionally, the current research focuses on haptics in two dimensions.

Austin and Sleight (1952) found that a combination of kinaesthesis, touching a "lined surface" and shear information (K+L+S according to the convention used in this thesis) resulted in superior accuracy in comparison with line information (L) alone. Using an Optacon, Craig (1980) found that a line plus shear (L+S) condition produced greater accuracy for identifying stimuli than did a line (L) alone condition. Cronin (1977) found that L+S and K+L+S exploration was superior to line alone exploration. Using large, raised line stimuli (15 cm tall variants on the letter S), Loo, et al.. (1983) reported that exploration in two conditions involving kinaesthesis resulted in equivalent performance, (K+L+S)=(K), and both conditions yielded superior performance compared to a third condition not involving kinaesthesis, (L+S). When the stimuli were reduced to 3 cm in height the differences between effects of conditions disappeared. Magee and Kennedy (1980) found that guiding a finger over a plain sheet of plastic, a condition they called kinaesthetic, although sheer information would have been present, produced more correct identifications of raised line drawings than did moving a raised line picture under a stationary fingertip; (K+S) vs. (L+S) respectively.

Jansson (1998) described an apparatus built around a modified Optacon that could be moved over a large, two-dimensional plane. This device could be used to separately assess the haptic components to a significant extent. The haptic constituents described were based on the "organs" that obtain the information – skin, muscles, and joints. The only results published were for a comparison of skin (L) with a combination of skin, muscles and joints (K+L). As an Optacon was used there could be no lateral deformation of the skin to produce shear (S). In terms of accuracy, the K+L condition was superior to the line-alone condition. Jansson has not further explored this issue by comparing other haptic components (personal communication, 12 September 2004).

Another device that may have been capable of separately testing some of the haptic components is the Heidelberg Tactile Vision Substitution System (Maucher, Schemmel & Meier, 2000). Quite similar to Jansson's (1998) device, a carriage was moved on rails in the x-y plane (approximately 16 cm by 16 cm). A 1.6 x 4.3 cm array of 48 piezoelectric actuators was mounted on the carriage to accommodate three fingertips. Virtual images can be produced from bitmap files or output from a video camera. One would imagine that this device could be used in a similar manner to that reported by Jansson. However, the published results were a comparison of exploration between blind and sighted individuals rather than an examination of haptic components, or between active and passive touch for that matter.

Kinaesthesis would seem to have a major role in haptics. Magee and Kennedy (1980) argued that it is the basis of perception of shapes in raised-line displays, and that the primary role of cutaneous information is to let participants know that they are making relevant motions. It signals "you are on the line" or " you are off the line". If the explorer is being guided and is therefore not responsible for deciding where to move, the information arising from the line should be unnecessary, or at least redundant, if kinaesthesis is the key to the task. However, cutaneous information is actually available in both conditions via the shearing forces that occur as a finger is dragged across a surface (or a surface dragged across a finger), a matter to be discussed later.

The device to be used in the current research is the Tactile Display System (see Chapter 2 for a detailed description). It can be employed to separate the main aspects of haptic perception and test them individually or in various combinations. Each of the haptic components described earlier – kinaesthesis, feeling a line under the fingertip, and the shear caused by the changing deformation of the fingertip integument – were examined.

3.1 Experiment 2: Haptic components

The contribution of haptic components was examined. Each component was tested individually where possible, and in various combinations. Measures were latency to correct identification of raised line letters and number of stimuli correctly identified.

3.1.1 Method

Participants

Fifteen blindfolded adults ranging in age from 19 to 26 years (*M*=21 years) were guided by the TDS in seven conditions. All participants were right-handed, with normal or corrected-to-normal vision. None had had any long term or extensive experience with Braille, raised line drawings or similar devices. All participants were volunteers recruited from throughout the Gippsland campus of Monash University via posters and word of mouth.

Materials

Raised line drawings of capital letters were prepared from a printout of standard Arial font (see Figure 3-1). The letters were chosen as representative of one or more of the following categories: letters containing straight lines only (e.g., the letter A), involving straight lines and curves (e.g., the letter B), involving "T" or cross intersection(s) (e.g., the letter R), involving oblique lines (e.g., the letter X), and letters that can be traced out with a continuous line without retracing (e.g., the letter Z) versus those that require retracing (e.g., the letter X).

ABGKMQRXZ

Figure 3-1. Raised line stimuli used with TDS.

All stimuli were approximately 7.5-10 cm along their longest axis and were prepared by drawing with a ball-point pen on a special plastic sheet resting on a rubber mat. This method produces well-defined raised-lines. The stimulus was then mounted on a board ready for use with the TDS. In addition, a sheet of unengraved raised line paper was used for conditions in which shear was present without a tangible line.

Apparatus

The TDS has been described elsewhere (see Chapter 2). It allows a passive subject to be yoked to an active explorer of two dimensional haptic stimuli, matching for position and speed. This is accomplished by the device first recording the movements of an active participant's finger, and then replaying them to a passive participant, whose finger was guided by the machine. The experimenter did not need to hold either participant's hand, and there were few limitations to the active explorer's movements. Thus, retracing, scanning, and multiple circuits were all allowed.

Procedure

After a brief overview of the experiment, participants viewed the TDS and saw it operating. Each participant then explored a raised-line picture of a square in two of the TDS conditions to familiarise them with the tasks and ensure that they were comfortable with the device and could relax sufficiently to allow themselves to be guided by the TDS. The two passive conditions used for familiarisation involved guidance of the finger over the drawing of a square and then the finger was held stationary while the drawing of a square was moved

underneath it. In each case it was ensured that the participant could clearly feel the raised line of the stimulus.

Participants were told that they would be blindfolded and would receive a series of capital letters as stimuli across a number of conditions, and that their task was to correctly identify each letter as quickly and accurately as possible. Each stimulus tracing was "near perfect" in that it was pre-recorded by the experimenter (without a blindfold) and was always "on the line". Each tracing lasted for 30 seconds, during which the participant was guided repeatedly around the letter, or the letter was moved under the finger.

In every case the exploration began from a point in the upper left corner of the stimulus field. This common point was chosen for consistency across subjects, and because the upper left corner is generally the starting point for reading English text.

The seven TDS conditions used are contained in Table 3.1, where:

- K = kinaesthesis (movement of finger, hand or arm)
- L = line felt under fingertip
- S = shear caused by lateral forces deforming the fingertip during movement across a surface offering frictional resistance
- S_m = minimal shear

Table 3.1
TDS Operating Modes During Tests of Haptic Components

Abbreviation	TDS operating mode
K+L+S	Finger moved over a stationary raised line drawing
K+S	Finger moved over a plain surface
K	Finger moved through the air
L+S	Line moved under stationary fingertip
S	Plain surface moved under stationary fingertip
S_m	Plain surface moved under taped stationary fingertip
L	Line moved under taped stationary fingertip

Each participant completed all seven conditions listed in Table 3.1 in random order, with two raised line capital letters in each condition. Each condition was tested in each order position at least once across the subjects. The nine letters were randomly allocated across conditions so that each letter was used approximately equally often and had an equal chance of being in any of the conditions. No participant had the same letter immediately repeated within any condition (i.e., a letter could be repeated from one condition to the next, but not within a condition).

Each stimulus was presented individually, with a short rest period of 10-20 seconds between stimuli to allow for the upload of a new pattern from a computer to the TDS. During this period the unit was also reset to the upper left corner of the stimulus field, and in some cases the configuration of the TDS was changed to present other haptic conditions. The participant remained blindfolded throughout the experiment. Once a participant provided a response the TDS was stopped. No feedback was provided to the participant until the completion of all conditions.

Design

The experiment was conducted as a within-subjects design in which each participant experienced all seven of the passive haptic conditions (see Table 3.1). There were two dependent variables: latency to letter identification, and number of raised line letters correctly identified.

3.1.2 Results

The time each participant required to correctly identify each raised line letter was recorded, as was the number of correct responses. The overall means for latency and number correct for each of the haptic conditions tested are shown in Figures 3.2 and 3.3, respectively (a table of descriptive statistics can be found in Appendix 7.2). The order of conditions in best-to-worst performance for latency and number correct showed similar but not identical patterns. In general, letters were identified more quickly and more accurately when the passive exploration involved kinaesthesis.

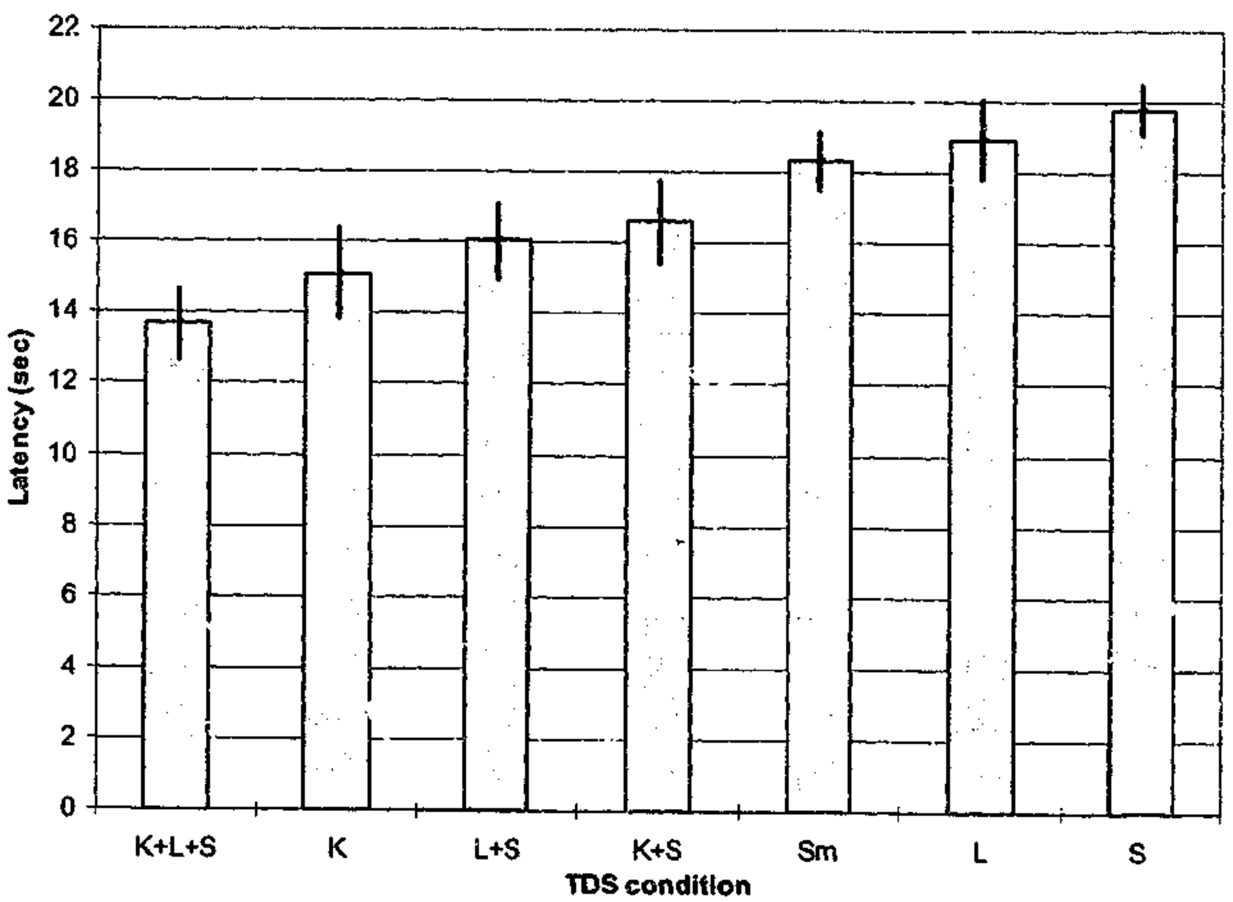

Figure 3-2. Mean latencies across haptic conditions with standard error values as error bars.

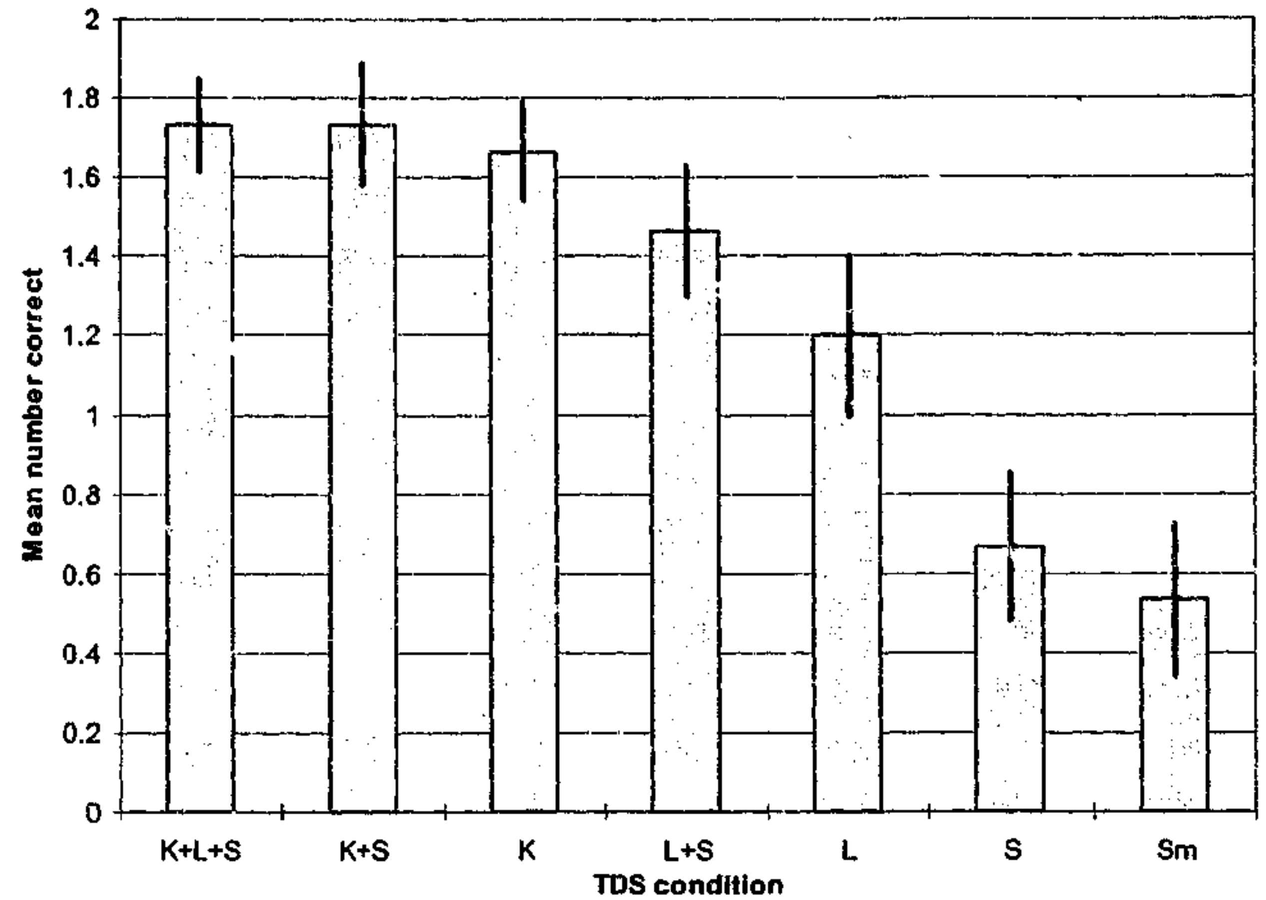

Figure 3-3. Mean number correct across haptic conditions with standard error values as error bars.

One condition provided kinaesthesis plus line plus shear (K+L+ S) and [illegible] can be considered to offer explorers the "most" information. This condition yielded the best performance in terms of latency (*M*=13.8 seconds). It also resulted in the highest mean number of correct responses, along with the condition in which the subject's finger was guided in the shape of the stimulus but a tangible line was not present (K+S). For the latency dependent variable the condition in which a plain surface was moved underneath a stationary fingertip (in the shape of the stimulus) resulted in the poorest performance. For the accuracy data the condition that resulted in the worst performance was an equivalent condition except that the fingertip had a layer of sticky tape between it and the plain surface.

Four participants achieved the shortest latency of five seconds in the conditions K+L+S with the letter X, twice with the letter Z in the K+S condition, and in the S_m condition with the letter R. The best latencies for the other conditions were six seconds for the K condition, nine for L+S, 11 for S, and eight for the line-alone condition. One participant achieved three of the best condition-times across the conditions, another attained two of the best times, and the five other shortest latencies were spread across participants. Overall, the letter Z figured most often in the short latencies (five out of the ten best condition-times), followed by the letter B (two of the quickest condition-times). The letters X, M and R were identified most rapidly one time each.

A one-factor repeated measures ANOVA was performed on the data for latency to correct identification using the SPSS statistical program[1]. A Mauchley's test of sphericity was not significant ($W(20)=0.61$; $p>0.05$) and so no adjustments were required. Overall, there was a significant difference in latency across the passive conditions ($F(6,174)=5.2$; $p<0.0005$), with a moderate effect size ($\eta^2=0.24$).

Least significant difference post-hoc pair-wise comparisons revealed nine significant differences between the conditions for latency at the 0.05 level of significance (see Table 3.2). Generally, conditions involving kinaesthesis resulted in the shortest latencies and conditions not involving kinaesthesis yielded equivalent mean latencies. However, guiding a fingertip over a raised line (K+L+S) produced performance equivalent to moving the fingertip through the air and, interestingly, moving the drawing underneath the stationary fingertip. The "full touch" condition also yielded significantly better performance than moving a fingertip over a textured surface in the pattern of the stimulus but without the line present. In addition, moving the line underneath a fingertip (L+S) resulted in a shorter latency than moving the line underneath a taped fingertip (L), a difference that approached significance ($p=0.055$).

Table 3.2
Significant LSD Pair-Wise Comparisons Across Haptic Conditions for Latency. Starred Cells Indicate Instances of Significant Difference.

	K	L+S	K+S	S_m	L	S
K+L+S			*	*	*	*
K				*	*	*
L+S						*
K+S						*
S_m						
L						

A one-factor repeated measures ANOVA was also performed on the accuracy data. A Mauchley's test of sphericity was not significant ($W(20)=0.09$; $p>0.05$). Overall, there was a significant difference in accuracy across the passive conditions ($F(6,84)=9.0$; $p<0.0005$), with a moderate effect size ($\eta^2=0.39$).

In common with the latency analyses, least significant difference post-hoc pair-wise comparisons (at the 0.05 level of significance) yielded nine significant differences out of a

[1] In this and other analyses performed using SPSS, missing values were assigned relevant group/series means – an SPSS option.

possible 21 comparisons (see Table 3.3[1]) for the analysis of number of stimuli correctly identified. However, while there were similarities, the pattern of differences was not identical for the two sets of analyses. Seven of the nine significant differences were common to both sets of analyses. Four of the common differences related to the shear-alone condition, in which performance was worse than each of the four kinaesthesis-involved conditions and the line+shear condition for latency and accuracy. Two more similarities involved the condition in which a plain surface was moved underneath a taped stationary fingertip (S_m). This minimal shear condition yielded significantly longer latencies and reduced accuracies compared with both the full touch condition and kinaesthesis-alone. Finally, the condition in which a plain surface was moved underneath a taped stationary fingertip resulted in worse performance than the full touch condition for both measures.

The additional two significant differences present in the accuracy analysis related to minimal shear conditions (S_m). More stimuli were identified in the conditions in which a finger was dragged across a plain surface (K+S) and the in which the line was moved underneath a stationary fingertip than the S_m condition. In addition, the comparison between moving the line underneath a taped fingertip (L) and shear-alone (S) approached significance ($p=0.055$).

Table 3.3
Significant LSD Pair-Wise Comparisons Across Haptic Conditions for Number Correct. Starred Cells Indicate Instances of Significant Difference.

	K+S	K	L+S	L	S	S_m
K+L+S				*	*	*
K+S					*	*
K					*	*
L+S					*	*
L						
S						

The presentation of stimuli in Experiment 2 was randomly ordered and each letter was used approximately equally often. Thus, any effects due to individual letters being easier (or quicker) or harder (or longer) to identify should be distributed evenly amongst the haptic conditions. However, for completeness the data were analysed on the basis of the stimuli used – this analysis can be found in Appendix 7.3.

Finally, it would be expected that the letters identified more quickly would also be the letters identified more accurately – a negative correlation. A Pearson correlation coefficient

[1] Note that the layout of the two pair-wise comparisons tables are different. They are organised as a function of best to worst performance, which differed for latency and accuracy measures.

between the variables was found to be more than moderate in strength and significant ($r(9)$= -0.77; $p<0.05$).

3.1.3 Discussion

Kinaesthesis seems to be the "most useful" component of the haptic sense. When it is involved in the exploration of two-dimensional drawings superior performance results, both in terms of latency to a correct response and number of correct responses. This finding is consistent with previous research, such as that reported by Austin and Sleight (1952), Cronin (1977), and Loo et al. (1983), who each found that "full haptics" (in this instance K+L+S) was superior to conditions in which there was no kinaesthesis, only a tangible line was present. The result showing that conditions involving kinaesthesis are no different from each other in terms of number of stimuli correctly identified was also reported by Loo et al. However the data in terms of latency did not conform to this pattern as kinaesthesis+line+shear resulted in a shorter mean latency than kinaesthesis+shear.

Magee and Kennedy (1980) found that moving a fingertip over a plain surface (K+S) resulted in more correct identifications than did moving a raised line drawing underneath a stationary fingertip (L+S). Based on this they emphasized the importance of the kinaesthetic component, and suggested that the provision of a tangible line really only serves to indicate to the explorer that they are making relevant movements. In the current research this difference was found to be non-significant for both accuracy and latency measures. In fact, the current research indicated that two other conditions that did not involve kinaesthesis resulted in latency performance equivalent to K+S: moving a textured surface underneath a stationary fingertip with an intervening layer of sticky tape on the fingertip (S_m), and moving the drawing under a taped stationary fingertip (L); the latter non-significant difference was also present in the accuracy data. The finding that any useable information could arise from such artificial and even "unnatural" conditions let alone performance equivalent to a condition that involves kinaesthesis is surprising in itself.

It could be argued that when an explorer is passive and so not required to decide where to move, the information that arises from a raised line passing underneath the fingertip should be equivalent to that from a textured surface moving underneath the fingertip, an argument supported by the latency data (although this comparison did approach significance) . In the current experiment the plain surface was un-embossed plastic raised line paper, which has more texture than plain writing paper. In his own experiment using an Optacon, Jansson (1998) was surprised to find that presenting such information to a stationary fingertip was useful at all: "The most astonishing result is…that the observers in the S[kin]

mode had such a high performance. This indicates that the information to the skin alone is quite useful." (p. 29). The current results show that the presence of the line, with or without friction arising from movement of the surrounding medium, is in fact better than relying on the movement of the raised line paper on its own. It may be that the line itself provides a point of focus for the explorer, or they do not expect to be able to make sense of the moving medium on its own and this becomes a self-fulfilling prophecy. However, as noted by Jansson, providing such basic information to the skin results in a better than chance performance: overall, almost one-third of the letters presented as moving texture under a stationary fingertip were correctly identified, substantially better than the 1-in-26 chance of guessing any particular letter presented correctly.

It is perhaps worth noting that all of the conditions in the present experiment involved movement. A condition not tested here was that in which something is pressed into the skin and held there, as Gibson (1962) did when applying a cookie cutter shape to participants' palms to compare active and passive touch. It is, however, doubtful that such contact really involves no movement. This proposition is supported by Gibson's own finding that the mean frequency of correct matches was 49% for a cookie cutter pressed into the palm, but when a mechanical lever was used to apply the passive pattern, a particularly contrived circumstance, recognition dropped to just 29%. Other than a possibly more consistent pressure, movement due to "jitter" on behalf of the experimenter is likely to be the main difference between the conditions.

In this Experiment the TDS allowed for a number of the components of haptics in two dimensions to be isolated and compared, with the principal finding that although kinaesthesis was the most important component, its contribution when alone was rivalled by cutaneous contributions. A reconfiguration of the TDS allows for another way of testing some of the haptic components compared in Experiment 2, that of pitting the components against each other.

3.2 *Experiment 3: TDS rotated letters*

Experiment 2 isolated various elements of the haptic experience when exploring a two-dimensional raised line drawing, either in combination or, where possible, on their own. It was assumed that the condition with the "most important" information or simply the most information would yield superior performance. An alternative method of addressing this issue would involve haptic components "competing" against each other. This approach is similar to studies of capture or dominance (see Chapter 5).

The TDS has two finger holders and two associated stimulus trays (see Chapter 2). When using the lower finger/stimulus set-up the stimulus is held stationary and the finger moved, either actively, under the explorer's control, or passively, guided by the pre-recorded exploratory movements of an active explorer. However, while using the upper finger/ stimulus configuration, the finger is held stationary and the stimulus is moved beneath it. The movement path followed by the stimulus tray is that pre-recorded during an active explorer's use of the lower finger holder[1].

The lower finger holder and top stimulus holder are physically located on the same carriage and so move together as a single unit over the 12 x 12 cm two-dimensional field (see Figure 3-4). Accordingly, while the lower finger holder is in use by either an active or passive explorer, the upper stimulus holder traces out the same pattern. However, relative to the upper finger holder the lower pattern is actually traced out "reversed", or more correctly, rotated through 180 degrees. For example, Figure 3-4 shows a "6" underneath the lower, moving finger. While the lower finger traces around this 6 the upper stimulus holder traces a "9" underneath the stationary finger. While the stimuli are identical (but rotated), both fingers feel the raised line at the same position in the stimulus.

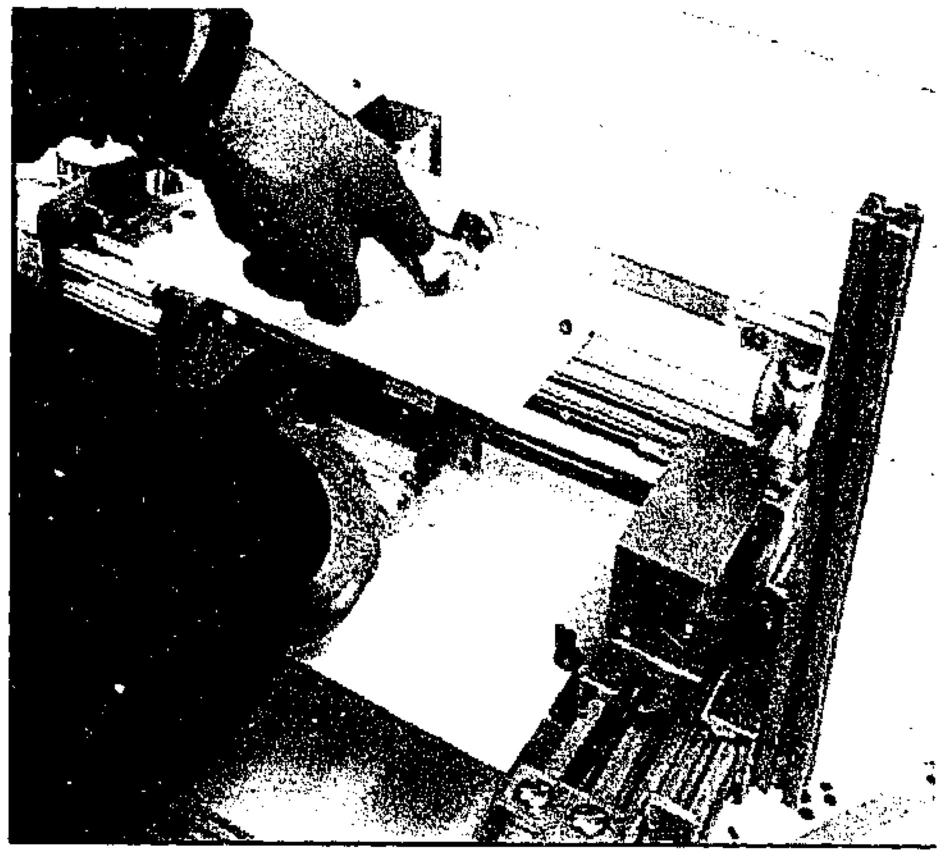

Figure 3-4. Using the TDS in two-tray mode. Left finger stationary and passively receiving raised line on upper tray, which is moving beneath it. Right finger actively or passively moves in lower finger holder, causing stimulus to move under left finger.

[1] the original intended purpose of this "upper tray" was to allow for passive haptics where the active participant has the use of kinaesthesis but the passive participant does not – see Experiment 2.

For "ordinary" use, the TDS has separate buttons for using the upper and lower stimulus holder/finger holder (see Figure 2-6), and the unit is programmed in such a way that the rotation is taken into account and the pattern is swept out "the right way up". However, if a participant places one index finger into the upper finger holder, and the other index finger into the lower holder, they can can actively explore a shape with the right finger and passively feel it with their left, albeit in a rotated form. If the stimuli mounted in both stimulus holders are identical (i.e., one is an exact replica of the other but rotated), then the participant will feel the raised line of any part of the picture at both fingers simultaneously. For example, in Figure 3-4 the lower finger is near the intersection of the 6. Simultaneously, the upper finger is near the intersection of the 9 – identical positions. In addition, if there are a number of stimuli where the two forms (i.e. both rotated versions) have independent meanings. In the instance shown in Figure 3-4 the lower finger "sees" a 6, while the upper finger "sees" a 9.

There are a number of simple stimuli that can be used where the two versions, one a 180 degree rotation of the other, can be recognised and named meaningfully. Examples include the 6 and 9 already mentioned, the lower case letters p and d, and the capital letters W and M (so long as the W is drawn with vertical strokes at each end rather than diagonal strokes, or the M is drawn with sloping outer lines). Experiment 3 used such stimuli.

Experiment 2 cast doubt on the proposition that kinaesthesis is the most valuable haptic element, where the performance in a number of non-kinaesthesis-involved conditions was statistically equivalent to that found in some kinaesthesis-involved conditions. The current experiment allows for a kinaesthesis-involved condition to be pitted directly against a non-kinaesthesis involved condition for identifying raised line drawings.

Other researchers have used experimental paradigms that require participants to mentally rotate stimuli explored haptically (e.g., Hunt, Janssen, Dagostino & Gruber, 1989; Dellantonio & Spagnolo, 1990). However, no research was found in which conflicting stimuli were presented to each hand simultaneously, or where each hand received stimuli in different haptic "modes" simultaneously.

3.2.1 Method

<u>*Participants*</u>

Twenty blindfolded adults ranging in age from 18 to 56 years (M=26 SD=11) participated. Six subjects were left handed on the basis of self-reported preferred writing hand.. None had had any long term or extensive experience with Braille, raised line drawings or similar devices. All participants were volunteers recruited from throughout the Gippsland campus of Monash University via posters and word of mouth.

Materials

Raised line drawings were prepared as described earlier in rotated-pair sets. Each raised line stimulus was approximately 7.5 cm along its longest axis. The stimulus pairs were 6/9, p/d, q/b and M/W, where each of the two stimuli of each set were identical but rotated (the "W" had vertical start and end strokes to make it identical to a rotated "M").

Procedure

Prior to commencement of testing, participants were shown the TDS and how it worked in both upper- (stationary finger holder) and lower (moving finger holder)-tray modes. At the conclusion of the instructions the participant was invited to place an index finger in each finger holder. The participant was not blindfolded at this stage nor was any bias introduced through the instructions or demonstrations to indicate to the participant which finger (left or right) they should use in each finger holder. All but two participants chose to use their "dominant" finger in the moving finger holder. When asked afterwards, no participant could offer a reason for why they used a particular finger in a particular finger holder.

Participants were simply told that they would feel a letter or number at the top and bottom trays at the same time, but one finger would be moving and the other stationary with the stimulus moving underneath it. They were then told that their task was to identify the letter or number. No mention was made of the rotation that existed between the trays, nor were participants directed to focus on either hand in particular. Each participant used each pair of stimuli, with one of the pair in the top tray and the other in the bottom tray. Thus, each participant underwent four trials. The order of stimuli and which of each pair was in which particular tray was randomly assigned between participants. Participants were blindfolded during the experiment and feedback was not provided until the end of the participant's trials.

In order to identify which tray the participant was focussing on most, they had to correctly name one of the two possible forms each stimulus set could take. Accordingly, neither latency nor number correct were recorded – each participant was provided with sufficient time to correctly identify one of the forms of each stimulus pair.

Four separate conditions were administered on a between-subjects basis:

1. Participant was active (i.e., they had control over their own movements) and could feel a line under both fingers simultaneously;
2. Participant was active and could feel a line under the stationary finger but the moving finger could feel only a lightly textured plastic surface. Feedback from the stationary finger was necessary to guide the action of the finger in the lower position.
3. Participant was passive (i.e., they did not have control over their own movements) and could feel a line under both fingers simultaneously; and
4. Participant was passive and could feel a line under the stationary finger but the moving finger could feel only a lightly textured plastic surface

In the passive conditions the movement pattern had been pre-recorded by the experimenter. Each participant had an equal chance of being assigned to any particular group.

3.2.2 *Results & Discussion*

Table 3.4 lists the between-subjects conditions tested. In half of the conditions the participant actively explored the stimuli with a moving finger, simultaneously guiding a rotated stimulus under a stationary finger of their other hand. In the other half of their conditions their movements were directed by the TDS from pre-recorded patterns. The pre-recorded movement patterns would not differ substantially from those made by the active participants. In half of the conditions a raised line drawing was present under the moving finger, while in the other half it was absent – there was always a raised line drawing under the stationary finger.

As all stimuli were correctly identified (of necessity to determine whether the kinaesthetic or cutaneous finger was dominant), accuracy was not recorded. Accordingly, the results are essentially qualitative. Whether the participant was active or passive seemed to make no real difference to the results. Responses indicated that kinaesthesis was the primary source of information only when a tangible line was provided with the kinaesthesis (see Table 3.4). When the inscribed raised line paper was replaced with plain raised line paper underneath the moving finger responses were dictated by what was felt at the stationary finger.

In a bid to determine whether participants were aware of the discrepancy between what the moving and stationary fingers were "feeling", a the completion of their trials they were asked what the experience had been like. All active explorers who had a raised line under both the moving and stationary fingers noticed the discrepancy between the stimuli. While they could not always articulate what the discrepancy was (i.e., one drawing was rotated 180 degrees relative to the other one), they knew it was there. Interestingly, none of these participants mentioned it during the trials or made any indication of confusion, such as asking which stimulus should be named (e.g., "should I name the 6 or the 9?"). The original instructions simply called on participants to name the letter or number. Thus the instructions always implied a single character was being explored, but in two different ways.

Table 3.4
Inferred source of response when stimuli were displayed to stationary or moving (active or passive) fingertips

Condition	Lower finger mode	Presence of raised line: Lower (moving) finger	Presence of raised line: Upper (stationary) finger	"Source" of responses	% to notice difference between fingers
1	Active	Present	Present	100% moving finger	100%
2	Active	Absent	Present	100% stationary finger	0%
3	Passive	Present	Present	100% moving finger	40%
4	Passive	Absent	Present	90% stationary finger	20%

When no tangible line was present underneath the moving fingertip all participants essentially ignored the kinaesthetic information, as evidence by their nomination of the figure underneath the stationary finger. When the moving finger was active none of the participants noticed the discrepancy between the upper and lower patterns. Indeed many still did not fully understand the discrepancy even when it was demonstrated visually at the completion of trials. When the moving finger was driven by the TDS in a passive-guided mode only 20% or one out of the five participants in this condition noticed the difference; that "there was something odd going on". In the other passive condition, with the tangible line present underneath the moving fingertip, 40%, or two out of five participants, noticed the discrepancy between the stimuli at the moving and stationary fingers.

Another avenue of research in which haptic stimuli are presented in rotated formats relates to investigations of hemispheric dominance. For example, O'Boyle and Murray (1988) traced words into participant's palms either right way up or upside down in either the left or right hands in order to determine which hemisphere processed such verbal information. In such experiments the participants were aware of the rotation and the task was to "unrotate" the stimulus in order to identify it. In the current experiment the participant was exposed to both orientations simultaneously and their response indicated which form they attended to or preferred. The current research does not seem to bear on questions of hemispheric laterality, although a manipulation of which hand was used in the lower tray and

the use of stimuli that are "verbal" (as in the current research) as well as stimuli that are not verbal may make the TDS a useful tool for investigating such questions.

A further area of study that makes use of rotated letters drawn on the skin surface relates to frames of reference research, where the aim is to determine the vantage point from which the subject interprets the stimulus (e.g., Cohen & Lewin, 1986, Parsons & Shomojo, 1987). For example, the number 6 drawn in the palm could be named as a 6 or 9 depending on whether the subject considers the stimulus from their own or the experimenter's point of view. The frame of reference can often be manipulated by changing the orientation of the hand, such as having the subject hold their hand above their head palm-up versus palm-up in front of their chest. Differing frames of reference should not be relevant to the current experiment as both hands were involved directly in front of the subject, both were below eye, head and chest level, and they were only separated by approximately 10 centimetres in height. Accordingly, the frame of reference should not be different between the hands.

While they did not use ambiguous stimuli, Bolanowski, Verrilo and McGlone (1999) did have subjects provide their own passive stimulation so that they were both active and passive explorers. In their method, subjects rolled steel balls between a fingertip and other parts of their body. The current method can also be thought of in these terms. The lower finger was actively exploring the stimulus and simultaneously supplying the upper finger with a stimulus in a passive touch mode. Bolanowski et al.'s results are not directly comparable because they used different areas of the body for the two touch modes. The finger was always the active element, but a variety of locations with glaborous or hairy skin were used for the passive mode. In the current experiment fingertips were used for both modes. As they did not use ambiguous stimuli, Bolanowski et al. could not objectively determine whether the active or passive component of the experience was being used to make judgements of the ball sizes.

3.3 General discussion

Experiment 2 used the TDS to isolate and test a number of haptic components: kinaesthesis, which involved the movement of the explorer's finger, hand and arm; line, in which a raised line was felt; and shear, which involved the sensation that arises at the fingertip as it is dragged over a textured surface or the textured surface moved underneath the stationary fingertip. In all, seven conditions of various combinations of these components were tested. No previous research was found in which there was a deliberate partitioning of the haptic sense into the current number of constituents.

Generally, conditions that involved kinaesthesis resulted in superior performance in terms of accuracy and time taken to identify raised line letters. This finding is largely consistent with those of Austin and Sleight (1952), Cronin (1977), Loo et al. (1983), Magee and Kennedy (1980), and Jansson (1998). However, this finding was not uniform. For example, a condition in which a fingertip was moved over a textured surface to trace out capital letters yielded performance equivalent to moving a surface with the stimulus underneath a stationary finger.

With kinaesthesis removed, the presence of a tangible line was next most important. The current results demonstrated superior performance for combinations involving the tangible line compared with the line alone, consistent with Cronin (1977) and Craig (1980), but unlike previous research the present finding was not statistically significant.

Conditions with supposedly minimal information, such as moving textured raised line paper underneath a taped fingertip, did not produce particularly high levels of performance. However, it is worth noting that these conditions did result in performance at substantially higher than chance levels. It is, perhaps, surprising that any useful information can be discerned when the fingertip is kept stationary and a plain sheet of raised line paper moved underneath it, even with sticky tape (Sellotape). Gibson (1962) too noted the "ability" of the haptic sense to interpret information arising from shear. Gibson's subjects had some success in estimating the speed and amount of displacement of a yardstick laterally moved underneath a stationary finger

The conditions involving kinaesthesis, included proprioception. Without measures such as the use of anaesthetic it may not be possible to separate the relative contributions of kinaesthesis and proprioception – movement-related information and joint angle information respectively. Some indication may be possible by splinting the finger, wrist, elbow and shoulder joints, similar to Loo et al.'s (1983) method. However, stimuli greater than a centimetre, as used here, require movement of the fingertip towards and away from the explorer. Unless the participant is seated on or stands on some sort of moveable platform that rolls in concert with the movements of the TDS, some change in joint angle(s) is required to fully explore the stimuli or else the subject would be pulled from their feet (or they would provide too much inertia for the device to manipulate their movements); even if it is just flexion of the ankle and toe joints.

In a related study, Experiment 3 pitted two conditions against one another. Regardless of whether the full-kinaesthesis condition was undertaken actively or passively (i.e., the explorer had full control over where and how to move versus a lack of such control), this

condition dominated or captured the non-kinaesthesis condition. This result is consistent with Experiment 2, which found a significant difference between these conditions for accuracy and latency, although all of the Experiment 2 conditions were passive. However, the non-kinaesthesis condition dominated the "lineless" kinaesthesis condition again regardless of whether the kinaesthesis-involved condition was active or passive. In Experiment 2 no significant difference was found between these conditions. It would seem that with a contrived inconsistency between the conditions that was not communicated to the participants, the presence of the tangible line is critical – a conclusion reminiscent of Magee and Kennedy's (1980) claim that the line serves to guide the principal haptic tool of kinaesthesis. Alternatively, it could be argued that kinaesthesis needs directly associated cutaneous information (as afforded when a line was present on the lower tray) if it is to capture the "cutaneous alone" display at the site of the upper tray. Or, it seems that only when cutaneous information accompanies kinaesthetic information on the same hand can kinaesthesis capture touch alone on the other hand.

Rao and Gordon (2001) guided subjects in a reference movement and asked them to then replicate this movement. They found that touching the subject's finger on a surface at the end of the reference movement produced increased replication accuracy compared to conducting the reference movement with kinaesthesis only. Relevant to the current study, they did not report an additional condition in which the subject's finger could have been dragged along either a plain surface or a raised line to the end of the reference movement. As they involved additional sources of information, these conditions could have resulted in increasing levels of replication accuracy. In Schellingerhout, Smitsman and Van Galen's (1998) study subjects either moved a finger along a textured surface during the reference movement or a textured surface was moved underneath their stationary fingertip. They used three different textures, one of which was smooth. Unfortunately they did not test a condition in which there was no texture – or kinaesthesis only. The current results indicate that even the shear forces of a smooth surface provide useful information to explorers. They did determine that the kinaesthesis present in the moving finger condition produced superior performance compared to the no-kinaesthetic condition, in which the textured surface was moved underneath the stationary fingertip. Schellingerhout, et al. called for "further research into sources of information in haptic space perception" (p. 112) – the TDS could be used to address this question, using various combinations of haptic components, as in the current research. The dimension of active versus passive movement could be incorporated as an additional dimension.

No previous research was found to which the results of Experiment 3 could be directly compared, and it is unclear whether the results have significance beyond that suggested here.

4. ACTIVE VS PASSIVE TOUCH IN 3-D

Symmons (2000) compared active and passive touch in two dimensions for a range of types of stimuli using a device called the TDS (see Chapter 2). Blindfolded active explorers inserted their finger into the device and freely explored raised line drawings of up to 12 cm by 12 cm in size. The active explorers could move anywhere in the stimulus field, retracing or pausing as they wished. This essentially unfettered movement was recorded by the TDS. Also blindfolded, passive participants then inserted their finger into the TDS and were guided along the same movement path taken by their active counterparts, matched for speed and position. Source of control was the central defining factor in the difference between active and passive exploration. The results may be of theoretical value and possibly of use in applications such as determining the best way to teach the blind about raised line drawings. However, the haptic sense is more routinely used for exploration of three dimensional objects rather than two-dimensional depictions.

The question of whether active or passive haptic modes are superior for three-dimensional exploration is of more practical value and has obvious implications for fields such as virtual reality, telesurgery, and skills training. However, there would seem to be no device currently in existence capable of providing the three dimensional equivalent of the TDS. Symmons and Richardson (2000) found that there is ecological validity in exploring two dimensional drawings with just one finger, but for three dimensional stimuli the whole hand would be the means of exploration. There are devices that can record free active movement, but they are not capable of guiding a passive explorer. Generally such devices can open a passive subject's hand (by adducting fingers) or stopping the hand from closing, but their construction will not close a passive hand or stop it from opening.

The Phantom force-feedback device (see Chapter 2 for a brief description) can be used to provide a degree of active and passive exploration in three dimensions, although it is analogous to using a probe or cane. Accordingly, it provides only one point of contact with the surface to be explored and does not allow contact between the finger(s) and the surface of an object. The Phantom is also restricted to exploration of virtual surfaces, rather than real objects. However, it does provide a means of testing active versus passive haptics in three dimensions. While this may be of limited practical use, it could provide a direction for the likely outcome should a device become available to properly test full active and passive exploration in three dimensions. It may be useful to briefly consider the findings of active versus passive touch in two dimensions before examining the more limited published research regarding three-dimensional exploration.

In a review of the literature, Symmons, et al. (2004) examined 76 separate comparisons of active and passive touch from 47 years of research. Of these comparisons, 39 indicated that active touch is superior, 15 suggested that passive is better, and 19 showed no significant difference between the two conditions. However, methodological issues (including confounding variables) made many of these active-passive tests questionable or the results not directly comparable between studies. The review suggested that 18 of the original 33 studies involved adequate control and the definitions of active and passive touch were consistent with the source of control variable mentioned earlier. These 18 studies reported 36 active-passive comparisons. Eleven of these comparisons (31%) indicated that active touch was superior, nine (25%) pointed to passive superiority, and sixteen (44%) concluded that there was no difference between the conditions. However, while some of the devices and methods used have provided a close match between the active and passive tasks (i.e., they have kept other factors constant), potential confounds can still be present. For example, Magee and Kennedy (1980) allowed the active subject free exploration of a raised line drawing but an experimenter physically held the passive subject's finger in order to guide it. Richardson, et al. (1981) mechanically yoked the active and passive subjects in real time, however the active subject may have been disadvantaged by having to overcome the inertia of moving the passive subject's arm.

In a carefully controlled examination of active versus passive exploration in two dimensions, Symmons (2000) found that passive-guided exploration was superior to active for individual raised line capital letters and pictures of simple objects such as the outlines of a Christmas tree, a fork and a giraffe. In further research by Symmons, it was found that active exploration was better for identifying a series of three raised line capital letters. Finally, when abstract shapes were used as stimuli, no difference was evident between the exploration modes.

No research has been found in which there is a comparison of active and passive touch for three dimensional exploration, in all likelihood due to the lack of a suitable device. Research has been conducted in which three-dimensional scenes have been converted into two-dimensional depictions for display with a planar (i.e., two-dimensional) stimulator, such as the Tactile Vision Substitution System (TVSS) (e.g., White, 1970), but not where the stimulation is three-dimensional. In a review of the haptics literature, Loomis and Lederman (1986) noted that they had not come across any such research either, but expected that active touch would be superior due to the wealth of information available to the exploring hand.

In the three experiments that follow there was a comparison of active and passive haptics using the Phantom. One of the experiments involved a set of stimuli similar to those used by Symmons (2000) with the TDS. This allowed a direct comparison between the TDS results and those obtained with the Phantom. As the stimuli were two-dimensional, this experiment was essentially a test of how useful the Phantom is for active versus passive haptics research. Another of the experiments reported here used simple three-dimensional shapes for the active-passive comparison. Finally, two Phantoms were yoked together to provide a real-time comparison of active and passive haptics rather than recording the pattern created actively to use for later passive-guidance. Again, simple three-dimensional shapes were used.

4.1 Experiment 4: Active vs. passive exploration of two-dimensional pictures using the Phantom

Symmons (2000) compared active and passive touch in two dimensions using outline drawings of simple objects and shapes based on those used by Magee and Kennedy (1980). The stimuli were around 7-10 cm along their longest axis and included drawings of objects such as a fork, an umbrella, and a wine glass. Symmons, and Magee and Kennedy, found that passive-guided explorers were quicker and more accurate than active explorers in identifying such pictures.

As a test of the Phantom's usefulness in exploring the active-passive issue, three of the stimuli used by Symmons (2000) were reproduced for use with the Phantom. As these stimuli were not three-dimensional, the principal difference between this study and the TDS-derived result of Symmons (2000) was the device used – the Phantom versus the TDS, but the experiment was also a test of how robust the finding of passive superiority might be.

4.1.1 Method

<u>Participants</u>

Twenty-four blindfolded adults ranging in age from 19 to 60 years (*M*=29 years, *SD*=12 years) participated. All but two of the participants were right-handed (on the basis of preferred writing hand), and nine of them were male. None had had any long term or extensive experience with Braille, raised line drawings, the Phantom, or similar devices. All participants were volunteers recruited at the Gippsland campus of Monash University via posters and word of mouth.

Materials

Three stimuli were prepared using a computer drawing program and converted into (virtual) tangible stimuli using the Phantom Explorer software (see Chapter 2) so that they could be felt as grooves with the Phantom's stylus. The stimuli were outline drawings of a Christmas tree, an umbrella, and the common stylistic representation of a heart (see Figure 4.1). A picture of a square was used as a practice stimulus.

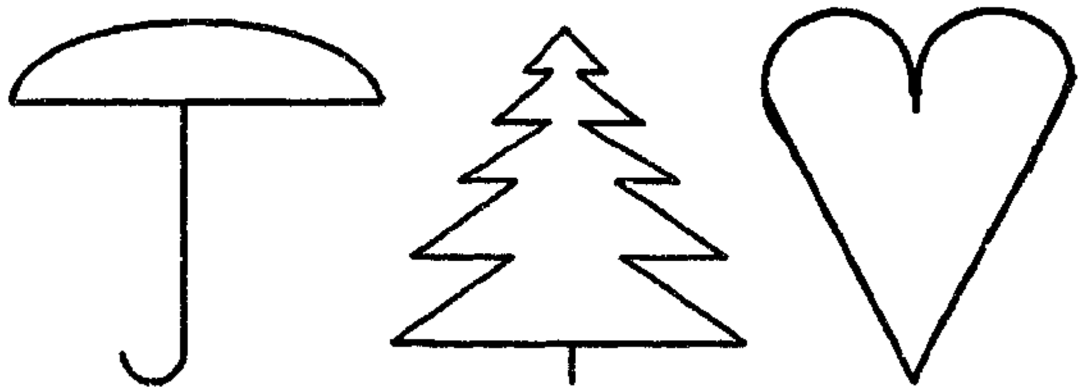

Figure 4-1. Stimuli used for Experiment 4 in which the shapes were depicted as grooves that could be followed with the Phantom's probe.

Procedure

Participants were randomly assigned to active or passive conditions. Each participant was shown the Phantom and used it to explore the practice shape of a square in their assigned condition (i.e., actively or passively). During the practice period subjects were allowed to watch their exploration and the practice shape on a computer monitor. During the trials the participants were blindfolded. Each active participant explored the three stimuli in counterbalanced order, while passive subjects received the stimuli in the same order as their particular active counterpart. All participants were asked to identify the stimulus as quickly as possible. In order to ensure a reasonable amount of recorded movement pattern to guide the passive participant, each active explorer was asked to continue to explore each stimulus, whether or not they had identified the stimulus, for at least sixty seconds. No feedback was provided until the end of each participant's three trials.

After six pairs of subjects had participated it was evident that overall performance was poor for both active and passive explorers. In a bid to avoid a floor effect, the experimenter began providing hints to both active and passive explorers after 30 seconds of fruitless exploration. For the Christmas tree the hint was "it's an outline drawing of a living thing", for the umbrella: "the outline drawing of a reasonably common household item", the heart: "it's a common, recognisable shape rather than an object – like the square is a common shape". As the comparison was between active and passive touch rather than between subjects per se, and the same clues were given to both groups at the same point during their

exploration (i.e., after 30 s), the data prior to and after the introduction of the hints were analysed as one set.

4.1.2 Results & Discussion

Based on earlier research, it was expected that the passive condition would result in a superior performance compared to active exploration. Passive subjects were quicker than active explorers in correctly identifying the stimuli (means of 52 and 61 seconds, respectively), a statistically significant difference ($t(70)=1.46$; $p<0.05$, one-tailed).

Overall, 44% of the stimuli were correctly identified. Passive explorers correctly identified 47% of their stimuli (17 out of 36) while active participants scored 39% accuracy (14 out of the 36 stimuli presented). A difference in independent proportions test indicated that this difference in accuracy was not significant[1] ($z=0.69$; $p>0.05$).

The current finding of a passive superiority for exploration of two-dimensional stimuli was consistent with previously obtained data using the TDS (Symmons, 2000). The earlier analysis was based on data collected using letters as well as pictures as stimuli. Those data can be reanalysed without the results that arose from exploring the letters to make a more direct comparison with the current finding. Figure 4.2 shows the latencies to correct identification and Figure 4.3 shows the percentage of stimuli correctly identified across both experiments (a table of results can be found in Appendix 7.4). The Phantom latencies are actually slightly lower for both the active and passive conditions. However, there are substantial differences in the number of stimuli correctly identified, with relatively more identified in both of the TDS conditions compared to the corresponding Phantom conditions.

The latencies and number correct recorded for picture identification using the TDS and the Phantom were combined in two, two-factor between-groups ANOVAs. The only significant finding in the two analyses was that passive exploration ($M=54$ s) resulted in a significantly shorter latency than that found for active exploration ($M=63$ s), ($F(1,140)=4.9$; $p<0.05$), although the trend to passive superiority extended to the number of stimuli correctly identified. Using the Phantom produced a shorter overall latency than using the TDS ($M=57$ s and $M=61$ s respectively), but the difference was not statistically significant ($F(1,140)=1.2$; $p>0.05$). Overall, these results indicate that the Phantom produces results comparable with those of the TDS for this task and seems appropriate for such measurements.

[1] The lack of significance in terms of number of stimuli correctly identified here and elsewhere in this chapter could be due to the fact that the maximum score achievable for each participant is three, resulting in a restricted range of scores.

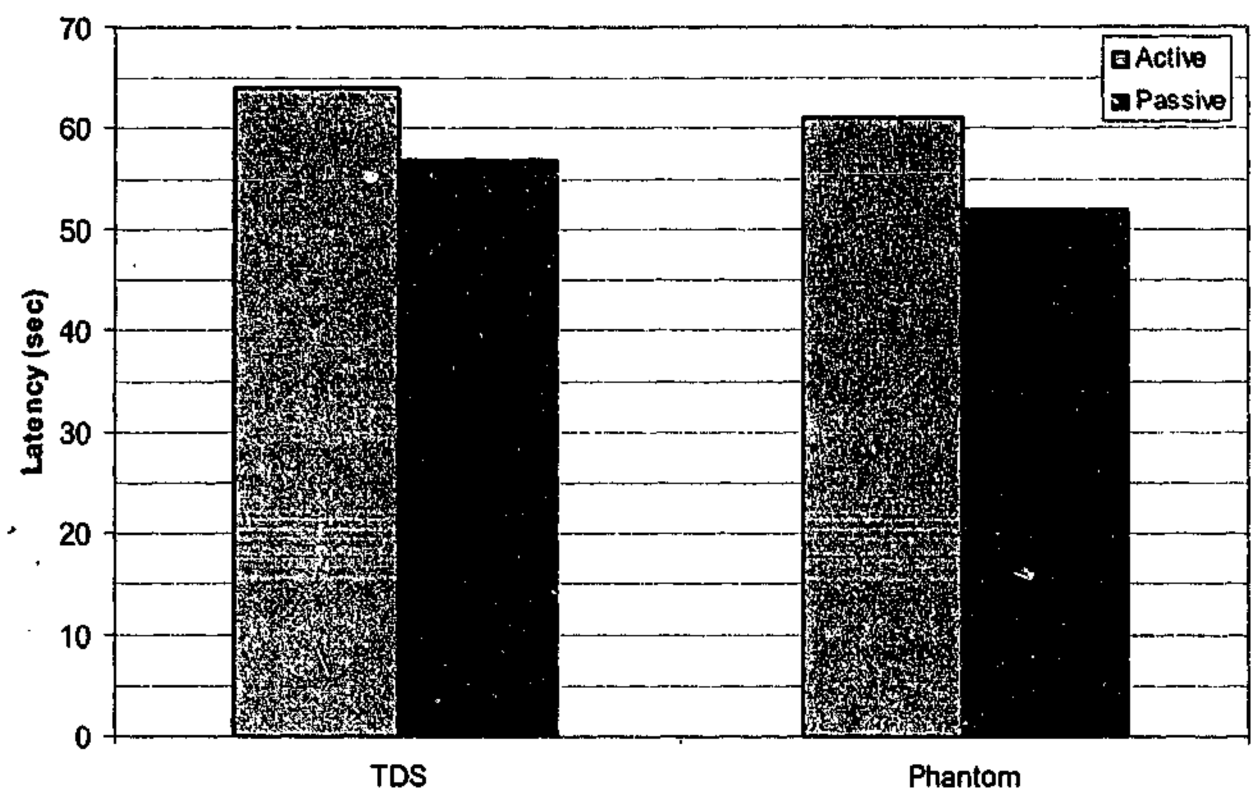

Figure 4-2. Latencies for TDS and Phantom in active and passive conditions.

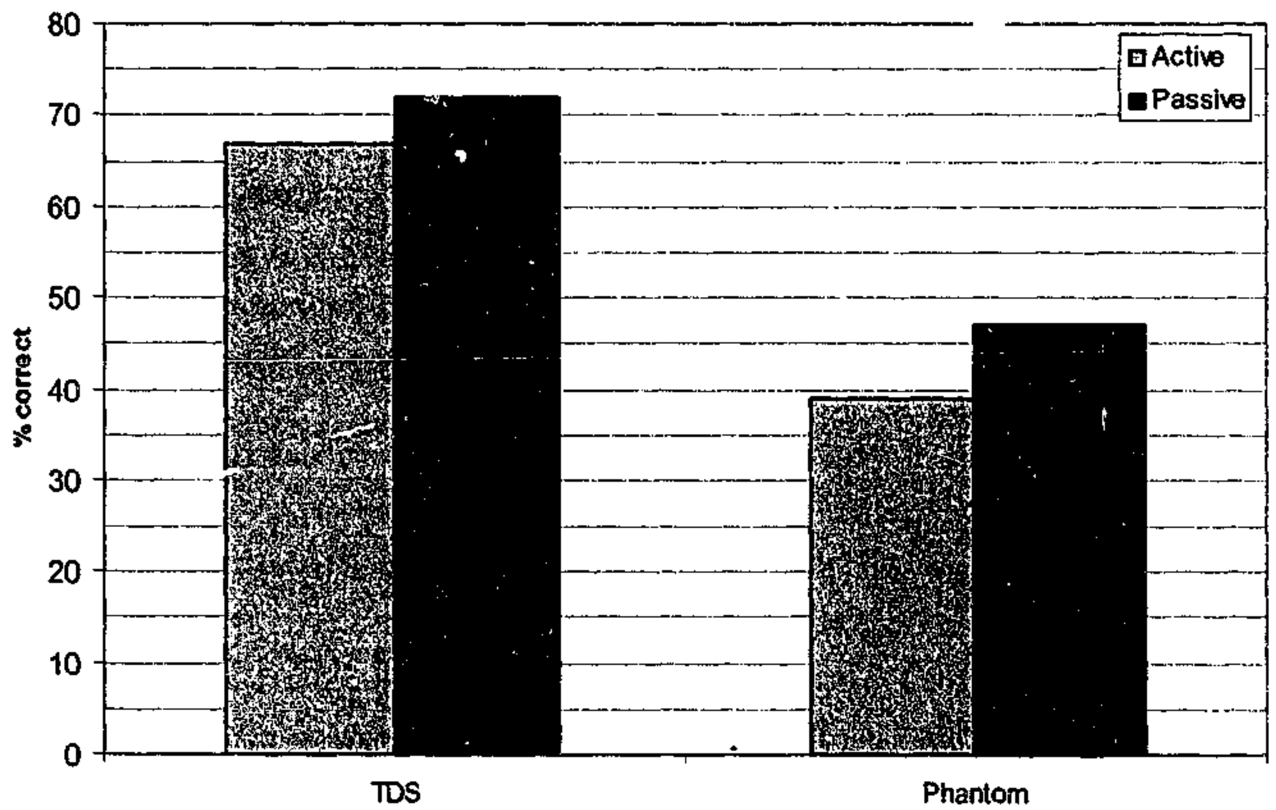

Figure 4-3. Percentage of stimuli correctly identified for TDS and Phantom in active and passive conditions.

4.2 Experiment 5: Active vs. passive exploration of three-dimensional pictures using the Phantom

In Experiment 4 a Phantom was used to compare active and passive exploration of two-dimensional pictures. The results were consistent with data collected previously using the TDS. A logical next step was to use the Phantom to examine active and passive exploration for simple three dimensional shapes – the purpose of Experiment 5.

4.2.1 Method

Participants

Twenty blindfolded adults ranging in age from 18 to 49 years (*M*=23 years, *SD*=8 years) participated. All participants were right-handed (on the basis of preferred writing hand), and five of them were male. None had had any long term or extensive experience with Braille, raised line drawings, the Phantom, or similar devices. All participants were volunteers recruited at the Gippsland campus of Monash University via posters and word of mouth.

Materials

Four virtual, three-dimensional stimuli were prepared using the Phantom Explorer program (see Chapter 2) – a cube, a cone, a cylinder, and a sphere.

Procedure

Participants were randomly assigned to active or passive conditions and each participant was shown the Phantom and practised using and holding it. Those assigned to the passive condition received a practice at being guided by the Phantom, while those in the active condition practised using it actively. The practice was undertaken with vision (i.e., participants could see a visual representation of the shape on a computer monitor), while the trials were undertaken blindfolded.

Each active participant explored three stimuli in counterbalanced order, while passive subjects received the stimuli in the same order as their active counterpart. In order to ensure a reasonable amount of recorded movement pattern to guide the passive participant, each active explorer was asked to continue to explore each stimulus for at least 60 seconds, as explained in the previous experiment. Jansson (1998) also allowed 1 minute for blindfolded Phantom users to identify the same shapes used in this experiment. No feedback was provided until the end of each participant's three trials.

Participants were told that the three-dimensional virtual shapes that they were to explore were reasonably common geometric shapes, and that they should try to identify them as quickly and accurately as possible. They were also told that they need not necessarily know the name of the shape; they could describe it and the experimenter would determine the "correctness" of their answer (e.g., answers such as "ball" would be acceptable in place of "sphere", "soft drink can" rather than "cylinder", etc. – but subjects were not provided with these examples). Participants were allowed just over one minute to identify the shape or the trial was terminated (and a missing value was allocated, which was substituted with the group mean during analysis using SPSS).

4.2.2 Results & Discussion

Active exploration (*M*=22 s, *SD*=16 s) was superior in terms of time taken to correctly identify simple geometric shapes compared with passive-guided exploration (*M*=32 s, *SD*=13 s), a statistically significant difference ($t(58)=2.7$; $p<0.01$). Active participants also identified more of their stimuli (26 out of 30 stimuli, or 87% accuracy) than did the passive explorers (22 out of 30, or 73%). However, a difference between independent proportions test indicated that the difference in accuracy was not statistically significant ($z=1.36$; $p>0.05$).

The accuracy rates found here for active exploration compare quite favourably to those reported by Jansson (1998). Jansson did not report an overall accuracy rate, but inspection of a published graph showing percentage of correct responses for individual 5 cm shapes indicates that they were correctly identified 90-100% of the time, compared with 87% here. Exploration time for Jansson's 5 cm shapes ranged from around 12 to 18 seconds, slightly quicker than the mean of 22 seconds found here. Jansson's subjects had an advantage, however, in that they were given descriptions of the set of possible shapes they would be exploring before beginning. As they were tested with each shape three times (at different sizes), there may have also been a practice effect. Indeed, Jansson noted that performance in the second and third trials for each shape was superior to the first trial. Any practice effects that may have occurred in the current experiment should be equivalent between the active and passive modes of exploration.

4.3 Experiment 6: Active vs. passive exploration of three-dimensional shapes using yoked Phantoms

Each of the active-passive comparisons conducted in two dimensions by Symmons (2000) and in three dimensions reported here involved a temporal separation of the conditions. While the active participant explored a stimulus their movements were recorded.

These movements were then used at some later time to guide a passive participant. This has the advantage of being able to test active and passive participants separately, as the passive pattern can be stored indefinitely. A single active pattern can also be used to guide many different passive participants, as was the case in Experiments 1 and 2. Testing the active and passive participants separately is also the most common method used in previous research.

In all of the active-passive research conducted by the author, participants were first familiarised with the apparatus (whether it was the TDS or the Phantom). During a description of their tasks, the active participant was told that their movements would be recorded to later guide another participant, and the passive participant was told that they would be guided by the recording of the movements of a previous active participant. However, passive participants were physically moved by a device sophisticated in appearance and attached to a computer. Passive subjects could either have high confidence in the guiding movements because they are generated by a computer, or lower confidence for the same reason (even if the actual level of confidence is not at a conscious level).

The purpose of the current experiment was to test whether the physical presence of the exploratory counterpart made an appreciable difference to either the active or passive explorer's performance. Using specially-written software (the Phantom Yoking program – see Chapter 2), two Phantoms were yoked. As the active participants explored simple three-dimensional shapes, the passive participant was moved in concert, in real time. It was also possible to arrange for each subject to undergo both active and passive trials.

4.3.1 Method

Participants

Eighteen adults ranging in age from 18 to 64 years (*M*=23 years, *SD*=10.5 years) participated, eight females and ten males. None had had any long term or extensive experience with Braille, raised line drawings, the Phantom, or similar devices. All participants were volunteers recruited from throughout the Gippsland campus of Monash University via posters and word of mouth.

Materials

The stimuli used here were the same as those used in Experiment 5: virtual three-dimensional shapes of a cube, a cone, a cylinder and a sphere. An ice-cream cone shape (a cone with the point down and a hemisphere on top) was used as a practice shape. All stimuli were "felt" using the Phantom.

Procedure

The yoked Phantoms program (see Chapter 2) was used to link two Phantoms so that the movements of the "master" Phantom were reproduced by the "slave" phantom in real time. The Phantoms were separated by a large divider so that subjects could not see one another. Immediately adjacent to each Phantom was a smaller divider so that when an operator was seated before the device and held the Phantom's stylus they could not see their Phantom or their own arm operating it, removing the need for blindfolds.

Participants were tested in pairs. Upon arrival at the laboratory, participants were briefed about the Phantom and the experiment to take place. Each participant then used a Phantom to explore the ice-cream cone practice shape. During this exploration the participants could see a visual representation on a computer monitor of what they were feeling; during testing neither participant could see the monitor. Sufficient time was devoted to this practice to ensure that both participants were comfortable and capable of operating the Phantom.

The pair of participants were then allocated to the master and slave Phantoms with the knowledge that movement of the master Phantom would guide movement of the slave Phantom. The master or active participant was told that if they moved the stylus directly upwards from the starting position they would come in contact with the simple three-dimensional geometric shape that they were required to identify. The stylus of each Phantom was placed in the same starting position (with the most distal arm of the stylus – with respect to the Phantom – hanging down) and the yoking program started.

Each participant had a sheet of paper placed in front of them that depicted all four of the possible shapes – cube, cylinder, sphere and cone. The task of both participants was to point, using the hand not holding the Phantom, to the shape they thought they were feeling as soon as they were reasonably certain of what the shape was. Subjects were asked not to verbalise their answer or say anything else during the trial as their counterpart was in the same room. Different experimenters watched each participant from behind, recording the latency for a correct response. Both participants were asked to continue with the task until told to stop, regardless of how certain they were in their identification of the shape.

The experimenters communicated non-verbally behind the participants, and as soon as both participants had successfully identified the stimulus the trial was ended. Participants then swapped roles. Each participant therefore undertook both roles, active/master and passive/slave, and explored two shapes, one actively and the other passively. As the order of

shapes was counterbalanced, no subject received the same shape twice, although they were not aware of this.

Between them, each pair of participants decided who would be active first. Each shape was presented within each condition equally often and was presented first or second equally often.

4.3.2 Results

Each participant completed two trials, one as an active Phantom user exploring a three dimensional shape and guiding a passive counterpart, and the other as a passive Phantom user being guided by the movements of an active explorer. Accordingly, each participant produced two latencies – one for active exploration and the other for passive exploration. These data were analysed in two ways using repeated measures (or matched subjects) t-tests[1]. In one analysis each active participant's latency was compared with their yoked partner's passive latency. In the other method each participant's active latency was compared with their own passive latency.

In the comparison across pairs of yoked participants, active explorers (M=46 s) took significantly less time to identify the stimulus than did their passive counterparts (M=70 s; $t(16)=2.4$; $p<0.05$). The latencies for these two groups were also moderately correlated ($r(17)=0.59$; $p<0.05$).

Each participant's active latency was also compared with their own passive latency. Again, active exploration (M=41 s) was significantly faster than passive exploration (M=63; $t(15)=1.9$; $p<0.05$, one-tailed[1]). The data from one trial (from an active-passive pair) were deleted before performing this analysis (hence the difference in degrees of freedom between the two sets of analyses). In the first of their two trials this yoked pair of participants performed in the expected manner. However in the second trial the previously passive participant simply could not successfully perform in the active mode. They did not identify the shape after several minutes, despite the requirement of only having to choose between four options presented visually in front of them. Interestingly, their passive counterpart had identified the shape after 22 seconds. Accordingly, the successful first trial was included in the analysis performed across active-passive pairs (the first analysis reported here), but neither trial was included in the analysis in which each participant's passive latency was compared with their own active latency, as neither participant had both an active and a

[1] Richardson et al (1981) used a within-subjects t-test for their comparison of physically yoked explorers.

passive latency that was considered valid. Other than this particular participant, all explorers correctly identified all of the stimuli; accordingly number of stimuli correctly identified was not analysed.

The data from Studies 5 and 6 were combined to make a comparison between the time-delayed and real-time yoking of the active and passive tasks. The overall mean latency for active exploration was 31 seconds (SD=30s), compared with 46 seconds (SD=36s) for passive exploration overall. A two-way between groups ANOVA yielded significant results for both the comparison between experiments and the comparison between modes. The overall latency of the time-delayed yoking (M=27 s) was significantly shorter than for the real-time yoking (M=58 s) ($F(1,90)=24.1$; $p<0.001$). Additionally, the overall latency for active exploration (M=34 s) was significantly shorter than the passive exploration (M=51 s) ($F(1,90)=7.5$; $p<0.01$). The interaction was not statistically significant ($F(1,90)=1.3$; $p>0.05$). The comparison between methods resulted in a moderately high effect size ($\eta^2=0.211$), while the comparison between modes yielded a relatively low effect size ($\eta^2=0.077$).

A Levene's Test of Equality of Error Variances was significant ($F(3,90)=18.8$; $p<0.001$), possibly rendering the above results questionable. According to Keppel (1991), unless the sample sizes are unequal, the F-test is quite insensitive to heterogeneity of variance. However. Keppel and others suggest applying a more stringent alpha level as a solution for variance heterogeneity. The results reported ere were all significant at .01 or better.

An alternative solution for variance heterogeneity is to use a nonparametric test, and in this case a pair of Mann-Whitney tests was carried out. Overall, the delayed yoking method (N=60, mean rank=41) resulted in shorter latencies to correct identification than the real-time yoking method (N=34, mean rank=60), a statistically significant result (U=609, $p<0.001$). Additionally, active exploration (N=47, mean rank=37) was significantly quicker than passive exploration (N=47, mean rank=58; U=1758, $p<0.001$).

It is perhaps surprising that the real-time yoking was not the superior method since participants knew they only had to select from four possible stimuli and these options were visible pictorially. In contrast, in the time-delayed method participants were told they would be exploring relatively simple three-dimensional geometric shapes, thus their range of options was potentially infinite, or at least substantially larger than a choice of four options.

[1] As the previous analysis resulted in a statistically significant advantage for active exploration, a one-tailed test was considered appropriate for this analysis.

Additionally, the time-delayed subjects (both active and passive) were all blindfolded, whereas the real-time yoked participants were not.

Other than the presence of the counterpart participant, another important difference between the methods was that the yoked participants continued until they had both identified the stimulus, the other participants were halted after 60 seconds, and indeed the overall latency for the yoked method was 58 seconds – basically equivalent to the maximum for the other method. The mean latency for the yoked passive participants was 70 seconds.

There was a number of reasons for asking the yoked participants to continue until correct identification and halting the time-delayed participants after 60 seconds. As the yoked participants had only four options to choose from and they were displayed visually it was expected that their latencies would have been substantially shorter – certainly less than 60 seconds. In addition, when recording an active participant's latency it can be difficult to encourage the explorer to continue after they are certain of what the object is, particularly if they identify it quickly – the quickest active identification in Experiment 5 occurred in four seconds, and eight correct identifications were made in ten seconds or less. It is quite likely that the active participant's exploratory procedure changes after they have identified the stimulus – although this should assist the passive participant and therefore act to support the null hypothesis.

4.4 General discussion

The results indicated that using a Phantom force-feedback device to actively explore simple three-dimensional geometric shapes (such as a cube or a cone) leads to better performance than being guided in a passive manner by the Phantom moving over the same movement path at the same rate as the active explorer. Significant results in favour of active exploration were obtained for latency to correct identification of the shapes. The number of shapes correctly identified reflected the same trend, but the results did not reach significance.

No other research was found comparing active and passive touch in three dimensions, but suggestions have been made in the past that such a comparison should yield active superiority (e.g., Gibson, 1962, Lederman & Klatzky, 1986). It is expected that active touch would continue to be superior for increasingly complicated stimuli and for tasks that allow the use of multiple sensory surfaces, such as more than one finger. The former hypothesis will be tested in future research using the Phantom and Phantom Explorer program, while the latter will have to wait until a suitable device is constructed.

The Phantom was also used to compare active and passive-guided movement for the exploration of simple, two-dimensional outline drawings (such as a Christmas tree). In this case the passive mode produced superior performance in terms of latency. Again, number of stimuli correctly identified followed the trend – in this case of passive superiority – but did not reach significance. This result is consistent with Symmons (2000) and Magee and Kennedy (1980) – two studies that compared active and passive touch in two dimensions. This passive superiority would seem to be quite robust, despite the different methods used for the comparison. For example, the TDS provides cutaneous information in the form of a tangible line and the sensation of relative movement between the skin surface and the surface to be explored. In contrast, the Phantom provides kinaesthetic information only, although it could be argued that there is some tactile information from holding the stylus, along with the resistance of pushing against the (minimal) forces supplied by the device.

Magee and Kennedy (1980) restricted the active explorer in terms of the amount of exploration they could undertake, and guided the passive subject by holding their hand; Symmons (2000) used a device that allowed free exploration by the active subject and precisely matched the passive participant to this movement, where the device held the subject's finger; and in the current research a virtual reality device was used so there was no actual contact between the tangible stimulus and the fingers or hand, and again retracing was allowed. The stimuli used were quite simple – the drawings were made up of few lines, there were few or no intersections, and all elements could be explored simply by staying on the line. However, constructing some sort of mental image of a spatio-temporal pattern lasting up to 60 seconds and retrieving the correct semantic name for it from memory could be a significant cognitive load. When the cognitive load was reduced, such as in the use of abstract shapes (Symmons, 2000), passive superiority was no longer observed. The issue of cognitive load will be discussed further in Chapter 6 of the thesis.

Why might active performance have been superior for the exploration of three dimensional stimuli? One possibility is that an active explorer experienced resistance against further movement when the probe of the Phantom met the virtual surface (Richardson, personal communication, 21 November 2004). The passive subject was merely following (or being dragged and pushed along) and did not experience a force-feedback in the same way, despite undergoing the same movements. This differs from the operation of the TDS where both active and passive explorers apply some pressure against the surface (and therefore experience force against their fingertip). However, this idea is somewhat contradicted by the observation that passive exploration produced superior performance for two-dimensional stimuli when using the Phantom.

5. VISION VS TOUCH

It is generally considered that vision is our dominant or most important sensory modality. Ro, Wallace, Hagedorn, Farne and Pienkos (2004) go so far as to say that this proposition is "common sense", evidenced by the fact that when our attention is triggered by one of the other senses (e.g., by a loud sound or a touch from behind), we typically orient our eyes to the source of the information to determine what produced it. However, in some instances this reorientation may be of the body rather than the eyes because it is easier to explore something haptically if it is in front of us, and sound is better localised in the medial plane. A further criticism of Ro et al's "common sense" observation relates to cooperation among the senses. For example, vision (and audition) can glean information from the environment at significantly greater distances than can haptics (and taste). So, hearing an attention-arresting noise from behind is likely to result in the hearer turning to orient towards the noise and using vision to scan the area for the source of the noise. Indeed, without audition the individual would not have turned in the first place. Haptics may then be brought to bear if the source is within reach. Upon turning towards the sound, it seems unlikely that the individual will block their ears, hold their breath and thrust their hands into pockets so that they may *only* use vision.

While most of our interaction with the environment involves multisensory information, there are situations in which one sense is more relevant or potentially more useful than the others. Ro et al's example might be better suited to vision, but if we see a textured surface that attracts our attention we are apt to reach out and touch it rather than try to look more closely at it. Signs that say "do not touch" are in places such as museums because we typically *want* to touch things in order to optimise our sensory experiences, even when the exhibit is meant to only be visual. There could hardly be a better example of our need to touch than being told we cannot do so, by people who know very well that we want to!

A common research paradigm for comparing the sensory modalities involves pitting the senses against each other on some ambiguous task or using conflicting stimuli, with the aim of determining which sense will dominate or "capture" the other. For example, vision can capture audition in relation to apparent movement (Soto-Faraco, Spence, & Kingston 2004), but audition can capture vision, such as with the flash lag effect (Vroomen, de Gelder & Vroomen 2004). In a series of experiments in which participants had to make size judgements while wearing "minifying" lenses, Heller, Calcaterra, Green and Brown (1999) found examples of vision prevailing over touch and touch prevailing over vision. It has also been found that individuals can mistake a rubber hand for their own if it is hidden from view and the rubber hand is placed in a position in which the individual might expect to see their real hand. Pavani, Spence and Driver (2000) found this effect present even when there was no attempt to trick the participants and subjects saw the false hands placed in their field of view. Ro, et al (2004) reported visual capture when brushing the left hand of subjects while they watched in a mirror (so that the image appeared where the right hand would be). Subjects knew their right hand was not being stimulated, yet reported sensations in their right hand. Capture situations have also been reported for conflicts involving taste versus vision, audition versus touch (Driver & Spence, 2000; Caclin, Soto-Faraco, Kingstone & Spence, 2002) and vision versus audition (McGurk & McDonald, 1976)

Sensory capture tasks generally do not compare the senses in terms of performance. Instead, it is usually concluded that we rely on one sense more than another in certain circumstances. In some conflict situations haptics may be at a disadvantage because the task is more "natural" for vision than for touch. For example, we are accustomed to watching our hands as our fingers palpate objects, so while our hand (or a fake hand) being stroked with a brush may not be a common occurrence, watching it happen is not a particularly peculiar visual event. However, for the haptic sense it is more "natural" for the hand to seek out stimulation rather than passively receive it (Gibson, 1962).

Additionally, conflict studies may not reveal the "best" sensory modality for a particular task. The conflict itself may have a differential effect on the senses under investigation, and this is hard to detect unless performance of each sense is measured so that we may determine whether some tasks are not at all achievable by, or are very difficult for, a particular sense. The task must be tailored to fit the senses or, in effect, be amodal. Hughes, Epstein, Schneider and Dudock (1990) suggested that information in stimulation could be considered amodal if two conditions are satisfied: "(1) the information is carried by spatiotemporal patterns of stimulation that exhibit the same form, and if (2) the information affords different perceptual systems with equivalen descriptions of environmental states or events" (p. 143).

Hughes, et al (1990) provided a haptic task using the vibrotactile display of an Optacon (Bliss, Katcher, Rogers, & Shepard, 1970), with the visual counterpart a matrix of LEDs lit in concert with activation of the Optacon's vibrators. The task, in terms of pattern identification was the same, but the information was presented in a different though equivalent way to the modalities under investigation. In each task, five separate ambiguous, non-symmetrical shapes "flowed" across the stimulators, vibrating pins for touch and LEDs for vision. A single presentation lasted for less than two seconds. In a similar method,

Apkarian-Stielau and Loomis (1975) provided stimulation via a 400-point TVSS (White, et al., 1970) for touch and a matrix of 400 globes for vision.

Bairstow and Laszlo (1978) compared haptics and vision for abstract patterns. The haptics group of subjects wielded probes and were guided around a grooved pattern. In the vision condition the patterns were traced out on a screen using a single point of light. In both groups only one circuit of the pattern was allowed, and subjects then chose the pattern from a set of similar standards. In both instances the experimenter tried to match the speed of movement with that of an active exploration condition. In Loomis, Klatzky and Lederman's (1991) comparison of touch and vision the stimuli were drawings of common objects. Haptic subjects explored these drawings as raised lines with either one or two fingers. In the visual conditions subjects touched a computer graphics tablet to reveal aspects of the drawing within a stationary aperture on a monitor.

Noll and Weber's (1985) apparatus consisted of two plates separated by 1 cm that could move relative to each other – the top plate could move over the bottom one or the bottom plate could move underneath the top one. The top plate contained an aperture and the bottom plate was lined with a textured surface that could be seen or felt through the window. Pairs of washers or buttons were attached to the bottom plate separated by gaps ranging from 5 to 25 cm. An experimenter provided relative movement between the plates at a constant rate of 5 cm/s and subjects were asked to estimate the distance between the stops in "moving window" and "stationary window" presentations.

Hughes et al. (1990), Bairstow and Laszlo (1978), Loomis et al (1991), and Apkarian-Stielau and Loomis' (1975) each used a different apparatus to present the visual and tactual stimuli. Noll and Weber (1985) used the same apparatus for both modalities. What they had in common was an attempt to match the tasks to "level the playing field" between the senses. In the experiments reported in this chapter, haptic and visual information were presented in different, sensory-specific ways. Additionally, the visual task was modified to approximate the way the haptic system receives information – spatio-temporally. In the haptic conditions subjects were guided around capital letters. In the vision conditions subjects watched these guidance pathways being plotted on a monitor. As a single fingertip was used in the haptic conditions subjects were limited to a fingertip-sized amount of information at any one point in time. Vision was constrained in a similar manner by only plotting a fingertip-sized portion of the pathway at a time. Accordingly, both the haptic and visual systems were obliged to operate spatio-temporally with the same information delivered at the same rate.

5.1 *Experiment 7: Haptics vs. vision for Phantom pictures*

In Experiment 7, capital letters were explored using either haptics or vision. Haptic exploration was provided using the Phantom. In the visual conditions the movement pathway administered by the Phantom was plotted on a computer monitor.

5.1.1 Method

<u>Participants</u>

Eighteen volunteers (four males and 14 females) ranging in age from 18 to 57 years (*M*=26 years, *SD*=9 years) took part. All participants were right-handed, with normal or corrected-to-normal vision. Participants were volunteers recruited at the Gippsland campus of Monash University via posters and word of mouth.

<u>Materials & Apparatus</u>

The stimuli used in this experiment were movement pathways that represented the capital letters B, E and K. These pathways were produced in two types of representation – visual and haptic. In the visual conditions the pathways could be seen to progressively trace out the letters (a function performed by the HVTP software – see Chapter 2). In the haptic condition blindfolded subjects were guided along the pathways by a Phantom force-feedback device.

The Phantom Explorer computer program generated tangible representations of the capital letters as grooved channels (see Chapter 2 for more detail). The experimenter followed the channels that made up the letters and the Phantom Explorer program recorded these active movements. The experimenter was not blindfolded during the recording process. No particular pattern or completely consistent manner of exploration was used by the experimenter, nor was any particular care taken to maintain a constant speed of movement. The experimenter simply traced the letters as though writing them with a pen, retracing them repetitively for sixty seconds. These movements were faithfully recorded and reproduced for all participants undergoing experimental conditions. The letters were approximately 10 cm along their longer axis.

The capital letters used to produce the movement patterns were B, E and K, chosen for a number of reasons. None of these letters could be considered the simplest or "easiest" in the alphabet. Starting from the top left corner and writing them in a "normal" fashion, neither the E nor the K can be produced with a single continuous stroke, requiring some backtracking (or lifting the pen from the page). All of the letters involve a vertical stroke, but

collectively they also involved circular elements, diagonals and intersections. Letters were chosen as a finite stimulus set to decrease the likelihood of a floor effect

<u>Design</u>

Experiment 7 was conducted as a within-subjects experiment. All 18 participants undertook each of the three tasks, one haptic and two visual. The single independent variable was the mode of exploration, with three levels. These three conditions were passive-guided haptic exploration, visual exploration in a "moving hole" mode, and vision in a "stationary hole" mode. Two dependent variables were latency to correct stimulus identification and number of stimuli correctly identified.

<u>Procedure</u>

Each of the three recorded movement patterns was used in each of the three conditions: one haptic condition and two visual conditions. In the haptic condition blindfolded participants were guided by the Phantom along the pre-recorded movement path. In the "moving hole" visual condition the movement path was plotted on a CRT computer monitor such that the viewer could see only 1 cm of the path at any one time. In this condition a segment of line could be seen advancing around the screen according to the movement path. In the "stationary hole" visual condition a 1 cm segment of the path could be seen in the middle of the screen and seemed to "dance" as the movement path was plotted without the segment moving from the centre of the screen. The use of 1 cm of line is consistent with Loomis, et al's (1991) study, in which the visual representation of a single finger's field of view was 1.1 cm.

The two visual conditions were approximately equivalent to moving an opaque sheet with a 1 cm hole around a shape (moving hole condition) and moving the shape behind a stationary hole (stationary hole condition). However, these analogies are not quite correct. For example, consider moving a real hole over a picture of a cross. When the hole is over the central point of the cross one would see the four lines radiating out from the centre, but if one were plotting only the exploratory movements made while feeling a cross with a fingertip, the arm of the cross perpendicular to the direction of travel would not be visible. In none of the conditions did the participant actually touch or see all or part of the letters (the stimuli) – they experienced only the movement patterns recorded as the experimenter explored the letters depicted by grooves. Secondly, a hole in a piece of paper has a visible edge. The holes used in this experiment were in fact regions of 1 cm diameter that had no visible boundaries.

Each participant experienced each of the movement path stimuli (representing the letters B, E and K), and the order of conditions was completely counterbalanced. Six different sets of combinations of condition order and stimulus order (out of the 36 possible combinations) were used. Three rounds of these six combinations were conducted, which required a total of 18 participants.

Each participant received a practice trial consisting of the movement path for the exploration of a square. Care was taken to ensure that each participant fully understood that they would be presented with movement pathways followed during exploration rather than the stimuli themselves. Participants were told that the movement pathways allowed the identification of capital letters and that they would have a maximum of sixty seconds to identify each letter. In the haptic condition participants were blindfolded so that they did not receive any visual cues from watching their arm move as they were being guided around the pattern by the Phantom.

Participants viewed the visual display binocularly and were seated at a comfortable distance from the monitor. In each of the conditions a maximum of 60 seconds was allowed for identification of the stimulus.

5.1.2 Results

All eighteen participants correctly identified at least two of their three stimuli. Five participants were unable to identify the letter presented in the stationary hole vision condition within the 60 seconds allowed. On one occasion the letter B was not identified and on two occasions each, the letters E and K were not identified. The latency data were analysed using SPSS statistical software. The five missing latency values were substituted with the relevant series means, using an SPSS option for dealing with missing data.

The moving hole visual condition yielded the lowest mean latency (M=11.9 s, SD=4.1 s), followed by the haptic condition (M=12.8 s, SD=4.5 s), and then the vision stationary hole condition (M=20.7 s, SD=12.9 s). A Mauchley's test revealed that the assumption of sphericity was violated ($W(2)=0.37$; $p<0.001$) and so the repeated measures ANOVA result was adjusted using the Greenhouse-Geisser method (epsilon = 0.61). The analysis indicated that the differences between the conditions were statistically significant ($F(1.2,20.8)=6.6$; $p<0.05$), with a moderate effect size ($\eta^2=0.37$).

Least significant difference pair-wise comparisons revealed that there was no significant difference between the latencies for exploration in the visual moving hole condition and haptic moving finger condition. However both of these conditions yielded

significantly lower latencies than did the visual stationary hole condition (haptic vs. stationary hole: $p<0.05$; moving hole vs. stationary hole: $p<0.01$). There were no significant differences in latencies attributable to the letters themselves (see Appendix 7.5 for a within-subjects ANOVA performed on the latencies as a function of the stimuli).

5.2 Experiment 8: Haptics vs. vision for TDS pictures

Experiments 7 and 8 were essentially the same from the point of view of the tasks – visual information was presented as a movement pattern and haptic cues were presented tangibly. A Phantom was used for the haptic condition in Experiment 7, but in Experiment 8 the haptic stimuli were presented with the Tactile Display System (TDS). In addition, Experiment 8 was a mixed design (within- and between-subjects variables), while Experiment 7 was a within-subjects (repeated measures) design. In Experiment 8 visual and haptic performance was compared using haptic data that had been collected earlier in two of the conditions of Experiment 2.

5.2.1 Method

<u>*Participants*</u>

The data used in this experiment were collected from 28 adults ranging in age from 18 to 27 years (M=20.5 years, SD=2.3 years). All participants had normal or corrected-to-normal vision and were volunteers recruited at the Gippsland campus of Monash University via posters and word of mouth.

<u>*Materials & Apparatus*</u>

As in Experiment 7, pre-recorded movement pathways were used as stimuli. In the visual conditions these movement pathways were displayed using the HVTP (see Chapter 2) in a manner identical to that described for Experiment 7. However, the form of the stimuli used in the haptic conditions differed from that employed in Experiment 7, in which virtual letters were explored by following channels with a Phantom. In the current experiment the haptic stimuli were raised line letters that were explored using the TDS. The capital letters used were A, B, G, K, M, Q, R, X and Z.

<u>*Design*</u>

Experiment 8 was a mixed design with stationary and moving holes as levels of the within subjects variable, and vision and touch as levels of the between subjects variable. Data for the haptic condition came from Experiment 2.

Procedure

In the visual conditions participants saw capital letters progressively displayed on a computer monitor. In the "moving hole" condition a segment of line 1 cm long traced out the letter according to how the experimenter had explored it haptically. In the "stationary hole" condition the 1 cm segment of line remained in the centre of the screen and appeared to "dance" – an effect similar to moving a drawn representation of the movement pathway behind a stationary hole. The order of these two conditions was counterbalanced.

Experiment 7 involved one haptic condition – passive-guidance using the Phantom. Experiment 8 used two haptic conditions presented by the TDS, and previously described in Experiment 2. In one of the haptic conditions the explorer's finger was moved over the raised line of the capital letter drawing, and in the other condition the raised line was moved beneath the stationary fingertip. The difference between the conditions was the presence or absence of kinesthesis. In Experiment 2 these two conditions were among eight presented in randomised order, with two letters in each condition. One data point for each subject in each of the two conditions of interest was used in the current analysis. Where the participant had identified both of their letter stimuli in Experiment 2 a mean of the latencies was used for the present experiment. If only one letter had been identified then this single latency was used. One participant in Experiment 2 had not identified either of their stimuli and so their data were not included in the current analysis.

5.2.2 *Results*

All of the stimuli in both the visual and haptic conditions were correctly identified (after the one subject's data were removed, as described above). Seeing the segment of line trace out the letter around the screen resulted in the lowest latency of mean letter recognition (see Table 5.1), followed by having a fingertip guided around the letter, then moving the raised line letter underneath a stationary fingertip. The slowest letter identifications resulted from seeing the segment "dance" in the middle of the screen, representing a stationary window.

Table 5.1
Mean & Standard Deviation for Latencies in Moving & Stationary Visual & Haptic Conditions

Condition	Mean latency (sec)	Std dev latency
Vision moving hole	12.1	3.8
Haptic moving finger	14.0	6.1
Haptic stationary finger	16.2	5.9
Vision stationary hole	16.7	6.0

A mixed-design ANOVA was conducted with moving versus stationary hole/finger as the within variable and visual versus haptic exploration mode as the between factor. The main effect for vision versus haptics was non-significant ($F(1,26)=0.20$; $p>0.05$), thus performance in the visual and haptic modes did not differ overall. However, there was a significant between-subjects effect for moving versus stationary conditions ($F(1,26)=6.08$; $p<0.05$) with a moderate effect size ($\eta^2=0.19$), meaning that overall, the moving (window/finger) conditions produced shorter latencies than the stationary conditions ($M=13.0$ vs. $M=16.5$, respectively). A pair of within-subjects t-tests indicated that there was not a significant order effect (i.e., latency for the second stimulus – haptic or visual – was not significantly shorter than the latency for the first stimulus) for either mode of exploration, suggesting that learning did not substantially affect performance (see Appendix 7.1.3).

Figure 5-1 shows a comparison of the results obtained in Experiments 7 and 8. Latencies were shortest for conditions in which the movement trace was a spatio-temporal pattern, plotted out around the screen in 1 cm segments for vision, or for haptics, the fingertip or Phantom probe being moved around the pattern (i.e., with kinaesthesis). Latencies were longest when the movement pathway was plotted out in the centre of the screen or the stimulus moved underneath a stationary finger (it is not possible to provide a "Phantom stationary" condition due to the lack of cutaneous stimulation analogous to that available with the TDS). Combining the data for the two experiments, latencies in the moving hole/finger/probe conditions were significantly lower than those found in the stationary hole/finger conditions ($F(1,54)=8.5$; $p<0.005$), however the vision versus touch comparison was not significant ($F(1,54)=3.3$; $p>0.05$).

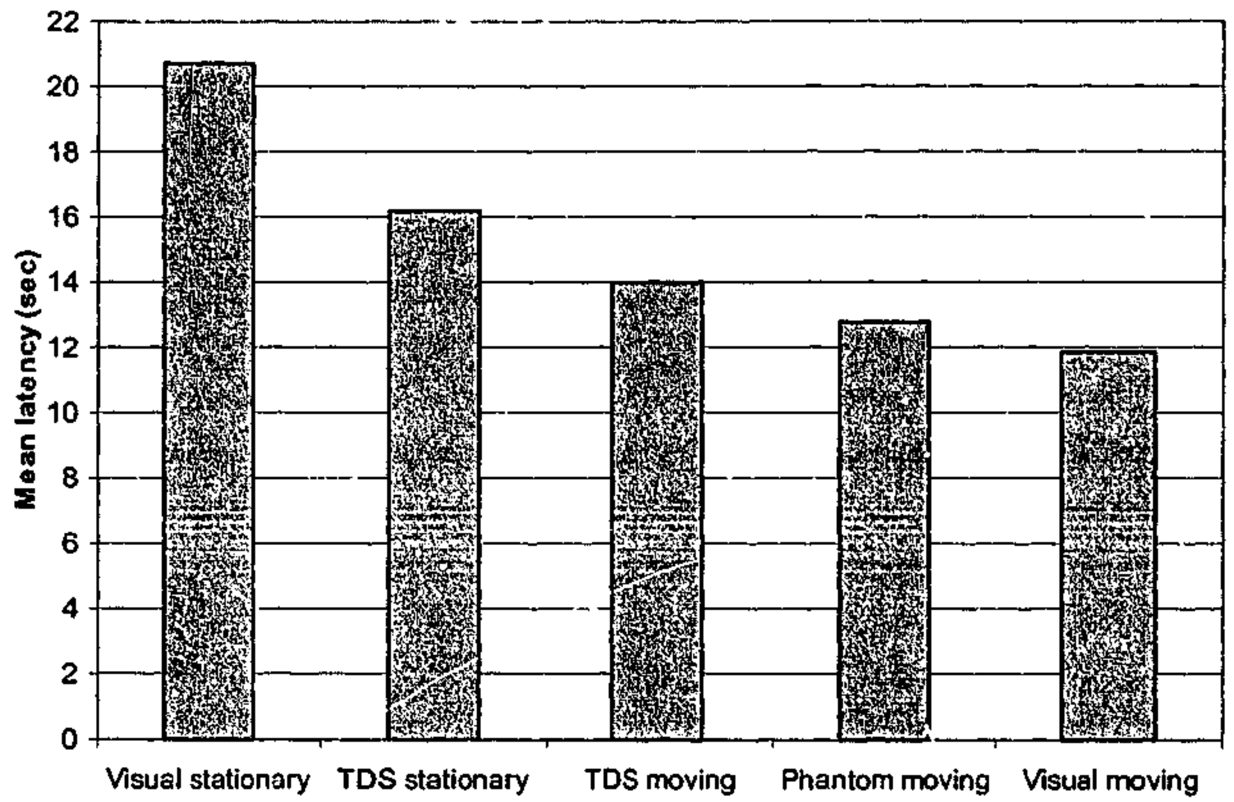

Figure 5-1. Latencies for the visual and the Phantom and TDS haptic conditions, for both the moving and stationary hole modes of presentation.

5.3 General discussion

The haptic sense is spatio-temporal in nature with much information arriving sequentially as well as in parallel. For example, the exploration of a three dimensional object with multiple fingers or multiple hands requires an integration across time as the fingers move over the surface of the object, as well as the integration of each of the fingers and other skin surfaces in contact with the object at any one point in time. Vision has more parallel inputs and relies less on sequentially arriving information. These differences would be apparent when asking subjects to name capital letters of around 10 cm in height. Normally all necessary detail is instantly present for vision but haptic information has to be gathered over time.

In order to match the tasks for vision and touch in the present experiment, the stimuli were presented 1 cm at a time as the letters were traced out; 1 cm was chosen as the approximate width of an adult's fingertip (Loomis, et al, 1991). There were two vision conditions. In the "moving hole" vision condition the 1 cm segment of visible line moved around a monitor, tracing out the movement path that represented each letter. In contrast, the "stationary hole" condition was similar to placing an opaque surface containing a small window (1 cm across) on top of a visual representation of the movement path undertaken while exploring the letter, and then moving the stimulus around under the stationary window,

always keeping the line in view through the window. Accordingly, the segment remained in the middle of the screen. It should be noted that the actual stimulus seen in the visual conditions was the movement pathway that corresponded to the haptic exploration of the letter, rather than a line drawing of the letter per se. However, since the experimenter recorded the movement pathways, a plot of the actual letter and the movement pathway would be very nearly identical (allowing for the size of the experimenter's fingertip). In Experiment 7 the haptic task was performed using the Phantom, whereas in Experiment 8 the TDS was used to present the haptic stimuli.

In both of the experiments reported in this chapter the haptic conditions did not differ from the visual conditions in terms of response time. This indicates that when these sensory modalities both function spatio-temporally and are matched in terms of the rate of information presentation, they perform equally. The other principal result reported here was that the moving finger/probe/hole conditions resulted in significantly better performance than the stationary finger/hole conditions, both within sensory mode (i.e., comparing the results within haptic conditions for the TDS and within vision conditions) and between sensory modes.

No previous research was found in which subjects had to identify visual stimuli based on movement pathways rather than a line drawing of the stimulus, where the movement represented more than a single pass over the stimulus. Bairstow and Laszlo (1978) were able to say that the stimuli they used in their visual condition represented movement patterns matched to haptic exploration because only one circuit was allowed of their abstract shape and the experimenter manually matched the speed of movement. Additionally, unlike the stimuli used in the present experiment, Bairstow and Laszlo's stimuli were continuous and involved no intersections, so that retracing was not necessary. Despite these differences, the current finding of equivalence between haptics and vision for identifying capital letters is consistent with their result for a task in which abstract shapes had to be matched to a set of standards.

Also consistent with the current result, Loomis et al (1991) also found that haptics and vision were equivalent when the former condition involved one finger exploring and the size of the "information window" in the vision condition was matched to this size. However, they also reported a set of additional conditions in which two adjacent fingers could be used to explore the raised line drawings and the size of the window in the vision condition was doubled accordingly. When the field of view was doubled for both modalities, Loomis et al found that the haptic performance did not change, but that performance in the vision condition improved significantly.

It is worth noting that both the haptic and vision conditions reported by Loomis et al (1991) were for active exploration, as the subjects retained control of where and how to explore, given the restriction to a single fingertip and equivalence of exploratory "windows". In the current research both the haptic and vision conditions were implemented as passive exploratory modes, as the experimenter determined the movements that made up the movement pathways. Accordingly, in the current research the movement pathway and rate of information delivery was the same across conditions. This did not apply in Loomis et al's research. While the results are consistent between the experiments, a comparison of active versus passive exploration cannot be made. Further research using the Phantom and/or TDS along with something like a graphics tablet as used by Loomis et al could investigate active-passive differences.

There were other differences of note between Loomis et al's (1991) research and the current experiments. In the earlier research the vision condition was actually a mix of haptics and vision because subjects chose the bits of the field they wanted to view through the movement of a probe that interacted with the graphics tablet. No stimulation was provided to this finger, unlike the raised line felt underneath the finger in the haptic condition, but it could be argued that this is not a purely visual condition. Of course kinaesthesis is also available in the vision conditions due to movement of the eyes, but Experiment 2 reported in this thesis demonstrated the importance of kinaesthesis in the haptic sense. Further, the window in the visual condition was always stationary, like the stationary window condition in the current research. In a subsidiary experiment, Loomis et al found that an aperture that moved in concert with the moving graphics tablet pen resulted in significantly better performance than the stationary aperture condition, consistent with the current finding that movement results in elevated performance. However, Loomis et al only performed this comparison within the vision mode, unlike Experiment 8 here where a moving and stationary fingertip were compared.

Krauthamer (1968) cut outlines of ambiguous shapes from plywood, like the inverse of a cookie cutter rather than a shaped block of wood. A stylus was moved along the cut-out path to draw the shape in a stationary palm. For the visual counterpart a focussed beam of light was shone through the stencil and traced the path of the object onto a translucent glass window. These conditions are comparable with the current moving window conditions for haptic and visual modes. Krauthamer used simultaneous presentation for comparison in each sense rather than a stationary window with moving medium. The number of trials required to train subjects to some criterion level on the 9 cm^2 stimuli was significantly smaller for vision

than for the haptic mode regardless of the stimulation method. In that situation vision demonstrated quicker learning rather than superior performance at identifying stimuli per se.

The results reported by Noll and Weber (1985), Apkarian-Stielau and Loomis (1975), and Hughes, et al. (1990) were derived from conditions that involved a slit rather than a window or aperture. When a slit is used, whether it moves over a stimulus or the stimulus moves under a stationary slit, the whole stimulus has been revealed in one complete left-to-right pass. Accordingly, exposure times are usually quite short; less than two seconds in the case of Hughes et al's research. In the current research the stimulus is substantially larger than the window, and so one complete lateral pass is insufficient to show the whole stimulus. Thus, the earlier results and those reported here may not be directly comparable. Nevertheless, the finding that a moving window/finger/aperture is superior to one that is stationary seems to be reasonably robust.

Both Apkarian-Stielau and Loomis (1975) and Loomis et al (1991) blurred the visual signal, using a screen and a pair of lenses in the former and an intervening screen in the latter. The purpose of this blurring was to compensate for the more limited spatial resolution of the fingertip. No such blurring was carried out in the current research. Loomis et al noted that this contingency was probably of no consequence because their pictures were not of particularly fine detail, and so the information lost to vision due to the artificial blurring was probably minimal. Apkarian-Stielau and Loomis did not mention how effective their blurring was in regards to reducing the information available to vision. The stimuli used in the current research were more basic still than those used by Loomis et al, and so it was not considered important to replicate this feature.

The finding that the moving window conditions can result in equivalent performance for the haptic and visual modes poses questions regarding memory. In order for a letter to be identified at all, the movement trace must be retained after the segment has moved on. Apkarian-Stielau and Loomis (1975) briefly pondered this issue for their slit-scan conditions, wondering whether the whole pattern is progressively integrated and kept in memory or whether just the relative movement is kept. The current moving window condition should be more taxing than Apkarian-Stielau and Loomis' slit-scan condition. In the latter the window extends for the full height of the stimulus field, whereas the window in the current research is 1 cm in size. Accordingly, one pass of the slit-scan window is sufficient to sequentially reveal all of the letter, while a number of passes and backtracking is required to present all of the letter in the present moving window condition. Therefore, a more complicated spatio-temporal integration is required to identify the letters in the moving window condition.

Another possibility could be added to Apkarian-Stielau and Loomis' (1975) suggestions about the operation of memory in these tasks. A significant proportion of the pattern could be at least initially ignored. Instead, viewers may preferentially retain aspects of the pattern that may seem to contain the most information – a discrimimant features analysis. For movement pathways this would likely be corners or changes in direction, whether they were circular, as in the rounded elements of the letter B, or angular as in the right-angled changes in direction at the top, bottom and midway down the vertical stroke of the B. Support for this proposition can be found in the ability of participants to identify letters in the stationary hole condition. It is easy to "lose" the shape of the pattern when often all there is to see is a straight line. However, changes in direction stand out. There is evidence too for this supposition in the way haptic explorers dwell on particular aspects of tangible patterns, such as intersections and other changes in direction (Symmons & Richardson, 2000).

The function of spatio-temporal memory, whether as some sort of sensory-specific store or, more likely a resource shared across senses, could be examined in a number of ways. At the conclusion of trials participants could be asked which were the more salient features of the stimuli – what most helped them to identify the stimulus. Alternatively, in a between-subjects paradigm the stimuli could be presented as a series of direction changes versus other elements. In future research there is a plan to modify the programming used here so that the vision conditions can be undertaken actively or passively. Movement paths could then be analysed to identify which elements explorers dwell on. This would be possible using the current haptic programming, but the data reported here were collected in haptic conditions that were passive rather than active. A further avenue of research would be to make comparisons of cross-modal training. Krauthamer (1968) found that successive stimulation, using a spatio-temporal pattern, led to uniformly good cross-modal transfer from vision to touch, and from touch to vision, however simultaneous presentation produced considerable interference. Krauthamer did not test a stationary hole condition.

With modifications to the programming, further research is planned to compare the movement patterns used here with movement of a window over an actual drawing (and movement of the drawing under a stationary window), and a sophisticated combination of both. That is, rather than simply displaying two lines, one for the movement path and the other for the drawing, the drawing would be displayed and the window would travel according to the recorded movement path, including errors in which the explorer slips off the line. To match the haptic condition, in the visual mode the line drawing would have to disappear when the movement path did not match the drawing: the equivalent of not being

able to feel the stimulus in the haptic condition when the explorer wanders off the line. Consideration is also being given to how a related experiment might match vision and haptics for three-dimensional stimuli using the Phantom.

6. GENERAL DISCUSSION

The research reported in this thesis hardly scratches the surface of what is to be learned about haptics. There is no counterpart in haptics for the body of knowledge underpinning research on vision. There are few paradigms in haptics research. For this reason, it is harder to relate new findings to past research in haptics than it is for vision and hearing. But there is every reason to expect, if only for the sake of parsimony, that haptic processes will more and more be found to mirror other senses with regard to efficient mechanisms already identified 'ı other senses. These include top-down and bottom-up processes, attentional mechani. triggered by change and distinctive features, Gestalt principles, and so forth.

However, unlike vision and hearing, for which stimuli are always distal, the haptic senses have to operate at both proximal and distal levels. A cutaneous input may signal anything from an itch to a representation of a complex (distal) shape, and a kinaesthetic input may signal anything from an aggressive shove (containing both proximal and distal information), to a representation of a similarly complex shape. In addition to handling inputs about proximal and distal stimuli, the haptic system has to cope with bi-directional links with the motor system that can turn thought into action. None of the other senses have such links to action (except perhaps taste). In this regard, they can be seen as passive detectors of what is happening in a world in which, using what the other senses tell it, the haptic system must take frontline responsibility for action. At best, our understanding of how the motor and haptic systems work together might be described as "emerging".

It was within this context that the experiments reported here were conducted. They sometimes had clear hypotheses because there was previous research allowing comparisons of results (e.g., active–passive studies), but at other times there was little or no context within which to interpret findings (e.g., the study concerning orientation of p, q, d and b performed using the TDS). In this thesis there was always more exploration than hypothesis testing, but this should not detract from the aim of improving our understanding of haptics.

A number of workers in the field of haptics research have noted the "poor cousin" status afforded the sense of touch in sensory research; from Katz in 1925 (Krueger, 1989) through to Loomis and Lederman (1986), and more recently Craig and Rollman (1999). According to Schrope (2001), there are only about 100 people researching touch worldwide, compared with thousands examining sight and hearing. With improvements in technology and the acknowledgement that haptics must be part of telepresence and full immersion in virtual reality applications, touch now enjoys a higher status. But there are still lots of areas in which research is needed. This thesis was concerned with three of these: the relative importance of a number of components of touch; active versus passive haptic exploration in two and three dimensions; and touch versus vision using a "fair" comparison.

The three preceding chapters contained relatively short discussion sections, with an emphasis on comparisons of results with past research. This chapter has as its focus a more detailed examination of each of the experimental areas followed by an attempt to draw the areas together in an overall discussion of the implications of the results.

6.1 The constituents of the haptics sense

Using a unique device called the TDS, the principal components of the haptic sense were isolated and combined in various arrangements to investigate their relative importance in the exploration of two-dimensional stimuli. The components that could be isolated and/or combined were:

- Kinaesthesis: arising from movement of the explorer's finger, hand, arm, etc.
- Line: arising from the provision of a raised line underneath the fingertip
- Shear: arising from friction due to the relative movement between a plain (but lightly textured) surface and the skin of the fingertip

Seven different conditions were tested. Each condition involved movement of either the hand (i.e., kinaesthesis was present), or of the stimulus underneath a stationary fingertip. In each condition the participant was presented with outlines of capital letters approximately 8 cm in height.

Three of the conditions tested involved kinaesthesis, and in general these conditions yielded better performance than those not involving kinaesthesis, both for stimulus identification accuracy and latency to correct response. This finding is consistent with a good deal of previous research (e.g., Austin & Sleight, 1952; Cronin, 1977; Loo, et al., 1983; Magee & Kennedy, 1980; Jansson, 1998). However, the conditions that involved moving a fingertip over a plain surface and moving a raised line drawing underneath a stationary fingertip were not found to differ in terms of latency or accuracy, a result at odds with that reported by Magee and Kennedy (1980). Accordingly, their assertion that a tangible line really only serves to indicate to the explorer that they are making relevant movements requires further examination.

Other components of haptic exploration in two dimensions can also yield unexpected levels of performance. For example, moving a textured surface underneath a stationary fingertip with an intervening layer of sticky tape was expected to minimise the shear component and not yield particularly good performance. This condition, and that of moving

the drawing under a taped stationary fingertip so that the line could be felt with minimal shear on the fingerpad, yielded equivalent performance, and both resulted in performance that was equal to that obtained to the aforementioned condition in which the explorer's finger is moved over a plain surface. These results, in which useable information was derived from such artificial and "unnatural" conditions is quite astonishing and warrants further examination. Limits to what can be transmitted to the brain via a stationary fingertip have yet to be determined but there could be some further surprises.

The stimuli used in much of the research reported here were raised line letters. There may be value in replication using stimuli such as abstract shapes that reduce memory load and can be matched with a visual array as a recognition set. Or tasks may be more basic, such as lines whose distances must be estimated or textures that must be compared. It may also be worthwhile using more complicated patterns. With such a variety of approaches it may be possible to establish upper and lower limits of usefulness for each of the haptic components tested.

The condition in which the stationary fingertip is taped is reminiscent of studies designed to examine improvement in tactile perception when a piece of paper is placed between the fingertip and the surface to be explored, so that there is little or no shear information available to the fingertip (Gordon & Cooper, 1975, cited in Krueger, 1989; Lederman, 1978). This technique, known to many carpenters, car body repairers and others who must feel for very fine scratches, is generally of advantage only when the texture to be examined is near the threshold of perception. This was not the case with the stimuli used in the current research, although some benefit due to a heightened level of sensation may still have been present. This is yet another topic of research.

6.2 Active versus passive touch in two and three dimensions

Symmons, et al. (2004) reviewed literature concerning active and passive touch in the exploration of two-dimensional stimuli and the results were equivocal: on some occasions active touch had been found to result in superior performance, on others passive exploration was better, and in some instances there was no difference in performance. One of the difficulties encountered in summarising this research was the variety of operational definitions used to describe the two modes of exploration. This point was picked up by Klatzky and Lederman (2003), "...a basic distinction has arisen between active and passive modes of touch. Unfortunately, over the years the meaning and use of these terms has proved to be somewhat variable" (no page number available). Accordingly, the research literature cannot necessarily be summarised as simply "active versus passive", partly because conditions were not comparable and partly given the lack of consistency in results.

6.2.1 Defining the difference between active and passive touch: Source of control

A standard dictionary definition for the word "active" includes words and phrases such as "given to action, working, effective", while for the word "passive", phrases such as "suffering action, acted upon, offering no opposition, submissive" are used. A theme running through these definitions is the question of where control resides; whether an individual retains control or they do not. In terms of touch, "active" would therefore indicate personal control of where and how one receives or attains information, while "passive" would denote that some outside agency imposes the information on the receiver. These comments are consistent with Gibson's (1962) definitions of active and passive touch:

> *"Active touch refers to what is ordinarily called touching. This ought to be distinguished from passive touch, or being touched. In one case the impression on the skin is brought about by the perceiver himself and in the other case by some outside agency"*
>
> (p. 477).

In a thorough classification of "tactual display modes" Kaczmarek and Bach-y-Rita (1995) differentiated between voluntary and involuntary control as the second tier in a hierarchical classification. Loomis and Lederman (1986) also classified touch on the basis of control.

Out of the 76 active-passive comparisons Symmons et al. (2004) reviewed, 65 could be classified as a comparison between perceiver- and other-controlled. Twenty-three of these comparisons indicated that performance was superior if an external agency – either the experimenter or some sort of device – controlled the exploration process, 39 comparisons resulted in superior performance if the subject retained control, and in three instances there was no difference between the modes.

6.2.2 Comparing active and passive touch

In comparing active and passive touch, the TDS centres on the issue of the source of control. Additionally, the active explorer essentially has total freedom in how they explore, and passive subjects experience the active subject's freedom. The only real constraint imposed by the device is that subjects are restricted to the use of a single finger. However, this may not be a significant limitation. Symmons and Richardson (2000) demonstrated that individuals spontaneously explore raised line drawings with a single finger. Nevertheless, the use of a single finger or a single finger and thumb is unlikely to be a common strategy for

exploring three-dimensional stimuli. We would tend to use the whole hand when possible – a point emphasised many times by Gibson.

It is not presently possible to compare active and passive haptic exploration in three dimensions with adequate control where active exploration is unfettered and the passive counterpart's movements are matched precisely to those of the active subject. However, if exploration is restricted to a probe (rather than a finger) then a high level of freedom and control is possible for exploration of virtual three-dimensional objects with a Phantom force-feedback device. Indeed, because the stimuli are virtual, the Phantom actually allows some types of exploration not possible in the real world – such as feeling the inside surfaces of "solid" objects, and the back of objects while "pulling" the probe towards the body. As with the TDS, the comparison between active and passive touch using the Phantom (and the Phantom Explorer software described in Chapter 2) ensures that all factors other than where control resides are matched between the modes of exploration (although there may be a critical difference between how the active and passive subjects experience the virtual stimuli used with the Phantom – a point further discussed later).

Using the TDS, Symmons (2000) compared active and passive modes for exploring raised line stimuli and found that the result was at least partially dependent on the class of stimulus used. For outline pictures of simple drawings or capital letters passive exploration led to better performance; when the stimuli were three-letter words active touch was superior; and when the stimuli were nonsense (abstract) figures there was no difference between the modes. The first result was further supported by the current research, in which simple two-dimensional outline drawings were identified more quickly and more accurately by passive users of the Phantom. The robustness of this result supports the use of the Phantom as a credible research tool.

Using the Phantom to explore simple, geometric three-dimensional shapes resulted in a superiority for active exploration. This was found in two experiments. In one study the active subject's exploration was recorded and then used by the Phantom to guide a passive subject at a later time, while in the second experiment two Phantoms were yoked in real time so that the active subject's movements resulted in simultaneous movement of the passive subject's hand.

6.2.3 A theory of cognitive load

In Symmons (2000) the manner in which active and passive exploration was compared did not differ for the three stimulus types used – simple pictures, abstract shapes and three-letter words. However, passive superiority, no difference, and active superiority were found to be associated with these three stimulus types respectively. Magee and Kennedy (1980) suggested that their passive superiority finding resulted from the active participant being disadvantaged in some manner by having to plan and execute exploratory movements, an idea significantly at odds with Gibson's tenets. If their reasoning was correct then active participants should have been equally (or nearly equally) disadvantaged for each of Symmons' three classes of stimuli rather than just for the outline pictures. As passive superiority was not evident for two of the three classes of stimuli, results cannot explained in terms of planning and execution of movement, unless they apply to outline drawings as a special case.

Richardson and Wuillemin (1981) countered Magee and Kennedy's (1980) claim with the observation that haptic perception is not taxed by having to plan and execute exploratory movements that are much more complicated (at least on the face of it) than a raised line. This is probably because we do not plan such movements in a way that may interfere with identification. We do not typically pause as we haptically examine a novel object to decide where and/or how to move next. There often *are* pauses for strategic, conscious decisions to do with considering what we have felt immediately prior and how to go about the "next bit". But these are arguably cognitive activities, moments that are strategic and part of the process of identifying the object. It might be expected that these considerations would actually *disadvantage* passive explorers simply because they cannot choose when to pause to make use of such strategies to assist with identification. Consistent with Gibson (1962), Symmons and Richardson (2000) reported very individualistic strategies used to explore raised line drawings. Subjects were asked to identify the stimuli rather than simply explore them, so these strategies were actually object *identification* strategies rather than object *exploration* strategies. This may be an important distinction since being able to use one's own unique identification strategies should be advantageous compared with not being able to use one's own strategies. Thus, being exposed (or subjected) to an active person's identification strategies would be expected to disadvantage the passive subject as they are unlikely to share their counterpart's strategies.

Richardson and Wuillemin (1981) suggested that rather than some sort of *perceptual* load being greater for active subjects, a *cognitive* load difference better explains passive superiority in some circumstances. Thus, active subjects are disadvantaged when the task is more cognitive than sensory – such as when an object depicted in a raised line drawing has to be accessed from memory. According to this argument, what is claimed to be a comparison of passive and active perception may be more a comparison of higher or lower cognitive load. At first glance this argument would seem to fit the range of results reported

by Symmons (2000). For example, a complex or detailed object may place a greater burden on memory, whether it be some sort of sensory store or short term memory (see later for a discussion of a possible specific kinaesthetic memory). Since touch must acquire information in a sequential manner, particularly when exploring with a single finger or a probe, one would expect that the explorer must retain as much of the pattern as possible as new elements are integrated, in order to identify the object. Whether passive superiority is best explained by cognitive or sensory loads remains unclear.

In current and previous research reported by the author, subjects were usually asked at the completion of testing how they thought they went about identifying their stimuli. Other than "I don't know", the most common response was something along the lines of "I just built up a picture in my head". This implies that the subject must be retaining as much information as possible to build up the "picture". No subject ever responded by saying something like "I only paid attention to the important bits, like intersections", although such a strategy would seem to be quite an efficient one, consistent with theories of distinctive features. An effective technique would seem to be to retain only the elements that provide the most information, such as intersections, changes in direction (whether they be angles or rounded corners) and so on – however this does not seem to describe how people actually function, at least at the conscious level. Further anecdotal evidence of an attempted "full retention" strategy arises from "of course" responses from subjects who were unsuccessful in identifying their stimuli, but recognition was immediate when they were able to view the stimuli at the completion of their testing. The "aha" moment was often then followed by a comment such as "I'd forgotten that bit that I felt at the start".

Other than building up a "mind picture", another aspect of identifying the stimuli in the current research is putting a verbal name to the stimulus. There is also anecdotal evidence for this concept. The author generally encourages subjects to "think out loud" while trying to identify the stimuli and records any potentially relevant utterances. Explorers often provide answers that are incorrect yet indicate that they did have some sort of spatial understanding of the stimulus. For example, a heart shape has been described as an ice-cream with a bite out of it, a response that *does* describe the shape of a stylistic heart. While exploring, the subject must simultaneously search their memory for a name to match to the object. This search would of course be more efficient for a visual representation as it is likely that such things are stored in memory verbally and visually rather than as haptic representations. Stimuli that are more likely to be stored in memory in a more touch-specific format are liable to relate to texture, vibration, and so on. For example, a carpenter asked to imagine comparing two grades of sandpaper is more likely to think about how they feel than what they look like.

Cognitive load is clearly involved in identifying two- and three-dimensional objects haptically. The next critical question is why and how does this cognitive load differ between stimuli such that one of active or passive touch is superior for identifying one class of stimulus and the other is advantageous for identifying another? Given a particular individual and their exploration strategy(ies), it is reasonable to expect that a larger and/or more complex stimulus will take longer to encode and therefore will place a greater burden on the relevant memory or spatial coding/mapping resources.

Other than an overall representation of the stimulus, it may also be important to cognitively assign some sort of priority to specific elements of the stimulus due to their distinctiveness or the information that they represent. Such elements may include intersections, angles and relative locations of end-points. The size of "empty" spaces between separated elements of a stimulus that require a subject to leave a line and cross a gap to another line may also be important in identifying or making judgements about a particular stimulus. There is some support for the notion that some elements of a stimulus are more important than others in Symmons and Richardson's (2000) finding that subjects tended to dwell on some parts of the stimulus. Deciphering or encoding these elements may be additional cognitive tasks to simply building up a gross overall spatial representation. For example, the subject who identified the raised line heart as an ice-cream with a bite out of it clearly had a reasonably accurate overall mental representation of the stimulus. However, this subject had misinterpreted the v-shape at the top of the heart. Clearly a bite would result in a concave indentation in the cone shape rather than the v-shaped indentation present in a heart shape. Overall spatial representation and interpretation of individual elements are related, but are not the same thing. Accordingly, the cognitive demands of each may be different, and possibly competitive for the same resources.

An increased cognitive load is also likely when the stimulus to be identified must be named from memory rather than simply matched to a standard set in a recognition task. This load would be greater when the set the stimulus belongs to is open rather than closed. For example, capital letters belong to a set of 26. Outline pictures of actual objects (e.g., a fork or a Christmas tree), regardless of how simple they are, belong to a potentially infinite set. Of course in both instances the set size may become progressively smaller as the subject explores the stimulus, although it is unlikely that explorers will progressively discard options as they traverse the stimulus. As cognitive tasks, building up a spatial representation of the stimulus, deciphering specific information intensive aspects, and retrieving a name for the

stimulus from memory are likely to interact, rendering it difficult or impossible to meaningfully compare results of previous studies.

"Fair" comparisons are those in which there are no potential confounds, and where active and passive exploration differs solely on the basis of source of control (i.e., with the subject or with some external agency). A number of such studies have involved two-dimensional stimuli that represent outlines of relatively simple objects, with no separated detail, of a size significantly larger than a fingerpad (i.e., 5 cm in height or more), and a task consisting of naming the object depicted from an open set. Under these conditions Symmons (2000), Heller and Boyd (1984) and Magee and Kennedy (1980) found passive superiority. When stimuli of this size belonged to a closed set (and for example, subjects chose from visually-presented standards), Heller (1980), Richardson and Wuillemin (1981), Heller, Nesbitt and Scrofano (1991), and Heller and Myers (1983) all found active superiority; while Bairstow and Laszlo (1978) and Loo, et al. (1983) found equivalence in performance in these exploratory modes. Symmons (2000) seems to be the only report of the use of more complicated patterns for the active-passive comparison – with sets of three raised-line letters. These stimuli were "complicated" from the point of view that they had many elements and an explorer could not encounter the whole pattern without venturing across an empty gap between elements. In that instance active exploration yielded superior performance. There would seem to be some consistency in the pattern of results using these methods to classify the studies, such that it deserves closer scrutiny. Plans are underway to more specifically test these ideas experimentally with sets of stimuli that should extend along a continuum of "cognitive complexity", examining "encoding complexity" and "memorial complexity".

The virtual three-dimensional objects in the current research could be considered to be simple in that once the subject contacts the surface with the Phantom's probe they need not leave that surface in order to encounter all of the object (although it is not possible for the subject to actually explore all of the object in the time allotted given that the contact point used by the Phantom is infinitely small). These stimuli could also be classified as belonging to a closed set since subjects were told that they were relatively simple geometric shapes, and in Experiment 6 the subjects knew that the size of the set of choices was four shapes, and they knew what the options were. Following the earlier line of thought, classifying the stimuli this way would suggest that active exploration should be superior; and it was. Alternatively, it could be argued that the fact that the shapes were three- rather than two-dimensional makes them complex stimuli (from the point of view of encoding them). This then makes them comparable to the three-letter word stimuli used by Symmons (2000), and again the results are consistent – superiority for the active mode of exploration. Again, further studies are needed using a variety of types of three-dimensional stimuli to see whether this line of argument holds up. For example, Jansson (2002) modified facial features on virtual faces as a manipulation of a stimulus complexity variable. As subjects explored the faces with a Phantom they had to determine whether the features were out of proportion to the face (e.g., the nose may have been too big). As the degree of complexity increased performance became worse. Jansson did not perform an active versus passive comparison.

6.2.4 Applying passive touch: Haptic learning

In terms of potential importance, the active-passive comparison in three dimensions is of greater applicability than the comparison in two dimensions. If a particular method of delivery or stimulus category can be found that *does* reliably yield passive superiority for three-dimensional objects this would be exciting news for those involved in learning and training fields. Most active-passive research has focussed on exploration activities with the end result the identification of some stimulus. However, if Richardson and Wuillemin's (1981) finding of passive superiority in maze learning rather than an exploration task generalises to learning for some tasks in three-dimensions then it may be possible to build devices capable of recording an expert's movements and "playing them back" to passive learners, resulting in a shorter learning period and/or an improved skill. This would be at odds with the prevailing wisdom, according to which active learning benefits from the trial and error learning processes, while in passive conditions this benefit is reduced or absent. Providing an expert movement pattern to begin with followed by allowing the learner to use trial and error to more closely approximate the expert's movements, hone their skills or adapt the skills to their own circumstances may prove a beneficial combination of both learning paradigms. In fact there may be advantages even if the two modes of learning are equivalent. For example, a device that "teaches" expert movements may in the long-run be more efficient than having the expert provide individual attention to a whole class of active learners.

Other than occasions of passive superiority, another line of research also hints at the possibility of learning through passive guidance. Brain imaging studies have reported that passively elicited movements and active voluntary movements activate similar cortical regions: "...training consisting of performance of passive movements could be as effective as active movements in eliciting reorganization in the primary motor cortex and possibly result in similar behavioural gains" (Lotze, Braun, Birbaumer, Anders & Cohen, 2003, p. 866).

There is general agreement in the literature that humans possess a kinaesthetic memory capable of "remembering" limb positions, movement velocity, and so on (Clark & Horch, 1986). For example, Klatzky and Lederman (2003) concluded that there was some form of kinaesthetic memory, or a kinaesthetic representation of space. By way of description they used the example of putting an object down in one's peripersonal space (i.e., within reach), leaving it and then being able to find it again without looking. They guided subjects' fingers to a point in space and back again, then asked the subjects to replicate the movement. They found greater accuracy in fulfilling this task than when subjects signified the distance of travel by a separation of hands, indicating some sort of kinaesthetic representation rather than knowledge of distance travelled. 'Haptic training' attempts to capitalise on kinaesthetic memory (Feygin, Keehner & Tendick, 2002).

In one such haptic training study, Lotze, et al. (2003) had subjects perform 300 wrist flexion-extension movements over a 30 minute learning period. Automatic feedback was provided to assist the subjects to learn a particular duration of movement. The active training session was recorded (including the feedback) and "played back" to a passive learner using a motorised device to control hand movements. After the training period subjects were tested to see how successfully they could perform the target movement in 50 trials. Active training led to better performance in the test than did passive training, with successful movement execution rates of 21% and 13% respectively. However, they did not report a baseline condition (i.e., no training) from which to assess the effectiveness of passive training in its own right.

Adamovich, Berkinblit, Fookson and Poizner's (1998) blindfolded subjects touched the end effector of a robot arm in the vertical plane directly in front of them and then returned their hand to a resting position. This movement was either active, where subjects moved their own arms but were nudged such that they successfully made contact with the robot arm, or passive, where the subject's relaxed arm was moved by the experimenter. The robot arm was retracted and subjects immediately attempted to move their finger to the same position in space. The active subjects completed this task more accurately than did the passive subjects. However, it could be argued that the active subjects did not fully control their own reference movement. Even though the experimenters tried to minimise intervention in the active condition, without vision subjects *required* the experimenter to exert control over the direction of their movement in order to make contact with the robot arm. An additional concern arises from the requirement that the passive subjects relax. If the passive subjects were not responsible for any muscle tonus during the reference movement they may not have encoded a kinaesthetic representation of the movement (or at least not one sufficiently accurate). It is possible that some sort of "proprioceptive" representation was encoded based on joint angles, resulting in performance better than chance, but that performance could have been better still had muscle movement been involved. The use of the TDS and the Phantom in the current research required passive subjects to exert some muscle force in order to support their own arm. Adamovich et al's passive subjects may not have needed any muscle tension at all.

Similar to the current research, Williams, Srivastava, Conatser and Howell (2004) used a Phantom to guide a passive explorer. However, rather than comparing active and passive exploration per se, their subjects were asked to freely follow a (virtual) visible movement pathway. Passive subjects were guided over the pathway before testing and more accurately replicated the movement than did active subjects. However, active subjects did not seem to have an equivalent amount of experience in using the Phantom prior to the testing, a potential confound since Jansson (1998) reported that learning effects do occur using the Phantom.

Gillespie, O'Modhrain, Tang, Zaretzky and Pham (1998) considered the concept of a virtual teacher who can impart sensorimotor knowledge by demonstrating a skill in the way a tennis coach might hold a student's hand to demonstrate a new swing or a music teacher might manipulate a student's hand to demonstrate a new way of generating a note. The amount of assistance could be controlled, as could the timing of the teacher's intervention, and so on. They suggested that if an individual is shown the optimal way to perform a task early on they can bypass some of the usual practice time – i.e., reduce the error component in the trial and error process. Gillespie, et al. designed a virtual teacher to train novices in a simulation of the specialised skills involved in moving a crane. Nine of the 16 participants thought that a human teacher would have been more effective, but those satisfied with the virtual teacher generally commented that it was more likely to be consistent and accurate. The expert skills were successfully learned in the virtual teacher group, however the average performance time of the specialised task did not differ between the trained group and another group who had received no training. However, a number of problems were identified. For example, Gillespie et al. considered that the teacher was too sophisticated, and Feygin, et al. (2002) thought that the task was probably too difficult for novices.

In a related application, there is some evidence for the efficacy of errorless (or error-free) learning. For example, a force-feedback joystick was used to ensure that stroke patients undergoing rehabilitation could not make mistakes in a haptic task (Connor, Wing, Humphreys, Bracewell & Harvey, 2002). Errorless learning could be applied either under fully passive conditions, or by providing a set of boundaries that still allowed some active

input. For example, a virtual channel can be made wide enough to permit active control without allowing the explorer to stray from the preferred path. In terms of learning performance, Connor et al. found no significant difference between errorless training and a trial and error method. However, this equivalence should provide sufficient encouragement to warrant further investigation.

In a final example of haptic training, Feygin, et al. (2002) placed subjects in one of three conditions: subjects in a visual condition watched a Phantom perform a moderately complicated series of movements in three dimensions that lasted for ten seconds; in the haptic condition blindfolded subjects were guided around the same model movement by the Phantom; and in the vision+haptic condition the subject watched the Phantom guide their hand over the same pathway. Subjects participated in two reference trials then immediately a test trial without vision, assessing accuracy for replication of the movement, both in terms of positioning and pace of movement. Practice effects were evident for each condition. The vision conditions were found to produce superior performance for position and shape, but the haptic-only training resulted in better performance for timing of movement. It was also observed that during the visual training condition a number of subjects tended to try to move their hands, head or torso in concert with the movement of the Phantom, possibly suggesting an attempt at kinaesthetic encoding. Feygin et al. did not report an active-learning condition for comparison.

Others have compared active and passive modes for cognitive tasks that do not involve the sense of touch (although varying degrees of kinaesthesis and proprioception are utilised by the active subjects). For example, Attree, Brooks, Rose, Andrews, Leadbeater and Clifford (1996) asked subjects to explore a virtual house looking for a range of objects. Active subjects controlled the exploration using a joystick while passive subjects watched the progress of the exploration on another monitor (i.e., they were "taken on the tour"). At the completion of a trial subjects drew the layout of the house from memory and answered questions about specific objects within the virtual house and their locations. Active subjects performed better in recreating the layout, but passive subjects had superior knowledge regarding the objects recalled from memory. It should be noted though that active subjects were able to explore both visually and haptically whereas the passive subjects only received visual information – the use of the joystick in the active condition was a confound. Had passive subjects received haptic information by a force-feedback joystick yoked to the active subject's joystick their performance may have been better in the house-layout test. Other studies using comparable tasks are similarly confounded by the use of a joystick (or some other haptic device) in the active route-finding condition but no haptic device in the passive condition. There is some support for the possibility that the use of a joystick by the active subject but not the passive subject does have a differential effect. For example, Gaunet, Vidal, Kemeny and Bethoz (2001) allowed active subjects to use a joystick and reported active superiority, whereas Wilson's (1999) active subjects chose their route using a keyboard and reported no difference between the modes of exploration; it could be argued that operating a keyboard is "less" of a haptic task. The TDS and/or Phantom (as employed in the current research) could be used to remove this confound and provide more flexibility than using force-feedback joysticks.

There would seem to scope to further examine haptic training, particularly in comparisons between active and passive motor learning. Since both the TDS and the Phantom (with the Phantom Explorer software) can exactly match the passive subject's movements to an active counterpart, they should be particularly useful in carrying out research along these lines. For example, Richardson and Wuillemin's (1981) maze task could be replicated using the TDS, and then a maze task in three dimensions using the Phantom could be considered. Kahane, Carlopio, Jarvi and Wickerman (1979) briefly reported an experiment in which mice were quicker to learn a maze if they had practice that involved being wheeled along the correct path in a covered vehicle; however, they did not seem to have included an active learning group, just a control group that appeared to have no extra attention at all. Alvis, Ward and Dodson (1989) guided subjects through a maze, but were interested in gender differences in learning rather than active versus passive learning. There may also be value in more closely examining differences in memory load as a function of active versus passive modes. For example, Kiphart, Hughes, Simmons and Cross (1992) suggest that short term haptic memory decays at different rates for active and passive explorers.

There seems to be no shortage of experiments that could be conducted to help clarify the role of active and passive modes of learning and exploration.

6.3 Vision versus touch

Vision and tactile performance were compared for a matched task. In this instance the term "matched" is not used to indicate that the tasks and all of the circumstances were equivalent, but rather that the mode of information gathering was relevant to each of the two senses and the task did not obviously favour either sense. In the touch condition subjects were guided around raised line capital letters with either the TDS or the Phantom using pre-recorded movement patterns (i.e., subjects were passive). In the visual conditions subjects saw the same movement patterns (rather than the stimulus itself) traced out on a screen. The

rate of display for the visual condition was the same as that for the haptic conditions, ensuring that the rate of information pickup was matched for the two modes. The sequential display for vision meant that that sense was required to integrate information spatio-temporally, as touch naturally does.

Not surprisingly, conditions that involved the most movement resulted in significantly lower latencies to identification. In these conditions the haptic sense benefited from kinaesthesis, while in the visual conditions a 1 cm segment of line could be seen moving around the screen showing where exploration of letter stimuli had taken place. Movement is perhaps one of the most critical cues for all senses: Katz suggested that movement is to touch what light is to vision. Like the other senses, a steady touch stimulus leads to adaptation – we become unaware of the fabric of our clothing or jewellery against our skin.

A more interesting finding in the current research was that haptics and vision performed equally well in terms of latency when both senses had to integrate the information over time. There was no interaction between display mode and sense, so regardless of whether or not the haptic sense involved kinaesthesis, and whether the visual condition involved the trace moving around the screen or remaining in the middle of the screen, a sort of moving window versus stationary window comparison, performance in the haptic and visual conditions did not differ. This is consistent with research in which a window moved over the stimulus, rather than over a representation of the movement pattern. For example, Becker (1935) and Yamane (1935) found that when the visual field of view was limited using a small aperture, the performance of vision and touch can be similar (both cited in Klatzky, Loomis, Lederman, Wake & Fujita, 1993).

In the current research touch was allowed to integrate information over time in a sequential pickup of information, arguably the most "natural" mode of exploration for this sense. However, touch *can* function in a purely spatial mode, with information provided in a simultaneous manner. For example, many active-passive comparisons have involved pressing a cookie cutter shape into the subject's palm. Devices such as the TVSS or the Optacon can also operate in a simultaneous mode, in which the vibrators are activated in the shape of the stimulus all at once and then turned off. While these examples may seem somewhat artificial, touch does sometimes use a simultaneous mode of information gathering. For example, Klatzky, et al. (1993) reported that allowing the hand to mould to an object results in better identification performance than allowing subjects to touch the object with multiple fingers, which in turn was better than restricting the subject to the use of just one finger. Further, Klatzky and Lederman's (1993) exploratory procedures for three-dimensional objects involve grasping with the hand, moulding the hand, and so on. It is not at all uncommon to attempt to use our whole hand to try to touch as much of an object as possible at once. Such a strategy is consistent with Katz's and Gibson's assertion that the hand as a whole functions as an integrated exploratory organ rather than a conglomeration of individual sensory organs (e.g., separate fingers, palm, etc).

Stimulating touch receptors in such a simultaneous manner makes touch operate more like vision does when we glance at a scene and apprehend all of the information at once; although it should be noted that we can seldom *see* everything in that scene at once. We typically need to move our eyes around to shift our focus or foveate in order to optimise the image. The current research would be complemented with additional conditions in which touch and vision operate in a simultaneous manner. It might also be interesting to investigate whether touch can "focus" on a particular element within a global scene (i.e., within its equivalent of a field of view, which would be the complete array of TVSS tactors or the overall surface in contact with the palm), to examine the efficacy of touch when it operates in a manner more like vision. However, such a study would have to take account of the resolving power of the two senses in order to continue to match the conditions "fairly".

There are plans to extend the current vision versus touch paradigm to three dimensions. Norman, Norman, Clayton. Lianekhammy and Zielke (2004) suggested that there are many similarities in how the visual and haptic systems detect three-dimensional shapes, and they both experience inaccuracies in the detection of local three-dimensional surface properties, such as depth and curvature. They used a matching task in which "natural" haptic objects had to be matched to their visual equivalent and vice versa. Klatzky, Lederman and Matula (1993) suggest that vision is likely to dominate or be a preferred (and superior) mode for tasks that involve geometric properties, such as shape, size and complexity. In extending the current research, a challenge will be to devise a visual condition without disadvantaging either sense. However, it is quite likely that haptics will outperform vision, consistent with Ballesteros and Reales' (2004) finding that touch is faster and more accurate when identifying three-dimensional objects than it is with two-dimensional displays. Interestingly, their finding that the reverse trend was true for vision was not replicated in the experiments reported here.

6.4 Loose ends

This section of the chapter is concerned with some issues not specifically tied to the three main experimental areas but of relevance to research on haptics. For example, using a Phantom as a research tool may result in potential limitations in generalising any results because the stimuli are not real, explorers must use a probe rather than being able to freely

palpate the objects using the whole or part of a hand, and the point of contact between the end of the virtual probe and the object being explored is infinitely small. The haptic system is very fast and accurate in the identification of real, common three-dimensional objects (Klatzky, Lederman & Metzger, 198[illegible]), provided that subjects are completely unconstrained in their exploration (Lederman & Klatzky, 2004). The Phantom does not allow such freedom.

Exploring the world with one finger, as is required with the TDS, may be a somewhat unusual method of exploration. It could be argued that exploration with a probe is also atypical. However, explorers have been found to spontaneously use one finger rather than multiple fingers (or multiple hands) at least 50% of the time to explore two dimensional stimuli (Symmons & Richardson, 2000). Further, others have found that using multiple fingers does not improve performance for such stimuli (e.g., Craig, 1985, Lappin & Foulke, 1973). However, exploration of three-dimensional objects may be different.

Jansson (2000) compared three-dimensional object identification of simple geometric objects with a Phantom and "natural" haptic manipulation. In the "real" exploration subjects could use multiple fingers and were not restricted in any way as to the amount of skin surface that could be brought to bear. The real objects were always correctly identified within seconds, while accuracy and exploration time required were substantially longer for virtual objects. Accuracy for the Phantom ranged from 67% for objects of 5 mm (the objects were not described so it is not known what dimension this measurement refers to) to 85% for 10 mm objects, to 96% for objects 50 and 100 mm in size. Exploration time decreased as the size of the object increased. Jansson did not report conditions in which only one finger or a real probe could be used to identify the real objects (the objects could have been mounted on thin vertical rods to allow exploration of most of the surface). It seems likely that performance for these conditions would have been poorer than that observed during "natural" exploration, and possibly equivalent to exploring with the Phantom.

Lederman and Klatzky (2004) did restrict subjects' exploration of real three-dimensional objects. When a single finger was used response times increased substantially compared with "free" exploration, however, recognition accuracy was almost as good. This suggests that the deterioration in performance was a function of having to integrate all of the necessary surfaces using just one finger rather than all of the fingers, the palm and so on, at the same time. Requiring the subject to use a rigid probe further degraded performance both in terms of accuracy and response time: accuracy was 100% for free exploration, around 90% for a single finger and around 40% for a rigid probe. In terms of response time, free exploration took just a number of seconds, a single finger around 30 seconds, and the use of a probe in excess of 80 seconds.

Klatzky, et al. (1993) found that allowing the hand to mould to an object rather than touching it with multiple fingers yielded better performance in identifying the object. Additionally, using multiple fingers resulted in superior performance compared to restricting the subject to the use of just one finger. Yet Klatzky and Lederman (1993) reported that a single finger is a preferred exploratory procedure (they called it contour following) for gaining information about global or local shape of three-dimensional objects.

While exploring with a probe may be unusual, it is not unheard of. For example, blind individuals can skilfully use a cane to navigate through the environment (although the sounds made by tapping the cane against surfaces are as critical to its usefulness for the detection of solid objects – Schenkman & Jannson, 1986). Holding a probe is likely to make the hand the exploring effector rather than the individual fingers physically contacting the probe.

An important difference between a real probe, such as a white cane, and the Phantom's probe relates to the fact that it is not a real, solid device at the point of contact with the (virtual) object – the manipulandum is, of course, physically real. The contact point with the Phantom is infinitely small, and it is not known how subjects perceive the fact that they can not actually touch the point of a corner or the apex of a pyramid or cone. Additionally, comments collected from subjects generally indicate that active subjects perceived the surface as a solid, whereas passive subjects did not. The passive explorers found it difficult to verbalise the experience, but when prompted with the question of whether they felt they were touching a solid surface most responded in the negative. Responses generally approximated the idea that they were simply being dragged around in space, rather than being dragged along a surface. However, this issue may not represent a serious flaw in using the Phantom for such research, as the results obtained for exploring two-dimensional stimuli with the Phantom were consistent with those obtained with the TDS using similar stimuli – namely, passive superiority.

As previously suggested, research on exploration in three dimensions rather than two has more potential applications. A further reason to concentrate on three dimensional objects is that two-dimensional stimuli are impoverished and additional compensatory resources are required to accomplish the task, placing a burden on subjects exploring with a single finger, which leads to poor performance (Klatzky, Loomis, Lederman, Wake & Fujita, 1993). From the point of view of sensory substitution systems, Bach-y-Rita (2003) agreed, claiming that

perceptual systems are invariably handicapped when the input is very impoverished or artificially encoded. Support for there being advantages in maintaining (or even increasing) the complexity of information available to the haptic sense (providing that it is complementary and relevant) can be seen in the haptic sense's ability to make use of a range of disparate types of information integrated across multiple fingers and both hands when using the Tadoma method of speech perception (Reed, et al, 1985).

6.5 A final word

Until relatively recently, most sensory research has concentrated on one particular sense at a time, or when multiple modalities are in question the aim is often to determine which sense dominates the other. However, the senses rarely act in isolation and acknowledgement of this is reflected in an upsurge of multimodal studies. For example, credible and true telepresence will not be achieved without the inclusion of each of the "main" senses, among which touch has recently been counted.

There is also an increased acknowledgement that the brain areas involved in operating the sense organs and interpreting the information received are more multimodal than previously thought. For example, James, Humphrey, Gati, Servos, Menon and Goodale (2002) suggested that the information about the structure of objects may be stored in a similar way by the visual and haptic systems. Amedi and colleagues claimed to have isolated an area of the brain specifically involved in processing information related to objects, activated by visual or haptic inputs but not auditory information (Amedi, Malach, Hendler, Peled & Zohary, 2001; Amedi, Jacobson, Hendler, Malach & Zohary, 2002). This area – the human lateral occipital complex (LOC) – apparently demonstrates a "preference" for graspable geometric objects (Amedi, Hendler, Malach & Zohary, 2002). Some sort of spatial processing centre has been hypothesised for some time. There is functional elegance in not duplicating a common function in multiple areas of the brain, but developing a central mechanism that can provide a common function to multiple senses.

Additionally, areas of the brain once thought to be exclusively used by one sense have been found to be active when information from other senses is being processed. For example, PET scan research has shown that when blind individuals read Braille, areas of the brain thought to be the preserve of vision were active, indicating cross-modal plasticity (Sadato, Pascual-Leone, Grafman, Ibanez, Deiber, Dold & Hallett, 1996; Hamilton & Pascual-Leone, 1998; Cohen et al, 1997).

It is suggested that the sense of touch is more capable and more useful than it is given credit for being; that there is a general lack of appreciation for the "...amazing capabilities of the sense of touch" (Bliss, 1970, p. 1). Examples of these capabilities abound, such as the impressive success of the Tadoma method. Experienced users of devices that provide additional or new information to the skin often "forget" and no longer notice that they are receiving vibration on their back, for example, but rather describe the experience in terms that suggests that they can "see" the object. A congenitally blind person can come to "see" and understand traditionally visual concepts such as parallax, perspective, depth, looming and zooming; and even the impression of a flickering flame (Bach-y-Rita, Tyler & Kaczmarek, 2003). Touch has the extraordinary ability to resolve the two dimensional output from a video camera into the perception of three-dimensional concepts such as perspective (Collins, 1977). Bach-y-Rita (2003) had an individual without peripheral sensation wear a glove that provided touch sensory information to the forehead. After becoming accustomed to the device the wearer experienced the glove-generated stimulation as though it was being presented to their fingers rather than their forehead[1].

For multimodal research to be truly useful, an important prerequisite may be sufficient knowledge of the capabilities, specialisations, and limitations of each sense on its own. It was asserted earlier that haptics research has not received as much attention as that devoted to vision and hearing. Accordingly, there are significant gaps in knowledge about haptics. For example, previous research has suggested that kinaesthesis is probably the most important element in the haptics experience, but more specific testing of individual components did not seem to have been reported thus far, and results reported here cast doubt on the necessary superiority of kinaesthesis. Additionally, there is a significant body of research concerning the issue of active versus passive touch for two dimensional stimuli. However, a lack of consistency in approaching this issue and potential confounds in the way it was tested mean that the question is far from resolved. More importantly, from the point of view of potential applications, there would seem to be no published research rigorously comparing active and passive touch for three-dimensional stimuli – an issue with significantly greater scope for application than the exploration of two-dimensional stimuli. The current research aimed to shed light on all of these matters. Possibly the most immediate and interesting implications of the results reported here concern two separate but related applications: telepresence and passive skill learning.

Haptic feedback devices available for use in telepresence applications are currently somewhat rudimentary. The results of Chapter 3 demonstrate the importance of including

[1] It should be noted that 'distal attribution' does not always occur. Epstein, et al. (1986) had naïve subjects wear an Optacon camera on their head, ostensibly to keep their blindfold on. Almost none of the subjects realised that it was the movement of their head that was producing the changes in the stimulation at their fingertip, or, for that matter, that they were wearing a camera on their head.

kinaesthesis as part of a high-fidelity haptic feedback system. However, the results also suggest that depending on the nature of the task to be monitored, there may be sufficient information in kinaesthesis alone. Alternatively, sufficient information may be available to the operator by providing a moving tangible line (or some other discriminable texture) underneath a stationary effector such as a finger. If this truly is sufficient information to reach a criterion performance for any particular application then devices that do not require kinaesthetic feedback would be significantly cheaper and easier to build and operate. The results of Chapter 5 indicate that touch can be as good as vision when the comparison is "fair". In many telepresence systems (and other systems with a rich information flow, such as aeroplane cockpits) additional information is provided to an operator who is not physically present to experience the environment (e.g., changes in temperature relative to ambient temperature). Generally, this sort of information is provided as a visual readout. Therefore, the overall visual display is often cluttered with a plethora of readouts, dials and gauges. It may be possible to convert some of these displays to haptic feedback, particularly since high-fidelity haptic feedback is still in development. For example, Schrope (2001) described a flight suit with in-built tactors placed to stimulate areas over the whole body. The tactors provided orientation information in relation to the ground and enabled pilots to quickly tell up from down. The provision of information in this manner was apparently very intuitive and "natural", such that with only minutes of training military pilots could fly blindfolded, even executing loop-the-loop and backward loop manoeuvres and "just knowing" when to level out.

Most of the active versus passive research reviewed here and in Symmons (2000) related to the identification of stimuli, whether it was naming the shape, matching it to a set of standards, or estimating roughness. No other studies were found examining this issue for three-dimensional stimuli. The current results indicate that active exploration produces superior performance for naming simple three-dimensional geometric shapes. However, if a type of stimulus or skill can be found in which the passive mode is superior or there is no difference between the modes, then there are significant implications for skills transfer. For example, an expert's skill could be recorded and used to teach many learners, or an expert could, in real time, teach a learner who is not present with the teacher. Even if such a paradigm were useful only for providing an overview which had to be followed by traditional trial and error learning, the attraction of starting with an elite "pattern" coupled with the advantages of only having to make a one-off recording from the elite operator for repeated and mass use, may make it a viable technique.

7. APPENDICES

Tables appearing in the appendices

Figures appearing in the appendices

7.1 Selected SPSS output

This section of the Appendix contains SPSS output used in the thesis. It is divided into sub-sections according to the relevant chapter. Only the statistics are reported here, see the relevant chapters in the thesis for a description and interpretation of the statistics.

Where the data are non-linear, SPSS provides one option for methodically dealing with missing data – insertion of the mean for that series. In the current data missing values occurred where subjects did not correctly identify the stimulus within the allotted time.

7.1.1 SPSS Output for Chapter 3

As conducted, Experiment 2 included eight rather than the seven conditions reported in Chapter 3. The condition not reported in the text of the thesis involved moving a plain surface underneath a stationary fingertip resting on a block of foam rubber. The purpose of this condition was to isolate and maximise a factor called "tug" (T), which refers to the forces that occur at the point(s) of contact between the finger and finger holder on the TDS. Tug was always present to some degree in each of the conditions tested because the subject's finger was held by the finger holder in each condition, and so it was an artefact of the testing procedure.

However, tug was maximised in the condition using a foam block and minimised when the fingertip was covered with sticky tape, and so some estimate can be made on the basis of its presence. Accordingly, both the latency and accuracy data were analysed with and without the maximal tug condition. The condition means remain the same, but the inferential statistics change with the inclusion of the tug factor.

Note that the names of the conditions below reflect the analyses performed with tug included as a factor. Within the text of the thesis (principally in Chapter 3) the conditions are named without tug, for instance L+T+S listed here is called L+S in the text. Additionally, the S condition takes the notation S_m in the text (minimal shear from moving a plain surface underneath a taped stationary fingertip).

<u>*Latencies of response to stimuli presented in eight conditions containing various haptic components, including "tug".*</u>

Table 7.1.1 contains latency summary statistics for each of the haptic component conditions tested in Experiment 2. Mean latency, with standard error, is plotted in Figure 3-2 (p. 36). Note that the tug condition is shown in the table but not included in Figure 3-2, but it is shown in Figure 7.1-1.

Table 7.1.1 *Mean, Standard Deviation and Standard Error for Latency for Each Haptic Condition Tested in Experiment 2, Along With Number of Missing Values Replaced With Series Mean*

Condition Name	Condition Num.	Mean	Std Dev	Std. Err	No. of missing values replaced
klts	1	13.692	5.4821	1.001	4
kts	2	16.583	6.4322	1.174	6
k	3	15.115	6.8849	1.257	4
lts	4	16.045	5.7023	1.041	8
ts	5	19.800	3.7856	.691	20
s	6	18.333	4.2885	.783	24
l	7	18.947	6.1278	1.119	11
t	8	22.125	2.8700	.524	22

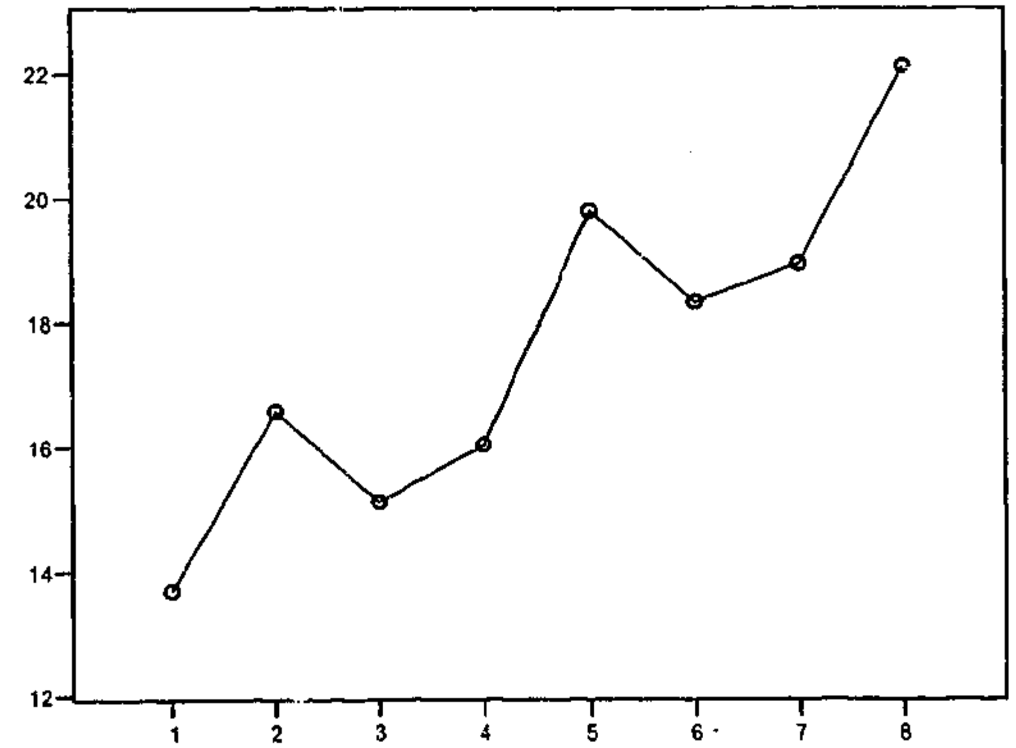

Figure 7.1-1. *Plot of latency means, x-axis values correspond to conditions in Table 7.1.1.*

Within-subjects ANOVAs were calculated for latency across haptic conditions both with and without the tug condition, with the latter reported in Chapter 3. In both instances tests for sphericity were non-significant (see Table 7.1.2), thus sphericity-assumed ANOVA statistics are reported in Table 7.1.3.

Table 7.1.2 *Mauchly Sphericity Statistics for Latency, With and Without the Tug Condition*

	Mauchly's W	Approx. Chi-	df	Sig.	Greenhouse -Geisser
With tug	.285	33.227	27	.194	.793
Without tug	.607	13.347	20	.863	.873

Table 7.1.3 *ANOVA Test of Within-Subjects Effects (Sphericity Assumed), With and Without Tug Condition*

	Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squ
With tug	factor	1576.779	7	225.254	8.975	.000	.236
	Error	5094.829	203	25.098			
Without tug	factor	868.623	6	144.770	5.179	.000	.152
	Error	4864.224	174	27.955			

Following the statistically significant result yielded by the within-subjects ANOVA performed on the latency data, pair-wise comparisons were conducted using the least significant difference method (see Table 7.1.4).

Table 7.1.4 *Pair-wise Comparisons of Latencies for Haptic Conditions Tested in Experiment 2. Shaded Cells Indicate Statistically Significant Differences*

I	J	I-J	Std. Err	Sig
klts	kts	-2.891(*)	1.367	.043
	k	-1.423	1.542	.364
	lts	-2.353	1.339	.089
	ts	-6.108(*)	1.140	.000
	s	-4.641(*)	1.263	.001
	l	-5.255(*)	1.290	.000
	t	-8.433(*)	.872	.000
kts	k	1.468	1.541	.349
	lts	.538	1.484	.720
	ts	-3.217(*)	1.264	.016
	s	-1.750	1.402	.222
	l	-2.364	1.423	.108
	t	-5.542(*)	1.248	.000
k	lts	-.930	1.335	.492
	ts	-4.685(*)	1.252	.001
	s	-3.218(*)	1.534	.045
	l	-3.832(*)	1.650	.027
	t	-7.010(*)	1.294	.000
lts	ts	-3.755(*)	1.213	.004
	s	-2.288	1.364	.104
	l	-2.902	1.443	.054
	t	-6.080(*)	.983	.000
ts	s	1.467	.979	.145
	l	.853	1.353	.534
	t	-2.325(*)	.867	.012
s	l	-.614	1.322	.646
	t	-3.792(*)	.944	.000
l	t	-3.178(*)	1.052	.005

__Number of correct responses to stimuli presented in eight conditions containing various haptic components, including "tug".__

Table 7.1.5 contains summary statistics for the number of stimuli correctly identified for each of the haptic component conditions tested in Experiment 2. Mean number correct, with standard error, is plotted in Figure 3-3 (p. 37). Note that the tug condition is shown in the table but not included in Figure 3-3, however it is shown in Figure 7.1-2. Maximum possible accuracy score is three.

Table 7.1.5 *Mean, Standard Deviation, and Standard Error for Accuracy for Each Haptic Condition Tested in Experiment 2*

Condition Name	Condition Num.	Mean	Std Dev	Std. Error	N
klts	1	1.73	.458	.118	15
kts	2	1.73	.594	.153	15
k	3	1.67	.488	.126	15
lts	4	1.47	.640	.165	15
ts	5	.67	.724	.187	15
s	6	.53	.743	.192	15
l	7	1.20	.775	.200	15
t	8	.53	.743	.192	15

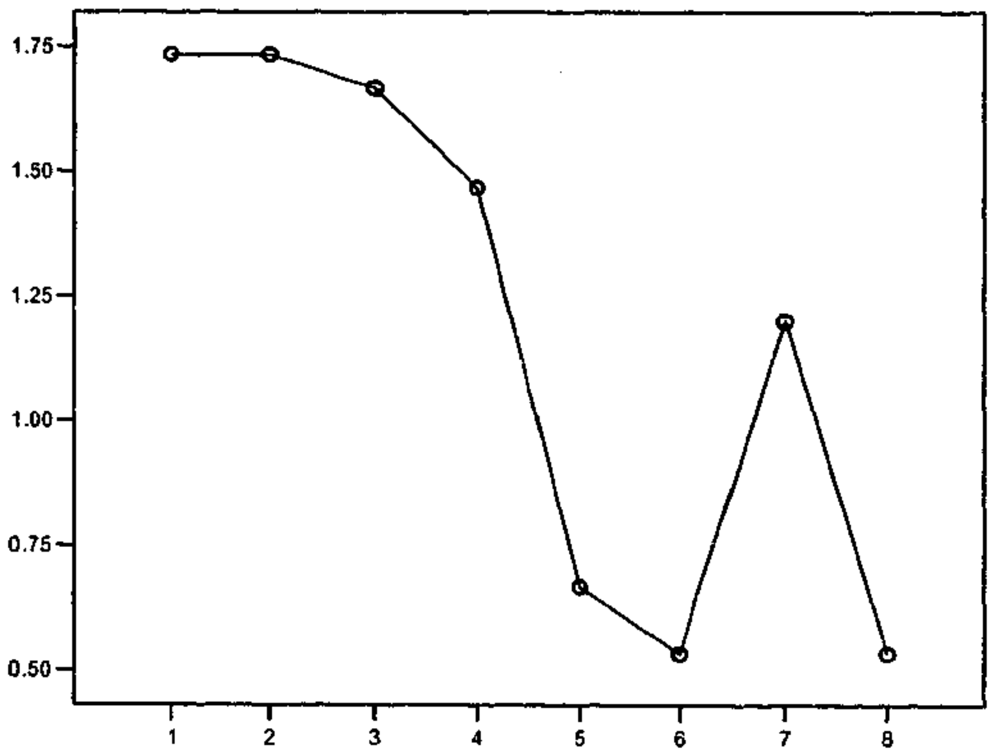

Figure 7.1-2. *Plot of mean number of stimuli correctly identied, x-axis values correspond to conditions in Table 7.1.5.*

Within-subjects ANOVAs were calculated for accuracy across haptic conditions both with and without the tug condition, with the latter reported in Chapter 3. The results of Mauchly's Sphericity tests are shown in Table 7.1.6 and the within-subjects ANOVA statistics are shown in Table 7.1.7. With tug included, sphericity was statistically significant

and so the Greenhouse-Geisser correction factor is shown in Table 7.1.7. The adjusted ANOVA was reported in Chapter 3.

Table 7.1.6 *Mauchly Sphericity Statistics for Accuracy, With and Without the Tug Condition*

	Mauchly's W	Approx. Chi-	df	Sig.	Greenhouse -Geisser
With tug	.008	55.036	27	.002	.598
Without tug	.087	28.711	20	.104	651

Table 7.1.7 *ANOVA Test of Within-Subjects Effects, With and Without the Tug Condition*

	Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squ
With tug	factor	Sphericity Assumed	30.458	7	4.351	10.42	.000	.427
		Greenhouse-Geisser	30.458	4.2	7.280			
	Error	Sphericity Assumed	40.917	98	.418			
		Greenhouse-Geisser	40.917	58.6	.699			
Without tug	factor	Sphericity Assumed	23.029	6	3.838	8.998	.000	.391
	Error	Sphericity Assumed	35.829	84	.427			

Following the statistically significant result yielded by the within-subjects ANOVA performed on the accuracy data, pair-wise comparisons were conducted using the least significant difference method (see Table 7.1.8).

Table 7.1.8 *Pair-wise Comparisons of number correct for Haptic Conditions Tested in Experiment 2. Shaded Cells Indicate Statistically Significant Differences*

I	J	I-J	Std. Error	Sig.
klts	kts	.000	.195	1.000
	k	.067	.153	.670
	lts	.267	.182	.164
	ts	1.067(*)	.182	.000
	s	1.200(*)	.223	.000
	l	.533(*)	.215	.027
	t	1.200(*)	.175	.000
kts	k	.067	.153	.670
	lts	.267	.228	.262
	ts	1.067(*)	.228	.000
	s	1.200(*)	.312	.002
	l	.533	.274	.072
	t	1.200(*)	.279	.001
k	lts	.200	.243	.424
	ts	1.000(*)	.195	.000
	s	1.133(*)	.236	.000
	l	.467	.291	.131
	t	1.133(*)	.192	.000
lts	ts	.800(*)	.243	.005
	s	.933(*)	.228	.001
	l	.267	.228	.262
	t	.933(*)	.228	.001
ts	s	.133	.307	.670
	l	-.533	.274	.072
	t	.133	.133	.334
s	l	-.667	.319	.055
	t	.000	.258	1.000
l	t	.667(*)	.287	.036

7.1.2 SPSS Output for Chapter 4

This section contains selected SPSS output for the analyses conducted for active-passive comparisons in two and three dimensions, as reported in Chapter 4.

Use of the Phantom and the TDS to identify 2-dimensional pictures

In Experiment 4 the Phantom was used to explore two-dimensional stimuli. This was then compared to a re-analysis of data collected in an earlier experiment in which the same stimuli were explored using the TDS. Table 7.1.9 contains the means and standard deviations for latency for both the Phantom and TDS conditions. A between-subjects t-test (see Table 7.1.10) was reported specifically for the active-passive comparison using the Phantom, although for a one-tailed test rather than the two-tailed result contained in Table 7.1.10.

Table 7.1.9 *Means, Standard Deviations and N for Latencies Using the TDS and Phantom to Explore 2-Dimensional Stimuli in Experiment 4 in Active and Passive Modes*

Device	Mode	Mean	Std. Deviation	N
Phantom	Active	60.9286	27.26009	36
	Passive	52.2222	23.21890	36
	Total	56.5754	25.52062	72
TDS	Active	64.3833	14.43174	36
	Passive	56.7222	22.07722	36
	Total	60.5528	18.91613	72
Overall	Active	62.6560	21.72601	72
	Passive	54.4722	22.60896	72
	Total	58.5641	22.47254	144

Table 7.1.10 *Levene's Homogeneity of Variance Statistic and Between-Subjects t-Test for Latency for Exploration of 2-Dimensional Stimuli Using the Phantom*

Levene's Test		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Diff
F	Sig.					
.003	.956	1.459	70	.149	8.7063	5.96804

A two-way between-groups ANOVA was conducted using the Phantom and TDS data (see Table 7.1.9 for means). A Levene's test for homogeneity of variance yielded a non-significant result ($F(3, 140) = 0.705$; $p=0.55$). The ANOVA results are contained in Table 7.1.11; the difference between the devices ("Device") was not significant, but the difference between active and passive modes of exploration ("group") was statistically significant.

Table 7.1.11 *Two-Way ANOVA for Latency Data Using the Phantom Versus Using the TDS to Explore 2-Dimensional Stimuli in Active and Passive Modes*

Source	Type III Sum of Squares	df	Mean Sq	F	Sig.	Partial Eta Sq	Obs Power
Corrected Model	2990.38	3	996.79	2.016	.114	.041	.509
Intercept	493884.33	1	493884.33	998.801	.000	.877	1.000
Device	569.50	1	569.50	1.152	.285	.008	.187
grp	2411.04	1	2411.04	4.876	.029	.034	.592
Device * grp	9.83	1	9.83	.020	.888	.000	.052
Error	69226.79	140	494.47				
Total	566101.50	144					
Corrected Total	72217.17	143					

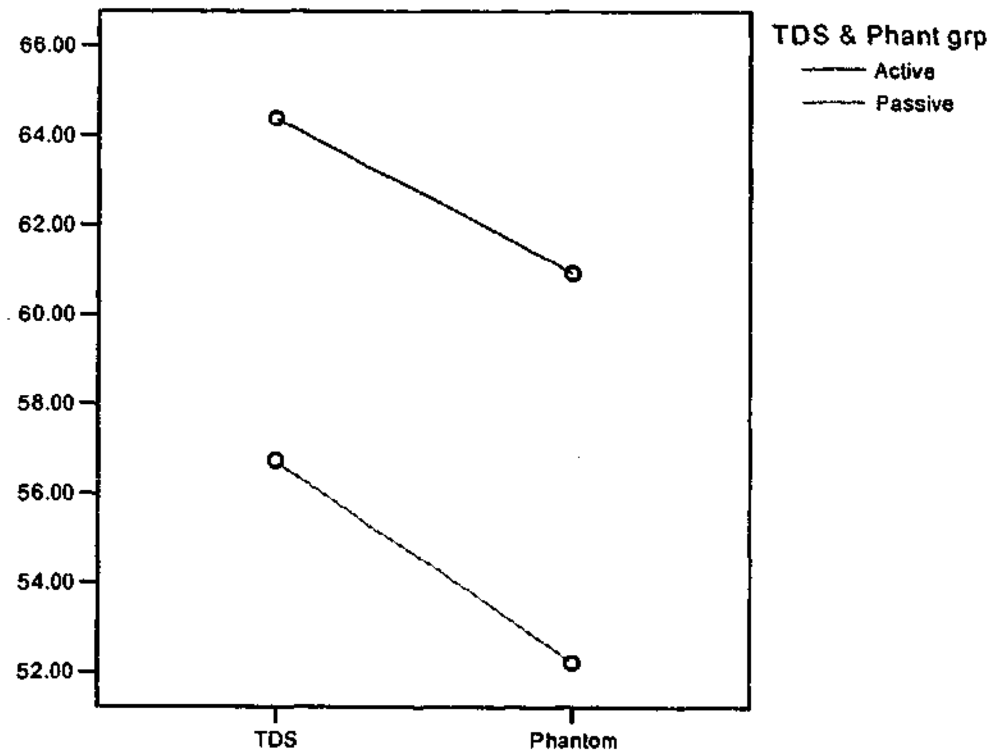

Figure 7.1-3. *Plot of mean latencies for active (upper line) and passive (lower line) exploration using the TDS and the Phantom*

<u>*Using the Phantom to Explore 3-D virtual objects in active and passive modes*</u>

Experiments 5 and 6 reported active and passive exploration of three-dimensional virtual shapes using the Phantom. In Experiment 5 the active explorer's movements were recorded and later used to guide a passive subject, while in Experiment 6 two Phantoms were used and the passive subject was guided by the active subject in real time; this was called delayed and real-time yoking, respectively. In Experiment 6 each subject was tested in both an active and passive condition, which meant that two active-passive comparisons were available within these data. The performance of each active subject was compared with that of their yoked passive counterpart, and each subject's active performance was compared with their own passive performance. Table 7.1.12 contains the mean, standard deviation and standard error of latencies for active and passive exploration in each of these conditions.

Table 7.1.12 *Mean, Standard Deviation and Standard Error of latencies for Active and Passive Exploration as a Function of Yoking Mode (Delayed and Real-Time) and Comparison of Own Active and Passive Performance*

Comparison		N	Mean	SD	Std. Error Mean
Delayed yoking	Active	30	21.96	15.984	2.918
	Passive	30	32.00	12.578	2.296
Real-time yoking	Active	17	45.76	41.472	10.058
	Passive	17	70.24	49.011	11.887
Active vs own passive	Active	16	41.00	37.722	9.430
	Passive	16	63.38	41.337	10.334

The delayed-yoking active-passive comparison was tested using a between-subjects t-test (see Table 7.1.13), yielding a significant result. The real-time yoking and active versus own passive comparisons were analysed using within-subjects t-tests (see Table 7.1.14); both were statistically significant with one-tailed tests.

Table 7.1.13 *Levene's Homogeneity of Variance Statistic and Between-Subjects t-Test for Latencies in Delayed-Yoking Exploration of 3-Dimensional Stimuli Using the Phantom*

Levene's		t-test for Equality of Means				
F	Sig.	t	df	Sig. (2-tail)	Mean Diff	Std. Error Diff
1.271	.264	-2.703	58	.009	-10.04	3.713

Table 7.1.14 *Within-Subjects t-Tests on Latencies for Real-Time Yoking and the Comparison Between a Subject's Active and Their Own Passive Latencies*

	Paired Differences			t	df	Sig.
	Mean	SD	Std. Error Mean			2-tail
Real-time yok..g	24.47	41.60	10.090	-2.425	16	.027
Active vs own passive	22.37	45.99	11.497	-1.946	15	.071

The delayed- and real-time yoking paradigms were compared using a two-way between-groups ANOVA. Table 7.1.15 contains the means and standard deviations of each approach and overall for active and passive modes. Figure 7.1-4 is a plot of the mean latencies for active and passive exploration for real-time yoking and delayed yoking. The ANOVA revealed that latency was significantly lower for the delayed presentation of stimuli compared with real-time presentation, and for active rather than passive exploration. The interaction between these two variables was not statistically significant (see Table 7.1.16). However, a Levene's test of Homogeneity of Variance yielded a significant result ($F(3,90)$=18.8; p<0.0005). Accordingly, two Mann-Whitney tests were conducted for yoking method and exploratory mode, and both yielded significant results (see Table 7.1.17 for ranking statistics and Table 7.1.18 for Mann-Whitney U statistics).

Table 7.1.15 *Latency Mean and Standard Deviation for Active and Passive Exploration as a Function of Yoking Mode (Delayed and Real-Time)*

Yoking	Active vs passive	Mean	SD	N
Real-time	Active	45.7647	41.47217	17
	Passive	70.2353	49.01088	17
	Total	58.0000	46.39815	34
Delayed	Active	21.9615	15.98379	30
	Passive	32.0000	12.57803	30
	Total	26.9808	15.13136	60
Total	Active	30.5712	29.88243	47
	Passive	45.8298	35.77850	47
	Total	38.2005	33.67015	94

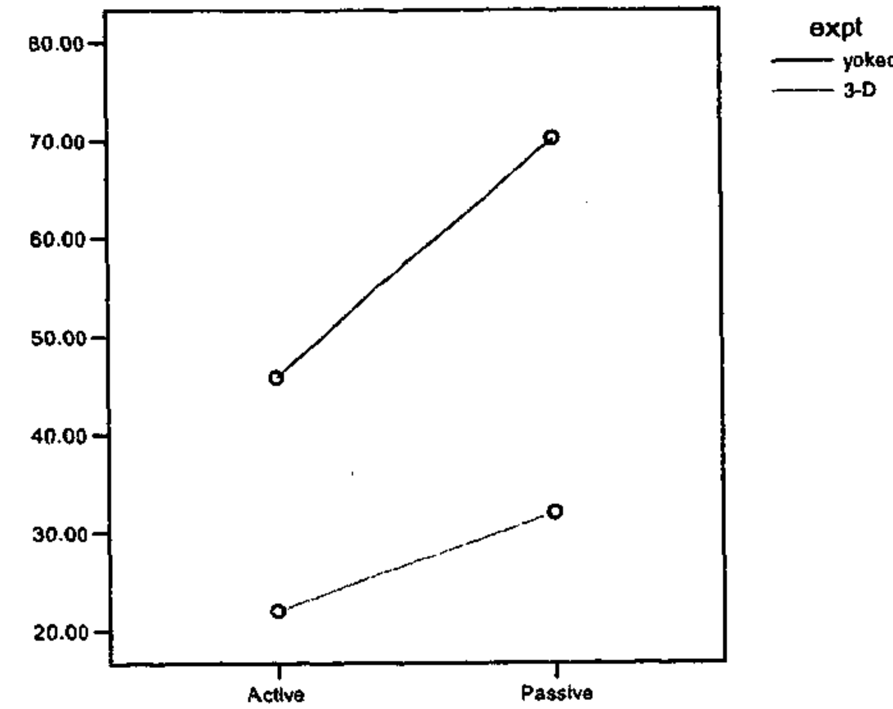

Figure 7.1-4. *Mean latencies for active and passive exploration for real-time yoking (yoked – upper line) and delayed yoking (3-D – lower line).*

Table 7.1.1 *wo-Way ANOVA for Latency Comparing Phantom Yoking Methods (Delayed and Real-ne) and Mode of Exploration (Active and Passive)*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Sq	Obs Power
Corrected Model	27483.071	3	9161.024	10.577	.000	.261	.999
Intercept	156726.931	1	156726.931	180.957	.000	.668	1.000
Yoking method	20881.628	1	20881.628	24.110	.000	.211	.998
Active v passive	6461.128	1	6461.128	7.460	.008	.077	.771
yoking * act-pass	1130.064	1	1130.064	1.305	.256	.014	.204
Error	77949.079	90	866.101				
Total	242604.237	94					
Corrected Total	105432.151	93					

Table 7.1.17 *Mean Rank and Sum of Ranks for Active-Passive and Yoking Comparisons*

		N	Mean Rank	Sum of Ranks
Mode	Active	47	37.39	1757.50
	Passive	47	57.61	2707.50
	Total	94		
Yoking	Real-time	34	59.60	2026.50
	Delayed	60	40.64	2438.50
	Total	94		

Table 7.1.18 *Non-Parametric Statistics for Active-Passive and Yoking Comparisons: Mann-Whitney U, Wilcoxon, Z and Significance*

Comparison	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)
Active-passive	629.500	1757.500	-3.594	.000
Yoking	608.500	2438.500	-3.240	.001

7.1.3 SPSS Output for Chapter 5

Chapter 5 describes two experiments comparing vision and haptics on a matched task using capital letters as stimuli. In Experiment 7 the Phantom was used to explore the stimuli in the haptic task, while the TDS was used in Experiment 8.

Table 7.1.19 contains the means, standard deviations, standard errors and number of missing values replaced with series mean for Experiment 7, in which capital letters were explored with the Phantom and visual representations of the haptic movement path were presented using the HVTP. The groups were compared using a within-subjects ANOVA. The assumption of sphericity was violated (see Table 7.1.20) and so an ANOVA result adjusted using the Greenhouse-Geisser method was reported in Chapter 5 (see Table 7.1.21). Table 7.1.22 shows the LSD pair-wise comparisons for the three groups.

Table 7.1.19 *Mean, Standard Deviation and Standard Error of Latencies for Stimuli Explored with a Phantom, and Two Visual Conditions. Moving and Stationary Hole*

	N	Mean	SD	Std. Error	No. of missing values replaced
haptic	18	12.83	4.515	1.064	0
mov_hole	18	11.94	4.108	.968	0
stat_hol	18	20.692	12.9269	3.047	5

Table 7.1.20 *Mauchly's Sphericity Statistics for Experiment 7 Comparing Phantom Haptic Exploration With Vision Conditions Moving and Stationary Hole*

Mauchly's W	Approx. Chi-sq	df	Sig.	Greenhouse -Geisser
.368	15.989	2	.000	.613

Table 7.1.21 *Within-Subjects ANOVA for Experiment 7 Comparing Latencies for Phantom Haptic Exploration With Vision Conditions Moving and Stationary Hole*

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Sq	Obs Power
factor1	Sphericity Assumed	834.472	2	417.236	6.582	.004	.279	.884
	Greenhouse-Geisser	834.472	1.226	680.870	6.582	.014	.279	.741
Error	Sphericity Assumed	2155.177	34	63.388				
	Greenhouse-Geisser	2155.177	20.835	103.440				

Table 7.1.22 *Pair-wise Comparison of Latencies for Experiment 7 Comparing Phantom Haptic Exploration With Visual Conditions of Moving and Stationary Hole. Shaded Cells Indicate Statistically Significant Differences*

I	J	I-J	Std. Error	Sig.
haptic	mov_hole	.889	1.263	.491
	stat_hol	-7.859(*)	3.299	.029
mov_hole	haptic	-.889	1.263	.491
	stat_hol	-8.748(*)	2.942	.009

A within-subjects ANOVA was used to compare latencies for the three letters used as stimuli in Experiment 7. Table 7.1.23 contains the summary statistics for each letter. A Mauchly's test of sphericity yielded a significant result (see Table 7.1.24) and so a Greenhouse-Geisser adjustment was made to the ANOVA result as reported for Experiment 7 (see Table 7.1.25 for ANOVA statistics). There was no stimulus-based effect (see Tables 7.1.25 and 7.1.26 – pair-wise comparisons).

Table 7.1.23 *Mean, Standard Deviation and Standard Error of Latencies for Letter Stimuli Explored with a Phantom, and Two Visual Conditions: Moving and Stationary Hole*

Stim	N	Mean	SD	Std. Error	No. of missing values replaced
B	18	12.471	11.0938	2.615	1
K	18	16.750	9.4899	2.237	2
E	18	14.687	4.6364	1.093	2

Table 7.1.24 *Mauchly's Sphericity Statistics for Experiment 7 Comparing Phantom Haptic Exploration With Visual Conditions Moving and Stationary Hole for Stimuli*

Within Subjects	Mauchly's W	Approx. Chi-Sq	df	Sig.	Greenhouse -Geisser
factor1	.650	6.881	2	.032	.741

Table 7.1.25 *Within-Subjects ANOVA for Latencies for Stimuli Used in Experiment 7 for Phantom Haptic Exploration With Visual Conditions Moving and Stationary Hole*

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squ	Obs Power
factor1	Sphericity Assumed	164.892	2	82.446	1.029	.368	.057	.215
	Greenhouse-Geisser	164.892	1.482	111.265	1.029	.351	.057	.187
Error(factor1)	Sphericity Assumed	2725.388	34	80.158				
	Greenhouse-Geisser	2725.388	25.194	108.178				

Table 7.1.26 *Latency Pair-wise Comparisons for Stimuli Used in Experiment 7 for Phantom Haptic Exploration With Visual Conditions Moving and Stationary Hole.*

I	J	I-J	Std. Error	Sig
B	K	-4.279	3.681	.261
	E	-2.217	2.955	.463
K	B	4.279	3.681	.261
	E	2.063	2.106	.341
E	B	2.217	2.955	.463
	K	-2.063	2.106	.341

In Experiment 8, haptic exploration of letters using the TDS was compared with the moving and stationary hole visual conditions using the HVTP. Only one haptic condition was possible in Experiment 7, as the Phantom can only be used with kinaesthesis. The TDS, however, was used to administer two haptic conditions in Experiment 8. A kinaesthesis condition (moving haptic) corresponded to the moving hole vision condition, while another haptic condition without kinaesthesis (stationary haptic) corresponded to the stationary hole vision condition.

Experiment 8 was a mixed-design, with visual versus haptic conditions as the between-subjects factor and moving versus stationary (within the haptic and vision conditions) as the within-subjects factor. Table 7.1.27 contains the latency means and standard errors for the visual versus haptic comparison. Table 7.1.28 contains the between-subjects portion of the mixed-design ANOVA, indicating a non-significant difference between the modes. Table 7.1.29 then contains the summary statistics for the within factor of moving versus visual presentation, a comparison that was statistically significant (see Table 7.1.30).

Table 7.1.27 *Mean and Standard Error of Latencies for Visual Conditions Administered Using the HVTP and the Haptic Conditions Administered Using the TDS: Experiment 8*

Mode	N	Mean	Std. Error
Vision	14	14.409	1.106
Haptic	14	15.107	1.106

Table 7.1.28 *Between-Subjects ANOVA for Latencies in Visual and Haptic Conditions in Experiment 8*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Intercept	12197.119	1	12197.12	355.80	.000	.932
bw_grp	6.817	1	6.82	.199	.659	.008
Error	891.281	26	34.28			

Table 7.1.29 *Mean and Standard Deviation of Latencies for Stimuli Presented in Moving and Stationary Modes for Both Vision and Haptic Conditions*

Presentation	Mode	Mean	SD	N
Moving	Vision	12.0714	3.79198	14
	Haptic	14.0000	6.11430	14
	Total	13.0357	5.08798	28
Stationary	Vision	16.7473	6.04643	14
	Haptic	16.2143	5.90539	14
	Total	16.4808	5.87089	28

Table 7.1.30 *Within-Subjects ANOVA for Latencies for Moving Versus Stationary Presentation Modes in Experiment 8*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squ
factor1	166.158	1	166.158	6.082	.021	.190
factor1 * bw_grp	21.207	1	21.207	.776	.386	.029
Error(factor1)	710.276	26	27.318			

7.2 *Table of latencies & correct responses for Experiment 2*

Table 7.2.1 contains the mean latencies and number of stimuli correctly identified for each haptic component tested in Experiment 2. These values are displayed in Figures 3.2 (see page 36) and 3.3 (see page 36). Note that Table 7.2.1 includes the "Tug" condition (see section 7.1.1 for an explanation), however this condition is not included in Figures 3.2 and 3.3.

Table 7.2.1 *Means & Standard Deviations for Latency & Number Correct for Each Haptic Condition Tested in Experiment 2*

Haptic condition	Latency (sec)		No. correct	
	Mean	Std dev	Mean	Std dev
K+L+S	13.7	5.9	1.73	0.46
K+S	16.6	7.2	1.73	0.59
K	15.1	7.4	1.67	0.49
L+S	16.1	6.7	1.47	0.64
S	19.8	6.8	0.67	0.72
S_m	18.3	10.3	0.53	0.74
L	19.0	7.8	1.20	0.78
T	22.1	5.8	0.53	0.74

7.3 *Analyses of Experiment 2 data on the basis of stimuli*

The presentation of stimuli in Experiment 2 was randomly ordered and each letter was used approximately equally often (see Table 7.3.1). Any effects due to individual letters being easier than others to identify should therefore be distributed amongst the haptic conditions. However, for completeness the data were analysed on the basis of the stimuli used.

Mean latencies across participants and conditions ranged from 15 seconds for the letter B up to 26 seconds for the Q – out of a maximum of 30 seconds (see Table 7.3.1). A between- groups ANOVA indicated that the overall effect of letters on latency was significant ($F(8,231)=4.485$; $p<0.0005$).

Table 7.3.1 *Number of Times Each Letter Used (N), Mean & Standard Deviation of Response Latency, Min & Max Latency, Number of Correct Identifications*

Stimulus letter	N	Latency (seconds)				No. correct
		Mean	SD	Min	Max	
A	27	22.3	8.9	10	30	13
B	27	14.9	6.6	9	30	25
G	26	24.5	7.7	10	30	12
K	28	22.1	7.8	10	30	18
M	28	24.4	7.7	9	30	12
Q	27	26.0	6.2	12	30	16
R	26	23.0	8.1	5	30	17
X	25	21.9	9.6	5	30	14
Z	26	18.8	10.3	5	30	16

Pair-wise comparisons (least significant difference) were used to assess which letters were statistically different (with $\alpha = 0.05$). All of the significant differences related to the letter B and the letter Z. B was identified significantly more quickly than all of the other letters except Z, which in turn was significantly more quickly recognised than the G, the M and the Q. The letter B was also correctly identified most often (in 25 of the 27 instances of use – 93%). The letter identified least often was the M (12 out of 28 – 43% correct identifications). It is not clear why the letter B should produce superior performance – it would seem to be no easier to identify than the letter Q. The answer may not relate to the ease of identifying the B, but rather to a possible uniqueness. The letter B may not be easier to identify in an absolute sense,, but may be more discriminable, or less likely to be confused with another letter.

Figure 7.3-1 displays a confusion matrix for the stimuli used in this experiment – summarising participant's responses for each of the capital letters used. As evidenced by earlier analyses, but shown here, most of the stimuli were correctly named across conditions more often than not (the exceptions being the M at 43%, G at 46%, and the A at 48%). An examination of the confusion matrix demonstrates that in many instances where the letter was not correctly identified the guess was "close" in that the response and stimulus were often alike. For example, the G was often confused with the letters C and O, Q with O, M with N, and the R was confused with the letter B. Interestingly, the greatest concentration of incorrect guesses occurred in two cells when the M stimulus was used.

The confusion of the M with the letter I would indicate that participants did not "notice" the diagonals of the stimulus. In regards to the confusion between the M and the W, participants may have been aware of the two diagonals and the two verticals and "W" came to mind first (although it appears later in the alphabet). An alternative explanation may relate to the fact that when the M is rotated it "becomes" a W (see Experiment 3 in which rotated figures are used as stimuli).

Resp \ Stim	A	B	G	K	M	Q	R	X	Z
A	13							1	
B	1	25		1			4		1
C			3			1			
D			1			1	1		
E	1								1
F	1			1				1	
G			12						
I					6				
J				1				1	
K				18					1
M			1		12				
N	2			1	4			1	
O			3			3			1
P	1		1				3		
Q						16			1
R	1			2		1	17		
S			2			1			
T									1
U			1						
W	1				6			1	
X								14	1
Y								2	
Z									16
No resp	6	2	2	4		4	1	3	3

Figure 7.3-1. *Number of responses elicited for each stimulus presented by the TDS. Shaded cells indicate congruence between stimulus & response.*

Mapping the correct letter identification according to the touch condition produces the distribution illustrated in Table 7.3.2. While most often identified overall, the B stimulus was not the most identified in each condition. Indeed no particular letter was identified most often – or even near most often – across the conditions.

Table 7.3.2 *Distribution of Correct Letter Identifications Across Conditions*

Letter	K+L+S	K	K+S	L+S	S	S_m	L	T	Total
A	2	2	5	3	0	0	0	1	13
B	3	4	5	3	3	1	5	1	25
G	3	4	3	1	0	0	1	0	12
K	5	3	1	1	3	1	3	1	18
M	5	1	0	2	2	1	1	0	12
Q	1	4	3	5	1	0	1	1	16
R	1	1	4	4	0	2	3	2	17
X	3	2	1	2	0	2	4	0	14
Z	3	4	4	1	1	0	1	2	16
Total	26	25	26	22	10	7	19	8	143

7.4 Means for Experiment 4

Table 7.4.1 contains the latencies to identification for the letter stimuli used in Experiment 4, along with the percentage correctly identified – for active and passive exploration with both the TDS and the Phantom. These values are plotted in Figures 4-2 and 4-3 on page 56 for latency and accuracy respectively.

Table 7.4.1 *Active & Passive Latencies & Percentage Correct for TDS and Phantom Exploration of 2-D Shapes*

Variable	Active		Passive	
	TDS	Phantom	TDS	Phantom
Latency	64s	61s	57s	52s
% correct	67%	39%	72%	47%

7.5 Analysis of stimuli effects for Experiment 7

An analysis was conducted to check whether there were any performance differences between the letter stimuli used in the haptics versus vision experiments.

Overall, the capital letter B tended to be correctly identified more quickly (M=12.5 s, SD=11.1 s), followed by the letter E (M=14.7 s, SD=4.6 s), and then the K (M=16.8 s, SD=9.5 s). However, the differences between these means was not statistically different ($F(1.5,25.2)=1.0$; $p>0.05$ – Greenhouse-Geisser adjustments made due to a significant Mauchley's sphericity value).

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