Université de Montréal

Haptic discrimination of two-dimensional angles: influence of exploratory strategy

Par
Myriam Levy

Groupe de recherche sur le système nerveux central
Département de Physiologie
Faculté de médecine

Mémoire présenté à la Faculté des études supérieures
en vue de l'obtention du grade de maîtrise (Msc.)
en Sciences Neurologiques

avril, 2006

Université de Montréal

Direction des bibliothèques

AVIS

L'auteur a autorisé l'Université de Montréal à reproduire et diffuser, en totalité ou en partie, par quelque moyen que ce soit et sur quelque support que ce soit, et exclusivement à des fins non lucratives d'enseignement et de recherche, des copies de ce mémoire ou de cette thèse.

L'auteur et les coauteurs le cas échéant conservent la propriété du droit d'auteur et des droits moraux qui protègent ce document. Ni la thèse ou le mémoire, ni des extraits substantiels de ce document, ne doivent être imprimés ou autrement reproduits sans l'autorisation de l'auteur.

Afin de se conformer à la Loi canadienne sur la protection des renseignements personnels, quelques formulaires secondaires, coordonnées ou signatures intégrées au texte ont pu être enlevés de ce document. Bien que cela ait pu affecter la pagination, il n'y a aucun contenu manquant.

NOTICE

The author of this thesis or dissertation has granted a nonexclusive license allowing Université de Montréal to reproduce and publish the document, in part or in whole, and in any format, solely for noncommercial educational and research purposes.

The author and co-authors if applicable retain copyright ownership and moral rights in this document. Neither the whole thesis or dissertation, nor substantial extracts from it, may be printed or otherwise reproduced without the author's permission.

In compliance with the Canadian Privacy Act some supporting forms, contact information or signatures may have been removed from the document. While this may affect the document page count, it does not represent any loss of content from the document.

Université de Montréal
Faculté des études supérieures

Ce mémoire intitulé :
Haptic discrimination of two-dimensional angles:
influence of exploratory strategy

présenté par:
Myriam Levy

à été évaluée par un jury composé des personnes suivantes:

Allan M Smith
président-rapporteur

Elaine Chapman
directrice de recherche

Pierre Rainville
membre du jury

Grade conféré
à compter du
2006 AOUT 0 3

ABSTRACT

The aim of this study was to define the relative contribution of self-generated cutaneous and proprioceptive feedback to haptic shape discrimination by systematically constraining the exploratory strategy. Subjects (n=17) explored pairs of two-dimensional, 2-D, angles (standard angle, 90°; comparison angles, 91° -103°) placed at arm's length from the subject, and identified the larger angle of each pair. The exploratory strategies included: static touch of the intersection of the two bars that formed the angle using the index finger, D2 (cutaneous feedback), dynamic scan of D2 over the entire object [combined cutaneous and proprioceptive (shoulder) feedback], and dynamic scans of the object using a hand-held tool (proprioceptive feedback, shoulder). When using D2 for exploration, discrimination thresholds (75% correct) were very similar for dynamic touch (5.1 ± 0.09°) and static touch, with thresholds in the latter case being independent of the duration of the static contact (< 1 s, 5.4 ± 0.9°; ~3 s, 5.7 ± 0.8°). These observations suggested that cutaneous feedback alone may be sufficient to explain 2-D angle discrimination, because the added proprioceptive feedback did not improve performance. Threshold also did not vary with the number of dynamic scans (one or two), suggesting that the critical information is gathered on the first pass over the angle. In contrast, when the angles were explored with the tool, threshold was increased, 10.8 ± 1.9°, in relation to the corresponding reference condition from the same session (dynamic scan with D2, 4.5 ± 0.8°). Thus, performance was poorer when only proprioceptive feedback was present, consistent with cutaneous feedback being relatively more important than proprioceptive feedback for 2-D haptic angle discrimination, at least in some conditions. The results are discussed in relation to clinical sensory testing and the development of haptic interfaces.

Keywords: active touch; shape; cutaneous; proprioceptive;human psychophysics

RÉSUMÉ

Le but de cette étude était de définir la contribution relative du feedback cutané et proprioceptive auto-généré dans la discrimination haptique de la forme en contraignant systématiquement les stratégies d'exploration. Les sujets (n=17) ont exploré des paires d'angles bidimensionnel, 2-D, (angle standard, 90°; angles de comparaison, 91° - 103°) placées à la longueur de leur bras en identifiant l'angle le plus grand de chaque paire. Les stratégies d'explorations incluaient : un contact statique court de l'intersection des deux barres qui formaient l'angle à l'aide du doigt d'index, D2 (rétroaction cutanée), ainsi qu'un toucher dynamique D2 au-dessus de l'objet en entier (rétroaction cutanée et proprioceptive combinée) et un toucher dynamique de l'objet a l'aide d'un outil tenu dans la main (rétroaction proprioceptive, épaule). En utilisant D2 pour l'exploration, le seuil de discrimination (75% correctes) était très similaires pour le toucher dynamique (5.1 ± 0.09°) et le toucher statique, avec des seuils dans le dernier cas indépendant du temps de contact statique (< 1 s, 5.4 ± 0.9°; ~3 s, 5.7 ± 0.8°). Ces observations suggèrent que le feedback cutané seul est suffisant afin d'expliquer une discrimination d'angle 2-D car le feedback proprioceptif ajoutée n'a pas amélioré la performance. Aussi, le seuil ne varie pas avec le nombre de scan dynamique (un ou deux), suggérant que l'information critique est récolté dans le premier scan de l'angle. En contraste, lorsque les angles furent explorés avec l'outil, le seuil a été augmenté (10.8 ± 1.9°), en relation avec la condition référence de la même session (scan dynamique avec D2, 4.5 ± 0.8°). L'observation suggère que la performance est inferieure lorsque seul la rétroaction proprioceptive est présente, mais non modulée avec seulement la rétroaction cutanée, que le feedback cutané est relativement plus important que la rétroaction proprioceptive pour la discrimination haptique d'un angle 2-D, au moins dans certaines conditions. Les résultats sont discutés en relation à l'examen clinique sensoriel et au développement d'interfaces haptique.

Mots clés: toucher actif; la forme; cutané; proprioceptive; psychophysique humaine.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE

LIST OF ABBREVIATIONS

2-D	2 dimensional
D2	index finger
dB	decibel
EP	exploratory procedure
fMRI	functional magnetic resonance imaging
GTO	Golgi tendon organ
HZ	Hertz
MIS	Minimally invasive surgery
PET	Position emission tomography
PPC	Posterior parietal cortex
RA	Rapidly adapting
s	seconds
S	Stimulus (Weber fraction =ΔS/S)
SI	Primary somatosensory cortex
SII	Secondary somatosensory cortex
SA	Slowly adapting
TOR	Tactile object recognition

ACKNOWLEDGMENTS

I would like to express my sincere thanks to my director of studies, Dr. C. Elaine Chapman for her valuable and precious guidance throughout the course of this project. Her devotion, competence and support have been of great help. Also, I would like to mention that my lab experiments were very enriching. Once again, I thank her very much.

Many thanks to all the persons that contributed to the successful completion of this project: René Albert, Stéphanie Bourgeon, Claude Gauthier, El Mehdi Meftah, Marie-thérèse Parent, Joanne Payette as well as Dr. Allan Smith and Dr. Pierre Rainville for evaluating my thesis. I would also like to thank them for their helpful comments.

I would like to take the opportunity to thank all of my seventeen subjects for their contribution to the advancement of knowledge.

My most heartfelt thanks to my parents Eliane and Charles, to my sisters and brother who have made my life a rewarding experience through their encouragement and devotion.

Thank you

To my parents, with love and respect

CHAPTER I

INTRODUCTION

The skin, which from head to foot relates us sensitively to the world in which we live, our matrix, is indeed our most consistently active and informing organ of sense. In a dark vacuum where only minimal sight, hearing, taste, smell and muscle activity would be possible, the skin could still report something of the nature of the surroundings: dry, cold, wet, hot, soft, hard, pressure. This was at one time our total awareness of the nature of the sheltering womb.

Joan M. Erikson, Wisdom and the Senses; the Way of Creativity, 1988

I.1. INTRODUCTION

The capacity of humans to recognize an object on the basis of its shape using somesthetic inputs from the hand is a complex ability. Sensory signals allow one to appreciate many parameters of an object such as its size, form, texture, consistency and temperature. The relevant sensory information is itself derived from multiple sources including receptors localized in the skin and in deep structures (muscles and joints). According to Gibson (1966), tactile abilities can be separated into three categories: 1) *Cutaneous touch*. This implies stimulation of skin and subcutaneous tissues, without joint movement. An example would be touching a surface, or being touched by an object; 2) *Haptic touch* implies stimulation of cutaneous structures (skin and adjacent tissues) together with movement of the joints. "Haptic", according to Gibson (1966), is derived from Greek word "haptikos" which means "to take hold of ". An example would be grasping and exploring any 3D object and; 3) *Dynamic touch* which is similar to haptic touch, with the added element being the sense of effort, as for example, when an object is lifted to estimate its weight.

The aim of this study was to investigate the effects of modifying the exploratory strategy on the ability of subjects to discriminate small differences in shape, specifically two-dimensional (2-D) angles, using haptic touch. Exploration was systematically constrained to determine the relative contribution of cutaneous and proprioceptive feedback to shape discrimination.

I.2. LITERATURE REVIEW

This review concentrates on four subjects that are important for haptic touch. These include a description of 1) the various mechanoreceptors involved; 2) the exploration strategies used to extract specific object properties; 3) the different modes of touch and 4) our current knowledge of the human ability to discriminate differences in shape.

I.2.1. Mechanoreceptors involved in haptic touch

I.2.1.1. Cutaneous mechanoreceptors

Our current knowledge of the cutaneous mechanoreceptors involved in discriminative touch is based on an extensive body of literature from both animal and human studies (reviewed in Darian-Smith 1984), derived in great part from studies of the glabrous, or hairless, skin of the hand. Cutaneous afferents have been categorized according to: 1) their speed of adaptation to mechanical stimulation. Slowly adapting, or SA, afferents discharge continuously during maintained pressure (over many seconds); in contrast, rapidly adapting, or RA, afferents respond only to the application and removal of mechanical stimulation, falling silent during the period of maintained stimulation; 2) their location on the skin (superficial or deep). The terminals of SAI (type I) and RAI afferents are superficially located while SAII and RAII endings are located in deeper layers of the dermis and; 3) the size of their receptive field. SAI and RAI afferents have small receptive fields while SAII and RAII afferents have large receptive fields. All four types of cutaneous afferents are thought to end in relation to specialized end-organs, and all are innervated by large diameter, myelinated afferents (A beta).

- It is presumed that SAI afferents end in relation to Merkel cells superficially located in the glabrous skin, in the basal lamina of the epidermal ridges. Individual SAI afferents branch over an area of approximately 5mm^2 in the deepest layers of the epidermis (Iggo et al. 1982). They are densely distributed over the fingertip. Their receptive field is small and well-defined, approximately 2-3 mm in diameter. In terms of the transmission of information, recordings from monkey SAI afferents indicate that they faithfully signal detailed information about the spatial structure of surfaces (Johnson 2001). They have a high spatial resolution and are extremely sensitive to local curvature (Lamotte et al.1987 a,b, Srinivasan et al. 1987, Goodwin 1997). In fact, they are the only type of cutaneous afferent that responds with sufficient acuity to explain human performance in spatial form (e.g. Braille characters) and texture recognition tasks. Their innervation density on the fingertip is approximately 12-38/mm^2 in humans (Bolton et al. 1966) and 47-60/mm^2 in monkeys (Paré et al. 2002). The responses of SAI units to repeated skin indentation are invariant (the variability is around 1 impulse/trial), and they are the only cutaneous afferents that respond linearly to skin indentation, up to 1.5 mm (Blake et al.1997). Overall, these afferents have properties that are consistent with an important role in signalling surface texture, spatial form and also local shape. Along with SAII afferents, they are the only cutaneous mechanoreceptors that can signal maintained touch/pressure. Finally, recent results indicate that their discharge also contributes to the sense of effort (Jones 2006).

- RAI afferents are presumed to branch to innervate Meissner's corpuscles. These end-organs are superficially located in the dermal papillae protruding up into the epidermis (reviewed in Johnson et al. 2000). Each RA afferent innervates a number of corpuscles. The receptive field is relatively small (around 3-5 mm in diameter) on the fingerpads but larger receptive fields are found on the proximal phalanges and the palm (Darian-Smith 1984). RAIs are thought to be critical for the detection of light touch (Johansson and Vallbo 1979) and respond well to transient deformation, particularly to low-frequency vibration (flutter) on the skin surface, < 60 Hz (Talbot et al. 1968). The most important function of RAIs may be the provision of feedback signals for grip control (Johansson 1996, Johnson et al. 2000).

- RAII afferents innervate Pacinian corpuscles (one afferent/corpuscle). The most sensitive mechanoreceptors, RAIIs have a large, poorly defined receptive field. Less densely distributed in the hand than either SAI or RAI units (around 350/finger and 800 in the palm), they are found in the deep dermis (Johnson 2001). They have three important characteristics:1)they can respond to 10nm of stain motion at 200 Hz (Brisben et al. 1999); 2) they have a powerful filtration system (60/dB/decade) so that low frequencies are filtered out; 3) they can follow (one-to-one) vibration frequencies of 100-150Hz. Because of these response properties, RAIIs produce a faithful neural image of transient stimuli transmitted through objects held in the hand and so may play an important role in perceiving objects through the use of hand-held tools (Johnson et al. 2000).

- SAIIs are thought to end in relation to Ruffini endings but this has recently been challenged (Paré et al., 2002). SAII afferents are reported in human glabrous skin (Knibestol et al.1970) but not in monkey glabrous skin (Johnson et al.2000). Slowly adapting, SAII receptive fields are five times larger than for SAI afferents. SAII sensitivity to skin indentation/deformation is six times poorer than for SAI afferents. They are more sensitive to lateral skin stretch than the SAI units. SAII units are thought to play an important role in signalling the position of the fingers and the hand, and so potentially contributing to global shape perception (Edin and Abbs 1991; Edin 1992; Edin and Johansson 1995). Cutaneous afferents including SAII afferents likely play a role in signalling movement about other joints (elbow, knee) as well (Collins et al. 2005). Microstimulation of SAI, RAI and RAII afferents elicits conscious sensations but activation of single SAII afferents in general does not evoke any sensation (Vallbo et al.1984).The latter observation, along with their poor spatial resolution (Phillips et al. 1990), makes it unlikely that SAII afferents contribute to discriminative touch.

I.2.1.2. Proprioceptors in muscle and joint

The term proprioception is derived from the Latin word “proprius”, meaning “one’s own”. Proprioceptive feedback plays an important role in motor control, and this at multiple levels, including the spinal cord (reflexes), and higher centers (balance, coordination, movement). This term also refers to the perception of three variables: movement (both amplitude and angular velocity), position and force (Jones 1994). Information about these parameters is largely, but not exclusively (see above), signalled by receptors located within the deeper tissues (muscle, tendon, joint capsules and ligaments).

Skeletal muscles contain two types of slowly adapting mechanoreceptors: muscle spindles and Golgi tendon organs.

Muscles spindles, known since before the time of Sherrington, are the most complex and studied mammalian proprioceptor (Gandevia et al. 1996). They are in fact considered the most important source of proprioception (Matthews1988). Anatomically, *muscle spindles* are small, encapsulated sensory receptors. Muscle spindles are found in the body of a muscle, aligned in parallel with, and embedded in, *extrafusal muscle fibers*. The muscle spindle is composed of small, specialized muscle fibers known as *intrafusal muscle fibers*, of which there are three types: dynamic nuclear bag fibers (bag$_1$ fibres), static nuclear bag fibers (bag$_2$ fibres), and nuclear chain fibers. Muscle spindles have both a *sensory* and *motor innervation.* There are two types of sensory endings: *the primary and secondary endings* which are found in the central region of the intrafusal fibers. *A single group Ia afferent* (the largest myelinated afferent) innervates all three types of intrafusal fibers, forming the annulospiral ending. *A group II sensory fiber (*intermediate size of afferents) innervates both the nuclear chain and static bag fibers forming the secondary endings (flower-spray endings on either side of the primary ending) (reviewed in Clark et al. 1986, Gandevia 1996). The motor innervation of the muscle spindle is provided mainly by the *gamma motoneurons*, or fusimotor axons that terminate exclusively on intrafusal fibers. Some spindles are innervated by beta motoneurons (skeletofusimotor) that branch to innervate both extra and intrafusal muscle fibers. Muscle spindle stretch sensitivity is controlled by gamma motoneurons: shortening the polar regions of the intrafusal fibers leads to stretching of the noncontractile central region (region where the sensory endings are located) and increased firing of the group Ia and Π afferents.

As reviewed by Matthews (1988), during muscle stretch, primary endings (group Ia afferents) fire more than the secondary endings. Ia afferents are sensitive to both muscle length changes (movement) and the velocity of stretch (dynamic sensitivity), while the secondary endings (group Π afferents) are sensitive to muscle length only (length detector/degree of stretch). Thus, the primary ending is more a movement detector while the secondary ending is more a length detector. The perception of limb position and movement are both thought to depend primarily on muscle spindle signals (Clark et al.1986, Jones 1994; Scott and Loeb 1994; Gandevia 1996). A contribution from the motor command, or efference copy, has been suggested (Gandevia et al. 2006).

- Golgi tendon organs (GTOs) are another type of encapsulated sensory receptor located in series with muscle fibers (unlike the muscle spindles which are located in parallel with muscle fibers) at the junction of the muscle fibers with the tendon. For the GTOs located at the muculo-tendinous junction, each tendon organ typically has ~ 10-20 muscle fibers inserting into it. It has been shown that more than 90% of Golgi tendon organs are located at the musculo-tendinous junction, while the remainder are found in the tendon (Gandevia 1996). The GTO is innervated by a single large diameter group Ib afferent. The terminal branches of the afferent are intertwined with the collagen bundles that form the tendon. When the muscle (and tendon) are stretched, the terminals are compressed, and the GTO discharges. Golgi tendon organs respond to stretch of the tendon fascicles, but are most sensitive to changes in contractile force when the muscle contracts (Jami 1992, Clark and Horch 1986, Gandevia 1996). Their primary role is to signal active muscle tension and not passive tension, ie. muscle stretch (Jami 1992). GTOs are considered to play an important role in the sense of effort, along with contributions from cutaneous afferents and the motor command or efference copy (Gandevia 1996, Jones 1994).

- Joint receptors are found both in the joint capsule and associated ligaments (Matthews 1988). A variety of specialized end-organs have been identified including Ruffini (especially in the capsule), Golgi (ligaments) and paciniform endings. These are innervated by larger, myelinated afferents. Both slowly and rapidly adapting response properties have been reported. In earlier studies, it was the joint receptors that were considered the most important proprioceptors for the sense of position and movement (reviewed in Matthews 1988). But, subsequent studies showed that joint afferents are most sensitive during extreme positions (flexion and extension) with only a few responding in the midrange (Clark and Horch 1986, Gandevia 1996). Muscular contraction can, however, change their operating range (Gandevia 1996). In general, joint afferents are now considered to play a protective role by signaling and preventing hyperextension and hyperflexion of a joint.

I.2.2. Exploration Strategies

We know that a variety of object properties can be recognized using haptic exploration. The haptic system uses both cutaneous and kinesthetic inputs generated during manual exploration and, possibly, knowledge of the motor commands generating the exploration (corollary discharge). Although movement is not essential, relative motion between objects and the skin improves the perception of qualities such as texture (Katz 1925). Lederman and Klatzky (1987, 1990) documented a number of patterns of exploratory procedures (EPs) used by subjects that depend on the attributes the subjects were instructed to explore: texture, hardness, thermal properties, weight, volume, and/or object function etc. Different stereotypical movements are used, depending on the distinct dimensions of knowledge sought. For example, when extracting information about surface texture the subject moves their hand repetitively, in a back-and-forth manner across a surface ("lateral motion" EP). When hardness is explored, the subject applies a force to one part of the object while another part of the object is stabilized with an opposing force. In the same pattern of thought, thermal properties are evaluated by “static contact” (an object is supported externally while one of the hands rests on the object passively). Weight is explored by an unsupported holding procedure and the subject lifts the object. The global shape and the volume of an object are extracted through an enclosure procedure, whereby the fingers and the palm of the hand are molded around the contours of the object. To extract global and precise shape, subjects use a contour following movement. Lederman and Klatzky noted that manual exploration of object shape consists of a two-stage sequence. The first stage is a highly generalized routine (“grasp and lift”) followed by a series of more specialized hand movement patterns. Thus a wide range of EPs are employed when exploring objects using touch, each being specialized to extract specific object characteristics.

Turvey (1996) adopted a different conceptual approach towards analysing haptic exploration. He focused on dynamic or effortful touch as a haptic subsystem. Dynamic touch was defined as the process that occurs when an object is grasped and wielded in different ways, such as pushed, raised, turned, lowered or transported, in order to judge the dimensions of the (unseen) wielded object (such as weight, length or width).

Another way to explore an object is by using some form of interface such as a hand-held tool. Recently there has been increased interest in determining perceptual abilities associated with tool use with a view to developing haptic interfaces for applications such as laparoscopic surgery and surgical training (eg. Kim et al.2004; Tholey et al.2005; Weiss et al. 2003). For example, Klatzky and Lederman (1999) studied the perception of roughness with the bare finger and also with a hand-held probe. They found that subjects can discriminate differences in surface texture (roughness) when this is explored using a hand-held probe, but performance was not as good as with the bare fingertip. In a similar way, Lederman and Klatzky (2004) reported that haptic recognition of familiar objects is poor when the objects are explored indirectly (probe or a rigid sheath) as compared to a bare finger.

In contrast to the results obtained with texture and object recognition, Lamotte (2000) found that subjects can discriminate the softness of rubber objects equally well with either the fingertip or a hand-held stylus. Subsequently, however, Tholey et al. (2005) reported diminished compliance discrimination when using a hand-held laparoscopic tool, possibly because of differences in the quality of the feedback with the tool. Further experiments are thus needed in order to determine, using other tasks, the extent to which performance is modified using a hand-held tool.

It is only recently that investigators have began to systematically explore the limits of human sensory capacities when interacting remotely with the environment. Soechting and collaborators (Henriques and Soechting 2003, Henriques and Soechting 2005, Henriques et al. 2004) have been using a 2-jointed arm with a programmable force field to produce shapes and assess how well subjects can synthesize information about shape. Their results have shown that subjects make consistent errors when reproducing haptic shapes, including errors in length estimations and angles (Henriques et al.2004), and distortions in overall shape depending on the complexity of the explored shape (Henriques and Soechting .2005).

I.2.3. Modes of touch

Sensory information can be gathered using active or passive touch, and there is an ongoing controversy as to whether the two modes of touch are equivalent. Gibson (1962) in particular proposed that passive touch should be regarded as an atypical or unnatural experience because the sensory signals are generated by external sources. He felt that active touch, being self-generated and involving simultaneous activation of deep and cutaneous receptors, is a different and richer sensory experience. In support of this, he showed that active touch is superior to passive touch in the tactile recognition of 2-D shapes.

Since Gibson there have been numerous studies comparing active and passive touch. Many tactile abilities are similar with active and passive touch (reviewed in Chapman 1994), although a few studies have reported a superiority for active touch (Heller 1984, 1986). Studies that found no difference did not control exploration time (Grunwald 1966, Vega-Bermudez et al. 1991), and this may be an important factor (Sinclair et al. 1991).

The absence of large differences between active and passive touch has led many authors to assume that sensory processing is the same in both situations (Vega-Bermudez et al. 1991). This conclusion is difficult to accept because there is paradoxically, a lot of evidence that sensory signals are suppressed, or gated, during active movement (reviewed in Chapman 1994, see also Seki et al. 2003; Bays et al. 2005).

How can we explain why studies do not find evidence that passive touch is actually better than active? In fact, there are three explanations for this paradoxical observation. Firstly, most psychophysical studies used discrimination tasks. Relative differences are, not too surprisingly, preserved with gating. Secondly, psychophysical studies comparing active and passive touch have generally used very slow movements. It may be that the movements were so slow that there was no, or minimal gating during active movement (Chapman et al. 1988). Thirdly, few studies controlled the length of time that subjects explored the stimuli.

It seems clear, on the other hand, that active touch enjoys an advantage over passive touch in that subjects collect their own sensory impressions, orienting the exploring digits so that the most sensitive skin areas are in contact with the object. Movement may also be slowed as critical features are explored (Chapman 1994). Together, these factors help to explain the perceptual equivalence of active and passive touch.

I.2.4. Haptic shape discrimination

Studies of haptic discrimination of object shape are difficult because shape is multidimensional. Extraction of global shape is difficult because multiple somatosensory mechanisms are involved in the extraction of 3-D information. The information can come from position cues involving multiple joints, and from a wide range of skin contact patterns with an object. One approach to the problem has been to study local curvatures, which are sensed with the fingertips. Goodwin et al (1991, 1992) reported that subjects can discriminate differences in local curvature about 10-18% (Weber fraction, ΔS/S) and this ability is independent of the area of skin contact. Gordon and Morison (1982) reported much less precision (differences of 83-86%) in discrimination performance with larger macro curvatures.

Another approach to define haptic abilities was taken by Roland and Mortensen (1987). They fabricated 3 series of solid objects (spheres, ellipsoids and rectangular parallelepipeda), systematically varying their dimensions. They found that the mean discrimination threshold for size decreased with decreased size of the spheres, following the law of Weber (ΔS/S) = constant. The Weber fraction was of the order of 1.6%-3.9%. Subjects were ten times better at detecting differences in curvature (ellipsoids pairs) than differences in size (spheres). The sensitivities for curvature and size were in turn better than sensitivity for linear variables e.g. side length of the parallelepipeda. It is striking that for a task that recruit's only cutaneous feedback (local curvature) the Weber fraction is much larger (10-18%) than for this task, exploring 3-D objects, that recruits both cutaneous and proprioceptive feedback is Weber fraction of (1.6%-3.9%). These results suggest that sensory performance is better in tasks that recruit multiple sources of sensory receptors (cutaneous, muscle, tendon and joint receptors) and where both cutaneous and proprioceptive feedbacks are present.

More recently, Voisin et al (2002a) measured the human ability to discriminate 2D angles, using a contour following EP that involved scanning the angles by moving the digit (D2) of the outstretched arm over the angle in a single to and fro motion. It was shown that subjects can discriminate angular differences as small as 5° (90° vs. 95°). Subsequently, they showed that that both cutaneous feedback from the skin of the finger and kinaesthetic feedback from the shoulder joints contribute equally to the performance of the task (Voisin et al.2002b). Cutaneous feedback was eliminated with the use of local anaesthesia of D2; proprioceptive feedback was eliminated by displacing the angles over the immobile finger. Threshold was increased when either source of feedback was suppressed.

Subjects could no longer perform the task when both sources of feedback were eliminated. These findings indicated that 2D angle discrimination is critically dependent on both cutaneous and proprioceptive feedback, i.e. haptic inputs. Cutaneous feedback comes from the pattern of the skin in contact with the angle, especially at the intersection of the angle. Proprioceptive feedback, in contrast, reflects the orientation of the two bars that form the angle. There was, however, some indication that proprioceptive feedback might be more important than cutaneous feedback because there was a larger increase in threshold when only cutaneous feedback was available (4.5°) as compared to when only proprioceptive feedback was present (3.2°). The authors concluded, conservatively, that both sources of information were equally important for haptic angle discrimination.

I.3. AIM OF THE STUDY

This study is a logical extension of previous work, now concentrating on defining the relative contribution of self-generated cutaneous and proprioceptive feedback to haptic shape discrimination by systematically constraining the exploratory strategy. In order to determine the contribution of *cutaneous feedback* to 2-D angle discrimination, we tested the ability of subjects to discriminate 2-D angles when the exploration was restricted to the angle of intersection. In this study, in contrast to Voisin et al. (2002b) which used passive touch, exploration was controlled by the subject (active touch), and consisted of either a short static touch (<1 s, reproducing the pattern of contact during scans of the whole angle), or long static touch (~ 3s) to eliminate the possible contribution of any movement-related gating of sensory input to the results (Chapman 1994; Williams and Chapman 2002). In order to determine the contribution of *proprioceptive feedback* to 2-D angle discrimination, exploration was performed using a hand-held tool instead of the finger. Using a tool, subjects evaluated either the orientation of the modified bar (so reducing the task to a single dimension) or the global 2-D form. For all experiments, the reference condition corresponded to an active scan of the index finger over the whole angle, providing both cutaneous feedback from the finger, and proprioceptive feedback from shoulder rotation.

CHAPTER II

Haptic discrimination of two-dimentional angles : influence of exploratory strategy

Haptic discrimination of two-dimensional angles: influence of exploratory strategy

by

Myriam Levy[1], Stéphanie Bourgeon[1] and C. Elaine Chapman[1,2]

Groupe de recherche sur le système nerveux central[1],
Département de physiologie[1], and École de réadaptation[2],
Faculté de Médecine,
Université de Montréal,
Montréal, Québec
Canada

19 pages, 4 Figures

Correspondence to:
C. Elaine Chapman,
Dépt de physiologie,
Faculté de Médecine,
Université de Montréal,
PO Box 6128, Station Centre Ville
Montréal, Québec H3C 3J7 CANADA
TEL: (514) 343-2304
FAX: (514) 343-6113
e-mail: [redacted]

Abstract

The aim of this study was to define the relative contribution of self-generated cutaneous and proprioceptive feedback to haptic shape discrimination by systematically constraining the exploratory strategy. Subjects (n=17) explored pairs of two-dimensional, 2-D, angles (standard angle, 90°; comparison angles, 91° -103°) placed at arm's length from the subject, and identified the larger angle of each pair. The exploratory strategies included: static touch of the intersection of the two bars that formed the angle using the index finger, D2 (cutaneous feedback), dynamic scan of D2 over the entire object [combined cutaneous and proprioceptive (shoulder) feedback], and dynamic scans of the object using a hand-held tool (proprioceptive feedback, shoulder). Discrimination thresholds (75% correct) were very similar for dynamic touch (5.1 ± 0.9°) and static touch (D2). In the latter case, the thresholds were independent of the static contact duration (< 1 s, 5.4 ± 0.9°; ~3 s, 5.7 ± 0.8°). These observations suggested that cutaneous feedback alone may be sufficient to explain 2-D angle discrimination, because the added proprioceptive feedback did not improve performance. Also, threshold did not vary with the number of dynamic scans (one or two), suggesting that the critical information was gathered on the first pass over the angle. In contrast, when the angles were explored with the tool, the threshold increased, 10.7 ± 1.8°, in relation to the corresponding reference condition from the same session (dynamic scan with D2, 5.2 ± 1.4°). Performance was poorer with proprioceptive feedback alone, which suggests that cutaneous feedback was relatively more important for 2-D haptic angle discrimination in the present experiment.

Keywords: active touch, shape, cutaneous, proprioceptive, human psychophysics.

Introduction

The human capacity to recognize objects on the basis of their shape, as defined by active exploration using the hand, is a complex ability. The actual exploration generally requires active movements, and so involves the motor system. The sensory information itself is derived from multiple sources, including receptors located in the skin and in deep structures (muscles, joints). Together this is referred to as haptic feedback (Gibson 1962). This laboratory recently developed a novel sensory task, two-dimensional (2-D) angle discrimination (Voisin et al. 2002a,b), with the aim of describing the sensitivity of the haptic system to features that contribute to defining haptic shape. A series of 2-D angles (90° to 103°), consisting of two bars and an intersection, were constructed, and subjects were asked to scan pairs of angles by sliding the index finger (D2) of the outstretched arm over the angles using a single to-and-fro movement. To date, we have shown that humans can discriminate angular differences of the order of 5°, 90° versus 95° (Voisin et al. 2002a), and that both cutaneous and proprioceptive (deep) feedback contribute to this ability (Voisin et al. 2002b). In all cases, the motor strategy was defined for the subjects (above).

This study is a logical extension of our previous work, now concentrating on defining the relative contribution of self-generated cutaneous and proprioceptive feedback to haptic shape discrimination by systematically constraining the exploratory strategy. Based on the results of our previous study (Voisin et al. 2002b), we concluded that cutaneous and proprioceptive feedback contribute in equal measure to 2-D angle discrimination, since threshold was systematically higher when either source of feedback was disrupted (local anaesthesia to block cutaneous feedback; passive movement of the angles over the immobile finger to eliminate proprioceptive feedback). These were, however, fairly dramatic disruptions in sensory feedback, and we could not rule out the possibility that the quality of the remaining sensory feedback was compromised. That is, the scanning movements might have been modified by the cutaneous anaesthesia of the index finger (D2), thus modifying the quality of the proprioceptive feedback. Similarly, the pattern of skin contact during passive scanning of the angles over the immobile D2 may not have been identical to that generated during active to-and-fro scans over the 2-D angle. Furthermore, the exploratory strategy was changed from active, self-generated feedback during the reference condition to passive touch (subject immobile) in the modified condition. Although we matched the parameters of movement used by the subjects themselves, it remains that the subject was immobile so that the sensory input may not have been optimized as in active touch (e.g. small adjustments in digit orientation that may occur during active scans).

In this study, we took another approach, systematically modifying the *exploratory strategy* in order to limit the source of sensory feedback available for 2-D angle discrimination. The aim was to determine whether one source of feedback is more precise than the other, or alternately whether there is some redundancy in the encoding of 2-D angles across the two modalities, cutaneous and proprioceptive. In all cases, the explorations themselves were active so that the inputs were self-generated.

In our task, salient cutaneous feedback is generated by the pattern of skin contact when D2 is scanned over the two bars that form the angle, but most particularly when the finger contacts the intersection of the two bars. Indeed, most subjects report using the pattern of cutaneous feedback from the intersection to perform the task, along with a mental image of the whole angle (Voisin et al. 2002a). In this study, we tested the ability of subjects to discriminate 2-D angles when the exploration was restricted to the angle of intersection (range, 90 to 103 °), a simple static touch (< 1 s), approximating the time spent in contact with the intersection during active to-and-fro scans. For comparison, a longer static touch (~3 s) was also tested to eliminate the possible contribution of any movement-related gating of sensory input to the results (Chapman 1994; Williams and Chapman 2002).

In our original design, movement was limited to the shoulder by placing the apparatus at arm's length from the subject. This was repeated here, but cutaneous feedback from the finger was now eliminated by substituting a hand-held tool for the finger. Using the tool, subjects evaluated either the orientation of the modified bar (so reducing the task to a single dimension) or the global 2-D form. For all experiments, the reference condition corresponded to an active scan of the whole angle, with cutaneous feedback from D2 and proprioceptive feedback from shoulder rotation.

Surprisingly, the results suggest that, at least for this range of 2-D angles, cutaneous feedback alone can be as good as combined cutaneous + proprioceptive feedback. In contrast, performance in conditions with only proprioceptive feedback was poorer than the combined condition. Altogether the results are consistent with cutaneous feedback making a relatively larger contribution to 2-D angle discrimination than proprioceptive feedback.

Materials and Methods

Subjects

Subjects were 17 healthy adults (11 women and 6 men; 19-32 years of age). All subjects were right-handed with the exception of one left-handed subject in experiment 2. Participation was voluntary and compensated. The institutional ethics committee approved the experimental protocol, and all subjects gave their informed consent before participating in the experiment. The first experiment (n=11) consisted of two sessions (60 and 90 min long). The second experiment (n=6) comprised a single 80-min session.

Angles

The angles were constructed of 1cm thick Plexiglass, as described by Voisin et al (2002a). The angles were formed by the intersection of two 8-cm long arms. The range of angles varied from 90° to 103°. During each trial, a pair of angles was presented consisting of the standard 90° angle and one of four comparison angles of 91°, 95°, 99°, or 103° (Fig 1B) inserted into an apparatus (Fig 1A). The first angle presented of each pair was either the standard or the comparison angle (order quasi-random and counterbalanced).

Haptic discrimination task

Subjects were seated in a chair with the experimental apparatus positioned at arm's length, at the level of the shoulder. The experimenter adjusted the apparatus so that the angles, once inserted into the apparatus, were perpendicular to the subject's outstretched arm. All testing was performed with the angles positioned at 30° to the right of the subject (Fig 1A). View of the apparatus was blocked with a mask attached to a hat (shaded area, Fig 1A). Auditory cues were blocked by having the subjects wear ear muffs (20dB noise reduction). At the beginning of the session, each subject received written and verbal instructions indicating that they were going to explore pairs of two-dimensional (2-D) angles and that their task would be to identify which angle of each pair was larger. Subjects were asked to keep their arm and finger straight throughout the scan, in order to limit angular changes to the shoulder joint, and were directed to position their finger on the angle such that the glabrous skin of the middle phalanx of the right index finger (D2) contacted the angle during the scan (nail up).

The general sequence of events in each condition was as follows: (1) the first angle was installed in the apparatus; (2) the experimenter guided the subject's finger to the starting position; (3) the subject explored the first angle then withdrew from the angle; (4) the second angle was installed in the apparatus and the exploration sequence was repeated (~ 5-s delay between scans); and (5) the subject then verbally reported which angle was greater, and the experimenter recorded this response. No feedback on performance was given. For the experimental conditions that involved dynamic scanning of the entire angle (see below), one angle of each pair was slightly shifted 4° on its vertical axis to encourage the subjects to evaluate the whole angle rather than only the second arm of the angle (Voisin et al. 2002a). Subjects were not informed of this shift, and the order of the shifted angle was counterbalanced across trials. Before starting a condition, the exploratory strategy was explained to the subject. This was then practised. The perceptual task was then described and practised by having the subject scan a pair of angles with a large difference (90° and 103°). Data collection began after subjects made two correct discriminations (2-6 trials). To minimize the subject's fatigue, there was a short pause between each condition. There was a total of 40 trials (10 trials for each pair of angles) per condition, order randomized according to a preset list (same for all conditions and subjects).

After each condition, subjects were asked to rate the difficulty of the condition using a scale of 0 (not at all difficult) to 10 (very difficult). At the end of each session, subjects were posed a series of questions regarding the strategy used to represent the angles. They were also asked to estimate the range of angles presented.

In order to describe the physical contact between D2 and the angles, subjects scanned several angles (90°, 95°, 99° and 103°) coated with ink and an imprint was then taken. Two conditions were tested: long static touch of the intersection and a one-pass dynamic scan over the angles (see below).

Experiment 1

The type of feedback, cutaneous (from the index finger) and/or proprioceptive (from the shoulder joint), was modified across six conditions tested over two sessions (A and B, order counterbalanced) separated by an interval of one week. For all sessions, testing in one condition was completed before proceding to the next. The order of the conditions was counterbalanced across all sessions and experiments.

The reference condition in Session A consisted of a single dynamic scan over each angle using the right D2 following the sequence *abc* (Fig 1B). Cutaneous feedback from the index finger and proprioceptive feedback from the shoulder contributed to the performance of the task in this condition. Three modified conditions were tested: two static and one dynamic. For the static exploration (Fig 1C), the subject was guided to contact the intersection, *b*, using either a brief touch (haptic glance: Klatzky and Lederman 1995) or a longer touch (~ 3 s). In both cases, only cutaneous feedback was available and subjects were specifically instructed to remain motionless during the contact. The dynamic modified condition substituted a tool (Fig 1C) for the finger, so that only proprioceptive feedback from the shoulder was available. The scan was limited to one sweep over the modified arm (*bc,* Fig 1B). The subject held a molded hand grip (Fig 1C), with a rigid circular rod (2-mm diameter, length adjusted to the length of the subject's D2) extending out between D2 and D3.

In session B, the reference condition was the same as that of session A, with the exception that subjects scanned each angle with two passes over the intersection, following the sequence *abcba* (Fig1B). This was identical to the exploratory strategy used in previous experiments from our laboratory (Voisin et al. 2002a,b; 2005). In the modified condition, the two-pass exploration was repeated using the tool instead of the index finger, in order to test performance in the presence of proprioceptive feedback only.

Experiment 2

Six additional subjects were recruited to repeat a combination of the conditions tested in sessions A and B of experiment 1. This approach was necessary as subjects show considerable intersession variability in threshold (Voisin et al

2002a). The testing in session B was repeated, adding up the reference condition from session A (single scan with D2, *abc*).

Data analysis

For each subject and each condition, (40 trials; 4 comparison angles paired with the standard angle), the discrimination performance was calculated by computing the proportion of correct responses (PC) for each angle pair. The results were fitted to the following logistic function (Voisin et al 2002a)

$$PC=1/\left(1+e^{d\,(\text{comparison angle-standard angle})}\right)$$

In this equation *d* is the unique degree of freedom of the logistic curve that was adjusted to fit the raw data. Discrimination threshold, T (75% correct), was then computed as follows:

$$T=d^{-1}\ln 1/3$$

The data from each session were analysed separately using either a repeated measures analysis of variance (ANOVA, Expt 1A and 2) and *post hoc* contrasts, or a paired t-test (Expt 1B). All analysis was done with Systat 9.0 (SPSS, Chicago, IL). The level of significance was set at $P< 0.05$.

Results

Experiment 1

Data were collected in two sessions from 11 subjects. Discrimination thresholds for short and long duration static touch of the angle of intersection, *b*, are plotted in Fig. 2A as a function of threshold measures obtained using dynamic touch (one-pass with D2, *abc*). Inspection shows that the data points are distributed equally on either side of the diagonal line (equality), i.e. there was little difference across the three conditions [short, 5.4 ± 0.9° (mean ± SEM) and long static touch, 5.7 ± 0.8°; D2 one pass, 5.1 ± 0.9°]. An ANOVA confirmed the lack of difference across the four conditions tested in session A (P=0.908; see also below). The similarity of the results, static versus dynamic, suggests that cutaneous feedback alone is sufficient to explain 2-D angle discrimination. Moreover, this information appears to be gleaned from the pattern of initial contact with the intersection, since there was no difference as a function of the duration of the static contact.

Figure 2B plots the results obtained using the tool (one pass, *bc*) as a function of the threshold measures obtained using D2 (one pass, *abc*; same as in Fig 2A). Inspection shows that the majority of data points are located above the diagonal, consistent with a modest but non significant increase in threshold from 5.1 ± 0.9° to 6.6 ± 1.0° when only proprioceptive feedback related to the orientation of the second arm of the angle was available. It should be noted, however, that the proprioceptive feedback when using the tool differed from that in the reference condition because the first arm of the angle was not explored. This was addressed in session B: both arms of the angle were scanned using either the tool or D2. The results (Fig 3) showed a significant increase in threshold when the tool was used (9.6 ± 1.0°) as compared to D2 (6.2 ± 1.0°, P=0.018).

The patterns of contact between the glabrous skin of D2 and the angles (90 - 103 °) were characterized in six subjects. For both static (long) and dynamic (one-pass) scans, each imprint consisted of two distinct skin areas on the middle phalanx (the radial and ulnar sides). The prints were digitized and a number of parameters measured: width and area of each skin area in contact; and the distance between the radial and ulnar contacts. No differences were observed as a function of the mode of exploration (static versus dynamic, independent t-tests). Two of the parameters were significantly correlated with angle ($P<0.01$): as the angle value increased: the distance between the radial and ulnar skin contacts declined as did the width of the ulnar skin area. In contrast, none of the parameters showed a significant difference when comparing measures at 90° with those obtained at 95° (corresponding, approximately, to threshold in these experiments).

Experiment 2

One possible explanation for the failure to obtain a significant difference when using either static touch or the tool in the first experiment (session A), as compared to the reference condition (one dynamic scan with D2, *abc*), was that performance in the reference condition may not have been optimal. In other words, threshold may have been higher in this condition as compared to when two scans (*abcba*) were used. This was addressed by recruiting a further six naive subjects and having them perform the conditions tested in session B of experiment 1 along with the reference condition from session A. The results confirmed those obtained in session B. Figure 4A shows that the thresholds were increased when the tool was substituted for D2 (10.7 ± 1.8° versus 5.2 ± 1.4° respectively). In contrast, no difference was seen for one-pass (4.9 ± 1.3°) versus two-pass scans using D2 (Fig. 4B). These impressions were confirmed with an ANOVA: there was a significant difference across the three conditions ($P=0.005$). *Post hoc* analyses indicated that thresholds were higher using the tool ($P=0.03$) as compared to the reference condition. No difference was seen between a single or double pass using D2 (P=0.49), indicating that a single pass provided sufficient information on which to base the perceptual response.

Subject reports

The perceived difficulty of the tasks varied considerably between subjects, from a low of 3/10 (relatively easy) to 10/10 (very difficult). Overall, the difficulty ratings showed no systematic changes across the various test conditions. For example, in session A (expt 1), subjects rated long static touch as the easiest of the four conditions (mean, 5.6 ± 0.5) and the tool as the most difficult (6.8 ± 0.5). The differences were not, however, significant (ANOVA, P=0.437). Although there was a weak trend for thresholds to covary with difficulty (linear regression, P=0.056), this was not confirmed in the other sessions.

For the conditions in which subjects explored both arms of the angle, most subjects used some form of mental imagery, visual or otherwise, to represent the angles (15/17). A majority of subjects recognized that one of the angles was 90°. The estimated range of angles was much larger (mean, 50°) than the actual range presented (13°, from 90°-103°) and the majority of subjects (9/17) thought that angles smaller than 90° had been presented.

Discussion

The present study showed that haptic discrimination of 2-D angles is surprisingly insensitive to large changes in the exploratory strategy, including restricting the exploration to a single pass over the angle or a single static contact with the intersection. Only one strategy, substituting a tool for the exploring finger, produced an increase in threshold. Taken together, the results suggest that cutaneous feedback may be relatively more important than proprioceptive feedback for haptic angle discrimination, at least in the experimental conditions studied here.

One- versus two-pass haptic exploration

The approach taken in this study was to strictly control the exploration strategy, to ensure that between-subject differences in search strategy did not contribute to the results. Many studies put no, or minimal, limits on exploration time, and there is evidence that some tactile sensory abilities are improved with increased exploration. For example, Sinclair and Burton (1991) found that texture discrimination threshold decreases when the number of passes over the surfaces is increased. Soechting et al (Epub 2005) more recently reported a similar observation for haptic recognition of shape, whereby accuracy in reproducing the contours of virtual objects is highest for contours that are explored the most. The present results, in contrast, showed no difference as a function of the number of passes over the angle, one or two. One explanation for this result is that it may be that further exploration (three or more passes) is required in order to demonstrate an advantage for haptic discrimination of 2-D angles with increased exploration. We would argue against this interpretation because similar results were achieved with an even more limited exploration strategy, static touch. An alternate explanation is that the critical information for haptic discrimination of angles is obtained during the first pass over the angle, with the second pass contributing little or nothing to task performance. Indeed, several subjects in one of our previous studies (Voisin et al. 2002a) reported using sensory cues generated mainly on the first pass over these same angles. Further to this, we have also found that the motor strategy used during haptic categorization of these same 2-D angles is characterized by slower movements on the first as compared to the second pass over the angles (unpublished observations, G Michaud, J Voisin, CE Chapman). The latter observation may, on the other hand, be task-specific: Voisin et al (2002a) reported that in the task used here there is no significant difference in speed across the first and second spans. Nevertheless, they pointed out that there was a trend for slower movements on the first (versus the second) pass.

Static versus dynamic haptic touch

No difference was found in 2-D angle discrimination threshold when static touch (cutaneous feedback from the intersection) was compared with dynamic touch (proprioceptive + cutaneous feedback as the subject scanned the two bars and the intersection). Thus, the presence of proprioceptive feedback did not appear to provide any additional information, so that cutaneous feedback alone may be sufficient for the task of 2-D angle discrimination. At first glance, this finding contradicts our previous conclusion that both proprioceptive and cutaneous feedback contribute to 2-D angle discrimination (Voisin et al 2002b). The latter conclusion was based on the demonstration that threshold increases when either source of feedback is selectively eliminated (see Introduction). Thus, logically, we expected to see an increase in threshold during static touch. Several factors may have contributed to our results. First, the results obtained with static touch may have been biased to lower values by the fact there was no shift applied to one of the pair of angles explored. In contrast, the reference condition testing (dynamic scan with D2) included a small 4° shift applied to the orientation of one of each pair of angles presented. We previously showed that threshold tends to be lower when no shift is applied (Voisin et al 2002a). Second, the results may reflect that fact that there is redundancy in the coding of 2-D angles – that both sources contribute equally, but the relative weight of each contribution may vary with the testing condition. At a minimum, the results confirm that cutaneous afferent feedback is important for 2-D haptic discrimination. Third, and perhaps most importantly, the methods for acquiring the cutaneous feedback were very different in the two studies. In this study, the cutaneous feedback was self-generated (active touch): subjects actively lowered their finger onto the unseen intersection. In our previous study, the cutaneous input was externally generated (passive touch): the subject was immobile, and the angles were displaced over the passive finger. Sensory feedback may not have been optimized in the latter study, as the subjects did not make the normal small adjustments in digit orientation and/or contact force that may occur during active scans. Following this reasoning, our failure to find the expected increase in threshold with static touch may, in fact, reflect the superiority of active touch over passive touch. This topic has been the subject of debate since the time of Gibson (1962), with some authors arguing that the two modes of touch are equivalent (Vega-Bermudez et al 1991). There is, on the other hand, considerable evidence that tactile inputs are gated during active movement, yet paradoxically there is almost no evidence to show that passive touch is superior to active touch (Chapman 1994).

Further to this, the long static touch condition (~3 s) was included to determine whether movement-related gating of cutaneous feedback contributed to haptic angle discrimination. We reasoned that cutaneous feedback during short touch (< 1 s), or what Lederman and Klatzky (1995) termed a “haptic glance”, might be compromised by the presence of movement-related gating (Chapman 1994; Williams and Chapman 2002). As threshold was similar in both conditions, we conclude that gating did not contribute significantly to the results. A role for gating cannot, on the other hand, be completely excluded because subjects tended to rate the long touch condition as less difficult than the short touch condition.

Tool use and haptics

When only proprioceptive feedback was available (tool substituted for the finger), threshold increased. This observation was in marked contrast with the lack of any change in 2-D angle discrimination threshold when only cutaneous feedback was available (static vs dynamic touch). Although we believe that the static results may have been modestly biased by the lack of a shift (see above), the results suggest overall that cutaneous feedback may be relatively more important than proprioceptive feedback for this task of 2-D angle discrimination.

Two factors may have contributed to the reduced performance when the subject wielded the tool. First, the cognitive demands of the task were modified by requiring that the subject manipulate the tool. The increased attentional demands when using the tool may have contributed to the increased threshold (Post and

Chapman 1991; Zompa and Chapman 1995). Second, the increased threshold may have reflected an interaction between the proprioceptive feedback and the diffuse cutaneous feedback from the hand holding the foam-covered handle of the tool. The latter may have served as a source of noise, degrading the quality of the proprioceptive signals generated during the exploration. Such a possibility could be tested by systematically changing the quality of this diffuse feedback, for example by replacing the polished surfaces of the angles with textured surfaces varying in, for example, spatial period. An increase in non-specific feedback would be expected to worsen performance.

The influence of tool use on other sensory abilities has been addressed by others, and mixed results have been obtained. Katz (1925), for example, showed that some textures can be discriminated as well with a hand-held probe as with the bare finger. More recently, Klatzky and Lederman (1999) reported that roughness discrimination is impaired when using a probe. They pointed out, however, that their results may have reflected some confusion as to what the subjects meant by their “rougher” judgments, given that the spacing of the tactile elements on the surfaces employed varied in more than one dimension (Connor et al 1990; Meftah et al 2000). As regards softness or compliance of objects, LaMotte (2000) found that subjects could discriminate the softness of rubber objects (with variable compliance) equally well with direct contact through the fingertip and through a hand-held stylus. Diminished performance was, on the other hand, reported by Tholey et al (2005). Finally, Lederman and Klatzky (2004) found that haptic recognition of familiar objects is reduced when a probe is substituted for the finger, or if the feedback is degraded (e.g. encasing the exploring finger in a rigid sheath). Clearly further experiments are needed in order to more fully characterize the human ability to explore the environment indirectly, using hand-held tools.

The importance of this issue comes from the fact that there is now considerable interest in developing haptic interfaces for different applications, including the remote operation of instruments and training surgical skills within virtual-reality environments. The various approaches taken all share a common theme in using force-feedback through a hand-held tool or implement to guide the operator in interacting with the remote or virtual environment. Studies have shown that force feedback can significantly improve human performance in real and virtual environments (Kim et al. 2004; Tholey et al 2005; Yao and Hayward 2005). Nevertheless, it does not appear that performance with the types of haptic feedback generated now is as good as with the bare hand (Tholey et al 2005), so that future applications may need to consider methods to amplify the feedback in order to enhance performance (e.g. Yao and Hayward 2005). Certainly one implication of the present results is that haptic interfaces should concentrate in providing cues transduced by cutaneous mechanoreceptors.

Nature of the sensory signals

Another implication of the present results is that the pattern of skin contact from the intersection of the two bars forming the angle provides sufficient information on which to base the discrimination. Although our imprint measures were not sufficiently precise to show differences across the patterns for the standard and modified angles at threshold level, the critical parameters appeared to be the distance between the radial and ulnar contact sites on the middle phalanx and the width of the ulnar contact, corresponding to the side of D2 that contacted the modified bar. Further studies are needed to clarify the important parameters. These observations do, however, provide some insight into the necessary response properties of cutaneous afferents that contribute to haptic 2-D angle discrimination. Thus, the afferents must have small, discrete receptive fields that can reliably discriminate small changes in the pattern of contact. The most likely candidates are slowly adapting type I (SAI) afferents and/or rapidly adapting (RA) afferents (see review by Johnson 2001), as both have been characterized as having small receptive fields. Of particular interest for this study, the spatiotemporal response profile of SAI and RA afferents elicited by scanning wavy surfaces (alternating convex and concave bars) and other shapes such as ellipsoids over their receptive field is relatively independent of the way in which the object comes into contact with the skin (contact force, orientation of the shape) (LaMotte et al 1994; LaMotte and Srinivasan 1996; cf Goodwin et al. 1995). Such characteristics would contribute to generating an invariant central representation of 2-D shape.

The latter suggestion is complementary to our recent proposal (Voisin et al 2005) that regional variations in proprioceptive acuity (proximal joints more sensitive than distal joints: reviewed in Clark and Horch 1986) may reflect an adaptation to generate an invariant central representation of haptic shape. This suggestion was based on our demonstration that 2-D angle discrimination is identical for explorations made with proximal and distal joints. Given that both explorations involved the index finger, however, we need to consider whether the previous findings should be reinterpreted. Could cutaneous feedback from the exploring digit have been responsible for the similar thresholds? While cutaneous inputs undoubtedly contributed, this was not the sole source of information because threshold increased when the proprioceptive feedback from the shoulder was modified by displacing the angles to a more eccentric position, further from the midline. Under the same testing conditions, threshold declined when the exploration was restricted to distal movements, consistent with both cutaneous and proprioceptive feedback contributing to 2-D haptic discrimination.

Acknowledgements. The authors would like to thank the following for the excellent technical assistance provided: René Albert, Jacques Bérichon, Marie-Thérèse Parent, Gaétan Richard, and Christian Valiquette. We also thank Trevor Drew and Allan Smith for helpful comments on the manuscript, and El-Mehdi Meftah for helpful suggestions throughout the course of the experiments. Funding from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Institutes of Health Research (CIHR: individual and group grants) are gratefully acknowledged. Stéphanie Bourgeon was supported, in part, by a bursary from the GRSNC (Groupe de la recherche sur le système nerveux central, a group supported by the Fonds de la recherche en santé du Québec, FRSQ, and the Université de Montréal).

References

Chapman CE (1994) Active versus passive touch: factors influencing the transmission of somatosensory signals to primary somatosensory cortex. Can J Physiol Pharmacol 72: 558-570

Clark FJ, Horch KW (1986) Kinesthesia. In: Handbook of Perception and Human Performance, eds K Boff, L Kaufman, J Thomas, Vol 1, chapter 13, Wiley, New York, pp 13-1 – 13-62

Connor CE, Hsiao SS, Philips JR, Johnson KO (1990) Tactile roughness: neural codes that account for psychophysical magnitude estimates. J Neurosci 10: 3823-3836

Gibson JJ (1962) Observations on active touch. Psychol Rev 69: 477-491

Goodwin AW, Browning AS, Wheat HE (1995) Representation of curved surfaces in responses of mechanoreceptive afferent fibers innervating the monkey's fingerpad. J Neurosci 15: 798-810

Johnson KO (2001) The roles and function of cutaneous mechanoreceptors. Curr Opinion Neurobiol 11: 455-461

Katz D The World of Touch. Hillsdale, NJ: Erlbaum (translated by LE Krueger, published originally in 1925), 1989

Kim HK, Rattner DW, Srinivasan MA (2004) Virtual-reality-based laparoscopic surgical training: the role of simulation fidelity in haptic feedback. Comput Aid Surg 9: 227-234

Klatzky RL, Lederman SJ (1995) Identifying objects from a haptic glance. Percep Psychophys 57: 1111-1123

Klatzky RL, Lederman SJ (1999) Tactile roughness perception with a rigid link interposed between skin and surface. Percep Psychophys 61: 591-607

LaMotte RH (2000) Softness discrimination with a tool. J Neurophysiol 83: 1777-1786

LaMotte RH, Srinivasan MA (1996) Neural encoding of shape: responses of cutaneous mechanoreceptors to a wavy surface stroked across the monkey fingerpad. J Neurophysiol 76: 3787-3797

LaMotte RH, Srinivasan MA, Lu C, Kusch-Petersen A (1994) Cutaneous neural codes for shape. Can J Physiol Pharmacol 72: 498-505

Lederman SJ, Klatzky RL (2004) Haptic identification of common objects: effects of constraining the manual exploration process. Percep Psychophys 66: 618-628

Meftah E-M, Belingard L, Chapman CE (2000) Relative effects of spatial and temporal characteristics of scanned surfaces on human perception of tactile roughness using passive touch. Exp Brain Res 132: 351-361

Post LJ, Chapman CE (1991). The influence of cross-modal manipulations of attention on the detection of vibrotactile stimuli in humans. Somatosens Motor Res 8: 149-157

Sinclair RJ, Burton H (1991) Tactile discrimination of gratings: psychophysical and neural correlates in human and monkey. Somatosens Motor Res 8: 241-248

Soechting JF, Song W, Flanders M (Epub 2005) Haptic feature extraction. Cereb Cortex doi:10.1093/crcor/bhj058

Tholey, G, Desai JP, Castellanos AE (2005) Force feedback plays a significant role in minimally invasive surgery. Ann Surgery 241: 102-109

Vega-Bermudez F, Johnson KO, Hsiao SS (1991) Human tactile pattern recognition: Active versus passive touch, velocity patterns of confusion. J Neurophysiol 65: 531-546

Voisin J, Benoit G, Chapman CE (2002a) Haptic discrimination of object shape in humans: Two-dimensional (2-D) angle discrimination. Exp Brain Res 145: 239-250

Voisin J, LamarreY, Chapman CE (2002b) Haptic discrimination of object shape in humans: Contribution of cutaneous and proprioceptive input. Exp Brain Res 145: 251-260

Voisin J, Michaud G, Chapman CE (2005) Haptic shape discrimination in humans: insight into the haptic frames of reference. Exp Brain Res 164: 347-356.

Williams SR, Chapman CE (2002) Time-course and magnitude of movement-related gating of tactile detection in humans. III. Importance of the motor task. J Neurophysiol 88: 1968-1979

Yao H-Y, Hayward V (2005) A tactile enhancement instrument for minimally invasive surgery. Comput Aid Surg 10: 233-239

Zompa IC, Chapman CE (1995) Effects of cross-modal manipulations of attention on the ability of human subjects to discriminate changes in texture. Somatosens Motor Res 12: 87-102

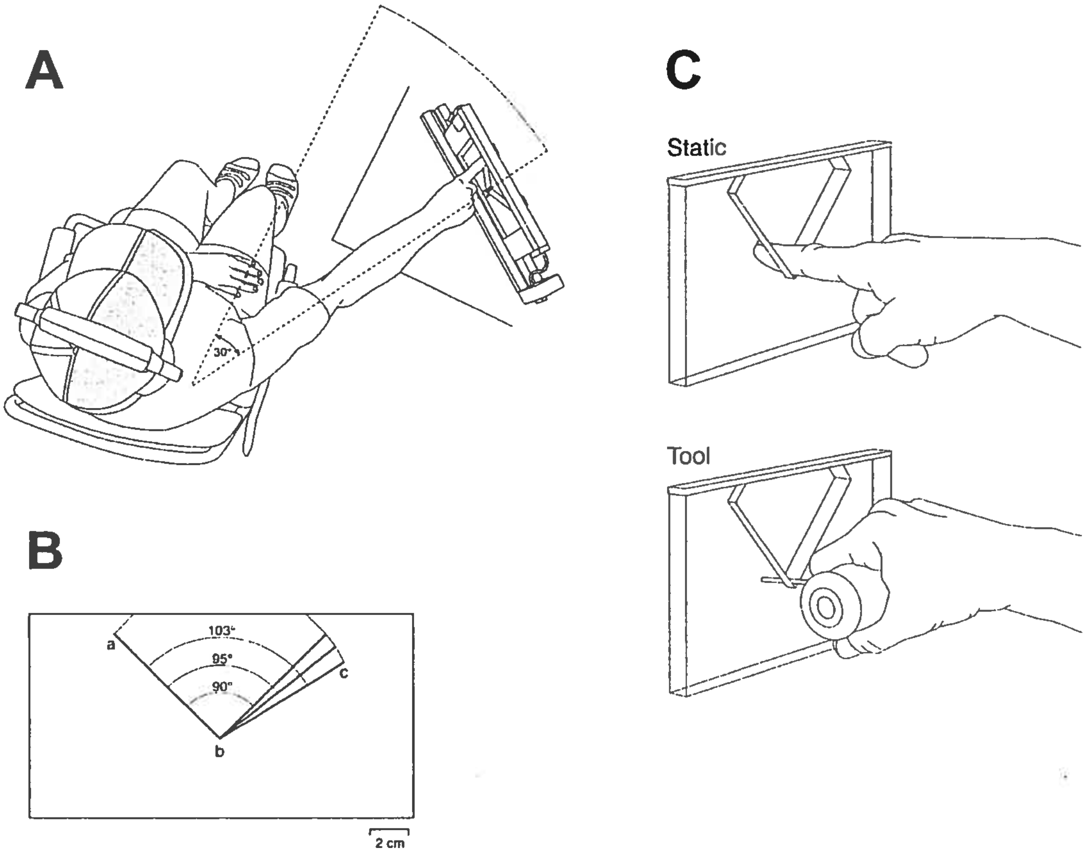


Fig. 1A. Start position for the reference conditions of the haptic discrimination task. The angles were held in an apparatus positioned 30° to the right. **B.** Schematic representation of the 2-D angles, including the standard angle of 90° and two of the comparison angles, 95° and 103°. The thick lines represent the surface scanned by the subjects. For all angles, the first arm (left, *ab*) was identical. The scans began either at position *a* (shown in A) or position *b* (shown in C). Subjects made either one pass (*abc, bc* or *b*) over the intersection or two passes (*abcba*). **C.** Angles were scanned with either the right index finger (*top*, static condition) or a tool (*bottom*).

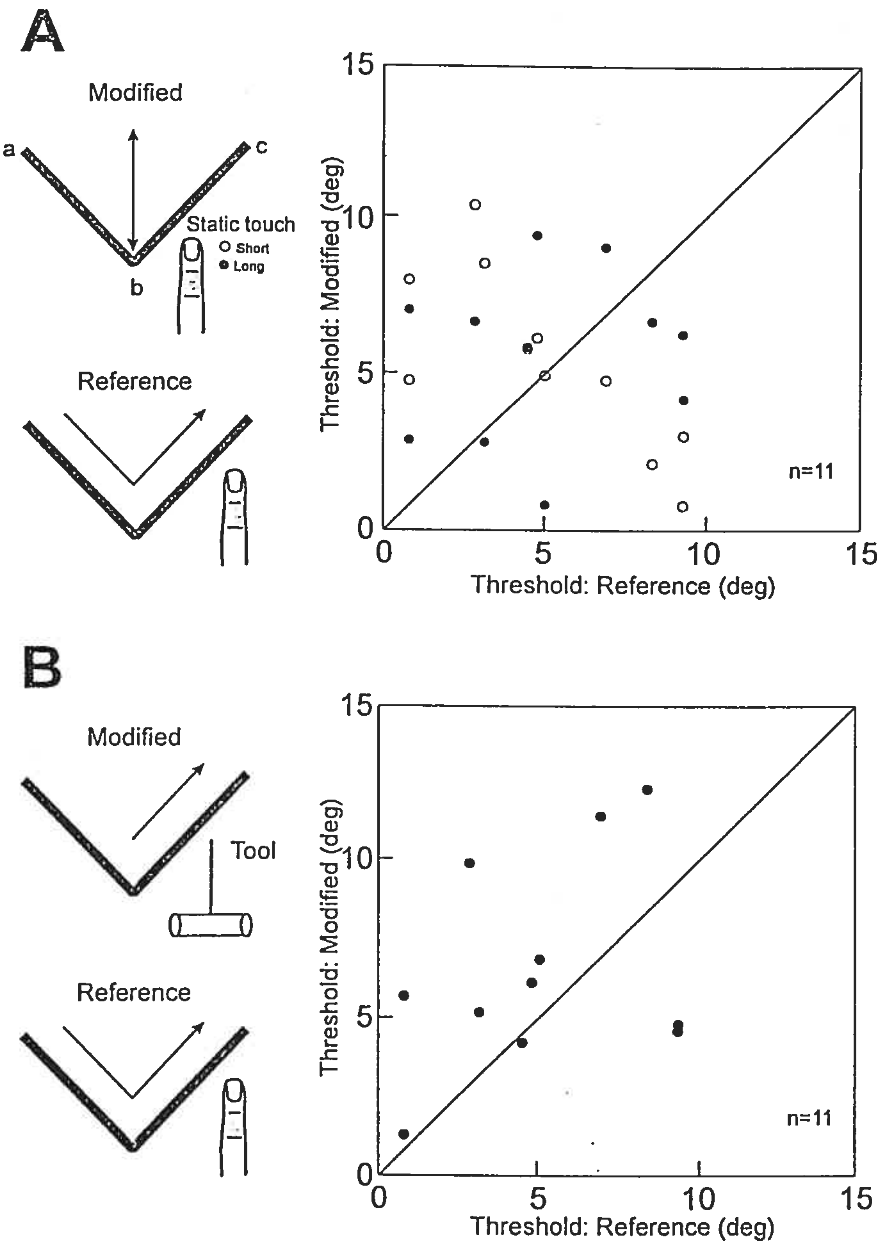


Fig. 2AB. Pooled results from 11 subjects in session A (experiment 1). Comparison of performance in the modified conditions [A, short and long static touch of intersection *b* (respectively, open and closed symbols); B, one pass, *bc,* with tool] as a function of the reference condition (one pass, with D2 *abc*). For A, the data are distributed around the line of equality (diagonal line). For B, in contrast, there was a trend for thresholds to be higher when using the tool.

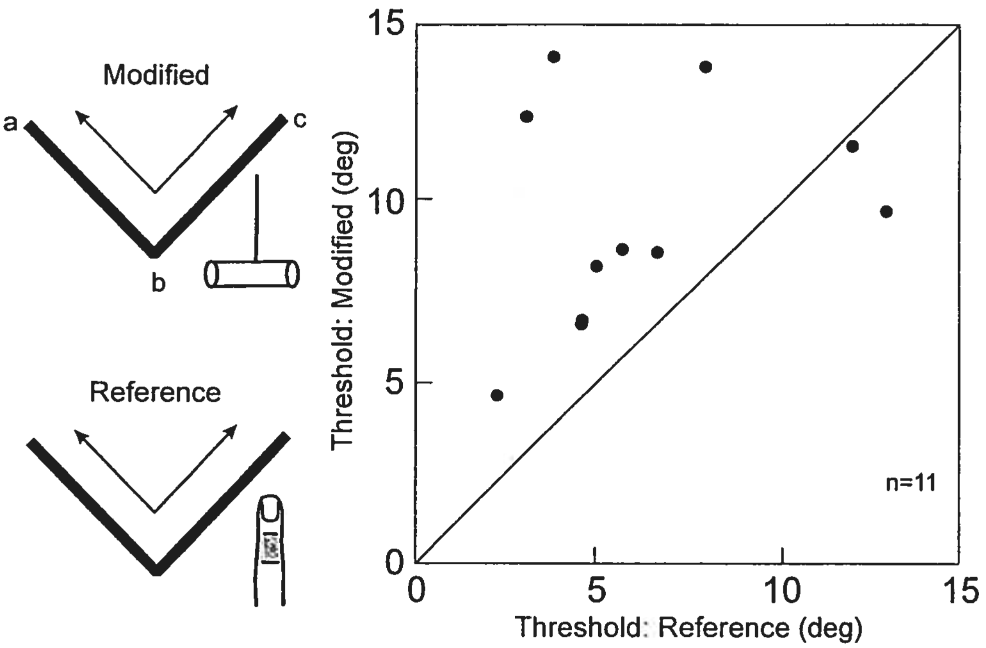


Fig. 3. Results of session B (experiment 1, n=11 subjects). Threshold was higher when the angles were scanned with the tool (two passes, *abcba).* Plotted as in Fig. 2.

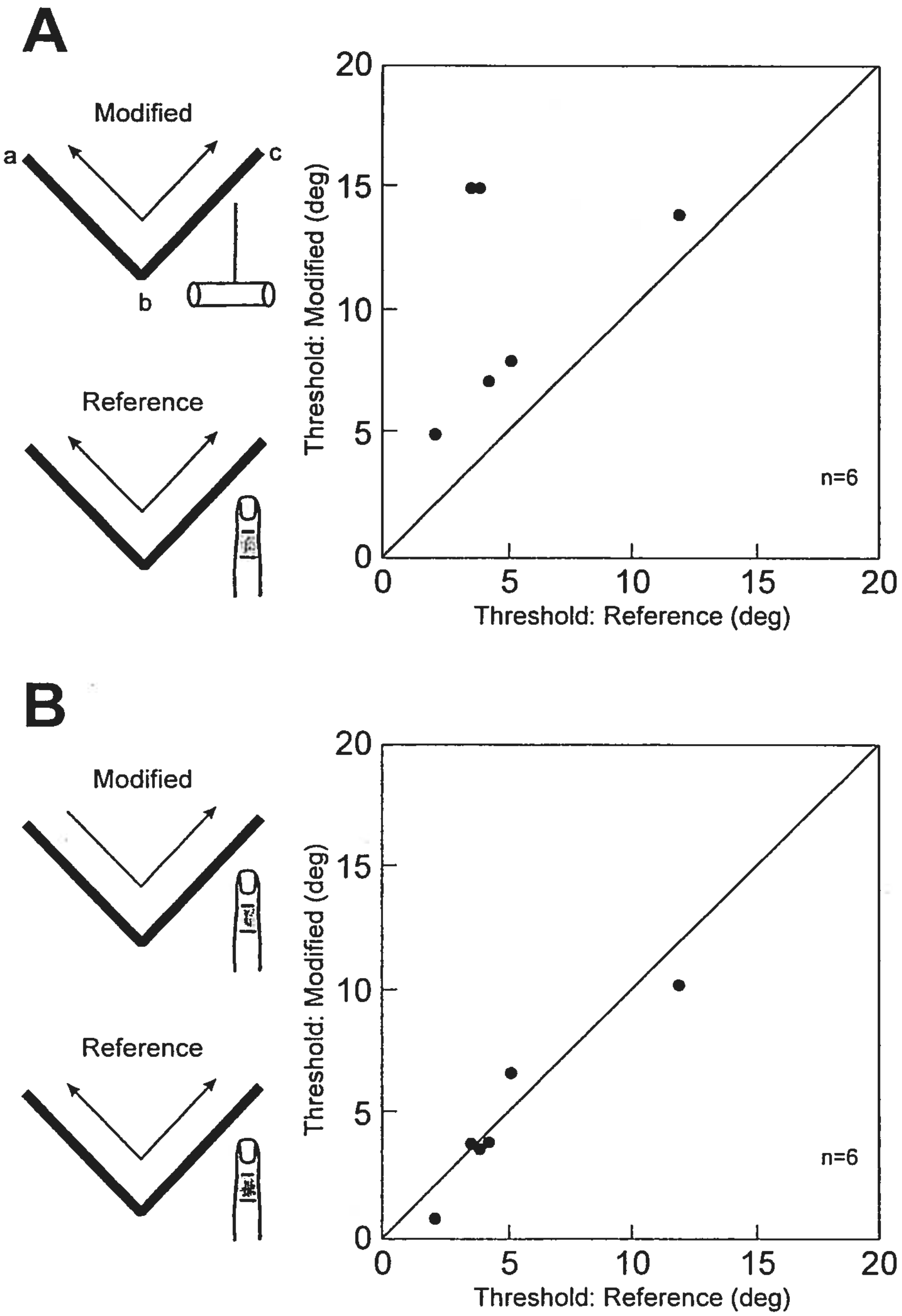


Fig. 4A-B. Results of experiment 2 (n= 6 subjects) **A.** Discrimination threshold using the tool was higher than for D2 (both two passes over the intersection, *abcba*) **B.** The number of passes made with D2 (modified, one pass; reference, two passes) had no obvious effect on threshold. Data plotted as in Fig. 2.

CHAPTER III

DISCUSSION

III. DISCUSSION

The present study has shown that haptic discrimination of 2-D angles is surprisingly insensitive to large changes in the exploratory strategy, including exploration that is restricted to a single pass over the angle (cutaneous and proprioceptive feedback) or a single static contact (cutaneous feedback) with the intersection. These results suggest that the presence of proprioceptive feedback does not appear to provide any additional information. Thus, cutaneous feedback alone may be sufficient to perform the 2-D angle discrimination task. This finding contradicts the results of a previous study from this laboratory, that suggested that both cutaneous and proprioceptive feedback contribute equally to 2-D angle discrimination (Voisin et al. 2002b). Several factors may have contributed to the apparent discrepancy. In particular, the quality of the remaining of sensory feedback may have been compromised by the procedures employed to suppress cutaneous or proprioceptive feedback. In addition, the methods used to acquire the cutaneous feedback were very different: in this study, the cutaneous feedback was self-generated (active touch), whereas in the previous study it was externally generated (passive touch). The sensory feedback may then not have been optimized in the earlier study (exact orientation of the digit, optimal contact forces).

Only one strategy- substituting a tool for the exploring finger produced a decrease in performance in this study. While this suggests that proprioceptive feedback on its own is not as precise as cutaneous feedback, we could not exclude the possibility that the other factors contributed to the increased threshold (cognitive demands, interaction between diffuse cutaneous feedback through the handle with the proprioceptive signals).Taken together, our results suggest that cutaneous feedback is relatively more important than proprioceptive feedback for haptic angle discrimination .

III.1. Methodological considerations

In this study, several factors may have contributed to the results, including the orientation of the head, the delay between successive scans, and the choice of angles.

Other experiments (G.Michaud, J.Voisin, CE Chapman, unpublished) showed no differences in haptic perception as a function of head orientation when the angles were explored either in front of the shoulder or 30° to the right-corresponding to the test position here, Therefore it is unlikely that this was a factor in the present study.

The delay between successive scans can also influence performance. Voisin et al. (2005) showed that under some conditions, performance was better with a longer delay (15 vs.5 s). This was not a factor in this experiment because the delay was constant across all conditions (~ 5s). We can speculate, on the other hand, that performance with the tool might improve with an increase in delay. Future experiments could test this hypothesis.

The range of angles used here was limited to 90°-103°. Angles less than 90° were not used because in this case, there is no guarantee that the finger can explore the entire intersection. Angles greater than 180° were also not tested: previous experiments from this laboratory (unpublished observations, J.Voisin and CE Chapman) found that the finger loses contact with the object at the intersection for this range of angles. Thus, cutaneous feedback is potentially compromised, justifying restricting the range of angles to 90°-103°.

The following text probes several practical applications of this haptic angle discrimination task, specifically its potential clinical applications and the design of haptic interfaces. To put the former into context, a brief summary of functional localization in the parietal lobe is first provided.

III.2. Potential clinical applications of the 2D angle discrimination task

Our knowledge of the functional role of different parts of the parietal cortex comes from anatomical, physiological and lesion studies. Inferences about function are, however, dependent on the functional measures used. In the following section, a summary of our current knowledge is presented followed by a brief description of the types of sensory testing used at present. At the end, the 2D angle discrimination task is proposed as a potential new clinical measure of haptic function.

III.2.1. Functional localization in the parietal lobe

The primary somatosensory cortex (SI) is located in the rostral portion of the parietal lobe, and the secondary somatosensory cortex (SII) is within the lateral sulcus. The posterior parietal cortex (PPC) is located caudally, and includes areas 5 and 7. SI comprises four distinct cytoarchitectonic regions (Brodmann's areas 3a, 3b, 1 and 2). Neurons in areas 3a and 3b project their axons to areas 1 and 2. Experiments on primates indicate that neurons in areas 3b and 1 respond mainly to cutaneous inputs whereas neurons in areas 3a and 2 receive proprioceptive information mainly from muscles and joints (reviewed in Chapman et al.1996). The hand representation of area 2 is a special case, in that ~50% of cells have a cutaneous receptive field. The remainder receive proprioceptive input (Iwamura et al.1978 a,b 1983 a,b 1985 a,b 1993, Hyvarinen and Poranen 1974, 1978 a,b, 1980). The present results indicate that damage to either the cutaneous or the proprioceptive representations of the hand can be expected to affect haptic perception.

Lesions of the various somatic sensory areas have provided valuable information regarding the functions of the different areas. Lesions in area 3 cause deficits in the discrimination of the texture, size and shape an objects; area 1 lesions result in difficulties in texture discrimination; and area 2 lesions result in difficulties in differentiating between objects on the basis of size and shape (Bannister 1985). Lesions of areas 5 and 7 (posterior parietal cortex) induce deficits that are more subtle (smaller increase in discrimination threshold) and more complex disorders. For example, lesions of the nondominant PPC can result in a neglect syndrome; with problems affecting both visual and somatosensory perception (body image, extinction of tactile and visual stimuli etc.)

Deficits in tactile shape perception are associated with a variety of lesions in the parietal lobe. One specific deficit is astereognosia whereby subjects are unable to identify objects by touch. This is now often referred to as a deficit in a tactile object recognition (TOR). Patients with astereognosia can have problems with elementary sensory abilities (after lesions of the hand region in SI) or can have preserved elementary sensory abilities and yet be unable to identify objects by touch. The latter is seen after lesions of SII (Garcha and Ettlinger 1980, Casselli 1993) and PPC (Binkofski et al. 2001).

Another approach to the localization of brain areas associated with haptic touch is through neuroimaging studies using methods such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI). The results of Bodegard et al. (2001) using PET support the notion that the representation of shape in humans is a distributed function that is hierarchically organized. Areas 3b and 1 are activated by a variety of stimuli, including surface curvature, and so may represent a low level analysis of shape. Area 2 is activated more by shape and curvature, as compared to roughness or brush velocity. Finally, regions in the intraparietal sulcus and the supramarginal gyrus are particularly active during active and passive shape discrimination, and so may represent a higher level representation of shape.

The picture that now emerges is that visual and haptic shape discrimination engage, in part, common cortical areas that are generally regarded as visual association regions. These include the lateral occipital cortex (an occipito-temporal region) (Amedi et al.2001; Zhang et al. 2004) and also the middle occipital area (James et al. 2002).

III.2.2. Brief description of tests used for somatosensory function

Neurological examinations consist of three categories of somesthetic tests classified as basic, intermediate and complex. Note that the following description concentrates on haptics, and so testing for pain and temperature sensitivity is not addressed.

1. Basic somatosensory functions are tested using relatively *simple standard clinical tests.* These can include a variety of measures to evaluate: touch, vibration, kinaesthesia (movement sense), position sense as well as quantitative measurements such as a two-point discrimination (calibrated in millimeters) or touch thresholds (Von Frey filaments). Some more sophisticated measures have also been developed (Novak et al. 2001).

2. *Intermediate* somatosensory functions can be evaluated in standard clinical assessments, for example double stimulation to test for the presence of tactile extinction. Quantitative measurements may be employed (weight, texture, dimension, shape, orientation), but these are generally used in research studies.

3. Even more *complex* somatosensory functions can be tested in the standard exam. The most complex and important ability, is TOR, or what was originally called stereognosia. It is evaluated by placing an unseen object in the hand and asking the subject to identify it. Common objects used can include a pencil, key, change, paper clip, etc. If patients are unable to describe an object and its function, this is categorized as a recognition failure (Casselli 1991,1993).

III.2.3. The benefits of using a 2D angle discrimination task

At present, relatively crude and unsophisticated measures of haptic perception are employed clinically. These range from simple tests of position sense (finger up or down) to TOR. More elaborate measures of position sense have been developed for experimental purposes, but none are easily transposed to the clinic. It is suggested that the 2-D angle discrimination task might provide a new measure for the clinical evaluation of haptic perception. Testing with the task is done rapidly. The task is easy, rapidly learned by subjects and the results are independent of the joints involved in the exploration (proximal vs. distal, Voisin et al. 2005). If subjects have some motor deficits (e.g. stroke), testing could be restricted to static touch. Finally, the 2-D angles are relatively inexpensive to fabricate.

To apply this 2-D discrimination task within a clinical setting, however, there is a need to collect normative data from a much larger sample of subjects, and this covering the lifespan (from children to the elderly, including both sexes). The first step, however, would be to perform some pilot studies to judge the interest of such a test for patients with neurological lesions. A range of disorders would need to be tested (peripheral neuropathies to central lesions including stroke victims).

III.3. Potential application of the results to the design of haptic interfaces

A haptic interface is defined as a mechanical system that senses forces in remote environments and delivers these forces to the hand of the user in the form of a haptic display accessed via a rigid link (Lederman and Klatzky 2004). There is now considerable interest in developing haptic interfaces for applications such as the remote operation of devices (e.g. Canadarm in the space station), minimally invasive surgery and training surgical skills within virtual-reality environments.

Minimally invasive surgery (MIS), often called laparoscopic surgery, has profoundly influenced modern times. This is a new and growing field that, as reviewed by Badsogan et al.(2004), requires extensive training. This type of surgery is done by inserting a long slender surgical tool along with a miniature camera into a small incision to explore and manipulate internal tissues (abdomen, joints etc). It has a number of important benefits for patients: they experience less pain, trauma and recovery is faster. Nevertheless, there are disadvantages for surgeons. First of all, the required psychomotor and perceptual skills differ from the traditional requirements because of limitations associated with the technique (Gallagher et al 2004). With this type of surgery, surgeons do not have vision of the entire field (only a small region). Also, the haptic feedback is greatly diminished. The surgeon cannot directly manipulate tissues with his hands. Instead all sensory feedback comes through the surgical instrument, and the haptic feedback is not as good as with direct exploration. The results of this study suggest that haptic interfaces should concentrate on enhancing cues transduced by cutaneous mechanoreceptors.

To date, there has been relatively few attempts to enhance surgical feedback. Several recent developments are, however, notable. Yao and Hayward (2005) developed a probe, consisting of an actuator and an accelerometer, to amplify the tactile feedback as the surgeon probes surfaces in the joint that are out of range of the camera. This was combined with auditory feedback as well. Their results indicated that performance is best with combined feedback, suggesting some crossmodal facilitation, but that either source of feedback alone improved task performance. Weiss and Okamura (2004) are developing another approach, mimicking the forces between the fingers that are felt when using scissors on tissue. At present, this new field is only just developing – further advances are expected in the near future.

A second, but related, approach has been the development of software and hardware so that medical students and residents can learn and practise surgical techniques within a *virtual environment.* This new approach is essential for training for laparoscopic surgery, and provides a number of advantages such as training without risk of injury to the patient, constant availability for practising, and immediate quantitative feedback on performance. One important question is, however, to know whether skills learned in a virtual environment transfer to a real environment. Kim et al (2004) recently compared real laparoscopic surgery with virtual surgery, modeling the real environment with various degrees of fidelity (linear vs. nonlinear modeling of organ elasticity). Force feedback led to significantly improved training transfer as compared to training without force feedback and the different levels of haptic fidelity affected the training. The latter is an important observation as it suggests that the quality of sensory feedback is a critical factor, an observation that is consistent with the present results.

The various approaches mentioned above all share a common theme in using force-feedback through a hand-held tool or implement to guide the operator in interacting with the remote or virtual environment. Further studies are clearly needed to explore the limits of human sensory capacities when interacting remotely with the environment. It is also essential to determine how haptic feedback could be improved. As reviewed above, the quality of the sensory feedback is a key factor. The present results suggest that future efforts should concentrate on increasing haptic feedback. Although cutaneous feedback looks to be the most important source of information, we cannot exclude the possibility that proprioceptive feedback (e.g. actual joint excursion) may also be an important factor.

CHAPTER IV

CONCLUSION

IV. CONCLUSIONS

1. In the present experiment no differences were found in 2-D angle discrimination when static touch (cutaneous feedback from the intersection; short or long contact) was compared with dynamic touch (proprioceptive + cutaneous feedback as the subject scanned the two bars and the intersection). The presence of proprioceptive feedback did not appear to provide any additional information, so that cutaneous feedback alone may be sufficient for haptic discrimination of 2-D angles.

2. When only proprioceptive feedback was available (tool substituted for the finger), threshold increased compared to the reference condition (cutaneous + proprioceptive feedback). This observation was in marked contrast with the lack of any change in 2-D angle discrimination threshold when only cutaneous feedback was available (above). Together, the results suggest that cutaneous feedback may be relatively more important than proprioceptive feedback for this task of 2-D angle discrimination.

3. The results indicated that there were no differences in 2-D angle discrimination as a function of the number of passes over the angle, one or two. This result was interpreted as suggesting that the critical information for haptic discrimination of angles is obtained during the first pass over the angle, with the second pass contributing little or nothing to task performance. It remains possible that

further exploration (> two passes) is needed to demonstrate an advantage for haptic discrimination of 2-D angles with increased exploration.

CHAPTER V

BIBLIOGRAPHY

V. BIBLIOGRAPHY

Amedi A, Malach R, Hendler T, Peled S, Zohary E (2001) Visuo-haptic object-related activation in the ventral visual pathway. Nat Neurosci 4:324-330.

Basdogan C, De S, Kim J, Muniyani M, Kim H, Srinivasan MA (2004) Haptics in minimally invasive surgical simulation and training. IEEE Comp Graph Appl 24:56-64.

Bannister SR (1985) Brain's Clinical Neurology (6th ed). Oxford University Press Oxford.

Bays PM, Wolpert DM, Flanagan JR (2005) Perception of the consequences of self-action is temporally tunes and event driven. Curr Biol 15:1125-1128.

Binkofski F, Kunech E, Classen J, Seitz RJ, Freund HJ (2001) Tactile apraxia. Bimodal apractic disorder of tactile object shape exploration associated with parietal lobe lesions. Brain 124: 132-144.

Blake DT, Hsiao SS, and Johnson KO (1997) Neural coding mechanisms in tactile pattern recognition: the relative contribution of slowly and rapidly adapting mechanoreceptors to perceived roughness. J Neurosci 17: 7480-7489.

Bodegard A, Geyer S, Grefkes C, Zilles K, Roland PE (2001) Hierarchical processing of tactile shape in the human brain. Neuron 31: 317-328.

Bolton CF, Winkelmann RK, Dyck PJ (1966) A quantitative study of Meissner's corpuscules in man. Neurobiology 16:1-9.

Brisben AJ, Hsiao SS, Johnson KO (1999) Detection of vibration transmitted through an object grasped in the hand. J Neurophysiol 81:1548-1558.

Casselli. RJ (1991) Rediscovering tactile agnosia.Myo Cli Proc 66:129-142.

Casselli. RJ (1993) Ventrolateral and dorsomedial somatosensory association cortex damage produces distinct somesthetic syndromes in humans. Neurology 43: 762-771.

Chapman CE (1994) Active versus passive touch: factors influencing the transmission of somatosensory signals to primary somatosensory cortex. Can J Physiol Pharmacol 72: 558-570.

Chapman CE, Tremblay F, Agerianioti-Bélanger SA (1996) Role of primary somatosensory cortex in active and passive touch. In: Hand and Brain. The neurophysiology and psychology of hand movements. AM Wing, P Haggard, JR Flanagan (Eds), Academic Press Inc, San Diego. pp 329-346.

Chapman CE, Jiang W, Lamarre Y (1988) Modulation of lemniscal input during conditioned arm movements in monkey. Exp Brain Res 72: 316-334.

Clark FJ and Horch KW (1986) Kinesthesia. In: Handbook of Perception and Human Performance 1: 13-57.

Collins DF, Refshauge KM, Todd G, Gandevia SC (2005) Cutaneous receptors contribute to kinaesthesia at the Index finger, elbow and knee. J. Neurophysiol 94: 1699-1706.

Darian-Smith I (1984) The sense of touch: performance and peripheral neural processes. In: Handbook of Physiology. The Nervous System. Physiol Soc 3:739-788.

Darian-Smith I and Oke LE (1980) Peripheral neural representation of the spatial frequency of grating moving across the monkey's finger pad Physiology 309:117-133.

Edin BB (1992) Quantitative analysis of static strain sensitivity in human mechanoreceptors from hairy skin J Neurophysiol 67: 1105-1113.

Edin BB and Abbs JH (1991) Finger movement responses of cutaneous mechanoreceptors in the dorsal skin of the human hand J Neurophysiol 65: 657-670.

Edin BB and Johansson N (1995) Skin strain patterns provide kinaesthethic information to the human central nervous system J Physiol 487: 243-251.

Gallagher AC, Lederman AB, Mcglade K, Satava RM, Smith CD (2004) Discriminative validity of the minimally invasive surgical trainer in virtual reality (MIST-VR) using criteria levels based on expert performance. Surg Endosc 18:660-665.

Gandevia SC (1996) Kinesthesia: roles for afferent signals and motor commands. In: Rowell LB, Shepherd JT (eds). Handbook of physiology, sect 12: exercise: regulation and integration of multiple systems. Oxford University Press, New York. pp129-172

Gandevia SC, Smith JL, Crawford M, Proske U, Taylor JL (2006) Motor commands contribute to human position sense. J Physiol 3:703-710.

Gibson JJ (1962) Observations on active touch. Psychol Rev 69:477-491.

Gibson JJ (1966) The senses considered as perceptual systems. Houghton Mifflin Co. Boston .

Garcha HS, Ettlinger G (1980) Tactile discrimination learning in the monkey: the effects of unilateral or bilateral removals of the second somatosensory cortex (area SII). Cortex 16: 397-412.

Goodwin AW and Wheat HE (1992) Human tactile discrimination of curvature when contact with the skin remains constant. Exp Brain Res 88 : 447-450.

Goodwin AW, John KT, Marceglia AH (1991) Tactile discrimination of curvature by humans using only cutaneous information from the fingerpads. Exp Brain Res 86: 663-672.

Goodwin AW, Macefield VG, Bisley JW (1997) Encoding object curvature by tactile afferents from human fingers. J Neurophysiol 78: 2881-2887.

Gordon IE and Morison V (1982) The haptic perception of curvature. Percept Psychophysics 31: 446-450.

Grunwald AP (1966) A braille-reading machine. Science 154:144-146.

Heller, MA (1984) Active and passive touch: the influence of exploration time on form recognition. J Gen Psychol 110:243-249.

Heller, MA (1986) Active and passive tactile braille recognition. Bull Psycho Soc 24:201-202.

Henriques DYP and Soechting JF (2005) Approaches to the study of haptic sensing. J Neurophysiol 93: 3036-3043.

Henriques DYP and Soechting JF (2003) Bias and sensitivity in the haptic perception of geometry. Exp Brain Res 150: 95-108.

Henriques DYP, Flanders M, and Soechting JF (2004) Haptic synthesis of shapes and sequences. J Neurophysiol 91: 1808-1821.

Hyvarinen J, Poranen A (1974) Function of the parietal associative area 7 as revealed from cellular discharges in alert monkeys. Brain 97: 673-692.

Hyvarinen J, Poranen A (1978a) Movement-sensitive and direction and orientation –selective cutaneous receptive fields in the hand area of the post-central gyrus in monkeys. Journal of Neurophysiology 283:523-537.

Hyvarinen J, Poranen A (1978b) Receptive field integration and submodality convergence in the hand area of the post-central gyrus in the alert monkey. Neurophysiol 283: 539-556.

Hyvarinen J, Poranen A, Jokinen Y (1980) Influence of atttentive behavior on neuronal responses to vibration in the primary somatosensory cortex of the monkey. Neurophysiol 43: 870-883.

Iggo A, Andres KH (1982) Morphology of cutaneous receptors. Annu Rev Neurosci 5: 1-31.

Iwamura Y (1993) Dynamic and hierarchical processing in the monkey somatosensory cortex. Biomed Res 14: 107-111.

IwamuraY, Tanaka M, Sakamoto M, Hikosaka O (1983a) Functional subdivisions representing different finger regions in area 3 of the first somatosensory cortex of the conscious monkey. Exp Brain Res 51: 315-326.

Iwamura Y, Tanaka M, Sakamoto M, & Hikosaka O (1985a) Diversity in receptive field properties of vertical neuronal arrays in the crown of the postcentral gyrus in the conscious monkey. Experimental Brain Research 58: 400-411.

Iwamura Y, Tanaka M, Sakamoto M, & Hikosaka O (1985b) Vertical neuronal arrays in the postcentral gyrus signalling active touch: A receptive field study in the conscious monkey. Exp Brain Res 58: 412-420.

Iwamura Y, Tanaka M, Sakamoto M, Hikosaka O (1993) Rostrocaudal gradients in the neuronal receptive field complexity in the finger region in alert monkey's postcentral gyrus. Exp Brain Res 92: 360-368.

James TW, Humphrey GK, Gati Js, Servos P, Menon RS, Goodale MA (2002) Haptic study of three-dimensional objects activates extrastriate visual areas. Neuropsychologia 40:1706-1714.

Jami L (1992) Functional properties of the golgi tendon organs. Arch Int Physiol Biochim 96: 363-378.

Johnson KO (2001) The roles and function of cutaneous mechanoreceptors. Curr Opin Neurobiol 11: 455-461.

Johnson KO, Yoshioka T, Vega-Bermudez F (2000) Tactile functions of mechanoreceptive afferents innervating the hand. J Clin Neurophysiol 17: 539-558.

Johansson RS (1996) Sensory control of dexterous manipulation in humans. In: Hand and Brain. The neurophysiology and psychology of hand movements. AM Wing, P Haggard, JR Flanagan (eds), Academic Press Inc, San Diego. pp 381-412.

Johansson RS and Vallbo AB (1979) Detection of tactile stimuli. Threshold of afferent units related to psychophysical thresholds in the human hand. J. Physiol 297: 405-422.

Jones LA (1994) Peripheral mechanisms of touch and proprioception. Can J Physiol Pharmacol 72: 484-487.

Jones LA, Piateski Erin (2006) Contribution of tactile feedback from the hand to the perception of force. Exp Brain Res 168: 298-302.

Katz D (1925) The world of touch (Hillsdale, New Jersey: Lawrence Erlbaum).

Kim HK, Rattner DW, Srinivasan MA (2004) Virtual-reality-based laparoscopic surgical training: the role of simulation fidelity in haptic feedback. Comput Aid Surg 9: 227-234.

Knibestol M and Vallbo AB (1970) Single unit analysis of mechanoreceptor activity from the human glabrous skin. Acta Physiol Scand 80: 170-195.

LaMotte RH (2000) Softness discrimination with a tool. J Neurophysiol 83: 1777-1786.

LaMotte RH, Srinivasan MA (1987a) Tactile discrimination of shape: responses of slowly adapting mechanoreceptive afferents to a step stroked across the monkey fingerpad. J Neurosci 7:1655-1671.

LaMotte RH, Srinivasan MA (1987b) Tactile discrimination of shape: responses of rapidly adapting mechanoreceptive afferents to a step stroked across the monkey fingerpad. J Neurosci 7: 1672-1681.

Lederman SJ and and Klatzky RL (1987) Hand movements: a window into haptic object recognition Cognit Psychol 19:342-368.

Lederman SJ and Klatzky RL (1990) Haptic classification of common objects: knowledge-driven exploration. Cognit Psychol 4:421-459.

Lederman SJ and Klatzky RL (1999) Tactile roughness perception with a rigid link interposed between skin and surface. Percept Psychophys 61: 591-607.

Lederman SJ and Klatzky RL (2004) Haptic identification of common objects: effects of constraining the manual exploration process. Percept and Psychophys 66: 618-624.

Matthew P BC (1988) Proprioceptors and their contribution to somatosensory mapping: complex messages require complex processing. Can J Physiol Pharmacol 66:431-437.

Novak CB (2001) Evaluation of hand sensibility. J Hand Ther 14: 266-272.

Pare M, Smith AM, Rice FL (2002) Distribution and terminal arborizations of cutaneous mechanoreceptors in the glabrous finger pads of the monkey. J Comp Neurol 445:347-359.

Phillips JR, Johansson RS, Johnson KO (1990) Representation of Braille characters in human nerve fibers. Exp Brain Res 81:589-592.

Roland PE and Mortensen E (1987) Somatosensory detection of microgeometry, macrogeometry and kinaesthesia in man. Brain Res 12:1-42.

Scott SH, Loeb GE (1994) The computation of position sense from spindles in mono- and multiarticular muscles. J.Neurosci 14: 7529-7540.

Seki K, Perlmutter SI, Fetz EE (2003) Sensory input to primate spinal cord is presynaptically inhibited during voluntary movement. Nature Neurosci 6: 1209-1316.

Sinclair RJ, Burton H (1991) Tactile discrimination of gratings: psychophysical and neural correlated in human and monkey. Somatosens Mot Res 8 : 241-248.

Srinivasan, MA, LaMotte RH (1987) Tactile discrimination of shape: responses of slowly and rapidly adapting mechanoreceptors afferents to a step indented into the monkey fingerpad. J. Neurosci 7: 1682-1697.

Talbot WH, Darian-Smith I, Kornhuber HH, Mountcastle VB (1968) The sense of flutter-vibration: Comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand. J Neurophysiol 31: 301-334.

Turvey MT (1996) Dynamic touch. American Psychologist 51: 1134-1152.

Tholey G, Desai JP, Castellanos AE (2005) Force feedback plays a significant role in minimally invasive surgery. Ann Surg 241:102-109.

Vallbo AB, Johansson RS (1984) Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. Human Neurobiol 3: 3-14.

Vega-Bermudez F, KO Johnson, SS Hsiao (1991) Human tactile pattern recognition: active versus passive touch, velocity effects, and patterns of confusion J Neurophysiol 65: 531-546.

Voisin J, Benoit G, Chapman CE (2002a) Haptic discrimination of object shape in humans: Two-dimensional (2-D) angle discrimination. Exp Brain Res 145: 239-250.

Voisin J, Lamarre Y, Chapman CE (2002b) Haptic discrimination of object shape in humans: contributions of cutaneous and proprioceptive input. Exp Brain Res 145: 251-260.

Voisin J, Michaud G, Chapman CE (2005). Haptic shape discrimination in humans: insight into haptic frames of reference. Exp Brain Res 164:347-356.

Voisin J, Lamarre Y, Chapman CE (2002b) Haptic discrimination of object shape in humans: contributions of cutaneous and proprioceptive input. Exp Brain Res 145: 251-260.

Weiss H, Ortmaier T, Maass H, Hirzinger G, Kuehnapfel (2003) A virtual-reality-based haptic surgical training system. Comp Aid Surg 8: 269-272.

Weiss DJ, Okamura AM (2004) Haptic rendering of tissue cutting with scissors. Stud Health Technol Inform 98: 407-409.

Yao HY, Hayward V (2005) A tactile enhancement instrument for minimally invasive surgery. Comput Aid Surg 10: 233-239.

Zhang M, Weisser VD, Stilla R, Prather SC, Sathian K (2004) Multisensory cortical processing of object shape and its relation to mental imagery. Cogn Affect Behav Neurosci 4: 251-259.

CHAPTER VI

ANNEXE

Université de Montréal

Faculté de médecine
Vice-décanat
Recherche et études supérieures

ANNEXE A

APPROBATION DU COMITÉ D'ÉTHIQUE DE LA RECHERCHE DE LA FACULTÉ DE MÉDECINE (CERFM)

Le Comité d'éthique a étudié le projet intitulé :

La contribution des afférences proprioceptives et cutanés dans la discrimination tactile des angles chez l'humain

présenté par : **Mme Myriam Lévy et Dre C. Elaine Chapman**

et considère que la recherche proposée sur des humains est conforme à l'éthique.

[redacted]

Dr Vincent F. Castellucci, Président

Date d'étude :	**16 décembre 2004**
Date d'approbation :	**Modifié et approuvé le 13 janvier 2005**
Numéro de référence :	**CERFM-61(04) 4 #147**

N.B. Veuillez utiliser le numéro de référence dans toute correspondance avec le Comité d'éthique relativement à ce projet.

Le Comité comprend que le chercheur se conformera à l'article 19 de la Loi sur les services de santé et services sociaux.

Le chercheur doit solliciter le CERFM pour toutes modifications ultérieures au protocole ou au formulaire de consentement.

Annexe B : Contributions of different authors to the article of the thesis

Myriam Levy: 80%

Stéphanie Bourgeon: 5%

Elaine Chapman: 15%

ANNEXE C
ACCORD DES COAUTEURS

1. Identification de l'étudiant et du programme

Levy Myriam
Msc. en Sciences Neurologiques

2. Description de l'article

Levy Myriam, Bourgeon Stéphanie, Chapman C. Elaine. Haptic discrimination of two-dimensional angles: influence of exploratory strategy. Article soumis pour publication dans Exp Brain Res.

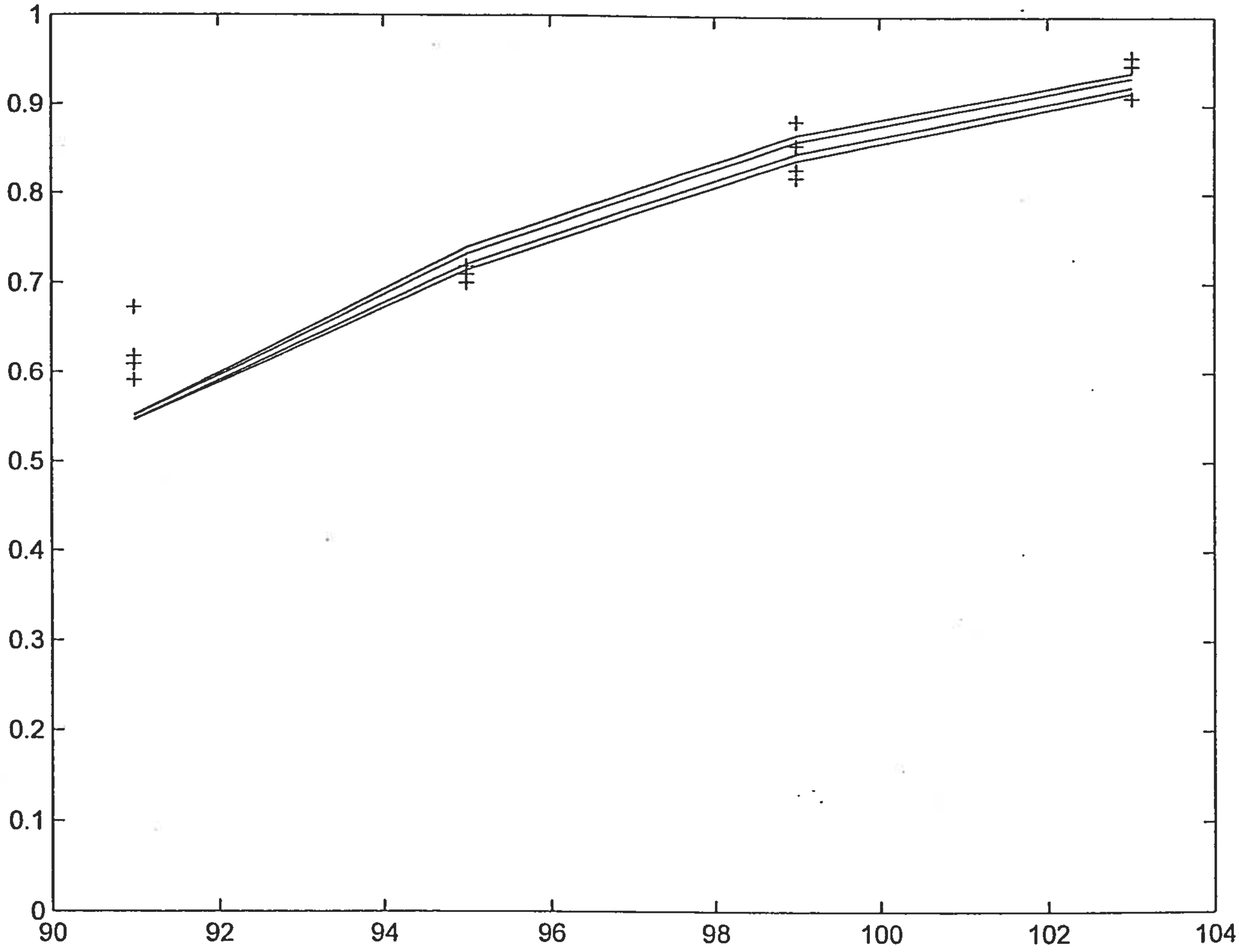
3. Déclaration de tous les coauteurs autres que l'étudiant

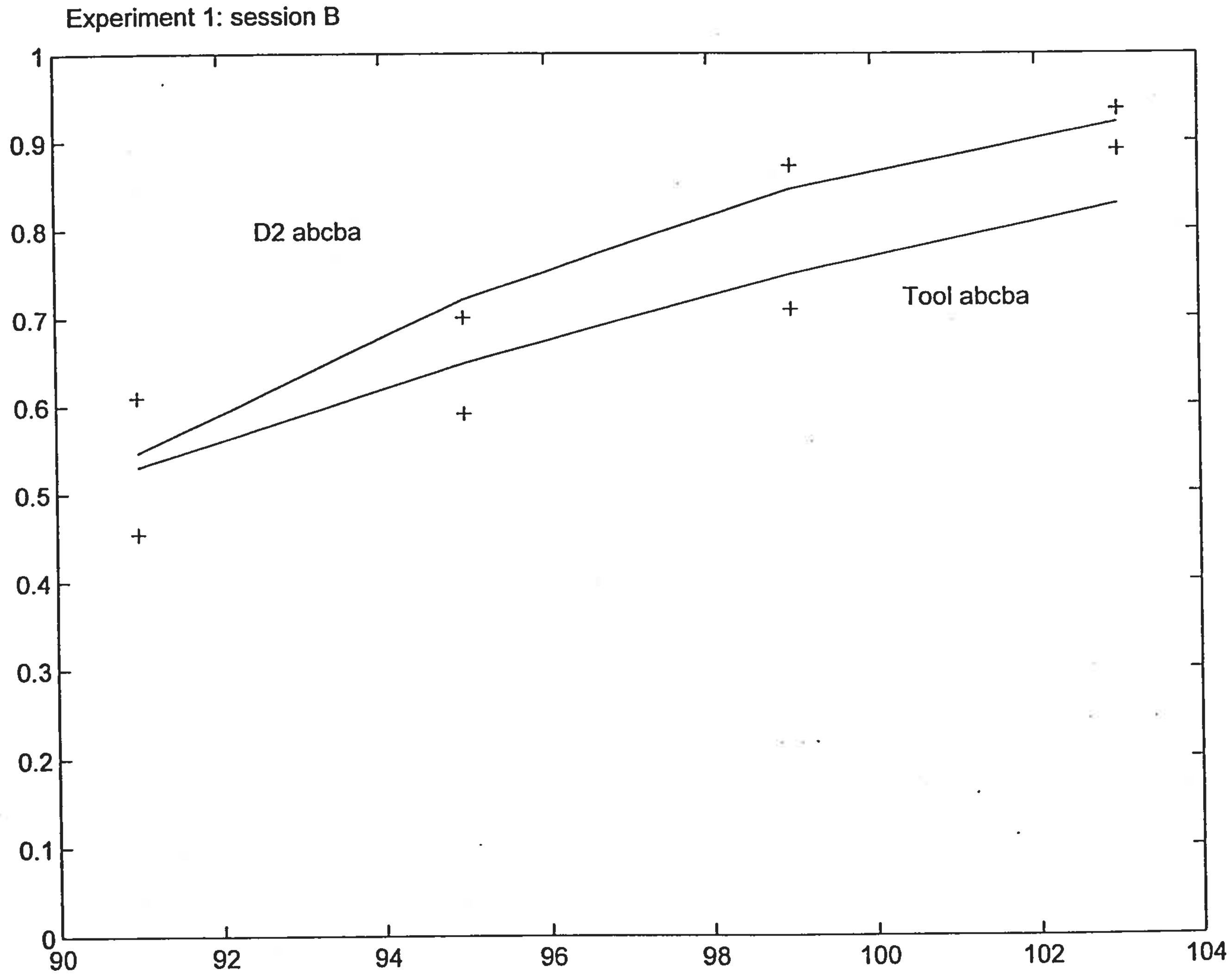
A titre de coauteur identifié ci-dessus, je suis d'accord pour que Myriam Levy inclue cet article dans son mémoire de maîtrise qui a pour titre Haptic discrimination of two-dimensional angles : influence of exploratory strategy.

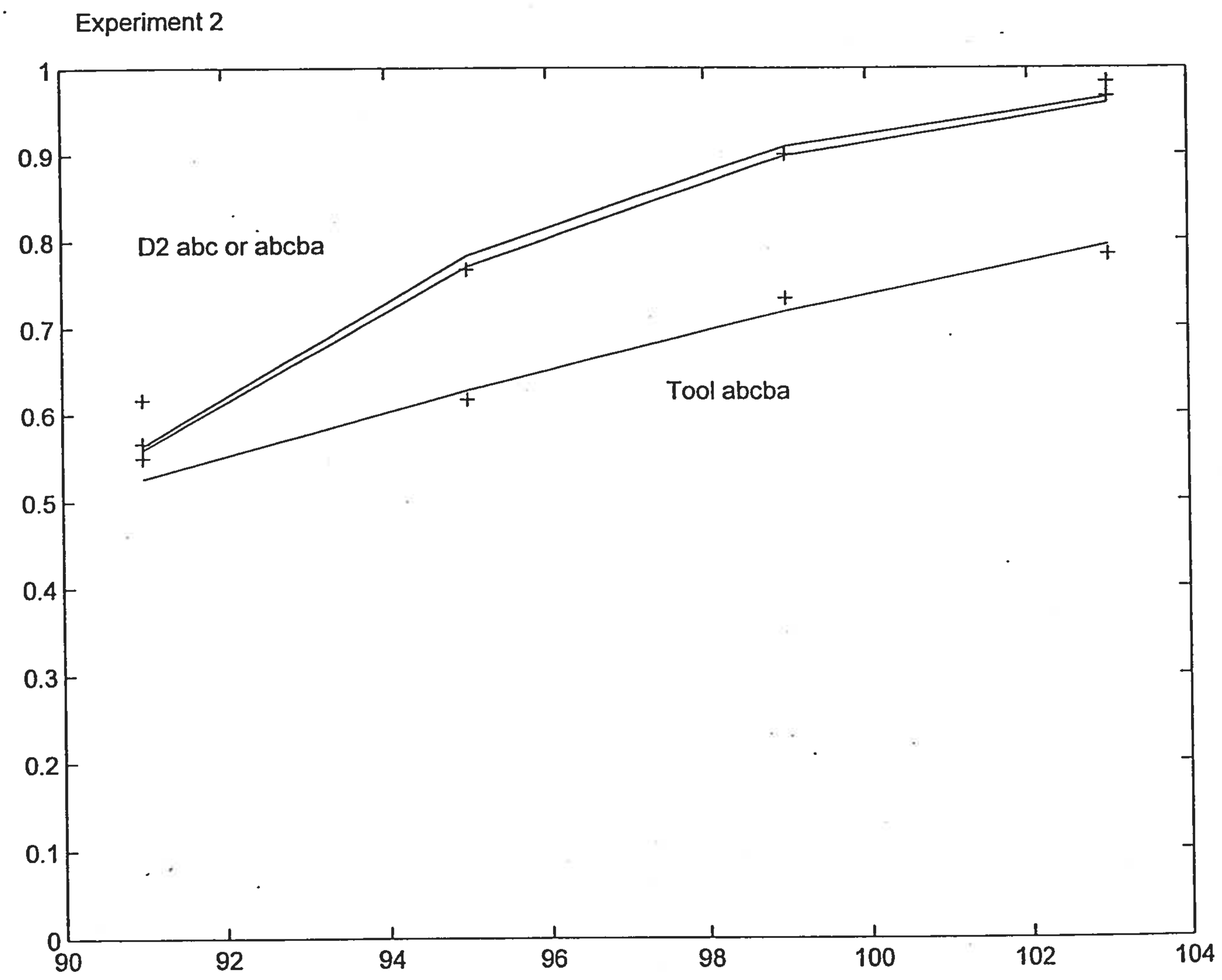
Coauteur signature date
BOURGEON Stéphanie [redacted] 28 avril 06

Coauteur [redacted] date
Chapman, C. Elaine 28/04/2006.

Experiment 1: session A




Experiment 1: session B
D2 abcba
Tool abcba
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
90
92
94
96
98
100
102
104


Experiment 2
D2 abc or abcba
Tool abcba
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
90
92
94
96
98
100
102
104