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Facteurs influencing haptic shape perception

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Facteurs influencing haptic shape perception

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ABSTRACT

The purpose was to determine the contribution of several factors (design of the task, angle orientation, head position and gaze) to the ability of subjects to perceive differences in two-dimensional (2-D) shape using haptic touch. Two series of experiments (n=12 each) were carried out. In all cases the angles were explored with the index finger of the outstretched arm. The first experiment showed that the mean threshold for 2-D angle discrimination was significantly higher, 7.4°, than for 2-D angle categorization, 3.9°. This result extended previous work, by showing that the difference is present in the same subjects tested under identical conditions (knowledge of results, visual test conditions, angle orientation). The results also showed that angle categorization did not vary as a function of the orientation of the angles in space (oblique, upright). Given that the angles presented were all distributed around 90°, and that this may be a special case as in vision, this finding needs to be extended to different ranges of angles. The higher threshold with angle discrimination likely reflects the increased cognitive demands of this task which required subjects to temporarily store a mental representation of the first angle scanned, and to compare this to the second scanned angle.

The second experiment followed up on observations that categorization thresholds are modified with gaze direction but not head position when the unseen angles are explored in an eccentric position, 60° to the right of midline. This experiment tested the hypothesis that the increased threshold when gaze was directed to the far right might reflect an action of spatial attention. Subjects explored angles located to the right of midline, systematically varying the direction of gaze (away from or to the angles) along with angle location (30° and 60° to the right). Categorization thresholds showed no change across the conditions tested, although bias (point of subjective equality) was changed (shift to lower angle values). Since our testing with far right gaze (away) had no effect on threshold, we suggest that the key factor contributing to the increased threshold seen previously (head forward/gaze right) must have been this particular combination of head/gaze/angles used and not spatial attention.

Keywords: haptic perception, shape, gaze, head position, spatial location

RÉSUMÉ

Le but de cette étude était de déterminer la contribution de plusieurs facteurs (le design de la tâche, l’orientation d’angle, la position de la tête et du regard) sur la capacité des sujets à percevoir les différences de formes bidimensionnelles (2-D) en utilisant le toucher haptique. Deux séries d'expériences (n = 12 chacune) ont été effectuées. Dans tous les cas, les angles ont été explorés avec l'index du bras tendu. La première expérience a démontré que le seuil de discrimination des angles 2-D a été nettement plus élevé, 7,4°, que le seuil de catégorisation des angles 2-D, 3,9°. Ce résultat étend les travaux précédents, en montrant que la différence est présente dans les mêmes sujets testés dans des conditions identiques (connaissance des résultats, conditions d'essai visuel, l’orientation d’angle). Les résultats ont également montré que l'angle de catégorisation ne varie pas en fonction de l'orientation des angles dans l'espace (oblique, verticale). Étant donné que les angles présentés étaient tous distribués autour de 90°, ce qui peut être un cas particulier comme dans la vision, cette constatation doit être étendue à différentes gammes d'angles. Le seuil plus élevé dans la tâche de discrimination reflète probablement une exigence cognitive accrue de cette tâche en demandant aux sujets de mémoriser temporairement une représentation mentale du premier angle exploré et de la comparer avec le deuxième angle exploré.

La deuxième expérience représente la suite logique d’une expérience antérieure dans laquelle on a constaté que le seuil de catégorisation est modifié avec la direction du regard, mais pas avec la position de la tête quand les angles (non visibles) sont explorés en position excentrique, 60° à la droite de la ligne médiane. Cette expérience a testé l'hypothèse que l'augmentation du seuil, quand le regard est dirigé vers l'extrême droite, pourrait refléter une action de l'attention spatiale. Les sujets ont exploré les angles situés à droite de la ligne médiane, variant systématiquement la direction du regard (loin ou vers l’angle) de même que l'emplacement d'angle (30° et 60° vers la droite). Les seuils de catégorisation n’ont démontré aucun changement parmi les conditions testées, bien que le biais (point d'égalité subjective) ait été modifié (décalage aux valeurs inférieurs à 90°). Puisque notre test avec le regard fixé à l’extrême droite (loin) n'a eu aucun effet sur le seuil, nous proposons que le facteur clé contribuant à l'augmentation du seuil vu précédemment (tête tout droit/regard à droite) doit être cette combinaison particulière de la tête/regard/angles et non l’attention spatiale.

Mots clés : perception haptique, forme, regard, position de la tête, position dans l’espace.

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LIST OF ABBREVIATIONS

aIPS	anterior part of the intraparietal sulcus
2-D	2 dimensional
D2	index finger
dB	decibel
fMRI	functional magnetic resonance imaging
GTO	Golgi tendon organ
Hz	Hertz
KOR	knowledge of results
LIP	lateral intraparietal area
LOC	lateral occipital complex
LOtv	lateral occipital tactile-visual
MI	motor cortex
PET	Positron emission tomography
PPC	Posterior parietal cortex
RA	Rapidly adapting
s	seconds
S	Stimulus (Weber fraction=$\Delta S/S$)
SI	Primary somatosensory cortex
SII	Secondary somatosensory cortex
SA	Slowly adapting
TOR	Tactile object recognition
VIP	ventral intraparietal area
VPL	ventroposterior lateral nucleus

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CHAPTER I

INTRODUCTION

I.1. INTRODUCTION

Tactile perception is essential for exploring, knowing and understanding our environment. People interact and manipulate objects constantly without vision. For example, when we dress ourselves (fasten the buttons on a shirt), this is done entirely using tactile feedback; likewise, when driving a car, we can change gears without looking at the gearshift. Touching and exploring an object gives us knowledge (“gnosis”) about the object. *Stereognosis,* a term introduced by Hoffman (1884), is the ability to perceive and understand the form and nature of objects by the sense of touch (Mosby’s Dental Dictionary, 2008). As such, this ability is critically dependent on feedback from both tactile receptors (skin) and from proprioceptors. How this information is combined to generate a perceptual whole remains an intriguing subject in neuroscience.

The term "haptics" is derived from the Greek word, haptikos, meaning "able to lay hold of". For Gibson (1966), haptics implied "the sensibility of the individual to the world adjacent to his body by the use of his body". In other words, the sensations associated with tactile exploration and manipulation of the surround, most often using the hand. Gibson (1966) defined three types of tactile perception: 1) *Cutaneous touch,* implies the stimulation of a region of skin and subcutaneous tissue. An example is the placement of an object, such as a $1 coin, on the palm (passive touch) or, conversely, the palm on the coin (active touch). 2) *Haptic touch* implies the stimulation of the skin and adjacent tissues combined with voluntary, self-generated movements of exploration that bring the hand into contact with an object; for example, exploring several coins in your pocket, with a view to finding a $1 coin. In this case, object identification critically depends on both cutaneous and proprioceptive feedback. 3) *Dynamic touch* is similar to haptic touch, but implies an added contribution of muscular effort and its sensory consequences. An example is hefting an object in the hand in order to estimate its relative weight.

Studies of haptic shape are complicated by the multi-dimensional nature and complexity of the subject. In the first case, shape itself is defined by many attributes, including local curvatures, surface orientation, edges, and the relationships between the various features. Second, information about object shape gained through haptic exploration is encoded by several different types of receptors, including both cutaneous and proprioceptive mechanoreceptors. Third, active exploration of objects necessarily involves exploratory movements, and movement itself can modulate the processing of sensory information (Chapman, 1994).

As a consequence, one approach to the study of haptics has been to concentrate on microgeometry, i.e. geometric features that can be explored with a single cutaneous contact, including local curvature, edges, and spatial patterns similar to Braille dots (Goodwin et al., 1991; Johansson et al., 1982; Phillips and Johnson, 1981). While these studies have provided a good deal of information on the cutaneous tactile system, the results provide only a partial description of haptic sensory capacities since the proprioceptive contribution to these tasks was nil.

More recently, investigators have begun to explore the macro-geometric features of object shape using tasks that involve active exploration of shapes, and that require an integration of both cutaneous and proprioceptive signals. Such studies are, however, only beginning to define the perceptual limits of haptic touch.

Following on from recent work in this laboratory (Levy et al. 2007; Voisin et al 2002a,b, 2005) , this study was undertaken in order to further investigate factors that modify the haptic perception of shape. Specifically, we determined the extent to which the haptic perception of two-dimensional (2-D) angles varied with the design of the task, the exploration strategy, the orientation of the angles in space, and the posture of the subject.

I.2. LITERATURE REVIEW

Tactile recognition of an object gripped with the hand implies 2 sources of information: cutaneous input from mechanoreceptors located in the skin and kinaesthetic information from receptors located in the muscles, tendons and articulations. Haptic inputs are usually generated using active touch (the subject explores an object).

I.2.1. Receptors involved in haptic touch

I.2.1.1. Cutaneous mechanoreceptors

Discriminative touch is mediated by mechanoreceptors in the skin, which allow us to sense the deformation produced by indentations or lateral motion across the skin, to sense the shape (local) and surface texture of objects. Much of our knowledge of cutaneous mechanoreceptors comes from studies of the innervations of the glabrous skin of the hand. The following account is focused on these.

The discharge properties of cutaneous mechanoreceptors have been characterized in anesthetized animals (including non-human primates) and in awaken humans, in the latter case using percutaneous microelectrode recordings. Overall the results in both species are similar. In the glabrous skin of the human hand four types of tactile afferent units have been founded: SAI, SAII, RA and PC (Johansson and Vallbo, 1979a). The 4 types of afferents can be differentiated in terms of their rate of adaptation to mechanical stimulation (slowly or rapidly adapting), and the characteristics of the receptive field (small and well defined, or large and indistinct).

Two types of tactile afferents are characterized by the presence of a small receptive field with well-defined borders (Johansson and Vallbo, 1979a, b). RA (rapidly-adapting) afferents are activated only at the start and the cessation of the stimulus (“on” and “off” responses); SAI (slowly-adapting type I) afferents in contrast discharge continuously during the application of mechanical stimulation. RA afferents are presumed to be connected to Meissner's corpuscles, located in the apex of the dermal-epidermal papilla. SAI afferents are thought to end in relation to Merkel cells which are disc-like endings founded at the base of the intermediate epidermal ridges that form the pattern of fingerprints (Johnson, 2001 review; Paré et al., 2002).

The remaining two types of fibers are both characterized by having large receptive fields with indistinct borders. The PC fibers (rapidly-adapting afferents), as indicated by their name, innervate Pacinian corpuscles; these multi-layered corpuscles are found in the deeper layers of the dermis as well as in other tissues (aponeuroses, tendons, muscles and even in the abdominal mesentery). The SAII afferents (slowly-adapting type II) are presumed to innervate the Ruffini endings which are located in the connective tissue of the dermis (reviewed in Bell et al., 1994; Johnson, 2001).

The four types of mechanoreceptors in the glabrous skin are innervated by large myelinated fibers (Aβ) with a conduction velocity from 20 to about 80 ms^{-1}. Their density and distribution varies across the hand, especially for SAI and RA fibers. Their density is highest on the fingertips (SAI, 70/cm²; RA, 140/cm²) and lower more proximally (digits, palm). On the other hand, SAII and PC afferents have much lower densities, 9/cm² (exclude nails) and respectively 21/cm² (Johansson and Vallbo, 1979). The tactile acuity of the glabrous skin of the hand is such that subject can discriminate the distance between two points ranging from 1 to 2 mm on the fingertips, comparatively to 10 to 11 mm on the palm or 70 mm on the back (Semmes et al., 1960).

Each type of cutaneous mechanoreceptive afferent is thought to play a differential role in discriminative touch.

SAI units may be the only afferents that respond with sufficient acuity to explain the task of local form recognition in humans such as Braille reading (Phillips et al., 1990). SAI afferents are sensitive to different degrees of skin indentation (Knibestol and Vallbo, 1980), and continue to discharge during static touch, so likely playing a role in the perception of maintained pressure. They are particularly sensitive to local stresses and strains making them sensitive to fine spatial details such as points, edges, bars and corners (Johansson et al., 1982b; Phillips and Johnson, 1981). They have a high spatial resolution and are extremely sensitive to local curvature (Goodwin et al., 1991; Goodwin and Wheat, 1992; Goodwin et al., 1995; Goodwin et al., 1997; Lamotte et al., 1987a,b; Srinivasan and LaMotte, 1987). SAI afferents are also thought to be essential for the tactile perception of texture (Connor et al., 1990; Connor and Johnson, 1992; Yoshioka et al., 2001).

SAII afferents have receptive fields that are five times larger than for SAI afferents and their sensitivity to skin indentation/deformation is six times poorer than SAI afferents (Johansson and Vallbo, 1979, 1980). Stimulating a single SAII afferent in general does not evoke any sensation in contrast with the SAI, RA and PC fibers which elicit conscious sensations of specific qualities (Macefield et al., 1990; Torebjork et al., 1987; Vallbo et al., 1984). Microstimulation of a single RA or PC fibers in alert human subjects evokes a distinct sensations of flutter or vibration depending upon the frequency of the stimuli (Vallbo et al., 1984). Because SAII afferents discharge during digit movements they are thought to play a significant role in signaling joint position and movement (Burke et al., 1988; Edin and Johansson, 1995; Macefield et al., 1990). Consistent with this, SAII afferents are particularly sensitive to tangential forces applied to the skin, increasing their discharge for stimuli applied in certain directions and decreasing for others (Edin, 1992; Edin and Johansson, 1995; Olausson et al., 2000). The latter observation suggests that SAII afferents may also play a role in encoding the direction of object motion across the skin (Johansson, 1978; Knibestol and Vallbo, 1970). The poor SAII response to raised dot patterns (similar to Braille patterns) and to curve surfaces makes it unlikely that these fibers contribute to detecting either fine spatial details or local form (Goodwin et al., 1997; Phillips et al., 1990).

RA afferents have a higher density than SAI afferents on the fingertips, but these afferents do not appear to resolve spatial detail as well as SAI afferents. They also do not respond to sustained skin deformation which differentiates them from the

SAI and SAII afferents. These afferents are insensitive to static contact but they are sensitive to low frequency vibration < 60Hz which produce a sensation of flutter (Johnson et al., 2000). These afferents are sensitive to light touch and signal the presence of surface features as small as 2 to 4 μm (Johansson and Vallbo, 1979; LaMotte and Whitehouse, 1986). These afferents are thought to play an important role in grip control because they are very sensitive to slip (Johansson and Westling, 1987a; Johnson et al., 2000).

The **Pacinian afferents** have large receptive fields, making it unlikely that they contribute significantly to fine discrimination of spatial details and local form. They have some important characteristics: 1) PC afferents are very sensitive to touch, responding to dynamic deformations of less than 1μm and high frequencies (from 100 to >500 Hz) with maximum sensitivity around 300Hz (Bolanowski et al., 1988; Brisben et al., 1999); 2) the PC afferents have a powerful filtration system (60dB/decade) so that low frequencies are filtered out. Psychophysical and neurophysiological studies have shown that PC afferents likely play an important role in sensing the vibration of tools held in the hand (Brisben et al., 1999; Johnson et al., 2000).

I.2.1.2. Proprioceptive mechanoreceptors

The term proprioception can be defined as “the sensing of the body’s own movements “. This term refers to the perception of three variables: movement, position and force. The information provided by exteroceptors and proprioceptors enables the system to organize a rapid response to a perturbation, to determine limb position, to differentiate between self-generated and imposed movements and to guide movements. Proprioception can be based on a broad range of mechanoreceptors including muscle spindles, Golgi tendons organs, joint receptors as well as cutaneous receptors, in particular the SAII afferents (Gandevia, 1996).

The *muscle spindle* is the sense organ involved in stretch reflexes like the knee jerk (patellar reflex). It is a slowly adapting receptor with a prominent rapidly adapting response (especially Ia afferents): the discharge in the afferent fibers continues for as long as the muscle is stretched. The muscle spindle is composed of small fibers known as *intrafusal muscle fibers* that lie in parallel with the *extrafusal muscle fibers* (ie skeletal muscle). The muscle spindle contains two types of sensory endings: *large-diameter primary endings* (innervated by group Ia afferents) that code for both the rate of change in dynamic stretch (and also sensitive to longitudinal vibration of the muscle) and the absolute change in the length of muscle fibers; *smaller-diameter secondary endings* (innervated by group II muscle afferents) that are sensitive to muscle length (reviewed in Clark et al., 1986; Gandevia, 1996). These two types of sensory endings terminate in the central region of the intrafusal fibers. Muscle spindles have their own motor innervation via the *gamma motoneurons* (the fusimotor system); some spindles are also innervated by beta motoneurons (skeletofusimotor fibers) that branch to innervate both extrafusal and intrafusal muscle fibers. The fusimotor innervation of muscle spindles controls their sensitivity to stretch by contracting the intrafusal fibers on either side of the central region; this stretches the central sensory region and so activates the primary and secondary endings.

A series of experiments on the effects of muscle tendon vibration on the perception of limb movement demonstrated the importance of feedback from muscle spindle receptors to the perception of limb movement (Goodwin et al., 1995). Goodwin and colleagues found that vibration of the tendon at a frequency of 100Hz (a stimulus that particularly activates primary endings of muscle spindles) produced the illusion that the elbow was moving into extension, as if the vibrated muscle were being stretched; vibration of the triceps tendon produced the opposite effect, an illusory flexion movement. Consistent with this, illusions of movement can also be produced by stretches as small as 0.5mm applied directly to the tendon in the awake human (McCloskey et al., 1983).

Compared with touch in which case acuity is directly proportional to the density of the mechanoreceptors, proprioception does not appear to be better for regions with a higher density of muscle spindles (Burke and Gandevia, 1990). If anything, proprioceptive acuity in relation to the amplitude of joint rotation for detecting movement (absolute threshold) is better developed proximally (shoulder, a region with lower spindle density) as compared to distally (finger, higher spindle density) (Hall and McCloskey, 1983). When the performance is described in terms of muscle length, however, the ``threshold`` is actually lower for distal joints (finger) as compared to proximal ones (shoulder or elbow) (Hall and McCloskey, 1983). The ability to detect limb movements depends on several factors including the amplitude of the movement and its velocity. The movement has to be sufficiently large to be perceived (> detection threshold). If the angular velocity of rotation is very slow, then threshold is high. This effect however, plateaus at approximately 1-10 deg/sec for, respectively, proximal and distal joints (Gandevia et al., 1983; Hall and McCloskey, 1983).Position sense, in turn, is the ability to recognise the position in which a limb is either passively placed or actively assumed; obviously, this is done with the eyes closed. Usually, position sense is measured at a single joint (hip, knee, shoulder, elbow, ankle, wrist or finger) but some studies have used combined movements of several joints. This ability is often measured using a matching procedure in which the subject is asked to align the position of two corresponding joints (left and right) of the body. The errors in matching the position of two corresponding joints are often high in normal healthy individuals. For example, for the proximal interphalangeal joint, the mean error is 2.7° over a range of 100° to 170° of finger flexion, with larger errors at 120° to 150° (Clark et al., 1995). Examples of the errors seen at other joints are: 3° for the metacarpophalangeal joint of the index finger and the wrist; 5°-6° for the elbow; and 12° for the shoulder joint.

There is evidence that position sense is better if the subjects move their limb actively rather than being moved passively by the experimenter. For example, Brouchon and Paillard (1968) showed that the errors for positioning the whole arm are substantially smaller when the subjects assumed the position actively (active, 6 mm; passive, 22 mm).

Golgi tendon organs (GTOs) are encapsulated receptors usually found near the muscle-tendon junction (90%). They are located “in-series’’ with the extrafusal muscle fibers, in contrast to spindles that are located in parallel (reviewed in

Gandevia, 1996). In human muscles, the muscular end of each GTO is attached to 10 to 20 muscle fibers (Bridgman, 1970). A single group Ib axon innervates each Golgi tendon organ. They are silent at rest and start to discharge as soon as the motor unit in series with the receptor starts to contract (Gandevia, 1996; Jami, 1992). Because GTOs are very sensitive to “in-series” forces, most GTOs are capable of signalling very small and rapid changes in contractile forces (Houk et al., 1971; Jami 1992).

Sensory information about changes in limb position and movement also arises from other sources, in particular receptors in the skin and joints. In contrast to the muscle spindle and GTO, the *joint receptor* is not a single, well-defined entity. Joint receptors vary in their location (joint capsule, ligament) and type (Ruffini ending, Golgi ending, paciniform corpuscle). Ruffini endings are capable of signalling joint position, displacement and angular velocity (Bell et al., 1994). Their sensitivity to joint position and movement is modified by increased tension in the joint capsule produced by the contraction of the skeletal muscles that insert into the joint capsule (Skoglund, 1956). Since joint afferents are most sensitive at the extreme range of motion with relatively little discharge in the midrange, it is unlikely that they provide reliable information about joint position during natural movements (Clark and Horch, 1986; Gandevia, 1996). In addition, total joint replacement does not modify joint position or movement sense. Nevertheless, intra-articular injection of local anaesthesia produces a partial reduction in the detection of movement, supporting the potential implication, possibly minor, of joint receptors in proprioception (Clark et al., 1989; Ferrell and Smith, 1987).

SAII afferents are cutaneous receptors that are thought to play a role in the proprioception. This is supported by the proprioceptive deficit seen in severe burn victims (large surface area of skin damaged) (Moberg, 1983). These afferents (above) are particularly sensitive to lateral skin stretch. SAII discharge may explain Gandevia et al.’s (1976, 1983) observation that the detection of movement imposed on the distal phalanx of D3 or D4 is partly preserved even when the muscles are disengaged by a particular posture (extension of all the fingers except flexion of proximal interphalageal joints of D3 or D4). Supporting this point of view, mechanical stretch of the finger skin generates an illusion of movement (Edin and Johansson, 1995). In addition, electrical stimulation of the dorsum of the hand and finger (hairy skin), presumably activating SAII afferents, also gives rise to kinaesthetic illusions (Collins and Prochazka, 1996).

I.2.2. Cortical centres involved in the perception of shape

Research in humans and nonhuman primates supports the idea that somatosensory information travels through a hierarchy of processing stages to accomplish haptic object recognition tasks. Cutaneous and proprioceptive information from the periphery is transmitted by large myelinated afferent axons (conduction velocities of 35-70m/s), through the dorsal columns to make their first relay in the dorsal column nuclei (nucleus cuneatus for the hand). After synapsing, the second order neurones cross the midline to form the medial lemniscus which conveys somatic sensory information to the ventroposterior lateral nucleus (VPL) of the thalamus. From here, third order neurones project to primary somatosensory cortex (SI) in the postcentral gyrus of the parietal lobe. SI is composed of four cytoarchitectonic areas (3a, 3b, 1 and 2), each of which contains a somatotopic map of the contralateral half of the body with the head lateral and the foot medial (Chen et al., 2005; Kaas et al., 1979; Pons et al., 1985). As described by Powell and Mountcastle (1959), SI cortex is organized in vertical columns with neurones of each column sharing the same modality preference, cutaneous or proprioceptive, and receptive field. Electrophysiological studies have shown that neurones in areas 3b and 1 respond to cutaneous inputs while neurones in areas 3a and 2 are activated by deep inputs, including muscle spindles (Iwamura et al., 1983a, 1983b, 1985a, 1985b; Iwamura, 1998; Kaas, 1983; Powell and Mountcastle, 1959). The hand representation in area 2 also receives cutaneous input (Pons et al., 1985). Single-unit recordings from these areas show the existence of an antero-posterior gradient in the complexity and size of the receptive fields (Iwamura et al. 1993, 1995a, b; Sakata et al., 1973). Receptive fields are small in area 3b, restricted to single phalanges on one digit, much as seen in the periphery. The dimension of the receptive fields enlarges in the more posterior areas (1 and 2) with multi-digit receptive fields in area 2 (Hyvarinen and Poranen, 1978b; Iwamura et al., 1983a, 1983b, 1985a, 1985b).

VPL sends a weaker projection to secondary somatosensory cortex (SII) located in the upper wall of the lateral sulcus (Burton and Jones, 1976, Friedman et al., 1986; Jones and Friedman, 1982). In SI, all four areas are interconnected (reciprocal connections): neurones in areas 3a and 3b send projections to areas 1 and 2; area 1in turn sends projections to area 2 (Jones and Powell, 1969a, b). The pattern of connectivity, along with the changes in receptive field properties in more posterior SI cortical areas is consistent with areas 1 and 2 representing higher stages of processing than areas 3a and 3b.

SI projects posteriorly to area 5 which in turn projects to area 7 (collectively termed posterior parietal cortex, PPC). PPC is a complex region that is considered to play an important role in motor control, specifically planning movements in relation to the sensory surround (Andersen and Buneo, 2002; Heekeren et al., 2008). Area 5 receives mainly somaesthetic inputs from areas 1 and 2 (Pearson and Powell, 1985; Pons and Kaas, 1986). Receptive fields are large (eg. whole limb) and are frequently bilateral. Area 7 receives somaesthetic inputs from area 5, as well as SII. These are directed mainly to the lateral part of area 7 (7b). Visual inputs are dominant elsewhere (area 7a, medial) but are also found in 7b. The cortex within the intraparietal sulcus has been subdivided into a number of areas (LIP, lateral intraparietal area; AIP, anterior intraparietal area; VIP, ventral intraparietal area, etc) each of which is considered to contribute to planning movements in relation to sensory stimuli (visual, auditory).

The results of experiments in SI primary somatosensory cortex in monkeys have shown that lesions of the anterior part of the postcentral gyrus nonselectively impair performance on several somaesthetic discrimination tasks including roughness and shape (concave-convex or square-diamond) discriminations (Carlson, 1981; Randolph and Semmes, 1974). Lesions in area 1 disrupt texture discrimination. Lesions of the posterior part of the postcentral gyrus, Brodmann’s area 2, selectively impair the ability to discriminate the shape and size of objects (Carlson, 1981;

Randolph and Semmes, 1974). This result suggests that somatosensory processing may be divided into channels for different properties of objects such as form and texture. It appears that areas 3a and 3b constitute an essential access point for proprioceptive and cutaneous information, respectively, because they receive the majority of the thalamic afferents. Thus, lesions or selective inactivation of these areas brings a quasi-complete loss of somaesthesia, similar to a major deafferentation (Randolph and Semmes, 1974).

An unresolved issue is the potential contribution of parietal opercular cortex, including SII to haptic shape discrimination. Lesions of human inferior parietal cortex in and around this region have been reported to impair haptic object recognition contralaterally, producing a deficit that has been characterized as tactile agnosia, a specific inability to recognize objects tactually despite otherwise intact somatic sensation (Caselli, 1993; Reed et al., 1996). This is in accord with the effects of SII lesions in monkeys, which impair their ability to discriminate shapes using the contralateral hand (Murray and Mishkin, 1984).

Single unit recording in both SI (areas 3b, 1 but also 2) and SII of monkeys have shown that neurones have graded responses to textured surfaces (gratings or raised dots with systematic changes in spatial period (Ageranioti-Bélanger and Chapman, 1992; Chapman and Ageranioti-Bélanger, 1991; Darian-Smith et al., 1982; Jiang et al., 1997; Pruett et al., 2001). As for the neuronal mechanisms underlying haptic shape, researchers have found units in area 2 which are selectively activated by objects with different shapes (fruits, rulers or blocks) that are grasped in the hand (Iwamura et al., 1985, 1995; Iwamura and Tanaka 1978). These observations have since been confirmed by Gardner and colleagues (Gardner et al., 1999). Also, Gardner and colleagues reported that area 5 neurones (hand representation) discharge as monkeys reach for and grasp objects, with some cells varying their discharge with the shape of the object (Gardner et al. 2007a, c).

Roland (1998), using functional neuroimaging techniques, reported activity in the anterior part of the intraparietal sulcus (aIPS) during haptic shape discrimination but not in roughness discrimination (Roland et al., 1998). Others study that made similar comparison did not report activation of this region (Servos et al., 2001; Stoesz et al., 2003). One explication of this discrepancy involves the results of others researchers that study haptic object recognition by manipulation of complex or simple smooth objects exploring macrogeometric features that involves somatosensory and motor informations. The aIPS was activated during manipulation of complex objects. The results of those studies concluded that aIPS is not a purely somatosensory region but instead interconnects somatosensory and motor information. Consistent with this, patients with a lesion of parietal lobe suffer from tactile apraxia, i.e. they are unable to recognize objects haptically because of inappropriate exploratory movements (Binkofski et al., 1998, 1999, 2001).

Two other brain regions have been identified in neuroimaging studies as playing a role in haptic shape discrimination. The lateral occipital complex (LOC), or more precisely lateral occipital tactile-visual LOtv, is activated during tactile object recognition process (Amedi et al., 2002; Reed et al., 2004; Stoesz et al., 2003; Zhang et al., 2004). Stoesz et al. found that LOC is activated bilaterally during the spatial form discrimination task (macrospatial) but not in gap detection task (microspatial). Also, LOC activity was greater on the right side than in left side even for stimuli presented to the right hand. Interestingly, this same area is also activated during visual object recognition tasks (Amedi et al., 2001; Stoesz et al., 2003). These results suggest that LOtv, like aIPS, is a bimodal area, involved in both visual and haptic shape perception. This idea is supported also by the case report of a patient with visual and tactile agnosia (despite intact somatosensory function) from a lesion presumably damaged the LOC (Feinberg et al., 1986).

The other region involved is the anterior insula, a polysensory area that receives a direct input from SII and may represent a higher level in the hierarchy of the processes underlying haptic object recognition (Bonda et al., 1996).

In conclusion, haptic shape recognition probably involves a network of different cortical areas in all fields of SI, SII and PPC. It should be stressed, moreover, that haptic exploration generally involves active exploratory movements. Movement and haptic exploration are closely synchronized by virtue of the interconnections existing between motor cortex (M1) and the various parietal fields involved in haptic touch, including SI (Jones et al., 1978; Mouncastle, 1984). In this regard, it is important to note that SI is the only primary sensory cortex to be directly interconnected with motor cortex, and that lesions of SI produce not only sensory deficits but also motor deficits (Brochier et al., 1999; Hikosaka et al., 1985). Finally, the act of movement itself modulates the transmission of sensory inputs to SI cortex (Chapman, 1994), potentially modifying the sensory feedback generated during haptic exploration.

I.2.3. Haptic discrimination of shape

Although, the psychophysics of haptic perception of shape has been the object of interest for many years, it is only recently that there has been renewed interest in the subject. As described earlier, stereognosis implies the recognition of the geometric properties of objects, including their curvature (local or global), the orientation of the surfaces that form an object, and detailed knowledge of the intersections formed by the constituent surfaces. These properties have been investigated using two different approaches: *real shapes* and *virtual shapes* (the subject manipulates a robotic device that creates the illusion of a contour)., The exploration can be either direct or indirect (using a tool in contact with the shape).

Real shapes

One approach to studying the human perception of larger scale *real* shapes was developed by Kappers and colleagues. Her experimental paradigm is based on presenting a reference bar (20 cm long) in one of nine locations distributed across a 70cm (sagittal plane) by 140cm (frontal plane) workspace and then asking subjects to rotate a second bar located elsewhere using their opposite hand so that it felt as if it were parallel with the reference bar. Bar orientation was systematically varied: 0°, 45°, 90° or 135°. Subjects make surprisingly large errors in judgement, up to 40°. She interpreted her results as suggesting that there is considerable bias (point of subjective equality) in the perception of haptic parallelism (Kappers, 1999, 2002; Kappers and Koenderink, 1999). Her results also showed that haptic perception of bar orientation is modified by both the spatial location of the bars, including the distance between the two bars in the horizontal plane (errors increased with an increase in distance) and the exploratory strategy (unimanual versus bimanual). Curiously, errors were larger in the bimanual condition even though the cognitive demands were reduced (no implication of memory as for the unimanual condition). Their explanation for this result was the interaction of two frames of reference for the representation of bar orientation, one egocentric (body-centred, related to the exploring arm) and the other allocentric (centred in external space).

Another approach to studying haptic shape, again using real objects, was developed by Voisin et al. (2002a). The discriminanda were 2-D angles (8×8cm) that, in this case, were explored using a predefined exploratory strategy, a contour following movement using the index finger (tactile feedback) of the outstretched arm. This design limited proprioceptive feedback to a single joint, the shoulder, and cutaneous feedback to one finger. The results were very different from those of Kappers et al. (above): subjects could discriminate angular differences of about 5° (90° vs. 95°) with some subjects being able to discriminate differences of less than 1°. This compares with up to 40° errors in bar orientation, relative to positions of 0, 45, 90 and 135° (above), and suggests that task design is critically important in assessing haptic perception.

Voisin et al. (2002b) also showed that their task was truly haptic in nature, relying on both cutaneous and proprioceptive feedback, since removing either one of the sources of sensory feedback, cutaneous or proprioceptive, led to an increase in discrimination threshold. When both sources were suppressed, the subjects could no longer perform the task. Performance in the task was shown to be relatively invariant as a function of the joints involved in the exploration (Voisin et al. 2005): similar results were obtained for movements involving distal joints (wrist + 2nd metacarpophalangeal joint) and proximal joints (shoulder). While they confirmed that the location of the angles in space can modify haptic perception (e.g. Kappers 1999; Kappers and Koenderink 1999), such effects were complex, being dependent on other factors including the exploratory strategy, the posture of the head, and the length of time between scans.

More recently, Levy et al (2007) investigated the influence of the exploratory strategy on haptic shape discrimination. Performance in the reference condition (as for Voisin et al., 2002a,b) was compared to that in two modified conditions, static touch (cutaneous feedback only) at the intersection and dynamic scan using a hand-held tool (mainly proprioceptive feedback). These strategies were thought to be more "natural" than those studied by Voisin et al. (2002b), namely digital anaesthesia to eliminate cutaneous feedback, and passive movement of the angles over the immobile finger to eliminate proprioceptive feedback. The results showed that performance with static touch was not different from that in the reference condition, if the contact time was very long (3s versus <1s as for active scans). This showed that cutaneous feedback alone is sufficient to explain 2-D angle discrimination. In contrast, performance was poorer using the tool (proprioceptive feedback only available), i.e. when meaningful cutaneous feedback was eliminated. Taken together, the results suggested that cutaneous feedback might be more important for haptic shape perception than proprioceptive feedback. One other observation in the same study was that threshold did not vary with the number of scans over the 2-D angles (one versus two). This result suggested that most of the information necessary for task performance is gathered during the initial sweep over the angle (the first part of the to-and-fro scan used in this task).

At first glance, it is not entirely clear why performance in this 2-D angle task is so much better than in the bar orientation task studied by Kappers and colleagues (above). An explanation can be found, however, in a more recent study from this same group (Hermens et al. 2006). Using the same task, they replicated previous findings of large errors in bar orientation when these were explored bimanually (e.g. Kappers 1999, 2002). More importantly, they found that the errors were substantially decreased when subjects reported the orientation of the bars verbally, instead of haptically. Thus, the errors were largely explained by difficulties in transferring the orientation from one hand to the mirror image on the opposite hand. Consistent with this interpretation, errors were much smaller when the bars were located in the same axis as the hand (or perpendicular to this). Together these findings reinforce the suggestion (above) that task design is critically important for studying haptic perception.

The influence of task design on haptic shape perception was also investigated by our laboratory. Recent results suggest that haptic perception of 2-D angles is more precise when subjects categorize individual angles as large or small, as compared to discriminating angle differences between pairs of serially explored angles (2.4° vs. 4.7° in Voisin et al., 2002a; unpublished observations, G.Michaud, J.Voisin, S.Bourgeon, C.E.Chapman). Several factors were, however, not identical in the two series of experiments. First of all, angle orientation was not the same: oblique for the experiments of Voisin et al. versus upright for the results of Michaud et al. Second, knowledge of results (success or failure in the response) was provided for one experiment (categorization) but not for the other (serial angle discrimination). Third, the cognitive requirements of each task differed. For the serial angle discrimination task, subjects had to generate a mental image of the first angle scanned, and keep this in short-term memory for comparison with the impressions gathered while scanning the second angle of the pair. The categorization task, in contrast, consisted of presenting a block of trials with small (< 90° angle) and large (>90°) angles. In this case, subjects had to develop their own implicit representation of the "standard" (90°, although they were not informed of this fact), and compare each angle scanned to this standard in order to classify the angle as small or large. Finally, the discrimination testing used a condition of no visual feedback, while the categorization testing provided a non informative view of the surround. Thus, questions remain as to how similar, or not, performance is in these serial angle discrimination and angle categorization tasks.

The effects of body posture on haptic shape perception have also been investigated. Voisin et al. (2005) reported that 2-D angle discrimination thresholds are elevated when angles are explored at a position to the far right of midline ("eccentric" location, 60°). Curiously, threshold fell down to levels seen with the angles located at a more central location when the head was subsequently oriented towards the unseen angles (no vision condition). They suggested that the results could be explained by competing frames of reference for the central representation of shape, one centred on the hand/arm and the other on the head. By orienting the head towards the angles, this conflict was resolved, and threshold declined. In contrast, studies by Michaud et al. (unpublished observations, G.Michaud, J.Voisin, S.Bourgeon, C.E.Chapman) indicated that head position has no effect on performance of the angle categorization task, at least for their test conditions (non informative vision). Instead, *gaze direction* appeared to significantly modify angle categorization: thresholds were increased when the head was oriented forward and gaze directed to the far right (towards the unseen angles). They ruled out the possibility that the difference could be explained by the visual feedback conditions (no vision vs. non informative vision), and suggested that the difference was related to task design, specifically the cognitive requirements of the tasks. In addition, they suggested that the increased threshold when gaze was directed to the far right might reflect an action of spatial attention.

One other factor that modifies haptic shape perception is the type of visual feedback, no vision versus non informative vision. In the experiments of Newport et al., (2002), subjects performed the haptic bar orientation task introduced by Kappers (above): the results showed that performance in the task was better with *non informative vision*, as compared to *no-vision*. Their results indicated further that the effects of non informative vision were dependent on the task design, whether the task dependent on an internal or an external frame of reference. When the task was modified so that it depended more on an external frame of reference (place bars parallel to one another), then performance was enhanced with non informative vision. Performance worsened when the task was based more on an internal reference frame (e.g. match bars in a mirror symmetrical orientation).

Virtual shapes

Henriques and Soechting (2003) investigated the ability of subjects to detect absolute curvature and discriminate different arcs varying in curvatures, by wielding the handle of a robot-driven manipulandum. While kinaesthetic feedback generated by the accompanying multi-joint arm movements is critical for this task, tactile feedback from the handle likely also contributes to the overall impression of shape. The shapes were explored at different locations and orientations, inside a horizontal planar region above waist level (workspace dimensions, 15 x 15cm). The exploratory movements involved multiple joints (wrist, elbow and shoulder). In the task to *detect absolute curvature*, the subjects were asked to report whether the hand path curved inward or outward from the body. The mean absolute bias or PSE (point of subjective equality) was 1.8m (0.56m^{-1} curvature) which represents the outward or inward value of curvature that subjects perceive as straight. The grand mean difference threshold for distinguishing between an outward versus an inward curvature was 1.11m^{-1} of curvature; this corresponded to a displacement of the hand of ~0.16cm in either direction from the bias arc. Their results suggested that haptic perception of curvature is invariant across the centrally located workspace that was tested. In the task of *curvature discrimination*, the subjects were asked to compare between pairs of arcs (one straight fixed reference and one curved arc or two curved arcs) and decide what arc was more curved. The arcs were located approximately about 25cm in front of the subjects. The mean difference threshold for arc comparison was 2.88m^{-1} which is much larger than for curvature detection (1.11m^{-1}). This discrepancy can be explained by the difference in path lengths: these were shorter in the curvature discrimination task (12cm) than in the detection task (15cm).

Henriques and Soechting (2004) also investigated how humans perceive more complex shapes, quadrilaterals formed by 4 contiguous boundaries. In this case, performance was assessed by having the subjects reproduce the explored shapes, either using the manipulandum in the horizontal plane (zero force field, eyes closed) or drawing the shape on a vertically oriented touch screen (eyes open). The results showed that subjects made errors related to the size of the object: when using the manipulandum, they overestimated the size of the shapes (15% larger); and when using the touch screen, they underestimated their size (45% smaller). Many factors may have contributed to these differences, including the influence of gravity, the presence or absence of visual feedback, and the absence of force feedback from the edges during the reproduction phase (manipulandum only).

The pattern of errors was, in contrast, similar for both modes of reproducing the shapes: in both cases, subjects tended to make the shapes more regular than they actually were, suggesting that the distortions were not motor in origin, but reflected inaccuracies in haptic perception. One interesting idea is that the differences may be explained by the "tangential-radial effect" whereby lines radiating out from the body in the horizontal plane are perceived as being longer than orthogonally oriented lines (tangential to the body surface, or perpendicular to the radially oriented lines) (Armstrong and Marks 1999; Hogan et al., 1990; McFarland and Soechting 2007). Similar distortions are also seen in the vertical plane (the "oblique" effect), whereby, for example, bar orientation is better for vertically oriented bars than for obliquely oriented bars (Kappers 1999; Kappers and Koenderink 1999).

I.2.4. Frames of reference for haptic shape

The spatial characteristics of an object have to be encoded with respect to some frame of reference. There are 2 classes of reference frames: *egocentric* (body-centered) and *allocentric* (centred on the external environment). An egocentric frame of reference is specified relative to the observer's body and can be centred on the hand (Paillard 1991), the arm (Flanders and Soechting 1995; Soechting and Flanders 1992, 1993), the head or the whole body (Luyat et al., 2001). In contrast, an allocentric reference frame is necessarily anchored on external cues. The importance of frames of reference can be illustrated by considering a simple task such as locating an object in space relative to the body (Millar and Al-Attar 2004). Locating an object haptically is easy if the body position remains unchanged after the initial exploration. If the body position is changed, however, one needs to use additional external cues from the surrounds to successfully locate the object.

One special case in haptics comes from studies of haptic bar orientation; this is a 2-D (not 3-D) task in which bar orientation is explored with one hand (the sensing hand). Reproduction of the bar orientation at some other location may involve either the same hand (unimanual, same hemi-space) or the opposite hand (bimanual, opposite hemi-space). Perceptual acuity is determined by measuring the error in positioning the second bar. This ability is dependent not only on haptic feedback but also gravitational influences. Available evidence from such studies suggests that, as for vision, haptic orientation perception is better for vertical and horizontal bars than for oblique bars (Gentaz et al., 2008), in other words there exists a haptic “oblique effect”.

I.2.5. Exploratory strategy: one or two hands

There are many approaches to studying haptic shape perception. In this laboratory (Voisin et al. 2002a), we developed a 2-D angle discrimination task in which subjects explored pairs of angles (located at the same spatial position relative to the body), using the same hand, and then identified the larger angle (first or second scanned) by making a verbal report. In this case, all of the sensory processing was localized in one hemisphere, contralateral to the angles. In contrast, studies of haptic bar orientation, as mentioned above (1.2.4), involve unimanual or bimanual explorations. In *unimanual bar matching experiments*, the sensory inputs from the exploring hand ascend to the contralateral parietal lobe; in this case both the exploration and the reproduction are carried out by the same hand, and so the same hemisphere. In *bimanual bar matching experiments*, the subject explores with one hand and reproduces the bar orientation with the other: this process necessarily involves transferring somaesthetic information from one hemisphere to the other with the added risk of some degradation in the quality of the salient somaesthetic signals.

In Table 1, the results of a selection of studies investigating haptic shape are summarized. Several conclusions can be made. First, a direct comparison of unimanual and bimanual explorations indicates that haptic errors are larger with bimanual exploration (Kapppers 1999), consistent with the notion that there may be some degradation of the quality of the somaesthetic signals when the task requires transfer across the hemispheres. Consistent with this, 2-D angle discrimination threshold can be as low as 1° for unimanual explorations (Voisin et al. 2002a); this contrasts with mean errors of 41° in bimanual bar matching (Kappers 2003). Second, there is no consensus as yet as to the frames of reference underlying haptic shape perception. Suggestions range from some form of intermediate frame of reference, based on elements of both an ego- and allocentric reference frame (Kappers 2002; Newport et al. 2002; Zuidhoek et al. 2003) to purely egocentric reference frames

(Voisin et al. 2005). The conflicting results are most likely explained by differences in task design. For example, Newport et al. (2002) found that non-informative vision improved performance on the bar matching task, but only when the task was set up so that it favoured an external (allocentric) reference frame. Altogether, it can be concluded that we are only now beginning to understand the frames of reference that contribute to haptic shape perception.

The relatively large errors seen in bimanual bar matching task (above) may have an additional anatomical component. The results of Jones and Hendry (1980), along with those of Killackey and colleagues (1983), showed that the representation of the hand and forearm in S1 (areas 3a, 3b, 1 and 2) lacks callosal connections, with the exception of a part of the area 2 representation. This may lead to some degradation in the quality of the sensory inputs, since interhemispheric transfers would have to occur using other pathways (e.g. S2), in which case the quality of the sensory feedback is lower (e.g. larger receptive fields).

	Task	**Exploration**	**Position of shape**	**Visual feedback**	**Posture**	**Others**	**Conclusions**
Kappers and Koenderink 1999	bar matching	unimanual	varied in horizontal plane	no vision	neutral*	haptic report	haptic errors correlated with horizontal distance between bars but not vertical; haptic oblique effect
Kappers 1999	bar matching	unimanual or bimanual	varied in horizontal plane	no vision	neutral	haptic report	Haptic errors larger with bimanual exploration
Kappers 2002	bar matching	unimanual or bimanual	varied in midsagittal plane	no vision	neutral	haptic report	Errors larger than for horizontal plane; egocentric frame of reference for bimanual; more allocentric for unimanual
Newport et al., 2002	bar matching	bimanual	varied in horizontal plane	NIV + no vision	neutral	haptic report	NIV improves haptic perception; biases perception to an allocentric frame of reference (task-dependent)
Zuidhoek et al., 2003	bar matching	bimanual	varied in horizontal plane	no vision	neutral	haptic report; varied delay	Better when add delay between exploring the reference & test bars; shift from ego to allocentric reference frame
Voisin et al., 2005	2-D angle discrimination	unimanual	varied in horizontal plane	no vision	varied	verbal report; varied delay between scans	Better with longer delay; 2 competing egocentric frames of reference (arm/hand and head-centred; latter predominates at longer delays)
Hermens et al., 2006	bar matching	bimanual	varied in frontal plane	no vision	neutral	haptic or verbal report	haptic errors due to interhemispheric transfer (better with visual than haptic reports)
Volcic et al., 2008	bar matching	bimanual	Varied in horizontal plane	no vision, NIV, visual interference	varied	haptic report	NIV improves performance in men (not women); head + gaze, ns; visual interference, variable effects. Crossmodal interactions between reference frames

*neutral= head/ eyes/ gaze forward
Abbreviation, NIV= non informative vision

Table 1. Summary of results in selected previous studies of haptic perception.

I.3. AIMS OF THE STUDY

Experiment 1

As described above, our recent results suggest that haptic perception of 2-D angles may be more precise when subjects categorize individual angles (2.4°) as compared to discriminating angle differences between pairs of serially explored angles (5.6°). This is an interesting hypothesis but there were 4 important differences in these two sets of experiments. First, the experiments were performed in different subjects, and so the difference might have reflected individual differences in haptic perception. Second, angle orientation was not the same for both tasks (respectively, upright and oblique angles), and there is evidence that oblique orientations are not perceived as well as either vertical or horizontal orientations (Appelle and Gravetter, 1985; Essock, 1990; Gentaz, 2000; Gentaz, 2001). Third, in previous studies of 2-D angle discrimination (Levy et al., 2007; Voisin et al., 2002a,b, 2005), vision was blocked during testing (no vision). In contrast, non informative visual feedback of the surround was provided during the categorization testing (Michaud, Voisin and Chapman, unpublished observations). Consequently, subjects in the present study were all tested in the same visual feedback conditions, corresponding to the no vision condition previously in this laboratory, thereby ensuring that this factor could not contribute to the results. Finally, feedback on performance (knowledge of results, KOR) was provided for one task (categorization) but not the other (discrimination), and this may have contributed to the better performance in the former task.

The present study examined the contribution of these factors to haptic perception by comparing performance in the two tasks, categorization and discrimination, in the same subjects and the same session. Knowledge of results was provided for both tasks, and the categorization task was tested with both oblique (corresponding to the orientation used for the discrimination task) and upright orientations. In addition, we also determined whether categorization thresholds were modified by changing the number of passes over the angle (one or two passes), since Levy et al. (2007) had shown that 2-D angle discrimination threshold is independent of the number of passes. We expected to confirm and extend this observation to the categorization task.

Experiment 2

This second study, restricted to the 2-D angle categorization task, was inspired by our recent observation that categorization thresholds are modified with gaze direction but not head position when the angles (unseen) were explored in an eccentric position, 60° to the right of midline: threshold was doubled when gaze was shifted to the right (towards the angles; head forward). When the head was directed to the angles, in contrast, gaze direction had no influence (to versus away, to the left) (unpublished observations, G.Michaud, J.Voisin, S.Bourgeon, C.E.Chapman). It was thought that the increased threshold when gaze was directed to the far right might reflect an action of spatial attention. This hypothesis was addressed here by having subjects categorize angles explored at two spatial locations (30 and 60° to the right of midline). The head was oriented to the angles and gaze direction symmetrically changed (to or away from the unseen angles).

CHAPTER II

Materials and Methods

Subjects

Two separate experiments were performed in young, healthy, volunteer subjects (n=12, each, six women and six men, 18-35 yr). All participants were naïve to the experiment, and all were remunerated. Each experiment consisted of a single 90 min experimental session. Two subjects participated in both experiments. All but two subjects were right-handed for writing (one from each experiment). The institutional ethics committee approved the experimental protocol, and all subjects gave their informed consent before participating in the experiment.

Stimuli

Experiments 1 and 2 employed an automated device to generate two-dimensional angles by positioning the orientation of a mobile bar relative to a second, fixed bar. In both experiments, the apparatus was oriented vertically, and the vertical bar was the mobile arm (Fig.1A). The apparatus consisted of two arms (22 cm long and 2 cm wide) intersecting as shown in Fig.1A (90° shown). Angles could be generated in all four quadrants of the 360° workspace (top right, top left, bottom left, bottom right), but only the top left quadrant was used for this experiment. The rest of the workspace was covered (Fig.1C) so that the dimensions of the two arms forming the angle were identical to those used in our previous experiments (Voisin et al. 2002a, b; 2005), 8 cm long. The cut edges at the intersection were beveled so that there was no gap. Movement of the mobile arm was generated by a DC motor (Johnson HC970) under computer control. The mobile arm was instrumented with a potentiometer to measure angle position. Angles of 60° to 120° could be reproduced with a precision of ± 0.1°. As shown in Fig.1B a strain gauge (full bridge, thin beam load cell, type LCL-005, Omega Engineering) was affixed to both extremities of each arm in order to measure contact force, and to calculate the position of the centre of pressure (m and m’ on the mobile arm; f and f’ on the fixed arm). For each condition, four pairs of angles were presented (Fig.1D): 80/100°, 84/96°, 87/93°, 89/91°. The first arm explored, *ab* (Fig.1C), was identical for all angles; the orientation of the second arm was varied, *bc*, to form the angle.

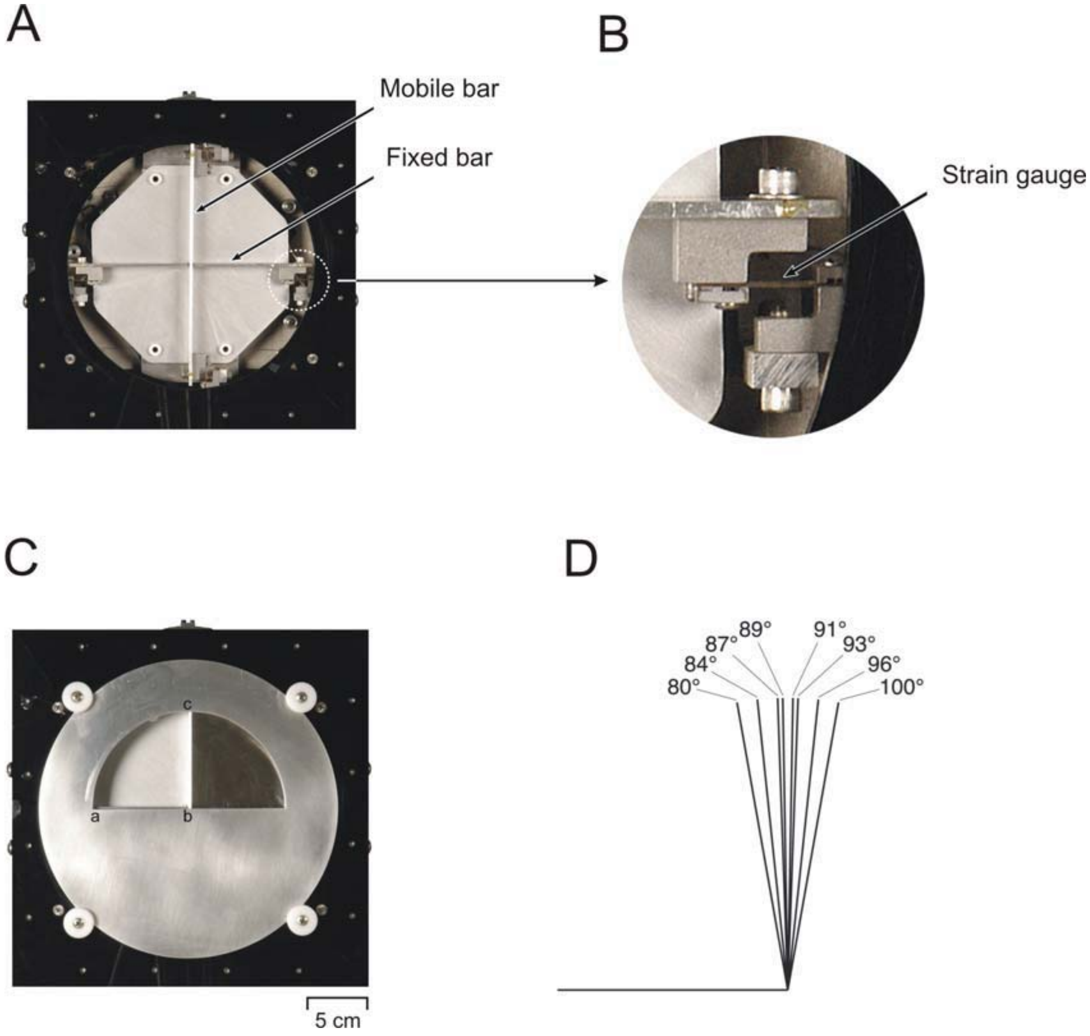

Fig. 1 Apparatus for the categorization task. **A.** Apparatus with all four quadrants visible and the two bars, fixed and mobile, that formed the angle. **B.** A strain gauge was mounted at the end of each bar to monitor contact force. **C.** Apparatus with top left quadrant visible. Movements followed the sequence *abcba* or *abc*. **D.** Schematic representation of the range of 2-D angles tested (upright orientation). Four pairs of angles were tested, starting with the largest angle difference: 80/100°, 84/96°, 87/93° and 89/91°.

Experiment 1 also employed the manufactured angles described in Voisin et al. (2002a). The angles were manufactured from 1 cm thick Plexiglas. Each arm of the angle was 8 cm long. As for the angles generated with the automated device, the angles were all identical over the first arm explored (*ab*, Fig.2). The orientation of the second arm (*bc*) varied to form angles of 90°-103°. They were secured in a device, which held the angles upright and perpendicular to the orientation of the arm.

Exploration strategy

The experimenter guided the subject's right index finger, D2, to the start position (see Fig.3) for each angle, which corresponded to position *a* in Fig.1C and Fig.2A in most experiments. Subjects slid the distal phalanx of D2 over the angle using a smooth movement over the first bar, the intersection corresponding to *b*, the second bar with *c* at the end and then back again so, the sequence of movement was *abcba*. The subjects were instructed to keep the nail oriented up throughout the scan. Vision of the angles was occluded in all experiments.

Perceptual tasks

In the first experiment we compared the ability of subjects to perform two tasks, angle categorization and angle discrimination. In the second experiment we employed only the categorization task. The exploration strategy was generally the same for both tasks, the major difference being that in the categorization task subjects scanned just *one angle* and categorized it as either small or large. In contrast, the subjects scanned *two angles* in the discrimination task and identified the larger angle (first or second scanned). Exploration was always made using the right index finger (D2). In all experiments, potential auditory feedback was avoided by having the subjects wear noise-attenuating headphones.

2-D angle categorization task

In this task, each subject received written and verbal instructions at the beginning of the experiment, indicating that they were going to explore 2-D angles, with a view of categorizing these as large or small.

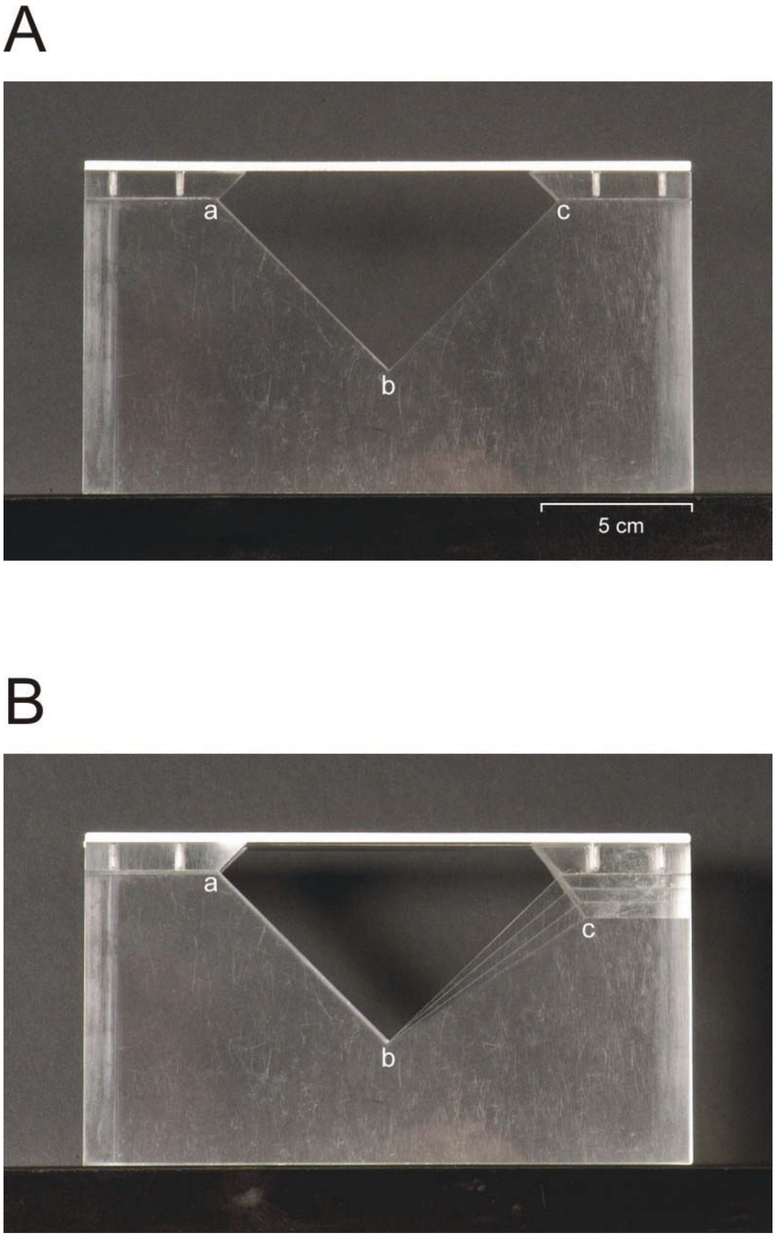

Fig. 2 Angles for the discrimination task. **A.** Standard angle, 90°. **B.** Comparison angles, 91°, 95°, 99° and 103°. Movements followed the sequence *abcba*.

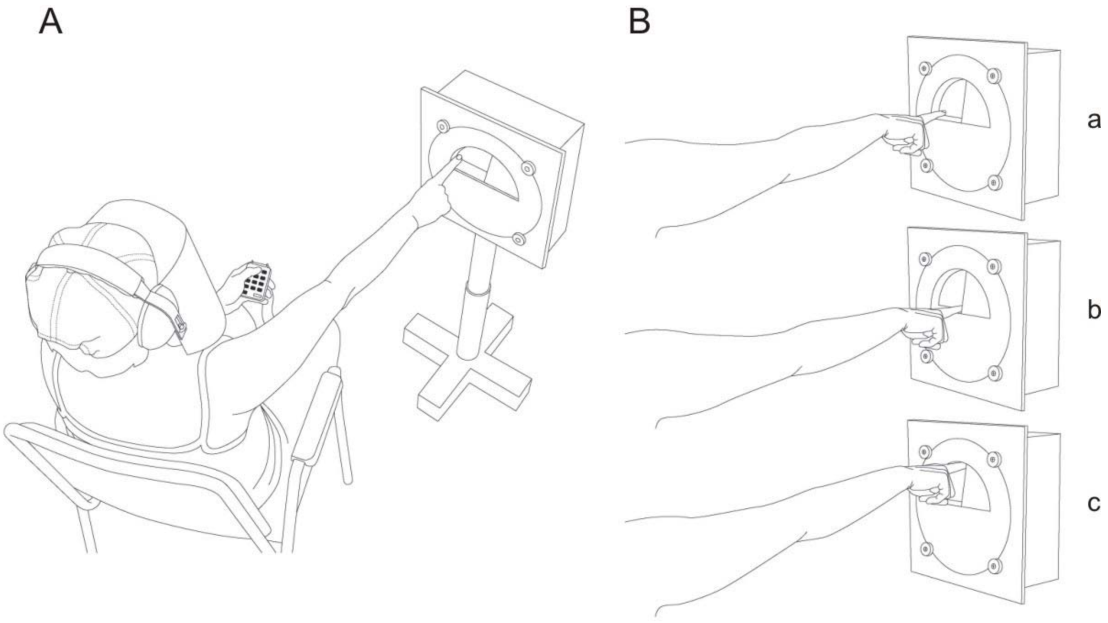

Fig. 3 Position of the subject for the categorization task in experiment 1**. A.** Start position for all conditions, with the apparatus positioned 30° to the right. **B.** Sequence of the movement for a one-pass scan (*abc*), from top (start, *a*) to bottom (end, *c*), passing through the intersection, *b* (middle).

As shown in Fig.3, the subject was seated in a chair with the angle device positioned at arm’s length and at the height of the shoulder, 30° to the right of a midsagittal plane running through the right shoulder. The device was oriented perpendicular to the out-stretched arm. In experiment 1, vision of the apparatus was occluded by a mask attached to a hat, and the head was oriented forward (Fig. 3). The arm and finger were fully extended, so that movement was restricted to the shoulder joint. In experiment 2, non informative vision was provided and movement was mainly distal (see below).

Subjects were not informed that the angles were distributed around 90°. At the beginning of the session, several practice trials were given using one pair of angles with a large difference (79°, the "small" angle and 101°, the "large" angle) in order to familiarize subjects with the exploratory movement and the categorization task. In combination with the feedback provided (correct or incorrect response), the subjects developed their own representation of what constituted small and large angles. After the subject made 4 correct categorizations (2 large and 2 small), data acquisition began.

Before each trial, the mobile bar was repositioned under computer control to generate either a small (<90°) or a large (>90°) angle. The experimenter guided the subject’s finger to the start position (Fig.3A). Following a 500 ms hold period, a tone prompted the subject to begin the scan. Subjects slid their finger over the angle using a to-and-fro scanning movement, keeping the upper limb rigid through (Fig.3B). After the scan, the subject categorized the angle as either small or large, by depressing one of two response buttons on a keypad with the opposite hand (Fig.3A). If contact with the bar was lost during the scan, the trial was rejected and repeated at the end of the block of trials. Feedback was given after each trial (correct or incorrect).

Testing started with the largest angle difference, 80/100°, and proceeded in decreasing order of the difference: 84/96°, 87/93°, 89/91°. There were 16 trials for each angle pair (8 large, 8 small: order quasi-random), to make a total of 64 trials for each condition. When the categorization task was tested first in the session, an extra 8 trials were included for the 80/100° pair of the first condition tested to ensure that the subjects had mastered the task. These data were not included in the analysis.

2-D angle discrimination task

For the discrimination task, the position of the subject and angles were identical to the categorization task (Fig.3). Both written and verbal instructions were given, indicating that they were to explore pairs of angles, in order to identify the larger angle of the pair. The exploratory strategy was as described above except that, as already mentioned, two angles were explored in each trial; the standard angle (90°) and a comparison angle (91°-103°). The order of presentation of standard and comparison angles was counterbalanced. After scanning the first angle, the subject withdrew D2 from the apparatus and the second angle was installed. The experimenter repositioned D2 at the start position and the scan was repeated. There was a delay of ~5s between the two scans (time to change the angle and reposition D2). Four comparison angles were tested (Fig.2B), with 10 replicates for each comparison angle (40 trials total). A pseudorandom list of trials, mixing together the 4 comparison angles, and the order of presentation of the angles (standard first or second scanned) was used for all subjects. When the discrimination task was tested first in the session, an additional 8 trials with the larger difference (90° and 103°) were included but these data were not included in the analysis. Feedback was given after each trial. Before starting the experiment subjects practiced the exploratory strategy and task by scanning a pair of angles with a large difference (90° and 103°). Data collection began after the subjects had made two consecutive correct discriminations (2-6 trials).The subject's response (angle identified as large) was recorded by the experimenter.

Experimental conditions

Experiment 1

The purpose of this experiment was to determine the extent to which haptic perception of 2-D angles varies with angle orientation, the exploration strategy and the design of the task. Four experimental conditions were tested. Three conditions were tested using the categorization task (Fig. 4A): 1) angle in the upright orientation (two-pass scan, *abcba*); 2) angle in the oblique orientation (two-pass scan); and 3) angle in the upright orientation (one-pass scan, *abc*, not shown). Testing in the discrimination task (Fig. 4B) corresponded to the second condition for the categorization task (oblique angle, two-pass scan). Half of the subjects started with one task (angle categorization), while the other half started with the other task (angle discrimination).

After each condition, subjects were invited to rate the difficulty of the task using a 10-point scale (1, easy; 10, very difficult). They were also questioned about the cognitive strategy employed to perform the task.

Experiment 2

In this experiment we tested the effect of angle position (30° or 60° to the right) and the direction of gaze (see below) on the ability of subjects to categorize 2-D angles under a condition of non informative vision (vision of the environment: a neutral, non structured background consisting of a black curtain). Subjects could see the surround, but a barrier attached to the chin support (see Fig. 5A) occluded vision of the angles themselves. Head position was directed toward the angles by having the subjects rest their chin on a support (Fig.5B). This was adjusted to either 30 or 60° to the right.

This experiment tested only the categorization task and the exploration strategy corresponded to the two-pass scan. The angles were explored with the apparatus placed at two different locations relative to the midsagittal plane of the subject, either 30° (Fig.5A), or 60° to the right. Head position was directed towards the angles (above). The right forearm rested on a support, and movement involved distal joints (mainly wrist, but also the second metacarpophalangeal joint), as in a previous study (Voisin et al. 2005). The sequence of movement was "*abcba"* (Fig.5A) or *cbabc*.

The direction of *gaze* was controlled by instructing subjects to look in the direction of a target prior to the start of each scan (Fig. 5A). When the direction of

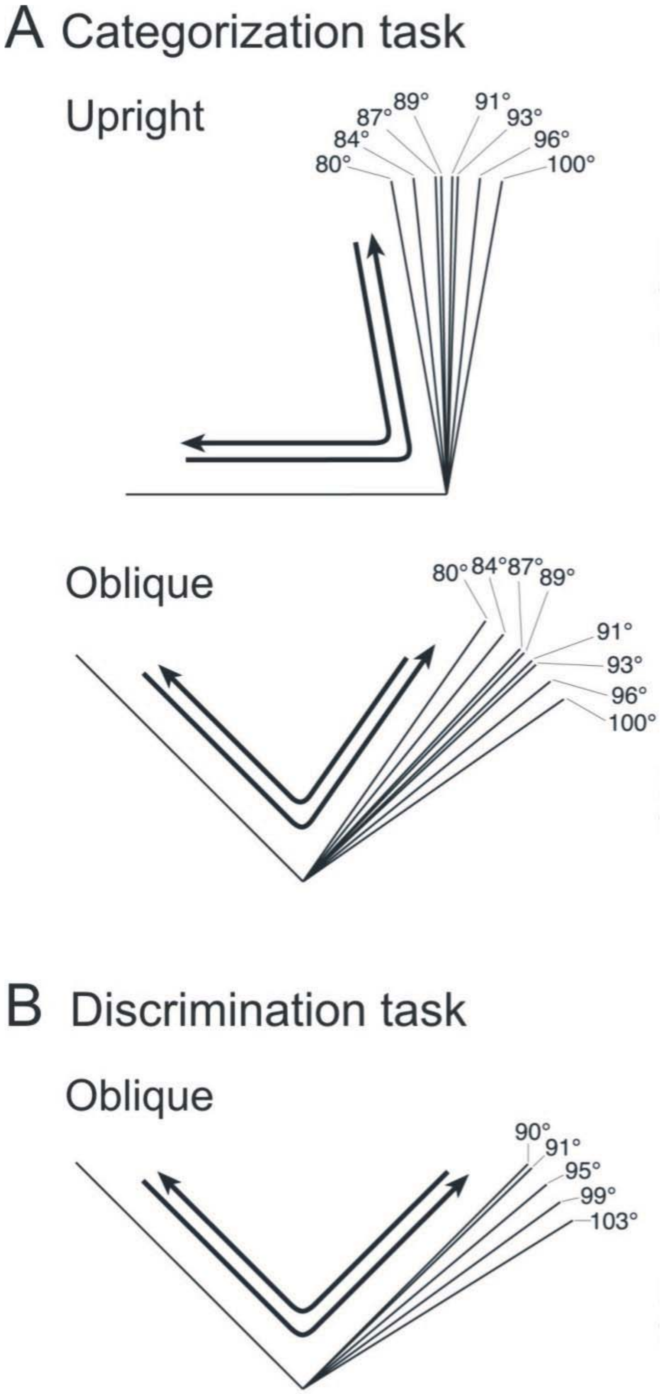

Fig. 4 Conditions for experiment 1. **A.** Categorization task. Upright angles were explored with a two--pass or one-pass strategy (top). Oblique angles were explored with a two-pass strategy. **B.** Discrimination task: Oblique angles (two-pass strategy).

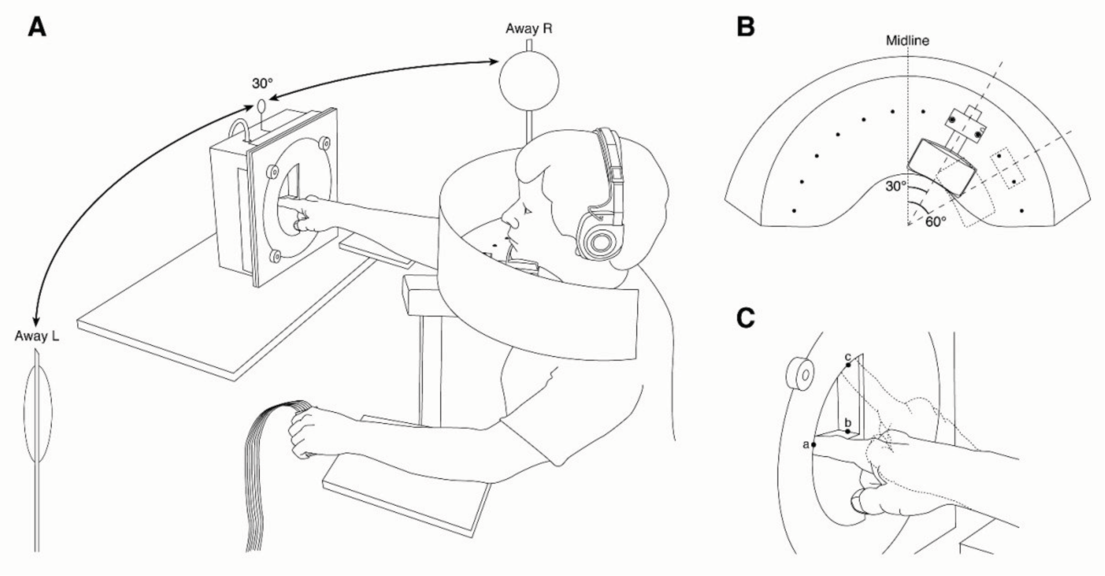

Fig. 5 A. Position of the subject for the categorization task in experiment 2. The apparatus was located 30º (as shown here) or 60º to the right. Subject shown with D2 in the start position; the forearm rested on a support so that the movement was mainly distal. A barrier precluded vision of the angle apparatus. Subjects could, however, see 3 targets: one positioned above the apparatus; the other two were located 60° to the right (R) or left (L) of the apparatus. **B.** Head position was controlled by having the subject rest their chin on the support; this was positioned at 30° (as in A) or 60°. **C.** Sequence of the movement scan: subjects alternated the start position (*a* or *c*) and used a two-pass strategy (*abcba* or *cbabc*).

gaze was *to* the apparatus, the subject looked at a small circular target, (3.5cm diameter; distance ~ 70cm) placed above the apparatus. For the direction of gaze *away* from the apparatus, the subject looked toward a larger visual target, a circle of 20 cm diameter, either to the far right or far left (60° from the apparatus in each case) (Fig.5A). Careful visual inspection ensured that all subjects followed the instructions throughout the trial.

Five experimental conditions were tested. In conditions 1 – 3 (Fig. 6A), the angles were positioned 30° to the right, with gaze directed *to* the angles or *away* from the angles, either to the *right* or to the *left* in each case. In conditions 4 and 5 (Fig.6B), the apparatus was positioned 60° to the right, and only two gaze positions were tested: *to* and *away* (~60° to the right). The angles tested and numbers of trials were as described for the categorization task in experiment 1, with the only difference being that no feedback on performance was given. This approach was taken so as to compare the results to those obtained previously. Half of the subjects started with the apparatus placed at 30° while the other half started with the apparatus placed at 60°.

As in the first experiment, after each condition subjects were invited to rate the difficulty, but also the discomfort, of the task using 10-point scales (1, no discomfort; 10, very uncomfortable).

Data acquisition and analysis

For the categorization task, angle position and data acquisition were controlled by a computer. The following data were collected with each trial: the times that the digit arrived at, and departed from, each position (*a*, *b* and *c*) during the to-and-fro scan of the angle, and the time of the response. Note that reaction times are not reported here because there was no requirement for subjects to respond as quickly as possible.

Performance in the angle categorization task for each subject in each condition was characterized by calculating the proportion of angles categorized as large (PL) for each angle presented (Fig. 7A). The results were then fit to the following logistic function where B corresponds to the bias (Δangle value at which

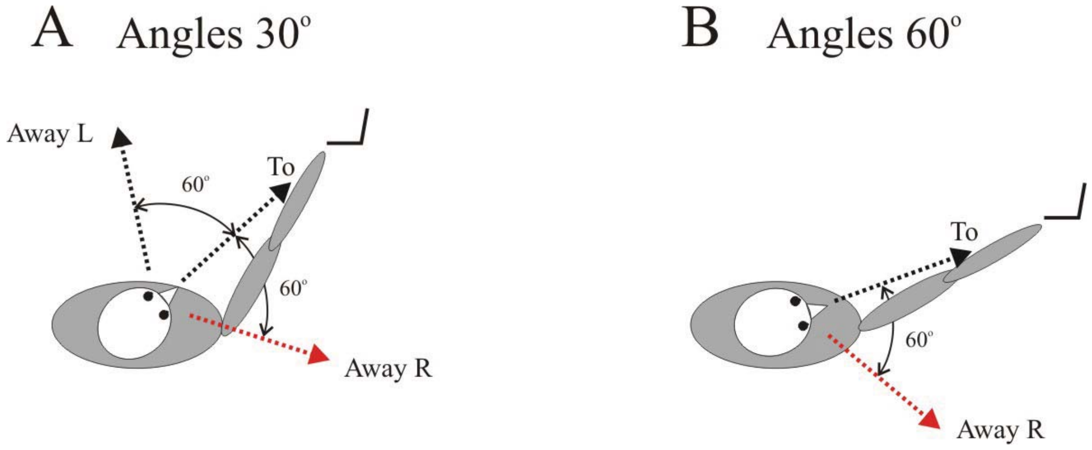

Fig. 6. Conditions for experiment 2 (categorization task). **A.** Three conditions were tested with the angles and head at 30° to the right: gaze to the angles or away (left, L and right, R). **B.** Two conditions were tested with the angles and head at 60° to the right: gaze to the angles and away (right).

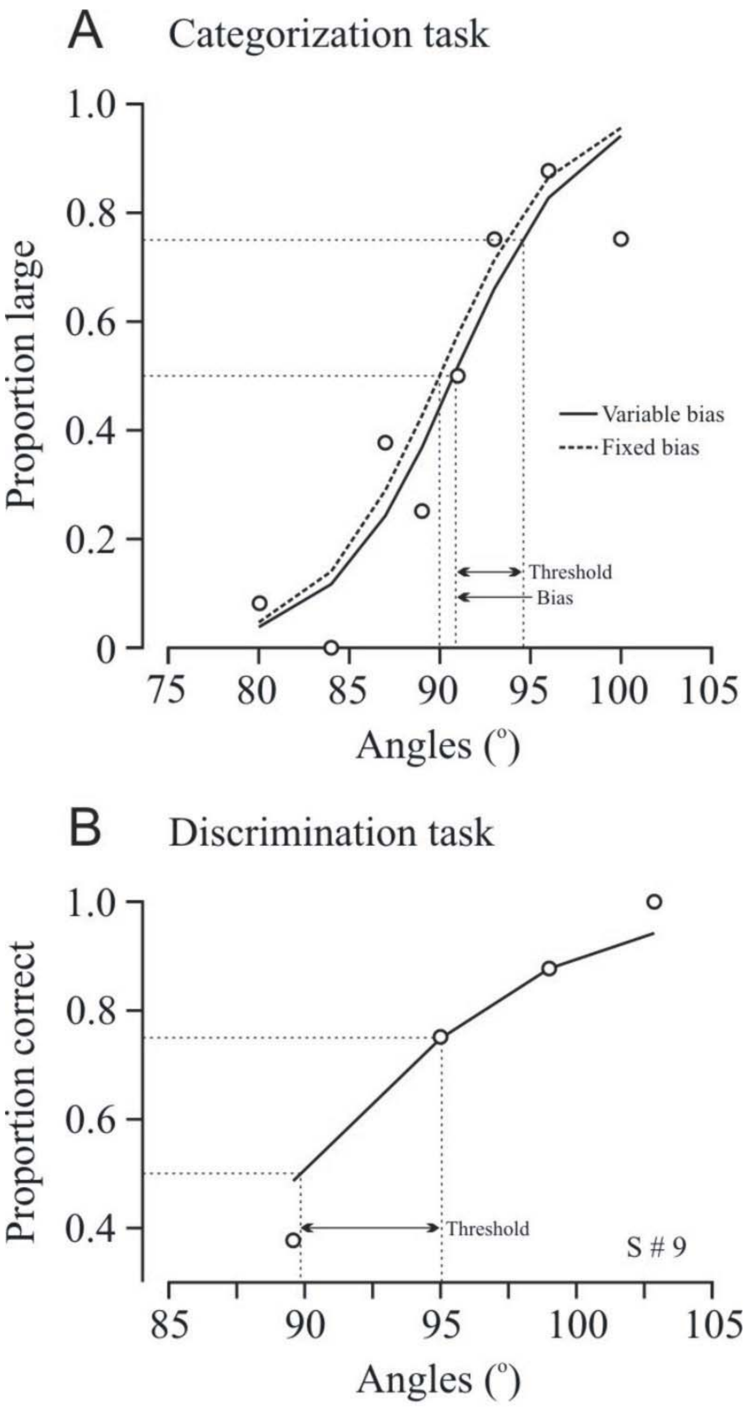

Fig. 7. Results for one subject in the 2-D categorization **(A)** and discrimination **(B)** tasks (oblique orientation) of experiment 1. Performance (proportion large, A, or correct, B) is plotted as a function of the angle explored. Logistic functions were fit to the data (16 trials per data point). For the categorization task, threshold (75% identified as large) was 2.95° and bias was close to 90°, 90.65°. For the discrimination task, threshold (75% correct) was 5.1°.

PL = 50%, Fig. 7A), and *d* is the unique degree of freedom of the logistic curve that was adjusted to fit the raw data:

$$PL=1 / (1 + e^{d(\Delta angle-B)})$$

From this, we then computed the categorization threshold (value of Δangle for which PL=75%). A similar approach was employed for calculating discrimination threshold in the 2-D angle discrimination task (proportion correct in this case, Fig. 7B), but in this case there was no bias term because this task used an explicit standard angle, 90° (Voisin et al., 2002a).

Statistical analyses of the data were performed using repeated measures analyses of variance (ANOVA) and *post hoc* comparisons. The main analyses evaluated the effects of the various experimental conditions on threshold, bias (categorization task) and also the subjective estimates of task difficulty or discomfort (experiment 2 only). Analyses were performed with either Systat (V 9.0, SPSS Inc.) or MATLAB (V7.0, the Mathworks Inc.). The level of significance was set at $P<0.05$.

CHAPTER III

RESULTS

Experiment 1

In this experiment, subjects explored angles located at 30° to the right; vision of the angles was occluded throughout the session. Examples of the logistic curves from one subject in both tasks, categorization (A) and discrimination (B) (oblique angle orientation), are shown in Fig.7. Performance in the task is plotted as a function of the angle explored. For both tasks, performance improved as the value of the angle was increased, and the individual data were well fit by the logistic functions.

Two curves are shown for the categorization task. In one case (dotted line), bias (PSE or point of subjective equality) was fixed to 90°, the real midpoint angle. In the other case (solid line), bias was allowed to vary. The angle at which performance is 0.50 corresponds to the PSE (bias) and was, in this case, 90.6°, very close to the actual midpoint, 90°. Threshold (75% large or correct) was lower in the categorization task, 2.95°, then in the discrimination task, 5.1°.

Figure 8 (A - C) summarizes the results from 12 subjects as they categorized angles under three different conditions. The corresponding data from the discrimination task are plotted in Fig.8D (note the change in scale). Overall the degree of variability across the subjects (amplitude of the SEM) was similar across all 4 conditions.

Figure 9A plots the mean logistic functions for all subjects and all conditions fitted to the pooled data. Inspection of the 3 curves for the categorization task shows these were very similar. The mean thresholds are summarized in Fig.9B and Table 2: 4.1 ± 0.7° (upright one-pass), 3.8 ± 0.6° (upright two-pass) and 3.9 ± 0.4° (oblique two-pass). Inspection of Fig.9A also shows that the curve for the discrimination task was shifted to the right, and threshold was higher than in the categorization task, 7.4 ± 0.6° (Fig.9B, Table 2). A repeated measures ANOVA showed that threshold varied significantly across the 4 conditions (P= 0.003). There was no obvious change in threshold across the 3 conditions of the categorization task (P=0.9). A post hoc analysis showed that the significant difference was explained by the nature of the task [F(1,11)=7.027, P=0.023, categorization vs. discrimination].

In the discrimination task, all comparisons were made to an explicit standard angle of 90°. In the categorization task, the “standard” was implicit. The angle value

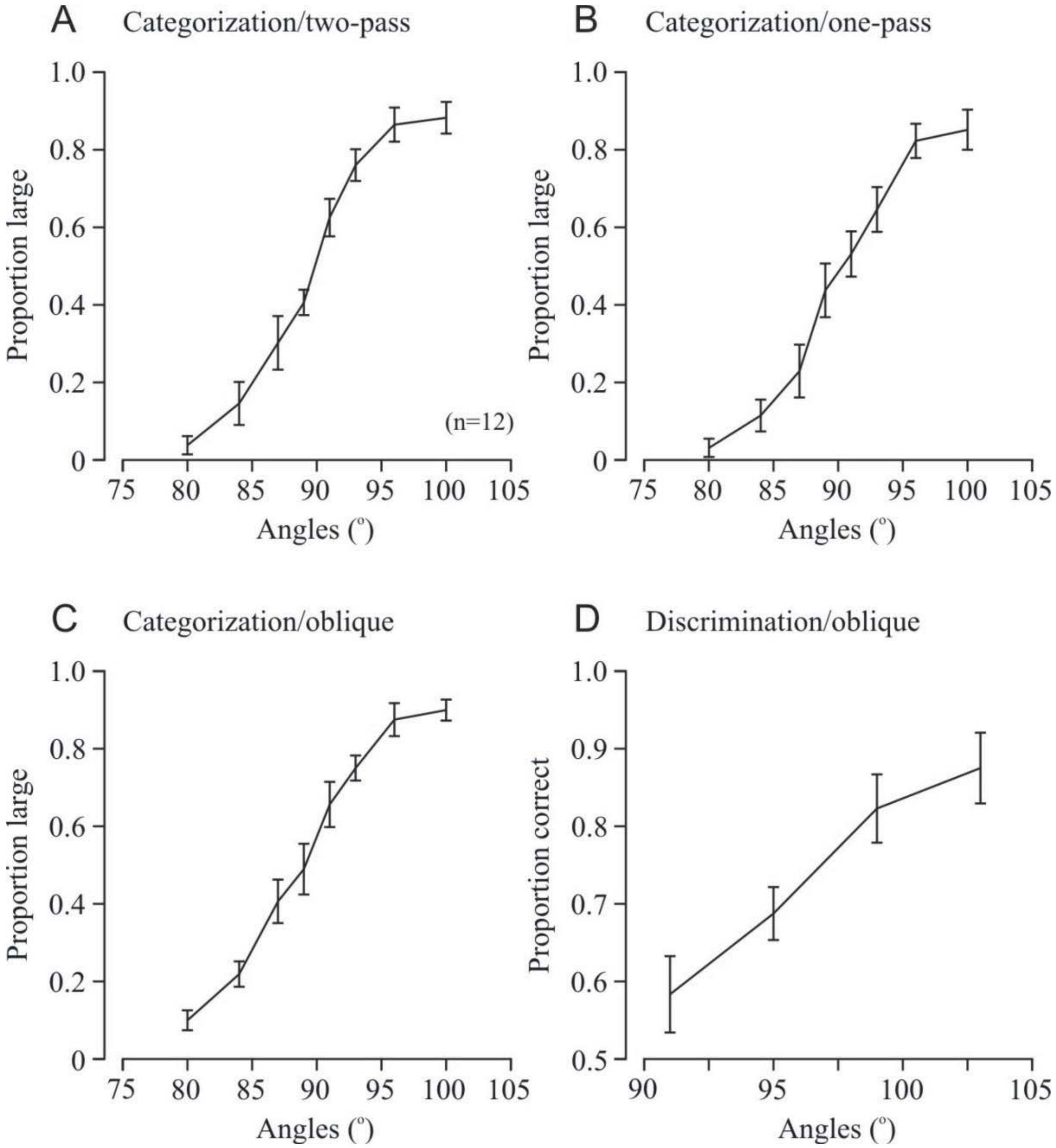

Fig. 8. Pooled results from 12 subjects in experiment 1**. A-C.** Categorization task. **D.** Discrimination task (note the change in scale). Variance was similar across all angles and conditions.

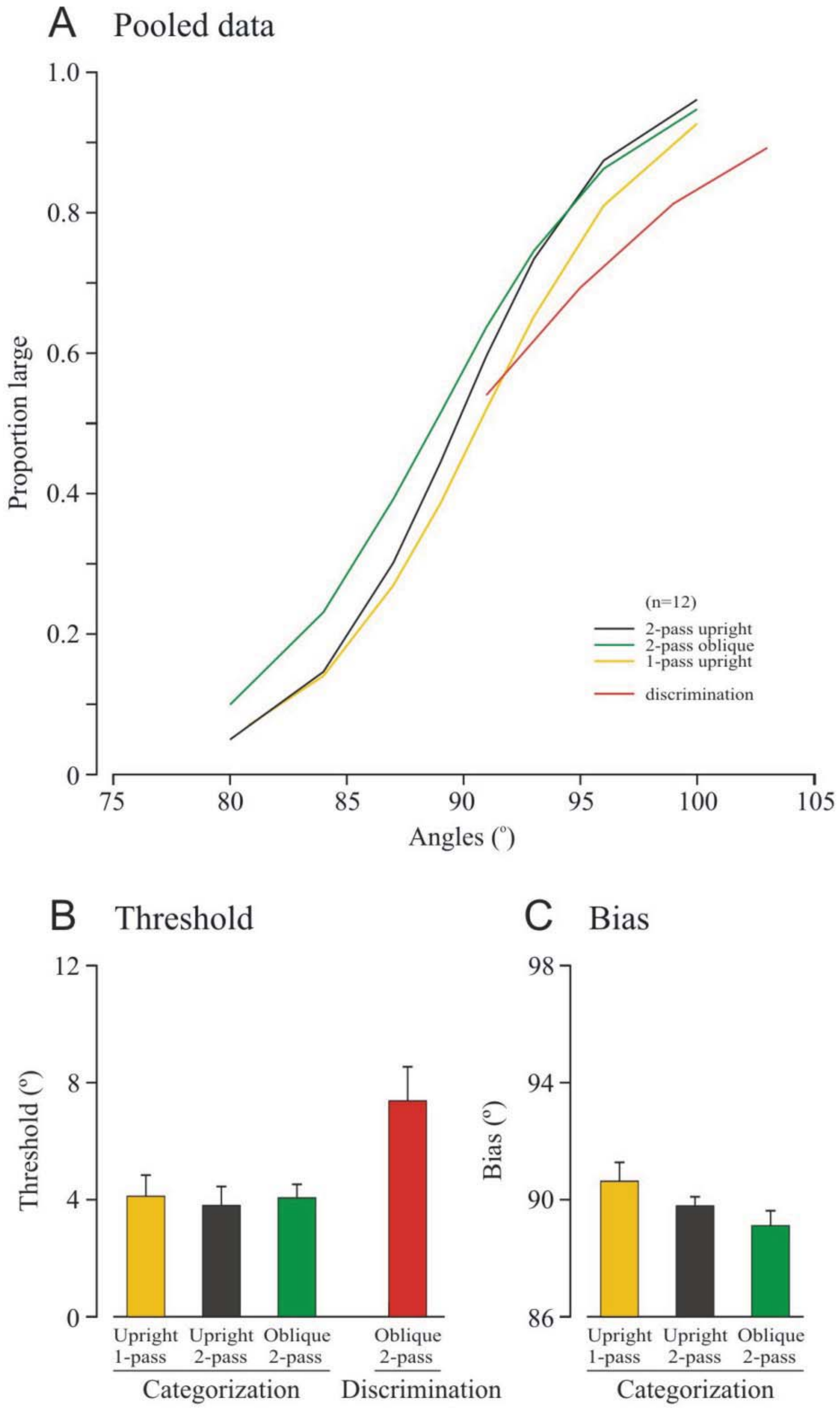

Fig. 9. Comparison of the results from experiment 1 across all 4 conditions. **A**. Mean logistic curves, calculated from the pooled data (n=12), are superimposed. **B.** Mean threshold from each condition (± SEM). **C.** Mean bias values from the 3 conditions studied using the categorization task.

Subject	**Condition upright one-pass**	**Condition upright 2-pass**	**Condition oblique 2-pass**	**Discrimi -nation**	**Sex**	**Laterality**
1	7.5	2.3	2.1	4.2	M	R
2	3.6	2.5	5.8	5.1	F	R
3	6.9	7.0	4.5	11.3	F	R
4	3.0	1.9	2.6	8.2	M	R
5	5.4	6.8	4.6	4.2	F	R
6	2.4	2.0	3.9	15.0	M	R
7	1.9	1.8	1.3	2.7	F	R
8	1.7	3.2	3.3	6.4	M	R
9	2.4	2.5	3.0	5.1	M	R
10	3.8	2.8	5.9	12.5	F	R
11	9.1	6.3	4.7	4.8	F	L
12	2.3	6.8	5.7	9.2	M	R
Mean	**4.2**	**3.8**	**4.0**	**7.4**		

Table 2. Threshold values (°) for individual subjects (experiment 1).

corresponding to the PSE, or bias, was close to 90° (Fig.9C and Table 3) and showed no systematic change across the 3 conditions of the categorization task (F(2,22)=3.114, P=0.07).

Finally, Fig.10 plots the threshold values for all 12 subjects as a function of the task (A), angle orientation (B, categorization task only) and exploratory strategy (C, categorization task only).

Two-D angle thresholds were significantly modified by the task (A, all other factors the same; *post hoc* comparison, df=11, P=0.006). The majority of subjects (9/12) had a higher threshold in the discrimination task than in the categorization task (points below the equality line). In contrast neither angle orientation, oblique vs. upright (B), nor the exploratory strategy, one-pass versus two-pass (C) was a factor for the categorization task (*post hoc* tests, df(1,11)=0.08, P> 0.60).

The data were also analyzed to determine whether the order of testing was a factor, but no trend was observed (ANOVA, F(3,33)=1.124, P= 0.353).

The perceived difficulty of the tasks varied considerably between subjects, from a low of 1/10 (easy) to 9/10 (very difficult). The results are summarized in Fig.11 for all conditions. The rating was slightly higher for the oblique 2-pass condition in the categorization task (green bar), but the difference was not significant [ANOVA, F(3,33)=0.669, P=0.577].

Experiment 2

In this experiment, subjects categorized angles at 2 spatial locations, 30° and 60° to the right, under a condition of non informative vision. The head was oriented to the angles, but gaze was systematically varied (see Fig.6, methods).

The results from 12 subjects were analyzed. The data from one subject were incomplete because threshold was not estimated in 1 of the 2 conditions tested with the angles located 60° to the right; the data from both conditions were omitted

Figure 12A plots the mean logistic functions for 12 subjects as they categorized angles under the 5 test conditions. Inspection shows that the forms of the curves were similar, but one curve (solid red line) was displaced to the right,

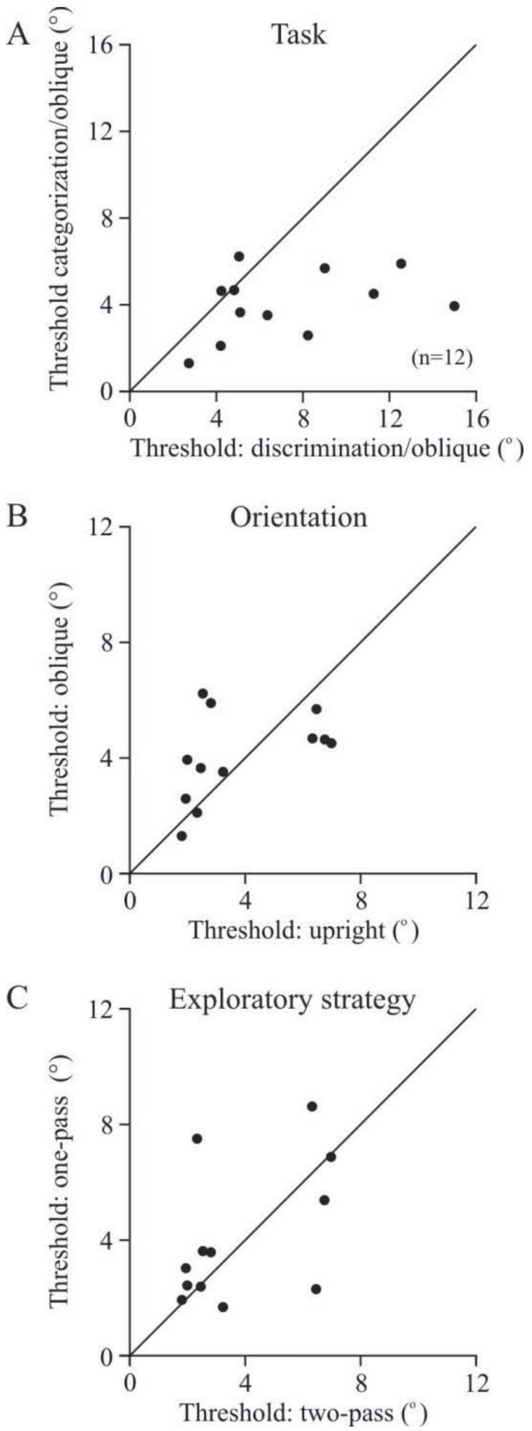

Fig. 10. Scatter plots showing how threshold varied across subjects as a function of the task **(A)**, angle orientation **(B)** and exploratory strategy **(C)** in experiment 1. Task, but not angle orientation or exploratory strategy, significantly modified the ability of subjects to evaluate the 2-D angles. The diagonal line corresponds to equality.

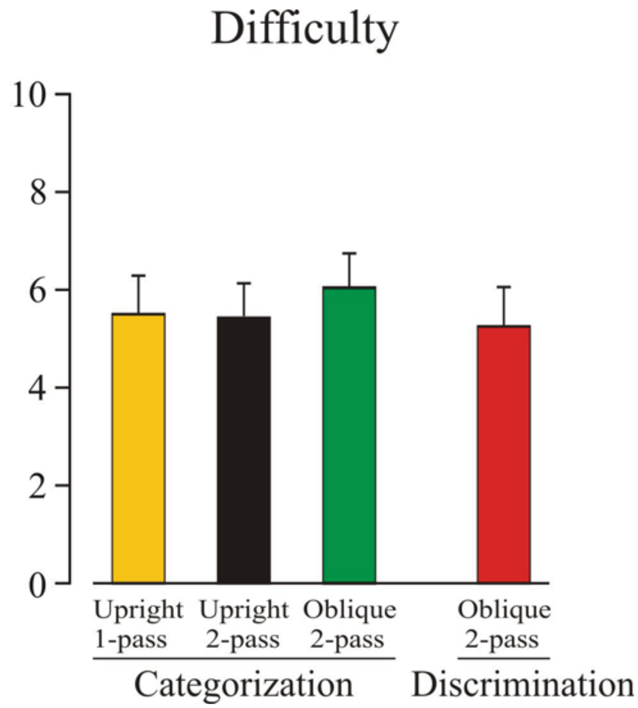

Fig. 11. Mean difficulty estimates (± SEM) assigned to each condition in experiment 1. No difference was observed (P=0.577).

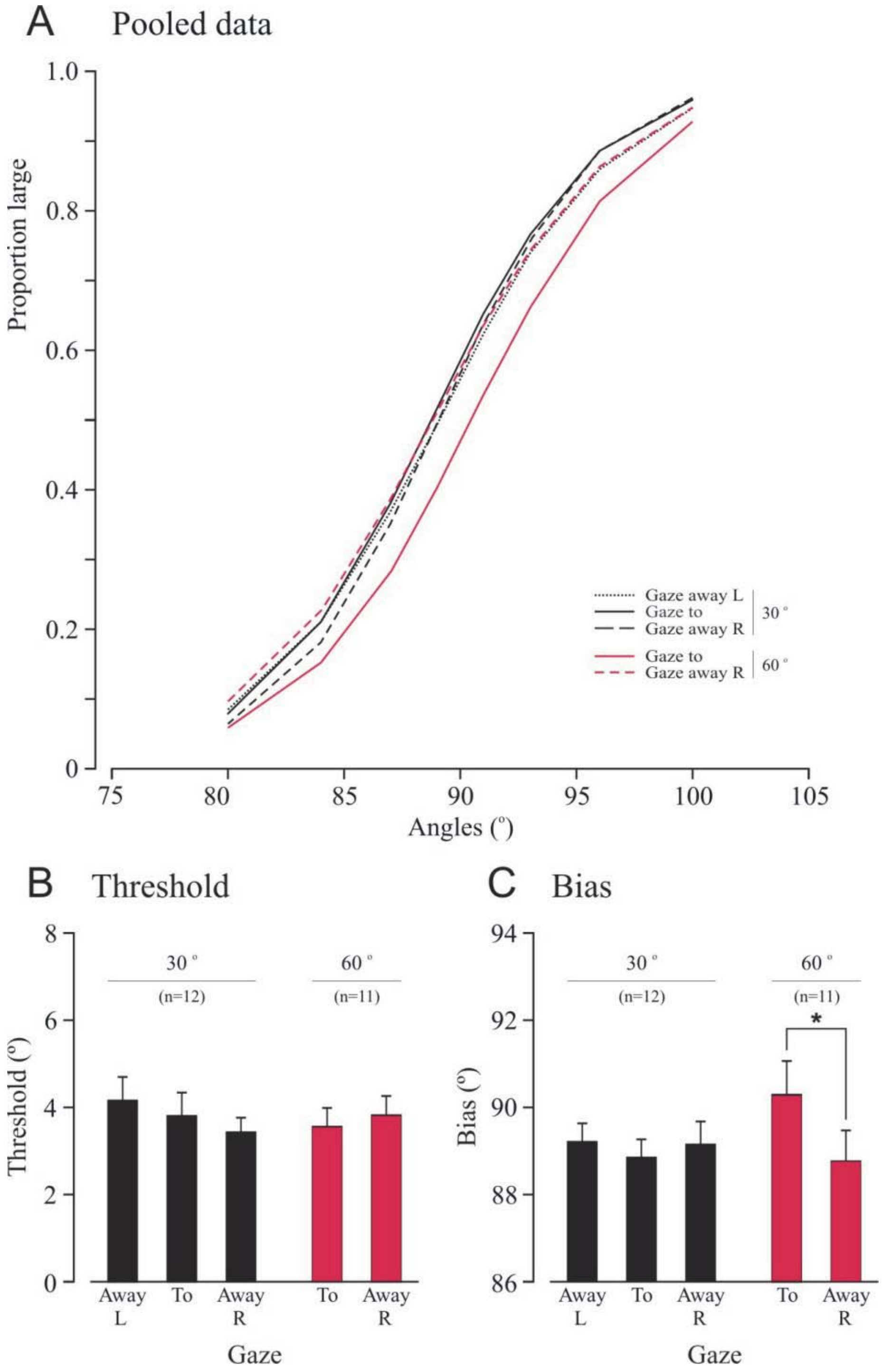

Fig. 12. Comparison of the results from 5 conditions in experiment 2 (categorization task). **A.** Mean logistic curves, calculated from the pooled data, are superimposed. **B.** Mean threshold from each condition (± SEM). **C.** Mean bias values from the 5 conditions, $^*P<0.05$.

SUBJECT	**Categorization upright 1-pass**	**Categorization upright 2-pass**	**Categorization oblique 2-pass**
1	95.5	90.1	88.7
2	89.9	89.1	88.9
3	88.8	90.0	88.2
4	88.5	89.5	87.8
5	90.4	90.6	87.8
6	91.8	91.3	87.8
7	91.0	90.0	90.3
8	90.2	87.8	87.8
9	90.0	91.3	90.7
10	90.5	89.9	91.1
11	87.8	89.1	87.8
12	93.3	88.9	92.7
Mean	**90.6**	**89.8**	**89.1**

Table 3. Bias measures (point of subjective equality, °) for individual subjects (experiment 1, categorization task only).

reflecting a change in bias (C) but not threshold (B). Fig.12B and Table 4 summarizes the mean threshold values for each condition: 4.2 ± 0.5° (30°, gaze left away), 3.8 ± 0.5° (30°, gaze to apparatus), 3.4 ± 0.3° (30°, gaze right away), 3.6 ± 0.4° (60°, gaze to apparatus) and 3.8 ± 0.4° (60°, gaze right away). A repeated measures ANOVA showed that threshold did not vary across the five conditions [F(4,40)=0.553, P=0.69].

Figure 12C and Table 5 summarize the mean bias for all subjects in each condition. A repeated measure ANOVA showed no change in bias across the 5 conditions [F(4,40)=1.493, P=0.22]. When the angles were explored at 60°, however, there was a clear difference, bias being higher with gaze oriented to the angles (paired t-test, P=0.046).

Finally, Fig.13 summarizes the mean discomfort (A) and difficulty (B) values. There was a trend for discomfort to vary significantly across the 5 conditions [F(4,40)=7.936, P=0.07]. Discomfort levels were modestly lower for the 30° position (means of 4.8 ± 0.4 at 30°, and 5.4 ± 0.6 at 60°). At each position, discomfort varied significantly (30°, F(2,22)=3.667, P= 0.04; 60°, df=10, P= 0.005), with discomfort being highest when gaze was directed away from the apparatus.

Difficulty rating were similar to these given in Experiment 1 and there was no evidence that difficulty varied across the 5 conditions (F(4,40)=1.186, P=0.3).

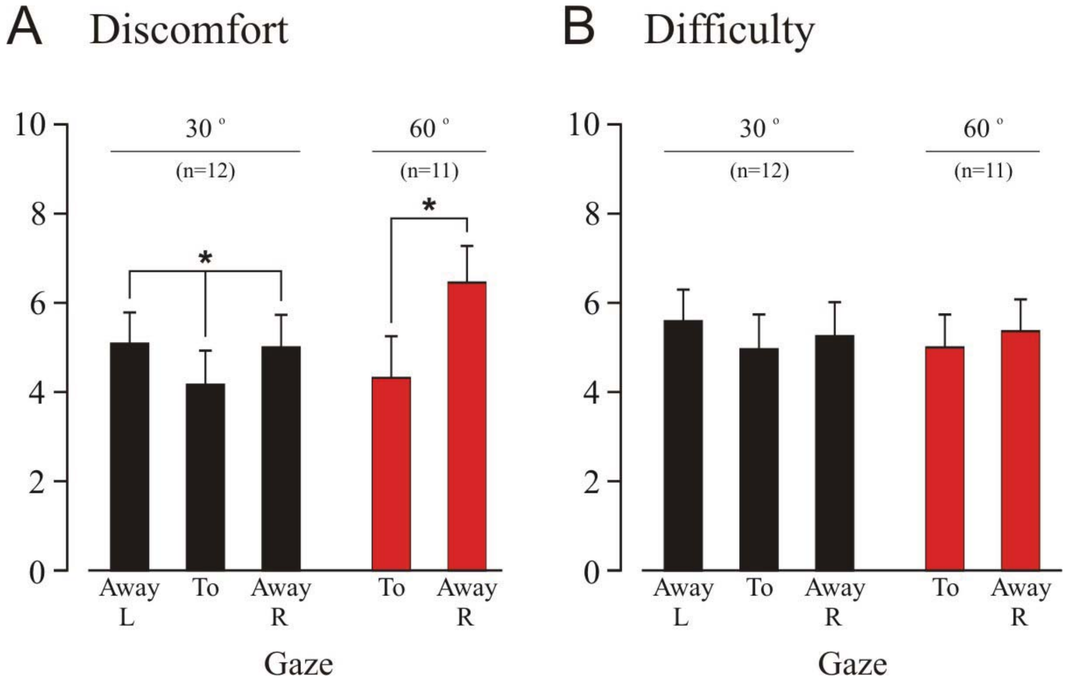

Fig. 13. Mean discomfort **(A)** and difficulty **(B)** estimates (± SEM) assigned to each condition in experiment 2. Significant differences are indicated by a star (P<0.05).

SUBJECT	Away L (30°)	To (30°)	Away R (30°)	To (60°)	Away R (60°)	Sex	Laterality
1	3.2	2.5	5.5	2.4	3.9	F	R
2	6.4	3.7	3.8	3.2	2.5	F	R
3	1.3	2.0	2.7	2.1	1.9	M	R
4	3.3	6.4	3.3	3.4	4.5	F	R
5	6.3	5.0	4.8	2.9	5.2	M	R
6	6.7	6.9	3.5	1.2	6.4	F	L
7	3.3	1.9	2.5	4.1	3.5	F	R
8	2.5	2.3	2.5	5.0	4.8	F	R
9	2.6	1.8	1.4			M	R
10	4.1	5.1	3.8	5.1	3.9	M	R
11	6.0	4.4	4.0	5.0	3.7	M	R
12	4.3	4.1	3.5	5.0	2.0	M	R
MEAN	**4.2**	**3.8**	**3.4**	**3.6**	**3.8**		

Table 4. Threshold values (°) for individual subjects as they categorized angles at different locations and with different postures (experiment 2).

SUBJECT	Away L (30°)	To (30°)	Away R (30°)	To (60°)	Away R (60°)
1	90.2	88.7	91.0	90.6	87.2
2	88.5	87.2	88.7	93.1	92.9
3	90.6	90.5	89.3	91.7	90.6
4	89.6	88.4	88.1	89.3	89.1
5	89.5	88.6	89.8	91.6	90.2
6	89.9	88.1	91.1	93.8	86.6
7	87.6	88.9	89.8	89.5	89.9
8	89.1	89.4	88.1	88.5	88.8
9	86.0	86.7	86.0		
10	91.1	91.7	91.2	92.0	89.5
11	89.8	89.7	90.3	86.7	85.8
12	88.8	88.5	86.5	86.5	85.8
MEAN	**89.2**	**88.9**	**89.2**	**90.3**	**88.8**

Table 5. Bias measures (point of subjective equality, °) for individual subjects (experiment 2, categorization task).

CHAPTER IV

DISCUSSION

Discussion

In this study, we demonstrated that haptic categorization of 2–D angles is independent of the orientation of angles in the space (upright versus oblique) and the number of scans over the angles (one-pass versus two-pass). In contrast, we found that the design of the task was an important factor since threshold was higher for the discrimination task as compared to the categorization task. Finally, we demonstrated that 2-D angles categorization is independent of the head position and gaze orientation in a condition of non informative vision.

Experiment 1

Categorization versus discrimination

This study was prompted by our recent results that haptic perception of 2-D angles appeared to be more precise when subjects categorized individual angles, mean 2.4° (unpublished observations G. Michaud, J. Voisin, C.E. Chapman), as compared to discriminating angle differences between pairs of serially explored angles, mean 4.7° (Voisin et al., 2002a). The physical dimensions of the angles were identical in both studies. Nevertheless, and as pointed out in the Introduction, a number of other factors were different in the two sets of experiments, and these were all controlled for in this study.

The first factor was that different groups of subjects participated in the previous experiments: one group performed the categorization task while a different group of subjects participated in the discrimination task. Further to this, Voisin et al. (2002a) reported that inter subject differences in discrimination threshold can be relatively large (range 0.7 to 12.1°), i.e. greater than the reported difference in threshold across the two tasks. This factor was eliminated in our experiment because the same group of subjects performed both tasks: categorization and discrimination. We also controlled for possible variations in performance between sessions, since both tasks were performed in the same session. Our results confirmed that discrimination threshold was higher in discrimination task, mean 7.4°, than in the categorization task, mean 3.9°. Thus, inter subject variations in threshold were not responsible for the differential effects seen across the two tasks.

Second, in previous studies from this laboratory (see above), the orientation of the angles for the discrimination task was different from that used in the categorization task. The angles were obliquely oriented in the discrimination task to form an upright V: the first bar scanned was oriented at 45° to the left of vertical, while the second bar was oriented to the right of vertical, with values ranging from 45° (to form the 90° standard) to 58° (largest comparison of 103°). In contrast, the angles in the categorization task had an upright orientation: one bar was vertical (fixed bar), while the other bar (mobile) was close to horizontal (± 10°). The higher thresholds in the 2-D angle discrimination task might be explained by what has been termed the haptic “oblique effect” (reviewed in Gentaz et al. 2008). This term was originally introduced in the visual field, where psychophysical studies that have shown that vertically or horizontally oriented stimuli are perceived with greater precision than those that are obliquely oriented (Appelle 1972). Similar results have been reported for haptic bar or rod orientation tasks: subjects have great difficulty in reproducing the position of obliquely oriented bars using haptic touch in comparison with bars or rods oriented either vertically or horizontally (Appelle and Countryman 1986; Appelle and Gravetter 1985; Gentaz and Hatwell 1995; Kappers 1999; Kappers and Koenderink 1999). In contrast to these results, the present study showed that performance in the 2-D angle categorization task did not vary with angle orientation, upright vs. oblique. Thresholds were practically identical for both orientations: means of 3.8° for the upright angles and 3.9° for the oblique angles.

The failure to confirm the existence of the haptic oblique effect can most likely be explained by differences in task design and/or the cognitive demands of the tasks. First, the exploratory strategies were very different. In our task, exploration was restricted to a contour-following movement of the index finger over the angle to be categorized; finger position was also specified (nail up) so that cutaneous feedback was limited to the glabrous skin of D2. In all cases, the arm was held out-stretched so that joint movement was also limited, in this case to the shoulder. In contrast, most previous studies of bar/rod orientation involved complex patterns of free exploration, involving the entire glabrous hand; in addition, joint rotation typically occurred at multiple joints both proximally and distally (digits/hand). It is possible that our approach of limiting the sources of sensory feedback during exploration may have resulted in higher quality sensory feedback and so better perceptual performance. Second, our task of angle categorization eliminated several potential sources of error, including the need for subjects to store one representation in short-term memory and to subsequently reproduce the explored orientation. Each of these steps has its own intrinsic source of errors that would have tended to degrade performance. While this would explain why angle discrimination is much more precise than expected from studies of rod/bar orientation, these same factors would also have been present for the vertical or horizontal orientations, thus arguing against this as a potential explanation. Third, and perhaps most importantly, the shapes in our task were all two-dimensional; in contrast, most studies that have reported the existence of the haptic oblique effect were restricted to evaluating only a single dimension, namely the orientation of a rod or bar in space. Perhaps the absence of a haptic oblique effect here can be explained by the fact that our shapes were presented within a 2-D context, rather than a single dimension, orientation. Thus, during each trial the subjects always had an external frame of reference formed by the intersection of the two bars. Alternately, the results may reflect the fact that there were two important sources of information in our task, not only bar orientation but also the pattern of cutaneous feedback from the contact with the intersection. As sensory input from the latter was entirely cutaneous in origin, the results may reflect the fact that cutaneous feedback can, under optimal conditions, substitute for haptic feedback (Levy et al. 2007).

The third difference between this study and previous work from the laboratory was that we provided knowledge of results (KOR) after each trial. In the earlier categorization study, KOR was also given after each trial (success or failure), but no KOR was provided in the studies of 2-D angle discrimination. Since KOR can assist subjects in developing an optimal strategy for task performance, including motor learning (e.g. Blackwell and Newell 1996), this might have contributed to the better performance in the categorization task. Despite providing KOR after every trial in this study, however, threshold was still significantly lower in the categorization task as compared to the discrimination task, suggesting that the difference was real and independent of the provision of feedback regarding task performance.

The final difference concerned the visual feedback provided during task performance. In previous studies of 2-D angle discrimination (Voisin et al. 2002a,b; 2005; Levy et al. 2007), vision was blocked during testing (no vision). In contrast, non informative visual feedback of the surround was provided during the categorization testing (Michaud, Voisin and Chapman, unpublished observations). This is a potentially critical difference as there is evidence that haptic shape perception is modified by the type of visual feedback (Newport et al. 2002; Zuidhoek et al. 2004). Specifically, performance in certain haptic tasks (bilateral bar matching) is improved (smaller errors) in the presence of non informative visual feedback as compared to no vision. Consequently, subjects in this study were all tested in the same visual feedback conditions, corresponding to the no vision condition used by Voisin et al., thereby ensuring that this factor could not contribute to the results. By confirming that performance is better in the categorization task as compared to the discrimination task, and this in the same no vision condition, we can conclude that this factor was not responsible for the differential effects seen previously in the two tasks.

The present results indicate that haptic perception of 2-D angles is indeed more precise when subjects categorize individual angles than when they discriminate angle differences between pairs of angles. So, how can we explain the difference between the two tasks? One possible explanation is that the difference is related to the added cognitive load associated with the task of angle discrimination. Subjects needed to develop a short term memory of the first angle scanned, which could be either the standard or a comparison angle. They then had to scan the second angle and finally compare this to the initial reference angle in order to identify the larger angle of the scanned pair. In contrast, the cognitive requirements of the categorization task were simpler. Angles (one large and one small) were presented in blocks of trials. Subjects scanned an angle and then categorized it. In these experiments, the PSE was close to 0°, corresponding to 90°. This leads to the suggestion that the subjects may well have recognized this very familiar orientation, making the task relatively easier.

Consistent with this, 4 of 12 subjects reported using an internal reference angle of 90°. This argument is not, however, supported by the subjective measures of difficulty in the two tasks since the ratings were virtually identical for both tasks (categorization, mean of 6.0; discrimination, 5.5).

Despite the lack of corroboration from the difficulty ratings, it remains possible that the use of an implicit standard of 90° for the categorization task may have influenced the results. For those subjects that reported using this strategy (above), it should be stressed that they adopted this strategy even though they were never informed of the value of the angles presented. In this light it would be interesting to determine whether performance in the categorization task might vary as a function of the value of the implicit standard, the angle about which the small and large angles are distributed. Future experiments should use either a smaller or larger implicit standard (e.g. 80° or 100°) to determine the extent to which performance in the categorization task is influenced by the value of the implicit standard.

Similarities between angle discrimination and categorization

The results of the present study confirm and extend some previous observations. First, Levy et al. (2007) recently showed that performance in the 2-D categorization task is as good when subjects made only a single pass over the angles, as compared to when they scanned the angles with a to-and-fro movement (corresponding to 2 passes). The present results extend this observation to the angle categorization task (Fig. 10C), reinforcing their suggestion that the majority of information is obtained during the first pass over the angle, with the second pass contributing little to task performance.

Second, as found previously using the 2-D angle discrimination task (Voisin et al. 2002a), there appeared to be no learning effect in the categorization task. Thus, subject performance did not change over the course of the experimental session, being the same in the final block of testing with this task as on the first block of trials.

Experiment 2

The second experiment investigated the influence of head position and gaze direction on the haptic perception of 2-D angles in a condition of *non informative vision*. We had hypothesized that our recent observation (G. Michaud, S. Bourgeon, CE Chapman, unpublished observations) of an increase in categorization threshold when gaze was directed to the far right (towards the unseen angles located 60° to the right; head forward) might reflect an action of spatial attention. Thus, we expected to see an increase in threshold when the gaze was directed to the far right, independent of the location of the angles. The present results did not, however, confirm our hypothesis. Instead we found that threshold did not change across any of the 5 conditions tested. Specifically, threshold showed no change as a function of either the position of the angles in space (30 versus 60° to the right), or the direction of gaze relative to the location of the angles (to versus away).

Spatial location of the explored angles

The absence of any change in threshold as a function of the location of the angles is in contrast with the results obtained by Voisin et al. (2005) using, admittedly, a different task. They demonstrated that performance in the 2-D angle discrimination task depends on the spatial position of the explored angles. Threshold was higher when the angles were explored in an eccentric position, angles at 60° to the right, as compared to the reference condition, 30° to the right. When the movement was restricted to the distal articulations, as in this study, similar results were obtained but this depended on the delay between the successive scans over the pair of angles: with a short delay, 5 s, then threshold was higher in the eccentric location; with a longer delay, 15 s, mean threshold declined close to the values obtained at the spatial location closer to midline. They suggested that the increased time between the first and second scan allowed subjects to resolve an apparent conflict between two egocentric (internal) frames of reference in order to provide an accurate representation of haptic space. Our finding of no difference with the change in position in this task of angle categorization, coupled with our use of the distal exploration strategy, suggests that the central haptic representation of the angles in this task may in fact be closer to the final frame of reference identified previously by Voisin et al. (2005).

Our finding of perceptual invariance as a function of spatial location is supported by the results of some previous studies. For example, Henriques and Soechting (2003) reported that subjective judgements of haptic curvature and circularity did not vary with the location of the discriminanda at least within a relatively constrained horizontal workspace located directly in front of the subject (~25 cm to either side of midline, extending out ~35 cm). In contrast, Kappers (1999) reported large systematic errors in relation to the spatial location of the discriminanda. In her case, subjects had to reproduce the orientation of a reference bar felt with one hand by adjusting the position of a test bar using the opposite hand. These experiments used a large horizontal workspace (70 x 140 cm) that extended 70 cm to either side of the midline. Their results showed that the errors increased as the horizontal distance from midline increased; in contrast, changes in the distance away from the body (close to the trunk or further away) had no effect. Similar results were obtained when the task was restricted to a single side (Kappers and Koenderink 1999). These latter findings can be reconciled with the present results since Hermens et al. (2006) have now shown that a large proportion of the errors in the bilateral matching task are independent of haptic perception *per se*. They found that subjects' verbal reports of haptic bar orientation were more precise than the haptic reproduction of bar orientation, indicating that a major source of error was the transformation required between the reference and matching bars.

Our finding of perceptual invariance for haptic shape with regard to spatial location is an important observation since the pattern of haptic feedback, particularly from proprioceptors, likely changed systematically across the work space. The implication of this result is that, at some higher hierarchical level, neurones involved in haptic shape appreciation should discharge in the same manner independent of the spatial location of the explored object.

Effects of gaze direction

In this study, gaze direction was systematically varied while subjects categorized angles presented at either 30 or 60° to the right of midline. No change in threshold was observed across the 5 test conditions, but there was a change in bias so that the PSE (50% correctly identified as large) was > 90° (90.3°) with the angles, head and gaze all at 60°. In contrast, the PSE was < 90° for all other conditions (mean, 89°).

Previous unpublished results from this laboratory showed that categorization threshold increases when gaze is directed to the far right, and the angles explored at the far right (60°), corresponding to the angle position used for two of the conditions here. In the same testing session, low thresholds were found when gaze was directed forward (head forward), as well as when the head and gaze were directed to the angles at 60°. Since threshold remained low in the latter test position, corresponding to that used here, when gaze was directed back to the midline (and away from the angles), it was suggested that spatial attention might be responsible for the observed increase in threshold.

The experimental testing conditions here were closely similar to those used previously. Non informative vision was given while the subjects performed the categorization task. Knowledge of results was withheld in both studies. The exploratory strategy was also the same: movements were restricted to mainly distal articulations; 2 passes were made over the angle; the start position was varied from one trial to the next (mobile or fixed arm); and the angles were in an upright position. Finally, a block design was used for all testing, so that all trials for a given condition (angle and gaze) were completed before moving on to the next (order of testing, counterbalanced).

While no change in threshold was found in this study, there was a change in the angle at which the small and large angles were judged equivalent, corresponding to the PSE (see above). This contrasts with the results of Michaud et al. in which case, the PSE showed no change across the 4 conditions studied. The mean PSE in the latter study was 90.3°, i.e. very close to the implicit standard of 90° about which the angles were presented and identical to the “elevated” PSE value found here for the 60° condition. This suggests that the PSE was not, in fact, elevated in the 60° condition (angles/head/gaze) – rather the PSE was reduced in the other 4 test conditions in this study (mean 89°). In other words, the logistic curves were all shifted to the left during this testing. Consistent with this interpretation, the mean PSE in these 4 test conditions was lower than in experiment 1 (89 vs. 89.8°).

There were 2 differences between this study and that of Michaud et al. First, their testing included conditions in which the head was oriented away from the explored angles, while head position here was always directed to the angles. Our results indicate that directing gaze away from the angles (head oriented toward the angles) does not modify the ability to categorize angles (at least for threshold measures); we extend the previous results to both directions (far right and far left). Second, their condition that was associated with an increase in threshold was not reproduced here: head forward/ gaze to the far right, towards the unseen angles located to the far right. Since our testing with far right gaze away from the angles had no effect on threshold, we suggest that the key factor contributing to the increased threshold with the head forward and gaze directed to the far right must have been this particular combination of head/gaze/angles used and not spatial attention.

Further to this, other unpublished results from this laboratory (G. Michaud, J. Voisin, C.E. Chapman) showed that angle categorization threshold does not vary with angle position, head or gaze orientation when the angles are explored at positions closer to the midline (angles directly in front of the shoulder or 30° to the right). In the former experiments, however, head and gaze orientation were restricted to this same workspace. The present results extend these observations to a larger range of gaze shifts (~120°).

The measures of bias here were, in general, close to the implicit standard of 90° - within 0.3 to 1.2° of 90°, corresponding to differences of 0.33 – 1.33%. A similar range was observed in experiment 1 (0.2 to 1%). These measures are larger than those reported by Henriques and Soechting (2003) who investigated haptic sensitivity to the orientation of straight paths within a virtual environment. In their study, the judgments of straightness of a 15 cm long hand path were within 0.27% of being straight. The difference can likely be explained by differences in task design. In their case, subjects were specifically instructed to judge path straightness, while in this study subjects were not informed of the value of the implicit standard of 90°.

Non informative vision versus no-vision

Haptic shape perception is not often carried out in isolation (e.g. in the dark with no vision) but usually without the context of a very busy environment (light, sound, etc). Our mental image of the environment is shaped by interactions across different senses, vision and haptics in the present case. Researchers have only recently begun to investigate how haptics and vision interact, specifically how viewing the surrounding environment, but not the discriminanda themselves, modifies haptic perception (*non informative vision*).

In our two sets of experiments, the visual feedback conditions differed. For experiment 1, vision was occluded, while non-informative vision was provided in experiment 2. The non informative feedback consisted of a view limited to the visual surround above the location of angle device, a neutral background, along with targets that were used to direct the subjects' gaze. Despite this difference, mean threshold was the same, 3.8°, for comparable test conditions (independent t-test, P=0.95). While the PSE was lower with non-informative vision, 88.9°, than with no-vision, 89.8°, the difference was not significant (P=0.1). Likewise, the mean difficulty ratings were similar across both experiments. The similarity of the results indicates that the nature of the visual feedback conditions did not modify performance of the categorization task. This conclusion goes in the same direction as our finding in experiment 1 that superior performance on the angle categorization task, as compared to the discrimination task, could not be explained bythe nature of the visual feedback provided during testing.

These findings are in direct contrast with several recent reports that non informative vision modifies haptic perception. Newport et al. (2002) reported that subject performance on a parallel bar matching task was better with non-informative vision, as compared to no-vision. These observations were confirmed by Zuidhoek et al. (2004). Newport et al. also reported that when the task was modified, so that subjects had to match bar orientation in a mirror-symmetrical fashion rather than setting them parallel, then non informative vision had no effect on task performance. They reconciled these results by suggesting that non-informative vision improved haptic perception when the task was based on an external frame of reference (set bars in parallel orientation) and not when it was biased toward an internal reference frame (set bars in mirror orientation). Our failure to see any improvement in the non-informative vision condition may thus reflect a dependence of the categorization task, and most probably the angle discrimination task as well, on an internal reference frame.

More recently, however, Volcic et al. (2008) reported the existence of large sex differences for the effects of non-informative vision. They found that non-informative vision improved performance in the parallel bar matching task in men but not women. In the present study, we found no significant differences in threshold or bias measures across the men and women in either experiment. Moreover our samples were balanced for gender, with equal numbers of men and women in each experiment. Since different subjects participated in the two experiments, we cannot make a direct comparison, non-informative vision vs. no-vision. Inspection of the mean thresholds (men, women) indicated that men had slightly higher categorization thresholds in the non-informative vision testing, while women showed the opposite pattern. The differences were, however, very small (0.5 to 0.65°). Together these results suggest that performance in our tasks was relatively independent of gender influences.

Frames of reference

As already discussed above, the design of the present tasks appears to have forced subjects to use an internal, or egocentric, frame of reference for evaluating the explored angles. This likely reflects the fact that each angle explored contained its own internal references, including the orientation of the two bars the formed the angle, and the angle formed by their intersection. As such, the present tasks are very different from experiments that have matched bar orientation since these provided information on only one dimension (Hermens et al. 2006; Kappers 1999; Kappers and Koenderink 1999; Newport et al. 2002; Volcic et al. 2008; Zuidhoek et al. 2003, 2004). Moreover, the experiments were confounded by having the reference and test bars in different spatial locations, either within the same hemi-field or opposite hemi-fields. While the underlying reference frame has been suggested to be intermediate between an allocentric (external) and egocentric (internal) reference frame (Zuidhoek et al. 2003), the exact weight of each component most likely depends upon the details of the experimental paradigm.

Consequently, it is not too surprising that there is little agreement across the two different approaches. For example, Zuidhoek et al. (2004), using the bilateral parallel bar matching task, found that orienting the head and gaze to the spatial location of the reference bar (always left) led to smaller errors than orienting to the test bar (right). They also found that non-informative visual feedback improved performance in an additive fashion, independent of the effects of head/gaze orientation. They suggested that visual feedback and head orientation exert independent effects on haptic perception. This suggestion is not supported by results obtained using the angle categorization task (present and previous results). First, visual feedback does not appear to confer any advantage in performance of our angle categorization task. Second, head orientation had no effect on task performance, although gaze direction was a factor. Taken together, these findings indicate that the frames of reference are indeed very different in these tasks (bar matching vs. angle categorization). Thus it is not surprising that performance is differentially modified by factors such as visual feedback, head and gaze direction.

There is, nevertheless, one intriguing parallel. Zuidhoek et al. (2003) reported that adding a 10-sec delay between perception and action resulted in smaller errors in the parallel bar matching task. They suggested that this reflected a shift from an initial egocentric (hand-centred) frame of reference towards an allocentric (fixed in space) reference frame. Interestingly, Voisin et al. (2005) made a similar observation for the 2-D angle discrimination task, whereby a position-dependent increase in threshold disappeared when the interscan delay was increased from 5 to 15-sec. Their interpretation of these findings was quite different from Zuidhoek et al.: since the position-dependent effect was also abolished by orienting the head to the unseen angles (no-vision, short delay), they suggested the existence of two competing egocentric reference frames for this task – one centred on the hand/arm and the other on the head.

Altogether, the results of this study and of previous studies provide a cautionary tale whereby relatively modest changes in task design can modify the effects of a range of physical factors, including the visual feedback conditions, the posture of the subject, and the timing of events in a trial, on haptic perception. This suggests that each task must be completely and systematically tested across a range of conditions in order to understand 1) the influence of physical factors on haptic perception; and 2) the frame(s) of reference that underlie haptic perception.

Future experiments

The present results, showing that angle categorization was not influenced by the orientation of the angles, upright vs. oblique, was surprising since there is evidence from a variety of sources indicating that haptic perception of vertical and horizontal orientations is better than for obliquely oriented orientations. While we found no difference across angle orientation, it may be that our results in the categorization task reflected our use of a 90° implicit standard. This cannot be ruled out with the present results, but could be addressed in future experiments by testing performance (upright vs. oblique) about different implicit standards, for example 80° (and so < 90°) or 100° (and so > 90°). If the 90° implicit really is a special case, then threshold as a proportion of the standard (Weber fraction, $\Delta S/S$) should be lowest for 90° and higher for the other standards, 80 or 100°. This would go against the well-known psychophysical observation that the Weber fraction is a constant over much of the range of an intensity continuum, deviating from this (becoming non linear) at the extremes of the range (Mountcastle, 1998). A deviation at 90°, i.e. well within the normal operating range for haptic angle perception, would be a novel and potentially important observation.

In a similar vein, it remains surprising that we were not able to provide any evidence for the haptic oblique effect – specifically performance on the categorization experiment in experiment 1 was identical for oblique and upright angle orientations. One possibility is that our results are limited to this task of angle categorization, in which relative differences across small and large angles were assessed. It would be interesting to evaluate the ability of subjects to scale the absolute magnitude of a range of 2-D angles explored in the two orientations (oblique, upright) in order to further explore the potential existence of a haptic oblique effect for these types of angles. The two orientations should be presented in the same blocks of trials, in order to ensure that subjects use a single rating scale for both orientations. If an oblique effect exists for the 2-D angles, then ratings should be systematically more variable for the oblique orientation than for the upright orientation. In addition, we expect that subjects will overestimate the values of the oblique angles, consistent with previous findings (Voisin et al. 2002a).

Clinical applications of the 2-D angle perception tasks

During most manual activities, the hand is used not only as a motor organ capable of transforming the environment by producing forces but also as a sensory organ capable of sensing the properties of the environment. In fact, these two functions of the hand are in general closely intertwined and coordinated at the cortical level. Lesions, stroke at the level of parietal cortex or disorders like Parkinson, can impair the ability of patients to identify objects using haptic touch (astereognosia, deficits in tactile object recognition).

At present, neurological examinations of somatosensory function are subdivided into basic, intermediate and complex testing. (Note: The senses of pain and temperature are not included in the following description because they are not part of the haptic sense.)

1. Basic somatosensory functions. The examination assesses touch, position sense, kinaesthesia (movement sense), vibration, as well as two-point discrimination.

2. Intermediate somatosensory functions. This refers to a number of clinical tests most of which more often are employed in research studies, although there are exceptions, for example double simultaneous stimulation to evaluate the presence of

tactile extinction. Other tests include weight, size and texture discrimination; 2-D or 3-D shape perception; and the appreciation of surface properties (soft/hard, slippery/sticky etc).

3. Complex somatosensory functions. Tactile object recognition is often tested in standard neurological examinations. The most common method is to ask patients to name familiar objects such as a pen, penny, fork, lock, or toothbrush placed in either hand. If the patient is unable to identify the object, then this is categorized as a recognition failure (Casseli 1991, 1993). Another method is to ask the subject to find a match for the object using their other hand. Matching is more difficult and requires more time than the first test.

Testing haptic touch in patients can, in combination with imaging techniques, provide insight into the functional role of lesioned central structures. A better understanding of the deficits in human haptics could lead to improvements in evaluating sensorimotor impairments of hand function, and eventually the development of new and innovative treatments of such conditions. Perhaps in the future we could apply this task of haptic angle discrimination in evaluation of different diseases that show some evidence for haptic touch deficits, including Parkinson’s disease, multiple sclerosis, carpal tunnel syndrome etc.

Haptic research is even now providing new insight into how people adapt to sensory losses. For example, blind people appear to use some form of mental imagery that activates occipital cortical areas during tactile discrimination tasks, even without ever having had any visual experience (congenitally blind subjects). Sadato et al., (1996) measured regional cerebral blood flow using PET. They found that blind subjects show activation of primary and secondary visual cortex (V1, V2) during Braille reading. In contrast, the same areas were deactivated in normal sighted subjects during the same task. These studies were later extended (Sadato et al. 1998) to show that these effects in blind subjects were accompanied by a deactivation of secondary somatosensory cortex (SII). Once again, opposite effects were seen in sighted individuals: deactivation of V1 and V2 along with activation of SII. This result suggests that in blind people the neural network usually reserved for visual shape discrimination processing is used for the evaluation of tactile information. This suggestion has recently been confirmed by Hamilton et al. (2000). They reported the case of a blind woman, a skilled Braille reader, who lost her reading skills with otherwise normal somatosensory perception after a bilateral occipital ischemic stroke.

There is also growing evidence that people with a sensory deficit such as blindness compensate by enhancing their perceptual abilities with the remaining intact senses. Thus, there is evidence for auditory hyperacuity in blind subjects (Lessard et al. 1998; Gougoux et al. 2004), as well as some evidence for tactile hyperacuity (Goldreich and Kanics 2003), although the latter is controversial (Grant et al., 2000). As regards haptics, Alary et al. (2008) recently reported that blind subjects outperform sighted subjects in the 2-D angle discrimination task described here (thresholds of, respectively, 4.3° and 5.7°). It would be interesting to follow up on these results by extending such testing to other patient groups (e.g. those with hearing impairments).

Applications to daily life of the results from haptic research

Investigations of human haptics offer insights into the functioning of the human body that should ultimately lead to new technical developments. The term, *haptic interface*, refers to a mechanical system (sensors) that allows an individual to directly interact – using touch - with devices that can range from a computer or a robot to, more commonly, personal electronic devices (iPOD, iPHONE, Blackberry etc.). Such applications are now becoming much more common, and sophisticated, improving the user-friendliness of many devices (e.g. more rapid searching for, and switching between, different applications by doing away with the multiple nested menus that one has to navigate in a system based on button pressing to navigate menus).

Different haptic interfaces are now used in medicine, so improving the ability to perform minimally invasive surgery (laparoscopic surgery). This procedure is a modern surgical method that uses a small incision (usually 0.5-1.5cm) to introduce the laparoscope which is equipped with a video camera. The advantage of this type of work is that there are decreases in the duration of the intervention, along with the associated pain and trauma; there is also increased precision leading to faster recovery than in classical interventions. Another particular advantage of this type of intervention is that the surgeon can execute more interventions with less fatigue. The required psychomotor and perceptual skills are, however, different from those associated with traditional interventions (Gallagher et al., 2004). In this method the haptic feedback is much lower than in traditional procedures because the surgeon does not manipulate the tissues directly with his/her hands. Instead, all sensory feedback is indirect, through the laparoscopic instrument. A challenge for the future is to improve the quality of enhancing sensory feedback provided by these instruments. One method to improve tactile sensitivity was developed by Yao and Hayward (2005). They developed an instrument consisted of an accelerometer and an actuator that magnified the tactile and auditory feedback associated with scraping the surface within a joint cavity (e.g. for orthopaedic surgery). The results showed that performance was superior with both sources of feedback as compared to only one source. This was taken to indicate the existence of some cross modal facilitation. Another approach was developed by Weiss and Okamura (2004) who designed haptic scissors that could feedback information about the forces exerted by the surgeon. Actually this technique is currently in development.

A second, but related approach has been the development of software and hardware capable of creating a virtual environment to train medical students and residents in various procedures. For example, laparoscopic surgical techniques can be taught, avoiding the risk of injury to the patient; such set-ups are permanently available for practice, and provide feedback on performance (on and off-line). Another example is the Virtual Haptic Back (VHB). This is a virtual reality simulation of the mechanical properties of the human back designed to aid teaching in palpatory diagnosis (detection of medical problems via touch). The VHB simulates the contour and surface compliance properties of the human back and allows these to felt through two haptic interfaces (Howell et al., 2008).

There are recent reports of research in which haptics have been studied for its potential in rehabilitation of patients with multiple sclerosis or stroke (Jiang et al., 2008). These patients may have impaired tactile and proprioceptive sensation and daily activities are very difficult to perform, even simple tasks like lifting a glass of water. Providing enhanced haptic feedback to the hand, using a portable haptic apparatus, has been shown to improve their ability to perform simple activities of daily living. Combining this with virtual reality (VR) environments is also being pursued as a promising tool for physical rehabilitation in stroke patients (McLaughlin et al., 2005). Using different levels of haptic feedback the patients can perform training tasks that range from precise fine motor movements to reaching movements involving full arm, shoulder and torso activity.

Certainly, research into human perception has benefited greatly from new developments in haptic technology (e.g. phantom robots); and the reverse is also true. This is a new and developing field with great promise. Future developments will undoubtedly include extending this work into fields such as the development of haptic aids for brain-machine interfaces to control, for example, prosthetic limbs in amputees or paralyzed limbs in the case of spinal cord injuries or stroke.

CHAPTER V

CONCLUSIONS

V. CONCLUSIONS

1. The first experiment showed that the mean threshold for 2-D angle discrimination was significantly higher, 7.4°, than for 2-D angle categorization, 3.9°. This result extended previous work, by showing that the difference is present in the same subjects tested under identical conditions (knowledge of results, visual test conditions, angle orientation). The results also showed that angle categorization did not vary as a function of the orientation of the angles in space (oblique, upright). Given that the angles presented were all distributed around 90°, and that this may be a special case as in vision, this finding needs to be extended to different ranges of angles. The higher threshold with angle discrimination likely reflects the increased cognitive demands of this task which required subjects to temporarily store a mental representation of the first angle scanned, and to compare this to the second scanned angle.

2. In second experiment categorization thresholds showed no change across the conditions tested, although bias (point of subjective equality) was changed (shift to lower angle values). Since our testing with far right gaze (away) had no effect on threshold, we suggest that the key factor contributing to the increased threshold seen previously (head forward/gaze right) must have been this particular combination of head/gaze/angles used and not spatial attention.

CHAPTER V
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Notre référence : CERFM-48 (03)4#100

Docteure Chapman,

Nous accusons réception de votre demande d'approbation éthique pour la modification au protocole du projet portant le titre : «**Facteurs influençant la perception de la forme à l'aide du toucher haptique**», dont vous êtes la chercheuse principale.

Nous vous demandons de nous transmettre une copie de l'affiche de recrutement qui sera utilisée afin de compléter cette demande.

Le Comité d'éthique approuve cette demande qui comporte la modification suivante :

– ajouter 12 sujets pour une étude psychophysique supplémentaire.

Nous vous remercions de votre collaboration.

Coordonnatrice
Comité d'éthique de la recherche
Faculté de médecine

/da

Université de Montréal
Département de physiologie

Annonce pour affichage à l'Université de Montréal

Sujets demandés pour une expérience scientifique

Nous sommes à la recherche de personnes (hommes et femmes) pour une étude sur le toucher. Cette étude vise à déterminer l'impact de la posture sur la capacité de catégoriser des angles à l'aide du toucher.

Les personnes devront être :

- en bonne santé
- agées de 18 à 35 ans
- disponibles pour les expériences (1 séance de 1h30 environ).

Les personnes ne devront pas :

- avoir des problèmes de peau au niveau de la main droite.
- avoir subi antérieurement un traumatisme au niveau du bras droit (fracture, etc.).

Chaque personne qui participe à l'étude recevra la somme de 12$ par séance, ou une somme proportionnelle à la durée de sa participation, en cas de retrait de l'expérience.

Pour plus d'information, veuillez téléphoner à Iuliana Toderita au 343-6111 poste 1927.

CERFM -48(03) 4#100

To: "Audet Diane" <diane.audet@umontreal.ca>
From: Elaine Chapman <c.elaine.chapman@umontreal.ca>
Subject: RE : Demande de modification (version papier dans le courrier)
Cc: Iuliana Toderita
Bcc:
Attached:

Merci!
On enverrai le formulaire modifié aujourd'hui ou demain.
Elaine Chapman

At 08:49 AM 17/11/2006, you wrote:

> Bonjour,
>
> Le CERFM accepte cette modification, mais vous demande de joindre le formulaire de consentement modifié.
>
> Une lettre d'attestation éthique vous sera acheminée sur réception du nouveau formulaire de consentement.
>
> Merci de votre collaboration.
>
> Dianne Audet
> Vice-décanat à la recherche et aux études supérieures
> Faculté de médecine, Pavillon Roger-Gaudry, local P-711
> COPSE/CERFM/Congrès des stagiaires<?xml:namespace prefix = o ns = "urn:schemas-microsoft-com:office:office" />
>
> Tél : (514) 343-6904 / Fax : (514) 343-5751
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> Faculté de médecine - Université de Montréal
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> Université de Montréal
> C.P. 6128, Succ. Centre-Ville
> Montréal (Québec) H3C 3J7
>
> -----Message d'origine-----

De : Elaine Chapman [mailto:c.elaine.chapman@umontreal.ca]
Envoyé : 15 novembre 2006 13:46
À : Audet Diane; yvette.lajeunesse@umontreal.ca
Cc : ltoderita@gmail.com
Objet : Demande de modification (version papier dans le courrier)

Université de Montréal

15 novembre 2006

Mme Yvette Lajeunesse
Présidente
Comité d'éthique de la Faculté de Médecine (CÉRFM)
Université de Montréal

Objet : Modification au protocole CÉRFM 48(03)4#100, "Impact de la posture dans une tâche de catégorisation d'angles par le toucher chez l'humain" (18 juin 2003)

Madame,

Le but de cette lettre est d'apporter une autre modification à un projet de recherche existant afin d'ajouter des sujets pour une expérience complémentaire. Les résultats de nos expériences ont laissé quelques interrogations non résolues, le pourquoi d'une étude psychophysique supplémentaire.

En bref, nous avons trouvé dans nos précédentes expériences que pour catégoriser les angles deux dimensionnels (2-D), la direction du regard est un facteur significatif pour le seuil perceptif quand la tête est orienté tout droit (0º) et les angles sont exploré dans une position excentrique de 60º à droite, avec une vision non informative (i.e. les sujets ne peuvent pas voir les angles). Ainsi, le seuil perceptif augmente lorsque le regard est orienté vers les angles (60º) par rapport à la condition ou le regard est dirigé tout droit (0º) (Fig.1A, rouge). Curieusement, la direction du regard n'est pas un facteur significatif quand la tête est orienté en direction des angles (60º) (Fig.1B). Cependant, la direction du regard par rapport à la tête, n'est pas orientée dans le même sens que dans la condition précédente (anti-horaire et horaire respectivement). On ne sait donc pas si les différences perceptives s'expliquent par la direction du regard ou par la position de la tête.

Pour lever cette interrogation, nous voulons effectuer une étude psychophysique dans laquelle on compare la performance des sujets avec la tête orienté vers les angles (60º) et le regard dirigé vers la droite (Fig.2A). Une condition similaire sera ajouté mais avec les angles positionnés à 30º à droite (Fig.2B). Notre hypothèse est que le seuil de catégorisation des angles sera augmenté quand le regard est orienté à droite (rouge), et ceci indépendamment de l'orientation du corps et de la tête dans l'espace. Douze sujets (hommes et femmes entre 18 et 35 ans) seront nécessaires pour effectuer cette étude. Les critères d'inclusion et d'exclusion resteront les mêmes (bonne santé, etc). Il y aura une séance expérimentale (durée ~ 1h30) qui comportera des pauses au besoin. À la fin de la séance, les sujets recevront une compensation financière de 12$ (prix de stationnement). Ces résultats nous permettront de voir si la différence entre les deux orientations du regard est réelle, ou plutôt reliée à l'orientation du corps dans l'espace.

Merci pour votre temps.

Cordialement,

C. Elaine CHAPMAN, PhD. Professeur titulaire, École de réadaptation et Département de physiologie
Iuliana Toderita, étudiante à la maîtrise

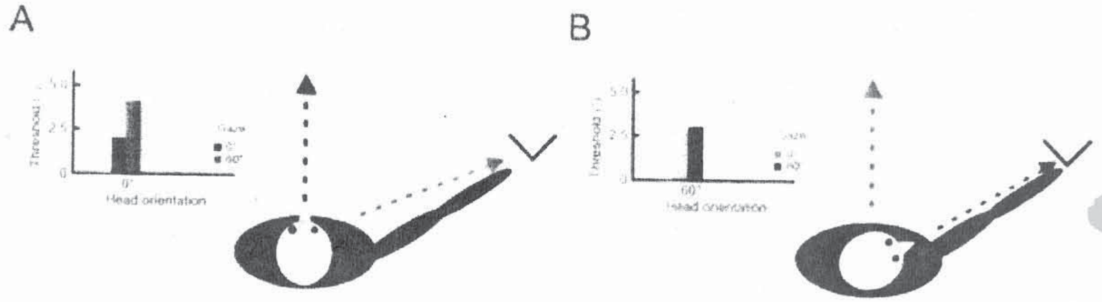

Fig. 1. Vision non-informative / angles à 60 à droite.
A. Tête tout droit. Quand le regard est dirigé vers les angles, les seuil augmente en comparaison avec le regard tout droit.
B. Tête orientée vers les angles. La direction du regard n'a pas d'effet sur le seuil.

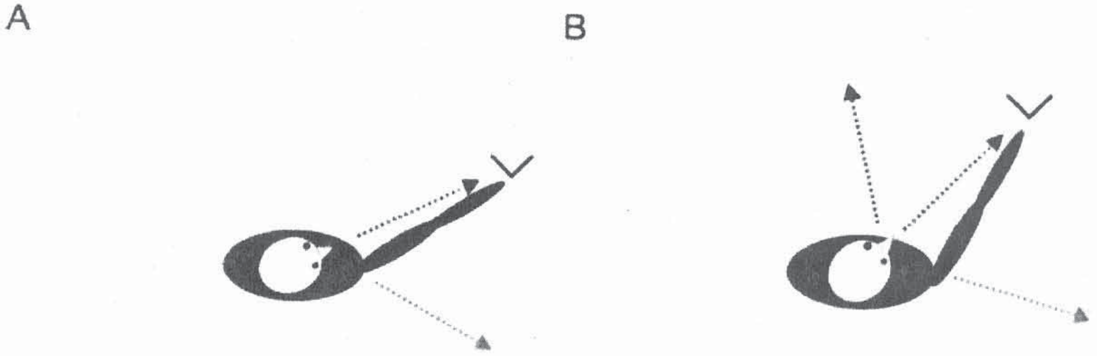

Fig. 2. Nouvelle expérience. Vision non-informative / tête orientée vers les angles.
A. Angles à 60. On attend que le seiul augmentera quand le regard est orienté à droite (rouge).
B. Angles à 30. On attend une augmentation du seuil, encore une fois, quand le regard est dirigé à droite(rouge), independamment de la position des angles dans l'espace.

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C. Elaine Chapman
Professeure