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Modulation of Corticospinal Excitability in the Context of Tactile Exploration

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*MODULATION OF CORTICOSPINAL EXCITABILITY IN THE CONTEXT OF TACTILE
EXPLORATION*

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B.Sc. (PT), University of Ottawa, 2006

Thesis presented to the Faculty of Graduate and Postdoctoral Studies
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of Master of Science in Human Kinetics

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LIST OF ABBREVIATIONS

ADL	Activities of daily living
ANOVA	Analysis of variance
APB	Abductor policis brevis
BP	Button pressure
CM	Corticomotoneurone
CS	Corticospinal
cm	Centimetre
cm³	Cubic centimetre
EMG	Electromyography
EP	Exploratory procedure
FDI	First dorsal interosseus
FM	Finger movement
Fz	Force in z axis
fMRI	Functional magnetic resonance imaging
Hz	Hertz
MEP	Motor evoked potential
M1	Primary motor cortex
MVC	Maximal voluntary contraction
mm	millimetre
ms	millisecond
µm	micrometer

μV	microvolt
N	Newton
PC	Pacinian
RA1	Rapidly adapting type 1
SA1	Slowly adapting type 1
SA2	Slowly adapting type 2
SICI	Short interval intra-cortical inhibition
SMA	Supplementary motor area
SI	Primary somatosensory cortex
SII	Secondary somatosensory cortex
s	second
TE	Tactile exploration
TMS	Transcranial magnetic stimulation
VPL	Ventral posterolateral
V	Volt
3D	Three dimensional

SUMMARY

Evidence indicates that the output of the motor cortex is modulated by task conditions with respect to the degree of dexterity involved. However, few studies have examined how corticospinal output could be modulated when the fingers are used for active exploration of patterns or objects. In the present study, we investigated this issue in young healthy participants with transcranial magnetic stimulation (TMS). Corticospinal excitability of the hand motor representation was examined under two task conditions. One condition (TE: tactile exploration task) consisted of exploring raised letters (6 upper case characters, 6-mm high) with the tip of the index finger for tactile recognition. In the second condition (BP: button pressure task), participants depressed a button with minimal force, again using only the index finger. In both tasks, TMS pulses (110% motor threshold) were delivered over the contralateral motor cortex at a delay of 2500 ms in the course of the 5 second trials. Corticospinal excitability was assessed by monitoring changes in the amplitude of motor evoked potentials (MEPs) in the 1st dorsal interossei (FDI) of each hand. Results (n=18) indicated a differential effect of task conditions on corticospinal excitability, with MEPs being larger during TE when compared to the BP task. These findings suggested that corticospinal excitability could be greatly enhanced when the hand is used for sensory exploration in comparison to simple motor performance. However, electromyographic (EMG) activity patterns differed between the two tasks, which could have contributed to differences observed in motor excitability. Therefore, a secondary experiment was performed with a subset of participants (10/18). In this experiment, motor facilitation elicited with the TE task was contrasted with a finger movement (FM) task. In the latter task,

participants reproduced the scanning movements performed when they explored the letter, but no stimuli was presented (smooth surface). The pattern of EMG activity was similar to that elicited in the TE task. Yet, comparisons between the two confirmed the task-specific increase in corticospinal excitability with the TE task. Overall, these results highlight the importance of behavioral demands in modulating corticospinal excitability during hand actions, especially when the finger is used for sensory exploration to acquire information about object and surface properties.

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GENERAL INTRODUCTION

We often take for granted the complex neural mechanisms that underlie our ability to manipulate objects and to recognize them by simple touch. It is only when the hand is exposed to cold for long enough to numb the fingers, when we suffer injury, or when we undergo the inevitable changes associated to aging that we appreciate our effortless skill in controlling and coordinating finger movements and in identifying features of an object.

The functions of the hand are numerous, and involve both manipulative skills and sensation. The hand is one of the most accurate organs of sensation in humans. For this reason, it has been a subject of intense research for many years. The haptic sense of the hand describes the combined use of the sensory receptors of the skin, muscles, joints and tendons, and of the purposeful movements of the hand and fingers which activate these receptors. Gibson (1962) hypothesized that active touch involved two components of stimulation, one exterospecific and the other propriospecific. He modified the former belief that perception was essentially a passive process. In fact, Gibson stated that perception is an acquired ability which is developed by exploring our environments, actively seeking the invariants (permanent structures of the physical world) in the relations between changing sensations. Therefore, active exploration, not passive sensation, is the essential process used to perceive objects in the physical world (Gibson 1962; Gibson 1966). Gibson's work was further elaborated by Klatzky & Lederman (1987) who have shown that human observers used a limited set of movement strategies or "exploratory procedures (EP)" to acquire information about the material properties of objects explored in the hand. The nature of the EP is largely dictated by the specific properties that is sought by the observers about the explored surface

or object (e.g., texture, consistency, weight, shape) (Lederman and Klatzky 1987a). Active exploration is the means by which skin bearing the highest density of receptors in the fingertips is brought in contact with a surface to be explored in a particular way. Creating motion allows for active control of either the normal or the tangential force during scanning. It also provides important proprioceptive feedback (Lederman and Klatzky 1987b).

Carlson (1984) first proposed that active manual exploration plays a critical role in the normal development of somatosensory perception in mammals. In his experiment, infant macaques aged between 7 and 25 weeks of age were trained on a number of tactile discrimination tasks. Results indicate that tactile discrimination capacity is not a function of age. In fact, size and texture discrimination scores were essentially the same for all infant ages and did not differ from adult macaques. However, size discrimination was acquired more rapidly in older macaques, while texture discrimination was superior in the infants. These findings were later confirmed in humans by Bushnell & Boudreau (1991; 1993). Infants aged between 4-6 months were evaluated on tactile exploration tasks. Results showed that, at all ages, active exploration was not continuous and generally involved only one hand. Strategies mainly became more active with age, involved more motion. These results confirmed that young infants are capable of developing an adapted manual exploratory procedure.

In spite of recent advances in deciphering the sense of haptic touch, there is still limited information as how people manage to optimize sensory information acquisition when exploring surfaces and objects by touch. The importance of understanding the mechanisms that underlie our ability to actively explore objects and surfaces with the hand is made evident by the sometimes devastating effects of aging, upper extremity injury, and stroke on

hand function and particularly on dexterity. These losses have been ascribed to various factors, including alterations in peripheral innervation and muscle function and alterations in the central nervous system. The ability to grip and manipulate objects may be the most important function of the hand, and any deterioration in this ability can lead to impaired ability to perform activities of daily living (ADLs) (Ranganathan et al. 2001). Declines in tactile sensation result in impaired tactile acuity, which may adversely affect the ability to perform haptic explorations. However, we do not know to what extent deficits in haptic perception may be affected by deterioration in hand function, particularly the ability to optimize sensory information acquisition through efficient tactile exploration strategies.

Most studies have focused on grasp and grips, while tasks such as tactile exploration have not been studied to this date. Such tasks can be particularly demanding such as when the finger is used to recognize raised patterns (e.g. Braille) by contour exploration. Tactile exploration represents a functionally demanding precision task, which also involves cognitive demands.

Therefore, the present work will try to address some of the issues stated above by looking at how corticospinal excitability in the hand motor representation is modulated by task conditions when the finger is engaged in tasks with varying degrees of behavioural demand. Furthermore, the effects of laterality will be observed by comparing findings obtained on both hands

CHAPTER I

LITTERATURE REVIEW

1. Neurophysiology of Hand Function

Within the domain of tactile sensation, it is important to distinguish between two modes of sensory information acquisition involving the hand. Tactile sensing is associated with acquiring sensory information when static or dynamic stimuli are applied to the immobile hand (i.e, passive touch). Haptic sensing, on the other hand, involves active contacts of the hand and fingers with surfaces and objects to acquire information about their properties through exploration (i.e., active touch) (Jones and Lederman 2006). This literature review will focus on haptic touch since this topic is central in the present work. In the following sections, I will first briefly describe the sensory and motor innervation of the hand that allow for haptic sensing. Then, I will review studies examining psychophysical and behavioral aspects of haptic sensing, focusing mainly on the modulation of corticospinal excitability in the context of tactile exploration. This second section of the review will also examine laterality effects on hand function.

a. Sensory innervation of the hand

Sensation allows us to investigate the world, to develop an internal representation of the environment in which we live. The hand being one of the most accurate organs of sensation, it is crucial to understand the mechanisms and pathways by which sensory information from the skin and musculoskeletal systems reach the brain to be interpreted. Sensory receptors are located at the distal end of peripheral nerves, and respond to a specific type of stimulus. Based on their characteristics, they can be divided into three classes: mechanoreceptors (responsible for touch, pressure, stretch and vibration sensation),

chemoreceptors (respond to substances released by cells) and thermoreceptors (sensitive to temperature). This discussion will focus on mechanoreceptors as they are central to this work.

The highly dense receptors of the hand play an essential role in the identification of objects by touch. Four different populations of mechanoreceptors have been identified in the glabrous skin of primates. The physiological and anatomical properties of these afferent populations have been subjected to several authoritative reviews in the recent years (Johnson 2001,(Goodwin and Wheat 2004)) and the following description will be based on these reviews. Slowly (SAI) and rapidly adapting (RAI) type I afferents have been implicated in the appreciation of texture and form, and in the detection of slip and low frequency vibration, respectively. SAI afferents are thought to originate from Merkel cell complexes and are sensitive to static skin deformation. They respond to a particular component of the local stress-strain field, making it sensitive to points, edges, corners and curvature. They respond to sustained indentation with a slow sustained, slow adapting discharge that is linearly related to indentation depth (depths of at least 150 μ m and is insensitive to the height of surface features above 300-400 μ m). Their great spatial resolution allows them to transmit an acute neural image of a tactile stimulus. Humans can discriminate curvature independent of contact force and contact area, which implies that they rely on the spatial profile of neural activity evoked by a curved surface rather than some intensive cues like total impulse rate. No other afferent type provides a representation on which curvature discrimination might be based (Johnson 2001).

RAI afferents originate from Meissner corpuscles and are sensitive to dynamic skin deformation, such as slip as mentioned above. Of the four different types of afferents, RAI

are the most important in determining forces that act on objects held in the hand. They have a crucial role in the provision of feedback signals for grip control. RAI afferents are as close to the surface of the epidermis as possible, which may account for their greater sensitivity to minute skin deformations relative to SA1 afferents. Contrary to SA1 afferents, RAI afferents have greater sensitivity but resolve spatial detail poorly and transmit a robust neural image of skin motion (Johnson 2001); (Jones and Lederman 2006).

Pacinian (PC) afferents originate in single PC corpuscles and produce a high-fidelity neural image of transient and vibratory stimuli transmitted by objects held in the hand.

PC afferents are responsible for the phenomenon by which when we become skilled in the use of a probe or a tool, we perceive events at the working surface of the probe or tool as if our fingers were actually present (Johnson 2001).

Finally slow adapting type 2 afferents (SA2) also innervate the skin of the hand. Their association with connective tissue in the dermis makes them responsible for detecting the direction and force of object movement and for perceiving hand shape and finger position through skin stretch (Phillips and Johnson 1981). SA2 receptors are sensitive to horizontal tensile strain (tangential forces) and less sensitive to indentation, also due to their deep location.

Sensory inputs arising from mechanical stimulation of the skin travel along large myelinated A- β fibers and enter the spinal cord via the dorsal root. The inputs are then conducted along the proximal axon into the spinal cord, where information ascends via projections in the white matter. Information about discriminative touch and conscious proprioception is transmitted via the dorsal column / medial lemniscus tract. This tract presents a somatotopic arrangement with axons conveying input from the hand being

adjacent to those conveying input from the arm and other adjacent areas. Tactile information is anatomically separated from proprioceptive information along the dorsal column / medial lemniscus pathway. Axons from proprioceptive neurones are located more ventrally, while those from sensory receptors travel along the dorsal aspect of the pathway. The dorsal column / medial lemniscus pathway forms two distinct fasciculi at the cervical level: the gracile and cuneate fasciculus. The gracile fasciculus ascends medially and contains fibers from the ipsilateral lower half of the body while the cuneate fasciculus conveys information from the upper half of the body. The two fasciculi terminate in the corresponding gracile and cuneate nucleus at the level of the lower medulla where they synapse on 2nd order neurons. These 2nd order neurons send projections that cross the mid-line and ascend contra-laterally in the medial lemniscus to reach the ventral posterolateral (VPL) nucleus of the thalamus. Third-order neurons from the VPL nucleus send projections in turn to the primary somatosensory area of the cerebral cortex (Brodmann's areas 3a, 3b, 1 and 2), located in the postcentral gyrus of the parietal lobe. The primary somatosensory cortex (SI) is somatotopically arranged and contains a map of the whole body surface. The hand, which has a high density of receptors, occupies a relatively large portion of the sensory homunculus. The somatosensory information that reaches the SI is also transmitted to a number of higher order areas located in the superior and inferior parietal lobule for sensory integration. There are also extensive interconnections between the SI and the secondary somatosensory (SII) cortex. Simple hand movements generate an abundance of sensory feedback which is modulated by the descending projections (Lemon 1999).

b. Motor innervation of the hand

The primate hand is endowed with more than 35 muscles (extrinsic and intrinsic) expanding over 27 bones (including wrist and carp), allowing for various and complex grasping and manipulative skills (Jones and Lederman 2006) (Wikipedia 2007). These muscles can be divided into two distinct categories: extrinsic and intrinsic hand muscles. Extrinsic hand muscles origin in the forearm and control the movements of the forearm, wrist and hand. These muscles can be further divided into two subcategories: flexors and extensors. The flexors originate from the medial epicondyle of the humerus or from the volar aspect of the radius and ulna. The muscle bellies travel down the forearm and are replaced by tendons as they approach the wrist. The second subcategory of extrinsic hand muscles, the extensors, arise from the lateral epicondyle and ulna and course down the dorsal side of the forearm. The second category of hand muscles, the intrinsic hand muscles, takes their origin and insertion within the hand. They control movements of the digits. There are four groups of intrinsic hand muscles. The thenar muscles about the thumb metacarpal bone are responsible mainly for thumb abduction and opposition. The hypothenar muscles located on the ulnar side of the hand abduct and flex the little finger. The lumbrical muscles originate from tendon and not from bones and attach to the proximal phalanges. The lumbrical muscles act together with the final intrinsic hand muscle group, the interosseus muscles to flex the metacarpo-phalangeal joints and extend the interphalangeal joints. All the muscles of the hand are innervated by the radial, median and ulnar nerves (Lundy-Ekman 2002); (Jones and Lederman 2006).

In humans and non-human primates, the control over the motor function of the hand relies largely on the corticospinal system and this system will be the focus of this review. At

birth, humans are unable to produce independent finger movements required for dexterity. This ability develops approximately 3 months following birth in monkeys and relies on the maturation of corticomotoneuronal projections to hand muscles (Lemon 1999). The motor descending tracts which arise from supraspinal centers can be divided into three functional groups: the medial descending system, which controls proximal and axial muscle groups, the lateral descending system which controls distal extremity muscles and finally, the nonspecific activation tracts which control the level of excitability in the spinal cord and facilitates local reflex arcs. The lateral system is of particular interest in this review as it is the one which assures control over the muscles of the arm and hand. The lateral corticospinal tract is the main component of the lateral system responsible for fine distal movements in humans. The rubrospinal tract is the second component but its functional importance is rather limited in humans. Generation of motor commands begins in the motor planning areas of the cortex which include the supplementary motor area (SMA), the premotor cortex and the primary motor cortex (MI). Corticofugal projections arising from motor areas in the frontal lobe travel down through the posterior limb of the internal capsule, the cerebral peduncles and the ventral pons; to reach the ventral aspect of the lower medulla. Then the fibers cross the mid-line to form the lateral corticospinal tract traveling down through the dorsolateral funiculus in the white matter. In the cervical and lumbar enlargement, axons in lateral corticospinal tract make synapses with the lateral pool of motor neurons in the ventral horn. The main function of the lateral corticospinal tract pertains to the fractionation of movement. Fractionation of movement refers to the ability to activate individual distal muscles independently of other muscles (Lundy-Ekman 2002), and is considered essential to fine motor control and dexterity. In contrast, tasks involving steady or power grip involve

co-contraction of the muscles of the hand and forearm for stability. In this case, muscles show a similar spatio-temporal pattern of contraction (Lemon 1999).

2. Psychophysical and Behavioural Aspects of Haptic Sensing

a. Exploratory Procedures for Tactile Exploration

As previously stated, haptic abilities are defined as our ability to acquire information through active touch (Smith et al. 2002). During haptic sensing, large amounts of cutaneous information are obtained from the receptors embedded in the glabrous skin of the palm and fingers. In addition to this cutaneous information, kinesthetic information is obtained from muscle, joint and tendon receptors which provide an extra source of information on object features such as material and geometry. Therefore haptic sensing is a multimodal perceptual task (Jones and Lederman 2006).

Lederman and Klatzky (1987b) described a number of stereotyped movement patterns generally adopted by observers during manual exploration of an object to study a specific feature or property. They regrouped these movements' patterns under the term "exploratory procedure (EPs)" and hypothesized that six different optimal EPs exists for different object features (texture, weight, hardness, temperature, shape, volume). In this review, we will focus on shape determination as it is of particular interest in the present work. The favoured EP for exploring object shape was found to be contouring the edges of the object with the fingertip. Optimal EPs differ in terms of precision, generality and duration, which differentiate them in terms of costs and benefits. While contour following provides more precise results regarding the shape of the explored object, this strategy is less efficient with

regards to other features. In addition, while most EPs provide information on a single object feature, contouring the edges of an object provides a relative amount of information on each attribute. When shape properties are being detected, Lederman and Klatzky (1987b) found that mean contouring time was estimated to 11 seconds. This represents the longest duration out of all 6 EPs. In 1993, Klatzky and Lederman (1993) further elaborated by dividing tangible object properties into two major categories. First, an object is defined by its constituting material (e.g. texture, compliance and thermal properties). Second, an object's geometry (e.g. shape and size) can be assessed. These properties can be detected at both the micro level which occurs at the fingertip, and the macro (larger than fingertip) level. Their studies on EPs concluded that strategies were more effective in identifying material properties than geometrical properties. Following initial contact with the object, a temporal discrepancy exists between availability of material and geometric information. Information on material properties is available for further haptic processing earlier than is geometric information. However, when vision is involved and favoured, geometric property identification is favoured over material perception (Klatzky et al. 1987) (Lederman et al. 1996).

Another factor that affects our ability to detect features of an object is the state of the finger and/or object: stationary or in movement. When there is no relative movement at the surface intersection, the sensory experience is degraded. Object properties are determined with less accuracy and longer reaction time. This is especially true for surface texture properties (Katz 1989) and large geometric differences (Lederman and Klatzky 1997). When given a choice, subjects will opt for haptic sensing over tactile sensing to acquire information on object properties.

People are extremely good at identifying objects that they are familiar with. They use information acquired using different EPs to identify attributes that converge to represent a specific object (Lederman and Klatzky 1987b). Recognition of two-dimensional raised outlined drawings of common objects has also been studied. Loomis et al (1991) suggested that such tasks put high demands on spatiotemporal integration and memory processes. This explains people's poor performance on such recognition tasks compared to performance when real three-dimensional common objects are explored (Magee and Kennedy 1980; Lederman et al. 1990). The detection of fingertip-sized two-dimensional raised patterns relies solely on cutaneous afferents. This is a sensory function that is very important for Braille reading for example. A debate exists about whether pattern recognition depends only on SA I mechanoreceptors with their small receptive fields, or if RA I afferents also play a significant role in discrimination (Johnson and Phillips 1981) (Phillips et al. 1990). Loomis's studies (1981a; 1981b; 1982) confirmed that tactile pattern recognition is spatially limited by the spacing limitation of the cutaneous system, as determined by the SA I mechanoreceptor receptive fields and spacing. A two-staged model was proposed for pattern recognition. "In stage 1, an internal representation of the tactile stimulus is formed and processed through a linear, low-pass spatial filter, followed by nonlinear compression of stimulus intensity. In stage 2, the internal representation of the tactile stimulus (a character) is matched to each stored representation contained in a character set" (Jones and Lederman 2006).

A study by Craig (1980) examined single-letter recognition performance. This work indicated that performance was affected by a number of factors such as display time, mode of pattern generation (static versus scanned), and the temporal relationship between the presentation of the target pattern and a masking stimulus. Pattern recognition performance

was good for patterns presented statically for as short as 4 s. For presentations below 200 ms, the static presentation mode produced consistently superior results than did the scanned mode. Performance reached quasi-maximal results at 50 ms in the static mode and at 400 ms in the scanning mode. These results may be partially explained by Gibson's findings (1962). He noted that when an external stimulus contacts the stationary hand, subjects tend to focus their attention on their internal sensations, which originate from local peripheral mechanoreceptors and thermal receptors before attaining higher levels. In contrast, when subjects use haptic exploration as a mean to acquire information about the object, their attention appears to be directed towards the external object and its properties. In Craig's 1980 study, it was also found that when intensity of the signal was increased by increasing the normal force applied over the pattern, performance was enhanced in the static condition while it remained unaffected in the scanned mode.

When trying to identify single raised letters, curvature is an important feature which allows discrimination between rectilinear and curvilinear letters. "Curvature is the rate of change in the angle of the line tangent to a curve as the tangent point moves along the curve" (Jones and Lederman 2006). Goodwin & Wheat (1992) confirmed that tactile sensing with the finger could allow for discrimination of a decrease of 13% in the radius of a spherically curved segment (standard of 3.5 mm). Pont et al (1998) added to this by confirming that curvature discrimination was best when the object was presented statically along the finger rather than perpendicular to it. In addition, it was shown that SA I and FA I mechanoreceptors were responsible for the coding of geometric parameters. More specifically, the spatial discharge patterns of SA I mechanoreceptors was the best indicator of object geometry (LaMotte and Srinivasan 1987b; LaMotte and Srinivasan 1987a;

Srinivasan and LaMotte 1987). Lechelt (1988) and Appelle (1972) demonstrated that for both tactile sensing and haptic sensing tasks, humans are more efficient in identifying lines that are either horizontal or vertical, rather than oblique. This is known as the “oblique effect” and may also affect performance in discriminating between rectilinear letters of the alphabet.

Another important consideration relative to recognition of tactile patterns is the direction of the skin stimulation with respect to the body and the external environment. Studies involving characters placed on different body parts revealed that pattern orientation perception differed from one area to another. Corcoran’s observations (1977) led him to state that pattern are perceived as if they were drawn on a transparent body via a “disembodied eye” located behind and slightly above the observer. A number of other studies involving haptic or active sensing have confirmed these results on perceptual pattern recognition (Oldfield and Phillips 1983; Loomis and Lederman 1986; Parsons and Shimojo 1987) suggesting the generalization of these concepts.

In a study by Smith, Gosselin & Houde (2002), participants were asked to explore a smooth plastic surface in search for either a raised or recessed tactile target. The authors noted that subjects preferred a side-to-side exploration strategy. This strategy may come more naturally as it requires less energy and resembles the common task of writing. While this strategy is in agreement with the EP proposed by Lederman and Klatzky (1987b), it contradicts the concept elaborated by Briznieks et al (2001). These researchers found that the majority of receptors are more sensitive along the long axis of the digit (proximal-distal direction) and prefer directions to tangential forces that are not uniformly distributed.

b. Laterality effects in the context of haptic sensing

Although born with two hands, most humans use one hand preferentially in unimanual task, such as haptic touch. For the majority of people, the dominant hand is the right hand. While some prefer the left hand, a second minority does not exhibit a hand preference. The dominant hand being more skilled, it performs better in tasks requiring fine motor control and dexterity. Despite handedness, no strong evidence exists to explain preferential patterns of use for one hand over the other. The factors responsible for the increased skill of the dominant hand remain unknown. This may in part be due to the fact that although one hand is dominant, humans use both hands combined for most tasks. In addition, fully left handed individuals are very rare. In fact, most left-handers will use the right hand preferentially for some tasks. Laterality is not a clearly defined variable, making it's effects difficult to assess.

The study of laterality effects has been a controversial subject for many years. In 1990, Summers & Lederman (1990) investigated the effect of dominance on dichhaptic matching of 3-D nonsense shapes (i.e., presenting two objects at the same time for haptic exploration by each hand). Their study found no significant effect of dominance on the performance. In their review of the literature on dominance effects, they established a critical review table of all the existing literature in the field of somatosensory asymmetry. When data drawn from studies with methodological biases and/or inadequate sampling were excluded, laterality effects became obvious and were in the predicted direction in favour the left hand being slightly more effective for haptic sensing in right-handed individuals. Therefore, they concluded that dichhaptic tasks were not effective in evaluating the effect of hemispheric dominance.

In 1997, Benoit-Dubrocard et al (1997) conducted another study involving the dichhaptic procedure. In this experiment, different levels of letter processing were studied: “shape recognition during a physical matching task, letter recognition in a verbal 'meaning' matching task and letter naming”. The purpose of their work was to investigate the effect of hemispheric dominance in such tasks and how information is processed from tactile exploration of letter shapes. The authors hypothesized that performance is influenced by the nature of the task and handedness. Results indicate that exploration strategies and response latencies were similar in right and left-handed subjects; however, left-handed individuals provided more accurate results on the verbal matching task. While the naming task did not discriminate between both groups, the physical matching task showed that right-handed individuals use different exploration strategies when compared to the left handed group.

Further studies on haptic processing continue to show inconsistent results with respect to laterality effects. Fagot et al (1993) tried to clarify the relation by studying the accuracy and the exploration strategies employed by subjects when sensing a tactile stimulus composed of “8” shapes whose junctions were not discernable. They recorded the number and duration of hand contacts with each cube. They found that accuracy measures were not affected by dominance or sex. However, when sensing with the left hand, subjects, especially male individuals, used a different exploration strategy when compared to the right hand. This asymmetry indicates that the study of exploration strategies is more sensitive to dominance effects than is the study of accuracy, in the context of haptic exploration. In 1994, Fagot et al. (1994) conducted a second study involving the same tactile stimulus. In this experiment, right-handed male subjects were asked to compare two simultaneously touched stimuli to determine whether they were the same or different. Results indicated that accuracy

was greater when the stimuli were touched with the same hand than when different hands were used for each exploration. When exploration strategies were investigated, it was noted that subjects spent more time sensing the superior and ipsilateral aspects of the stimuli with both hands. However, the times spent touching each cube was not as evenly distributed when exploring with the right hand when compared to the left hand. These findings indicate that the process of tactile information is affected by contextual, biomechanical and cognitive (hemispheric dominance) factors. This project will investigate the effect of hand and hemispheric dominance by studying whether corticospinal excitability is enhanced when tactile exploration is performed with the dominant, preferential hand or with one hand in particular for most participants which would suggest that such tasks are controlled by one hemisphere more than the other.

c. Task-dependant Modulation of Corticospinal Excitability

The function and modulation of the corticospinal tract has been a subject of interest for many years. The importance of the corticospinal tract is illustrated by the devastating effects of a stroke, a central lesion which causes severe deficits in the periphery. The first attempts to understand the mechanisms that underlie corticospinal excitability modulation date back to the 1950s. At this time, single-cell recording was developed to record activity in the primary motor cortex. Edward Evarts was one of the first to conduct electrophysiological recordings in awake behaving primates in the 1960s (1962; 1968b; 1968a). One of the first demonstrations of a task-dependent modulation of corticospinal output was obtained by Muir & Lemon (1983), who compared the activity of corticomotoneuronal (CM) cells in a precision pinch grip to that of a general power grip in trained monkeys. Their results showed

that a large proportion of CM cells in the MI cortex were activated only during fine precision grip, while the same cells were quiet during a power grip, in spite of the large increase in muscle activity. These results demonstrated that fine dexterity relies on the existence of neurons in the motor cortex which have strong direct excitatory connections (i.e., CM cells) with motoneurons controlling intrinsic hand muscles. These CM connections appear to be particularly critical for movement fractionation in tasks requiring discrete independent finger movements (Muir and Lemon 1983; Lemon 1999).

In 1985, the technique of transcranial magnetic stimulation (TMS) was introduced by Barker and al (1985) allowing safe electrophysiological explorations of the corticospinal system in humans. TMS is a non-invasive, pain-free procedure that involves a magnetic field generated by a coil and stimulator. When applied to the scalp, the magnetic field generates an electrical current that stimulates the pyramidal cells trans-synaptically (Rothwell et al. 1991). The action potentials are conducted along the pyramidal tracts and reach the motoneurons in the ventral horn to produce a brief muscular response known as a motor evoked potential (MEP). MEP's characteristics in terms of amplitude and latency provide information on the corticospinal excitability (see Figure 1). This method has contributed significantly to our understanding of how the corticospinal excitability is modulated by peripheral and central factors in humans.

Like single-unit experiments in trained monkeys, several studies have shown task-dependent variations in corticospinal excitability. A recent study by Bonnard et al. (2007) investigated the effect of precision force control on the modulation of the corticospinal system. The task required subjects to maintain an isometric thumb-index pinch grip. While the average force level was similar in all task conditions, the precision demands were

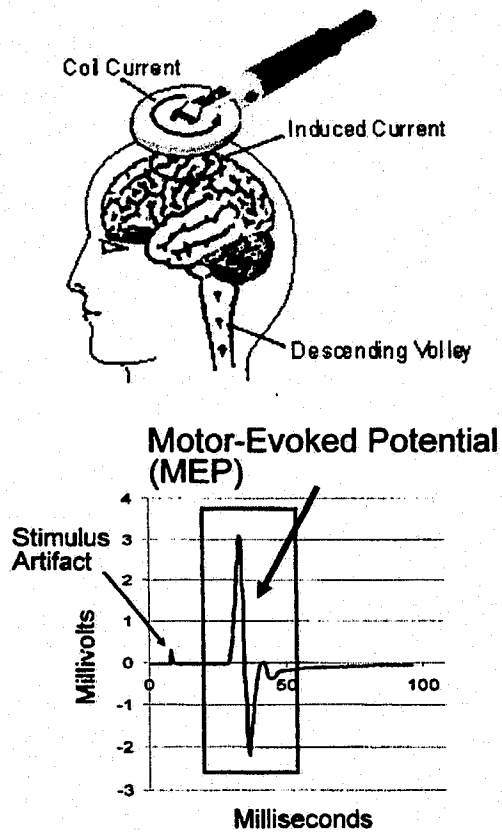


Figure 1. Exploration of brain excitability with transcranial magnetic stimulation. MEP's elicited through TMS of the motor cortex allows for the study of corticospinal excitability in humans. The amplitude and latency of the MEP are influenced by of local intra-cortical changes in excitability at the motor cortex level as well as by the level of spinal motoneuronal excitability

modified by varying the cursor size on the computer screen used to track force production. Results indicated that when precision demands increase, the corticospinal excitability was enhanced to either the index or thumb, but never to both muscles at once.

A functional magnetic resonance imaging (fMRI) study by Milner et al (2007) investigated the neural mechanisms involved in simple and complex manipulation tasks. The simple task consisted of squeezing a soft foam ball, while the complex manipulation task involved balancing a weighted flexible ruler in an unstable equilibrium position, always using only the right hand. Data were compared to resting values to measure the effects of both task conditions. The authors hypothesized that activity in the primary motor cortex would be similar in both conditions since muscle activation was matched. In addition, they postulated that the cerebellum would be selectively activated during the ruler balancing task as this requires fine adjustments based on an internal dynamics model. Both of these hypotheses were confirmed. Interestingly, they also found selective activation of the secondary somatosensory cortex and the insula in the complex manipulation task. These areas are thought to integrate tactile and proprioceptive information to provide appropriate feedback to the motor cortex.

Duque et al. (2005) evaluated the effect of digital anesthesia of the thumb and index fingertips on the control of a maximal pinch force. The amplitude and latency of MEP's in the first dorsal interosseus was recorded to investigate the effects of cutaneous information on force production control. Results showed that corticospinal excitability was similar before, during and after digital anesthesia. However, maximal pinch force was reduced by 29% following anesthesia. These results diverged from findings of a number of studies that found that local anesthesia significantly decreased corticospinal excitability (Rossi et al.

1998). In Duque et al's experiment, digital anesthesia was restrained to a very limited skin surface at the thumb and index fingertips. Therefore, it is suggested that proprioceptive input from the muscles and joints compensate for the lost of cutaneous information and ensure proper corticospinal modulation. The significant decreased in maximal pinch force supports the theory that cutaneous afferents play a critical role in the control of pinch force.

In a recent neuroimaging study, Carey et al. (2006a) investigated the level of activity in the primary motor cortex produced with respect to differences in task demands. Using fMRI, cortical activation was measured under three different conditions: 1) Rest, 2) Track (accurate control of a cursor with flexion / extension finger movements and 3) Move (uncontrolled simple flexion / extension finger movements) Results showed a significant increase in the activity of the motor cortex in the more demanding track condition when compared to the move conditions. These findings confirm the involvement of the motor cortex in not only the production of movement, but also in its spatial and temporal processing.

In conclusion, there is now strong evidence that the output of the motor cortex is modulated by task demands in terms of precision and complexity when performing hand actions; more demanding tasks being associated with greater motor activation and increased descending facilitation to task-relevant muscles. However, as stressed earlier, the evidence so far has relied on observations focusing on the motor aspect of hand function, neglecting its important sensory role. The primary goal of the present work was to address this issue.

d. Objective of the present work

The primary objective this descriptive study was to determine how corticospinal excitability in intrinsic hand muscles (FDI) was modulated when the finger is engaged in

sensory exploration movements. To this end, we compared variations in MEP amplitude under various finger task conditions which differed in terms of behavioural demands. Our working hypothesis was that the attention-demanding tactile exploration task would lead to greater corticospinal facilitation in the FDI as compared to less demanding motor tasks.

A secondary objective was to determine whether asymmetries in corticospinal facilitation could be detected depending upon whether the right or the left hand is engaged in tactile exploration. The hypothesis was that the increased attentional demands associated with left-hand engagement in the task (in right-handers) would lead to greater corticospinal facilitation.

The methods used and the results of the study are presented in the next section in the form of a scientific paper. This form of presentation was preferred by the author and her supervisor over the more traditional thesis approach. The next section described the main findings of the project. An abridged version of the paper was presented at the XVIIth biannual ISEK conference in June of this year and is also included in the thesis as an appendix.

CHAPTER II

RESEARCH PAPER

**SELECTIVE INCREASE IN CORTICOSPINAL EXCITABILITY
IN THE CONTEXT OF TACTILE EXPLORATION**

(paper submitted to Brain Research, August 2008)

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Running Title: Corticospinal excitability during tactile exploration

Key words: motor tasks, tactile discrimination, transcranial magnetic stimulation, motor cortex

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Abstract

In the present study, we compared changes in corticospinal excitability elicited under various task conditions engaging the index finger of each hand. The tasks varied in terms of functional demands from simple motor contraction to more demanding sensory exploration. In the first set of conditions, we contrasted facilitation elicited in the first dorsal interosseus (FDI) by monitoring changes in motor evoked potentials (MEP) amplitude and latency when participants ($n=18$) performed a simple button pressing (BP) action as opposed to a more demanding tactile exploration (TE) task (i.e., discrimination of small raised letters). The result showed that the TE task elicited significantly larger MEP facilitation in the FDI (~40% increase in amplitude) than the simple BP action, irrespective of the hand tested. The two tasks, however, also differed in terms of background electromyographic (EMG) activity, which could have accounted for some of the differences observed in MEP facilitation. A subset of participants (10/18) was therefore tested in a third finger movement (FM) task, where participants simply move the tip of the index finger over a smooth surface. The latter task produced a pattern of EMG activity similar to that produced for the TE task. Comparison of MEP amplitude between the FM and TE tasks in the subset of participants confirmed the presence of an extra facilitation in the FDI of equal magnitude in the two hands (~30% increase for TE compared to FM task). These results, altogether, provide further insights as to the effect of task conditions on corticospinal excitability in hand muscles. Our findings stress in particular the importance of task demands in terms of precision and attention, such as when the finger is moved to acquire sensory information, in modulating corticospinal excitability.

INTRODUCTION

Voluntary contraction is known to lead to facilitation of motor responses evoked from transcranial magnetic stimulation (TMS) of the motor cortex ((Hess et al. 1987; Mills and Kimiskidis 1996)). In contracting muscles, this facilitation is seen as an increase in the size of the motor evoked potential (MEPs) along with a decrease in onset latency (Mills and Kimiskidis 1996). The origin of this facilitation has been shown to vary depending on the level of effort and the intensity of the contraction. At low levels, the facilitation has been linked primarily with an increase in number and size of descending volleys elicited in the pyramidal track, with further contribution of spinal mechanisms (i.e., raise of motoneuronal excitability) as the level of contraction and effort increases (Di Lazzaro et al. 1999; Abbruzzese and Trompetto 2002). Further investigations on the origin of MEP facilitation showed that, beyond the level of contraction, the nature of the task itself was a major factor in influencing the level of facilitation. These investigations were initiated after experiments with monkeys showed that the activity of pyramidal tract neurons was influenced by task conditions, with stronger modulation being observed for tasks involving fine independent finger movements as compared to power grasping actions; despite the greater EMG activity recorded in the latter task (Buys et al. 1986). Consistent with these observations, MEP facilitation elicited in small hand muscles was shown to be greater for fine precision than for power grip tasks. (Datta et al. 1989; Flament et al. 1993; Huesler et al. 1998; Bonnard et al. 2007). More recent TMS and neuroimaging studies in humans have confirmed that the level of precision was indeed a critical factor in modulating activity in the corticospinal system. For instance, (Bonnard et al. 2007) showed that when the precision demands increased for

the thumb-index grip force, corticospinal excitability also increased selectively in either the 1st dorsal interossei (FDI) or the abductor pollicis brevis (APB), but not in both. Modulation in the activity of the corticospinal network involved in the control of hand actions is also influenced by the functional demands of the task, with greater facilitation being seen for more complex tasks. Sale and Semmler (2005), for example, reported a selective increase in MEP facilitation in the FDI during a tool-oriented scissoring action as compared to a power grip. Thus, both the degree of precision and complexity involved in the task appear to be determinant factors in modulating corticospinal output during hand actions.

In the present study, we were interested in looking at task-dependant facilitation in the context of a class of actions that has been largely neglected in the TMS literature, i.e. when the finger is used as a sensory probe to detect tactile features. Tactile exploration involves bringing the fingers in contact with surfaces or objects to acquire information about their material or spatial properties. Such tasks can be particularly demanding such as when the finger is used to recognize raised patterns (e.g. Braille) by contour exploration (Lederman and Klatzky 1997). Thus, tactile exploration tasks represent the archetypical example of a functionally demanding precision task. Yet, most TMS studies on MEP facilitation have ignored this important aspect of hand function, turning their attention to grasping actions. In this report, we described our observations as to the effect of different task conditions on MEP's elicited in small muscles in the context of isolated index finger movements. Our primary goal was to determine whether tactile exploration would lead to greater enhancement in corticospinal excitability as compared to simpler motor tasks. A secondary goal was to look for a possible asymmetry between the two hands in terms of MEP

facilitation elicited by task conditions. Part of this work has been presented in abstract form
(Oliver and Tremblay, 2007)

Methods

Participants

Eighteen young adults (9 males and 9 females; mean age \pm SD, 24.1 \pm 2.1 years; 15 right-handed) volunteered to participate in this study. All subjects provided informed consent prior to participation in this study. Procedures were approved by the local Institutional Ethics Boards at the University of Ottawa and the Elisabeth Bruyere Research Institute. Prior to testing, participants were asked to fill out a health questionnaire to determine their healthy status and to rule out any contra-indications to TMS. In addition, a sensory screening evaluation with the "Rydel-Seiffer" tuning fork was performed to rule out possible sensory abnormalities (Pestronk et al. 2004). All exhibited vibration extinction thresholds within the range of norms reported for young adults (i.e. threshold $>$ 6.5 /8, (Martina et al. 1998). Hand dominance was determined with the Edinburgh Handedness Questionnaire (Oldfield 1971).

Electromyographic recording and TMS

Electromyographic (EMG) activity was recorded using small auto-adhesive surface electrodes (10-mm diameter, Ag-AgCl) placed over the FDI of each hand. EMG signals were amplified (200 μ V/div) and filtered (bandwidth, 10 Hz to 1 kHz) with a polygraph amplifier (RMP-6004, Nihon-Kohden Corp.). Signals were digitized at 1 kHz sampling rate using custom software on a PC running under Microsoft WindowsXP™ equipped with a digital/analogue acquisition card (BNC-2090, National Instrument Corp.). Each recording consisted of 5 s epoch.

TMS was administered with participants comfortably seated in a recording chair. Magnetic stimulation was delivered with a Magstim 200 (Magstim Co. Dyfed, UK) connected to a figure-eight coil (70 mm loop diameter). To determine the optimal site to evoke MEPs in the contralateral hand muscles, participants were fitted with a Lycra swimming cap with marking grids traced onto it. A U-shape neck cushion was used to restrain head movements. With the coil held $\sim 45^\circ$ in the mid-sagittal plane, the approximate location of the hand motor area on each hemisphere was explored in 1-cm step until reliable MEPs could be evoked in the target muscles (FDI). This site was then marked with a red dot to ensure consistent coil positioning. During the experiment, the coil was held in place manually by one of the experimenters. Following this procedure, the relaxed motor threshold was determined using the method advocated by Mills and Nithi (1997). Starting from supra-threshold intensity, the stimulator's output was gradually decreased in 1% steps until no MEP could be evoked for 10 consecutive stimuli. This TMS intensity corresponded to the lower threshold value. From this point, the intensity was gradually increased until MEPs of a least 50 μV peak-to-peak amplitude could be evoked in 10 consecutive stimuli. The latter intensity determined the upper threshold value. The relaxed motor threshold was defined for each participant as the median intensity between the upper and lower threshold values. The TMS intensity was then fixed at 1.1 X threshold for the remainder of the experiment.

Task description: tactile exploration and button pressure

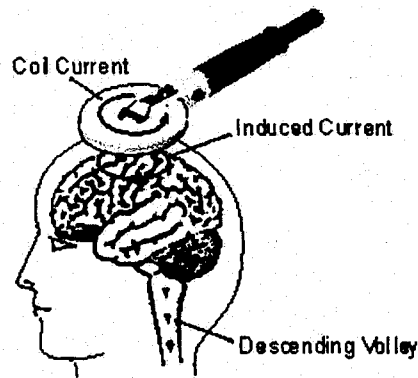
Participants were initially tested with two tasks: a tactile exploration (TE) task and a motor task (i.e., button pressure (BP)). A subset of participants (10/18) was also tested subsequently with a third task (see below). The TE task required them to recognize six

different raised letters (A, G, S, D, X, F) with their index finger. Letters were presented individually in the familiar orientation, as if the participant were to read them. Each individual fingertip size letter (Upper case, 1-mm relief, 6-mm height) was made from flexible nylon material and mounted on top of a small wooden block (2.5 cm³; see Figure 1). Prior to testing, subjects were familiarized with the six letters. The TE task required subjects to scan the presented letter and report its identity within a 5 s trial. In order to ensure participant's attention was focused on the task at hand, they were told that performance would be measured by calculating the number of errors made. In this study, attention is defined as a process during which psychological resources are allocated to specific features of the environment, or to specific modalities (i.e. vision, space, sensation) to enhance information processing. Therefore, information is filtered to focus on selective input, in this case being spatially located at the fingertip, are largely dependant on cutaneous information from this area.

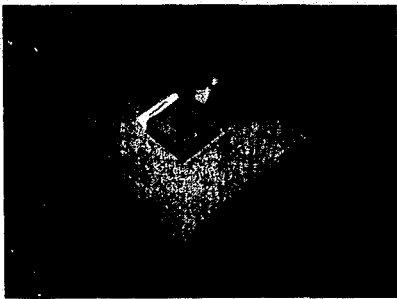
The motor task (BP) consisted of depressing a spring-resisted button with the tip of the index finger using the minimal force required (i.e., ~1-2 N). The button, like the raised letters, was mounted on top of a small wooden block (2.5 cm³). During testing, the block itself was inserted into a cavity cut into a larger piece of high density Styrofoam, which formed a rectangular base (5-cm x 4-cm, 0.7-cm thick) to ensure proper stabilization. Both the block and its stabilizer were affixed on top of a tactile force plate designed to measure contact force (Tremblay et al. 2005). The tactile plate itself was mounted in front of the recording chair at the level of the armrest to allow finger contact. The tactile plate consisted of an aluminium box (10 cm) instrumented with high resolution (sensitivity range 0.01-5 N)

force transducers. The force signals generated in the normal direction (F_z) were recorded along with EMG signal @ 1 kHz sampling rate and stored for later analysis.

Twenty-four trials were completed with each hand (i.e. 2 trials/letter and 12 button pressure), the two task conditions (TE and BP) being presented in a random order within a block of 24 trials. During each trial, a TMS pulse (1.1 X threshold) was delivered at mid-duration (i.e, 2.5 s interval) in the course of the trial. Prior to each trial, participants were informed about the nature of the task to be presented (either TE or BP). An auditory signal (300 Hz tone) lasting 5 s was used to indicate the beginning and end of the trial. Subjects were blindfolded throughout the experiment. Once the 24 trials were completed on one side, the opposite hand was tested by moving the tactile plate on the other side and stimulating the contralateral hemisphere. The same procedure was then repeated on the other hand. The order of testing between the two hands was counterbalanced across participants. A schematic of the experimental paradigm used is shown in Figure 1.



Tactile Exploration (TE)



Motor Task: Button Pressure (BP)

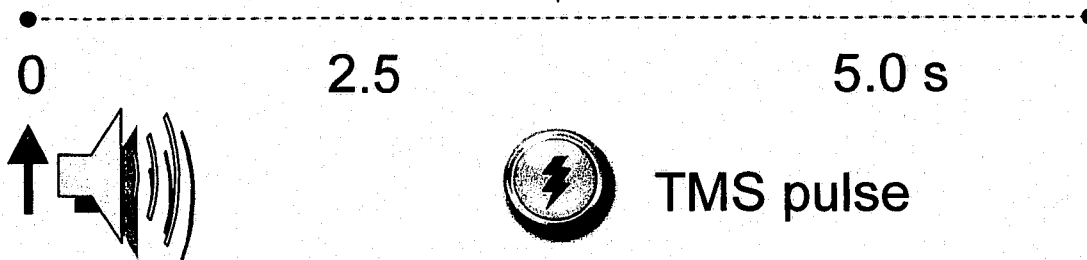
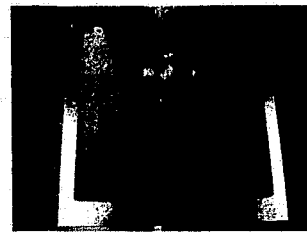


Figure 1. Schematic illustration of the experimental paradigm used. For the TE task participants scanned each raised letter (upper case, A, G, S, D, X, F; 6 mm in height) with the tip of their index finger, whereas for the motor task (BP), they depressed a button for the (contact force ~ 2 N) for duration of the trial. Each trial lasted 5 s. TMS pulses were delivered at mid-duration (2.5 s). Twelve trials were performed for each task condition (TE and BP), the two tasks being presented in a random order within a block of 24 trials.

Finger movement task

As stated above, a subset of 10 participants was tested under a third condition: finger movement (FM) task. The latter task was added subsequently in order to compare MEP facilitation elicited under the TE condition with movements with similar kinematics but without the sensory discrimination component. For the FM task, participants were simply asked to move the tip of the index finger to reproduce the scanning movement used to identify the raised letter patterns previously, but this time the surface (made of the same flexible nylon as the letters) was entirely smooth. The experimental procedure was identical to that described above for presentation of the TE and BP tasks. Twelve trials were performed with each hand.

Analysis of MEP data and background EMG

Variations in MEP amplitude (peak-to-peak) and latency in the task conditions were measured off-line and averaged for both the right and the left FDI in each participant to derive mean individual values. EMG traces were also analysed off-line to measure background EMG produced in each muscle under each task condition. For this analysis, the EMG activity recorded in the 1000 ms time window preceding the TMS pulse was rectified and averaged to get average EMG values.

Data analysis and statistics

Two-factors repeated-measure analyses of variance (ANOVAs) were conducted on each set of variations measured in MEP amplitude, MEP latency and background EMG

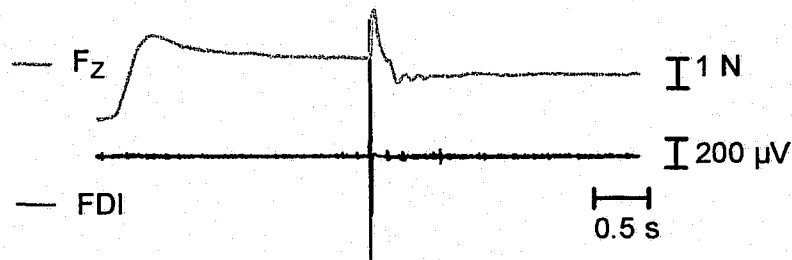
activity to determine the impact of “task conditions” (TE vs. BP; TE vs. FM) and “Hand”(Right vs. Left) and look for possible interactions. The level of significance was set at $p < 0.05$ for all tests. Additional analyses were performed as described in the Result section.

RESULTS

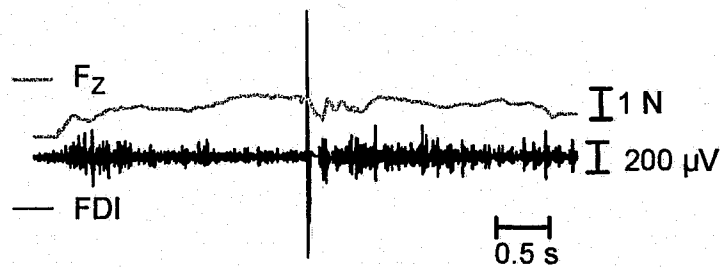
Task Performance: TE vs. BP

Mean relaxed motor thresholds determined on the right and left hemispheres were comparable (40 ± 7 and 42 ± 5 %, respectively, maximum stimulator output). Therefore, the stimulation intensity used to assess corticospinal excitability was similar for both hemispheres (mean right, 44 ± 8 %; left, 47 ± 6 %). Participants had no difficulty in performing the TE task with letter recognition success rate > 90 % correct. Participants typically used small flexion/extension at the mid-interphalangeal joint to explore contour of the letter and deployed on average ~ 1 N of force in the normal direction on each hand (right, 1.2 ± 0.5 N; left 1.1 ± 0.8 N). As shown in Figure 2, this performance was associated with a phasic modulation of EMG activity in the FDI. In contrast, the BP task was associated with a steady low-level tonic EMG activity in the FDI. The force deployed to depress the button averaged ~ 2 N (right, 2.1 ± 0.4 N; left, 2.1 ± 0.6 N). In general, the dynamic modulation of EMG activity during the TE task was associated with higher levels of background EMG level than in the BP task in both the right (15.6 vs. 6.0 $\mu\text{V}\cdot\text{s}$, $p < 0.01$) and the left hand (16.5 vs. 7.4 μV). This difference in background EMG between the two tasks was confirmed by ANOVA ($F_{1,17} = 23.3$, $p < 0.001$), as well as the absence of difference between the two hands ($F_{1,17} = 0.42$, $p = 0.52$).

Button Pressure (right index finger)



Tactile Exploration (right index finger)



subject EB16Y

Figure 2. Example of background EMG activity elicited in the right FDI during performance of the two tasks along with the contact force produced in the normal direction (F_z). Note the difference in the level of EMG activity between the two tasks and in the facilitation level in the MEP elicited at mid-duration. Each trace represents an average of 12 trials.

Task-dependant facilitation of MEP's: TE vs. BP

Figure 3 shows typical examples of task-dependant variations in MEP amplitude observed under the TE and BP conditions for the two hands. It can be seen that in both participants MEP elicited under the TE task were larger than those evoked during the BP task. In fact, MEP's were on average 40% larger for the TE task, irrespective of the hand tested. The average variations measured in MEP amplitude and latency between the two tasks is shown for each hand in Figure 4. The ANOVA confirmed the large effect of task conditions on MEP amplitude ($F_{1,17}=31.4$, $p<0.001$). The main effect of "Hand", however, was non significant ($F_{1,17}=0.9$, $p=0.36$) and no "Task X Hand" interaction was found ($F_{1,17}=2.2$, $p=0.15$); indicating that MEP's in the two hands were similarly affected by the task conditions. Variations in MEP latency were not affected either by task conditions or by "Hand" ($F_{1,17}=1.4$, $p=0.25$).

To further determine the influence of task conditions on MEP amplitude facilitation, MEP's recorded in each hands under each task condition were entered into an ANOVA with the corresponding variations in background EMG as co-variates. The results showed that the level of background EMG activity had no effect ($F_{1,15} < 2.0$, $p > 0.30$) on task-dependant variations in MEP amplitude in the FDI. This lack of association is illustrated in Figure 5 showing the relationship between the two variables for each hand during the TE task. Thus, the level of task-related facilitation was not influenced by the level of background EMG produced in the FDI during task performance.

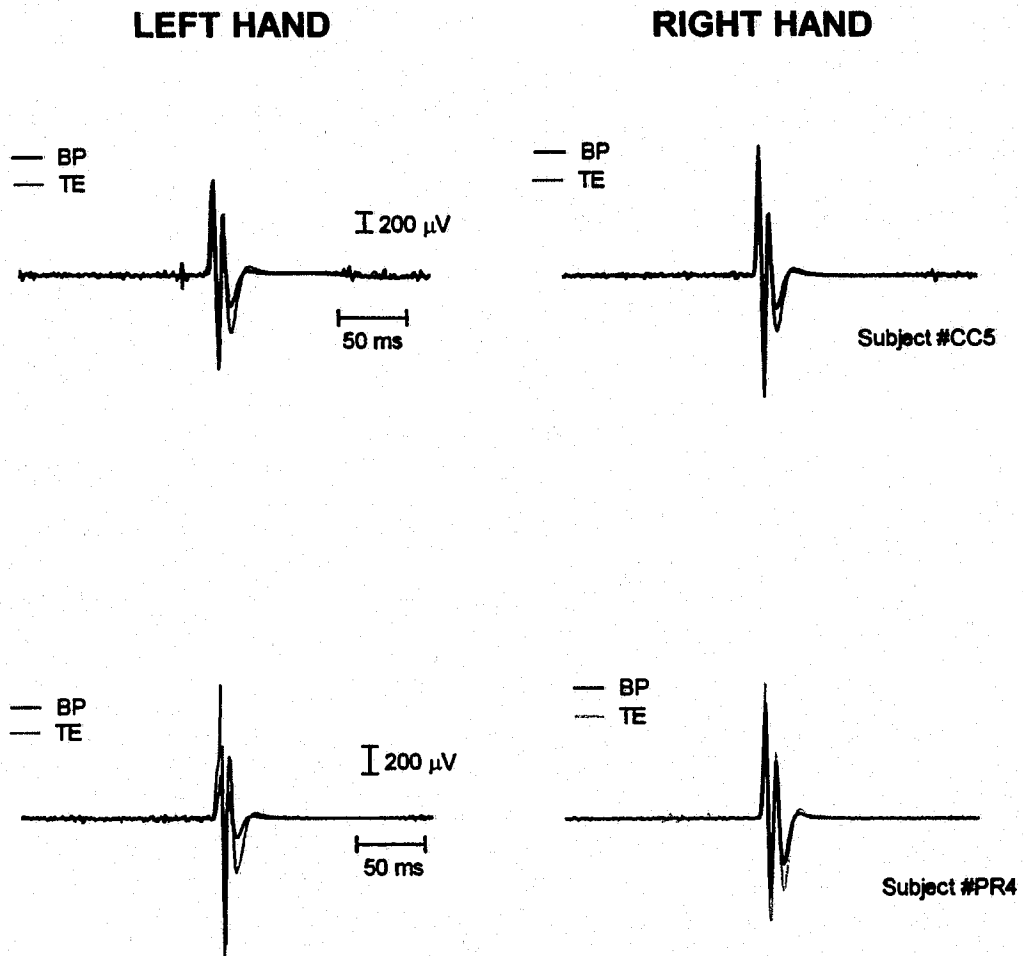


Figure 3. Typical examples of task-dependant MEP facilitation recorded in the FDI of the two hands under each task condition (TE: Tactile exploration; BP: button pressure). Note the enhanced amplitude facilitation elicited during the TE task. Each trace represents an average of 12 trials.

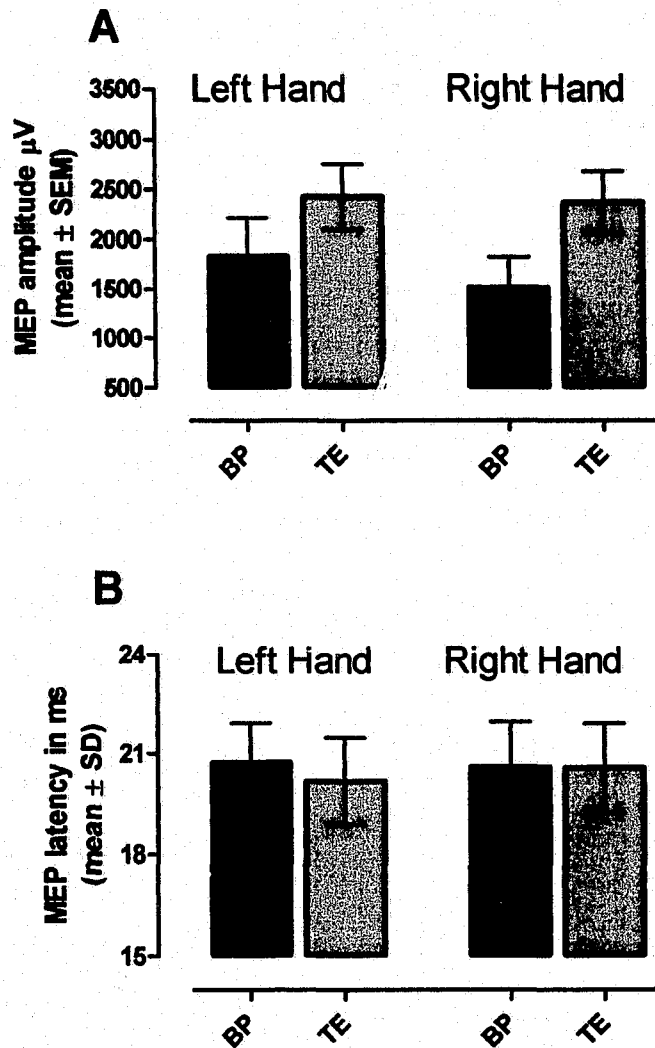


Figure 4. Mean task-dependant variations measured in MEP amplitude (A) and latency (B) in each hand under the TE and BP task condition. Each column represents an average of the mean individual values computed in each condition from all subjects (n=18). Note that the task effect was highly significant ($p < 0.001$) for the difference in MEP amplitude between the TE and BP conditions, whereas no “HAND” effect was detected. Variations in onset latency were not influenced by task conditions.

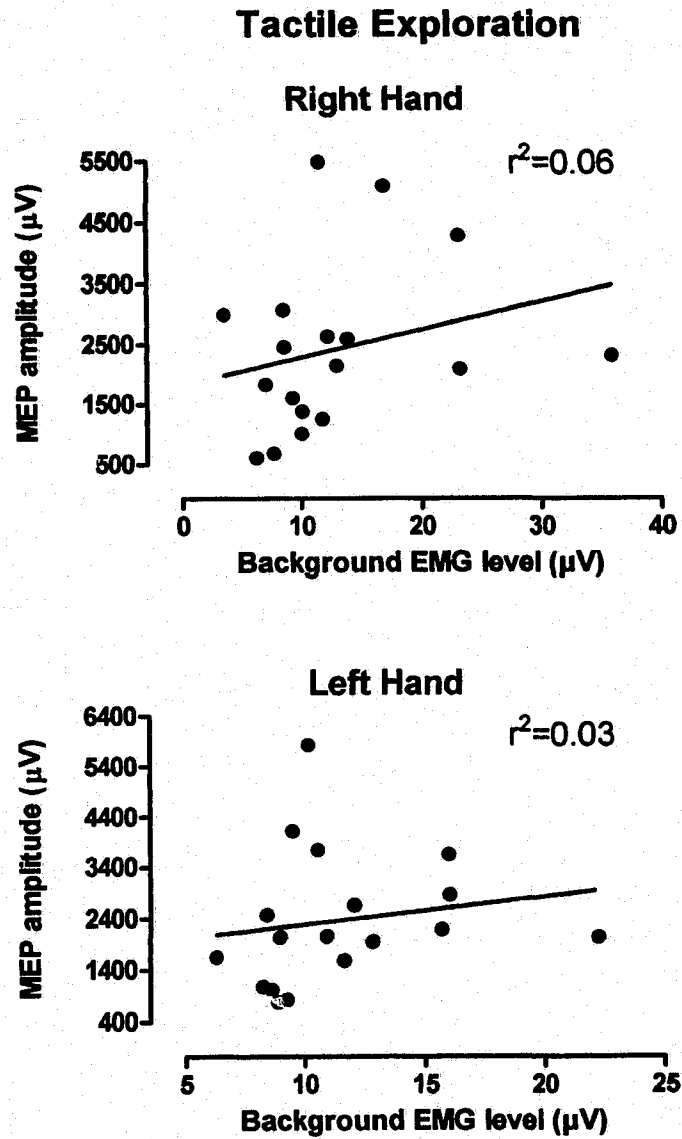


Figure 5. Relationship between MEP amplitude measured in each participant's hand (n=18) and corresponding levels of background EMG activity produced in the FDI during the performance of the TE task . Note that the level of MEP facilitation was largely independent of the level of background EMG, as evident in the low r^2 values ($p>0.2$)

Task-dependant facilitation of MEP's: TE vs. FM

In the subset of 10 participants tested with the FM task, the pattern of EMG activity elicited in the FDI was very similar to that seen in the TE condition. An example of such a pattern is shown in Figure 6. It can be seen that the pattern of phasic modulation in EMG activity when moving the finger reproduced the pattern elicited during exploration of the letters. In fact, the level of background EMG in the two tasks was very comparable for the two hands (mean left and right combined, TE, 14.2 μ V; FM, 18.2 μ V), which was confirmed by the ANOVA, where the effect of both "Task" and "Hand" was found to be non significant ($F_{1,9} < 0.61$, $p > 0.45$). When modulation in MEP amplitude was compared between the TE and FM tasks, however, a significant effect of task conditions was detected ($F_{1,9} = 8.9$, $p = 0.02$), owing to the increase in MEP facilitation (~30% on average) associated with performance of the TE tasks. This effect is illustrated in Figure 7 A. No effect or interaction was detected for the factor "Hand" ($F_{1,9} < 0.4$, $p > 0.55$). Finally, as for the previous comparisons, variations in latency were not affected by the factors (Figure 7 B).

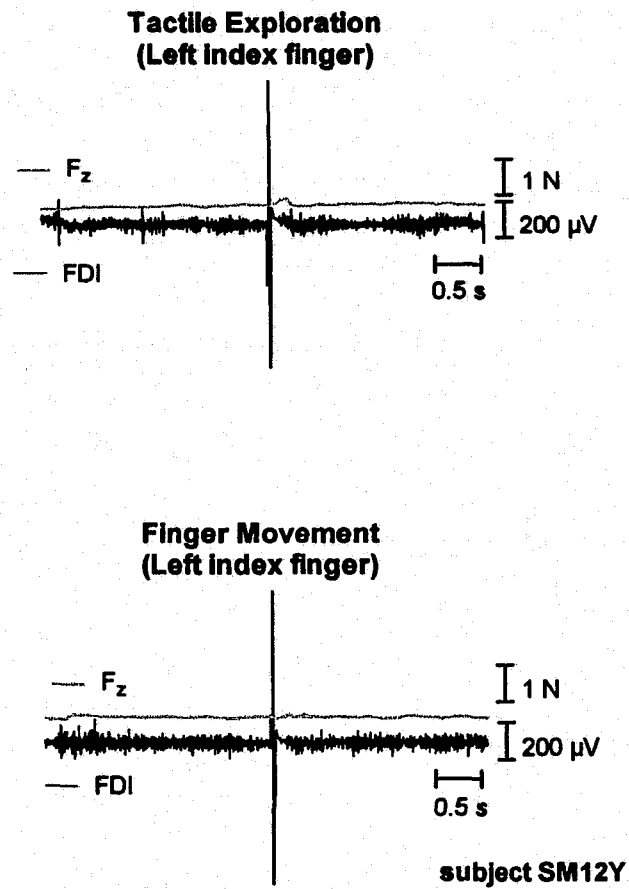


Figure 6. Example of background EMG activity recorded in the left FDI during performance of the TE and FM tasks along with the contact force profile in the normal direction. Note similarity in the pattern and in the level of EMG activity between the two tasks. Each trace represents an average of 12 trials.

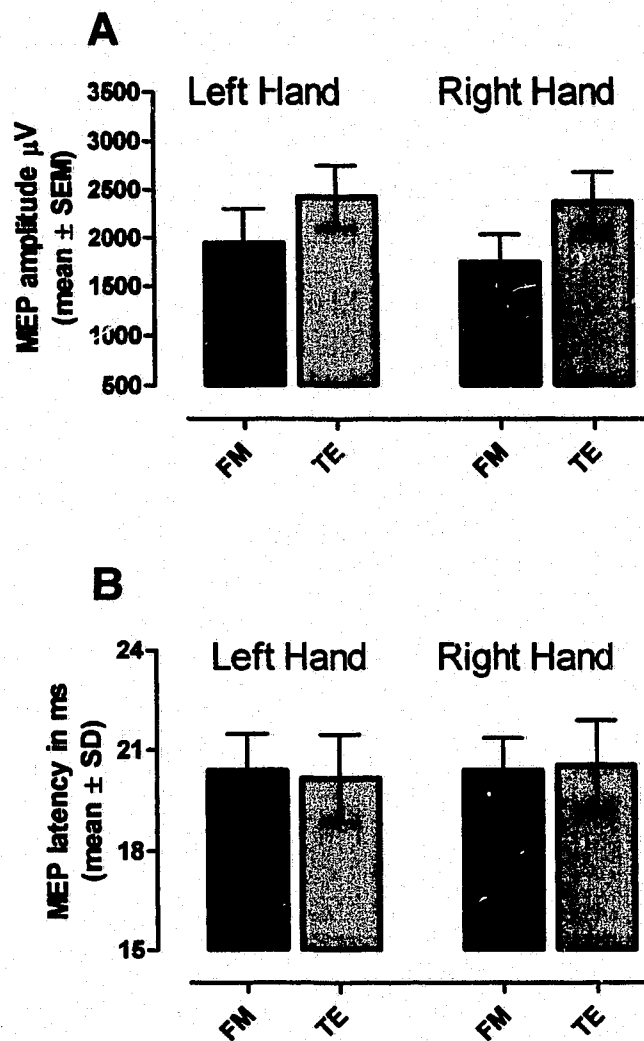


Figure 7. Mean task-dependant variations measured in MEP amplitude (A) and latency (B) in each hand under the TE and FM task condition. Each column represents an average of the mean individual values computed in each condition from the subgroup of participants tested (n=10). Note that the task effect was significant ($p=0.02$) for the difference in MEP amplitude between the FM and TE conditions, whereas no “HAND” effect was detected. Variations in onset latency were not influenced by task conditions

DISCUSSION

In the present study, we contrasted changes in corticospinal excitability elicited in hand muscles under various task conditions engaging the index finger of each hand. We were interested in testing in particular whether engaging the finger in a functionally demanding tactile sensing task would lead to greater enhancement in excitability as compared to tasks relying on simple motor actions. In this regard, our results showed that engaging the finger in tactile sensing to recognize raised patterns elicited greater MEP enhancement than corresponding tasks engaging the finger in simple actions but without a sensing component. Our results also showed that this facilitation elicited in the FDI during tactile sensing was similar in amplitude in the two hands.

Task conditions and MEP facilitation

Our first comparison involved two task conditions, which both required minimal force production and precision in execution but also differed on two critical aspects. First, the BP task involved a steady modulation of EMG activity to maintain the desired level of force, whereas the TE task required a dynamic modulation as the finger explored the letter. Second, the TE task was more demanding adding an extra attentional load owing to its discriminative nature; i.e. participants had to attend to cutaneous information arising from contact with the touched pattern. Thus, the two tasks presented different constraints both in terms of control strategy and in terms of functional demands.

With regard to control strategies, the steady modulation of EMG activity in the FDI during the BP task was associated with significantly lower background levels as compared to the TE task. This difference in background EMG might have influenced the level of MEP

facilitation in the two tasks, irrespective of the task requirements in terms of attention. In fact, in intrinsic hand muscle even small differences in background EMG can lead to large changes in MEP amplitude when contracting at low-level of effort (i.e., <20% MVC), as shown by Wu et al (2002). The same authors also showed that, at such low-levels, MEP latencies were not affected by increase in effort and this may explain why variations in latency were not affected by task conditions. Given the reported effect of low-level contractions on MEP amplitude, one would have expected a simple direct relationship between the size of MEP's and individual levels of background EMG produced during the TE task, but this was not the case. In fact, this variable had no effect on variations measured in MEP amplitude during the TE task (see Figure 5). Thus, the influence of control strategy might have arisen not from a difference in the level of background EMG but from a difference in the type of contraction; i.e. static vs. dynamic. In a recent study, Ni et al (2006) compared MEP amplitude facilitation in the FDI under static and dynamic conditions during a force precision task, controlling for the level of EMG activity. Their results showed that, for the same level of background EMG activity, MEP amplitude was consistently higher in the dynamic condition than in the static condition. Thus, part of the difference observed between the TE and BP tasks in terms of MEP facilitation was likely a reflection of the different mode of contraction used in the two tasks; the dynamic nature of the exploration tasks leading to a greater MEP facilitation.

As for the role of attention, the comparison with the FM task in the subgroup of participants allowed for a clearer interpretation of this factor's contribution. Indeed, when performing the FM task, participants actively reproduced the pattern of EMG activity that was seen with the TE task; without the discrimination component. Yet, the comparison

between the FM and TE tasks revealed the presence of an extra facilitation in the FDI, pointing to the importance of the attentional component linked with letter discrimination. Participant's attention towards this task was highlighted by their great performance with the number of correct letter identities reported being greater than 90% on average. In this regard, our results are entirely consistent with recent TMS studies (Rosenkranz and Rothwell 2004; Stefan et al. 2004; Conte et al. 2007) showing that the effect of tactile inputs on the motor cortex is strongly modulated by top-down mechanisms associated with attentional demands. For instance, Rosenkranz and Rothwell (2004) showed that TMS responses in small hand muscles varied depending on whether participants attended to vibration such that TMS responses elicited in both the non stimulated and stimulated muscles were enhanced when attention was directed towards the vibrated hand. This effect of spatial attention was associated with reduction in short-interval intra-cortical inhibition (SICI). Very recently, Thompson et al (2008) confirmed that SICI could be reduced when spatial attention is directed toward the hand being stimulated as compared to when the attention is directed towards the non stimulated hand.

To summarize, the effect of task conditions on MEP amplitude reflected, in part, differences in control strategy when the BP task and TE task were contrasted, whereas the comparison with the FM task highlighted the importance of tasks demands in terms of attention in leading to extra facilitation.

Hand effect

In the present study, no difference was found between the two hands in terms of task-dependant MEP facilitation. The issue of hemispheric asymmetries in corticospinal

excitability remains a controversial topic in the TMS literature generating conflicting results. When present, asymmetries were generally revealed in the active state during simple execution and pointed to a difference in favor of a greater excitability of the non-dominant (i.e., right), as compared to, the dominant hemisphere, especially in right-handers (Semmler and Nordstrom 1998; Tinazzi and Zanette 1998). Our group of participants were right-handed for the majority (15/18) and, thus, it is unlikely that the presence of the few left-handers could have masked potential asymmetries between hands. In fact, our observations on the absence of asymmetry are entirely consistent with the recent results of Sale and Semmler (2005) who also found no differences between hands in terms of MEP facilitation in the FDI of young adults during grasping actions engaging the index finger (e.g., scissoring action).

Origin and site of the facilitation

The extra facilitation observed when participants explored the letter with their finger could be ascribed to excitatory influences exerted either at the spinal or cortical level or both. While a contribution of spinal mechanisms cannot be rule out, a cortical site of action is more likely. As explained earlier, the low-level contraction produced to move the finger likely provided a constant background of spinal facilitation upon which increasing cortical descending volleys acted, accounting for the extra facilitation seen when the TE task was contrasted with either the BP or the FM task. The origin of this increase in the descending drive could have come for three sources. First, the cutaneous input generated as the finger explored the contours of the letter might have contributed to increased cortical responsiveness. Indeed, there is evidence that cutaneous afferents are capable of modulating

cortical excitability in the hand motor area through changes in SICI, as shown in experiments using controlled digital nerve stimulation (Ridding and Rothwell 1999; Ridding et al. 2005). The second source is likely in the motor cortex itself since the high degree of precision required by the exploration task might have led to a greater engagement in controlling the index finger to optimize sensory acquisition as opposed to simple actions. A recent functional imaging study Carey et al (2006b), confirmed the influence of task precision in leading to greater activation of the motor cortex. They compared motor activation when participants used their index finger either in a precision tracking task or to perform simple flexion/extension movements. The results showed an increase in both the extent and intensity of the signal bilaterally in the motor cortex in the tracking task as compared with the simple task. Finally, as we referred to above, the other likely source of facilitation is related to top-down influences arising from cortical areas activated by the attentional requirement of the task and acting on the motor cortex. Such influences might have originated in particular from the dorsolateral prefrontal cortex and the premotor cortex since both areas are known to be highly active during fine tactile discrimination with the fingers (Stoesz et al. 2003; Harada et al. 2004) and both are interconnected with the motor cortex (Dum and Strick 2002; Dum and Strick 2005). In addition, paying attention to a motor action, like the TE task here, has been shown to enhance coupling between activity of the prefrontal cortex and the premotor regions (Rowe et al. 2002).

Conclusion

The present results provide further insights as to the effect of task conditions on corticospinal excitability in hand muscles. Our findings show in particular that corticospinal

excitability is greatly enhanced when the index finger is engaged in a functionally demanding tactile exploration task. In addition, we show that this task-dependant facilitation is similar in the two hands. These findings have some clinical implications for the rehabilitation of hand function in patients with motor impairments after stroke. Clinically, it may be optimal to use more functional tasks that involve greater attention and cognitive demands to rehabilitate hand function than tasks relying on simple movement execution.

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CONCLUSION

Results obtained partially confirmed working hypotheses. In fact, data clearly indicates that corticospinal excitability is enhanced in the hand motor area when the fingers are used for tactile exploration. The higher attentional demand and dexterity associated with the exploration tasks are likely responsible for this enhanced facilitation. Although these findings concern young healthy adults, it would be very interesting to repeat this study in the older populations or in patients with sensory or motor impairments following a stroke, or in individuals diagnosed with Lou Gehrig's disease. Based on our findings, emphasizing sensory exploration with the hand might be an optimal strategy to promote recovery of function.

Our second hypothesis concerning the asymmetry in favor of greater facilitation on the left was not confirmed, however. In fact, we found no evidence of asymmetry with regard to the effect of task conditions between the two hands. The presence of few left-handers in our group of subjects was unlikely a factor in masking the potential asymmetries between hands. The symmetry of the task-dependant MEP facilitation reported here was, indeed, very robust. In this respect, this finding is consistent with the results of previous TMS studies, and, as we have referred to earlier, asymmetries between the two hand in terms of sensory performance have been hard to document. Thus, further studies will be required to address the issue of asymmetries between at the neurophysiological and behavioural level.

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APPENDIX I
HEALTH QUESTIONNAIRE

**QUESTIONNAIRE
ÉTAT DE SANTÉ/HEALTH STATUS**

Nom/Name : _____ Date de naissance/Birth date : _____
 Sujet #/Subject # : _____ Genre/Gender F • M •

Directives/Directions :

S.V.P. Lire les questions suivantes et répondre en cochant la case appropriée. Noter que toutes ces informations seront gardées strictement confidentielles.

Please read the following questions and check the appropriate answer. Note that all information will be kept strictly confidential.

Votre médecin vous a-t-il déjà parlé que vous aviez une maladie chronique (e.g., malaise cardiaque, problème respiratoire, arthrite, diabète, sclérose en plaques, paralysie, accident cérébro-vasculaire, Parkinson, condition dermatologique) pouvant nuire grandement à votre capacité de faire de l'activité physique ou des tâches domestiques?	OUI • NON •
Votre médecin vous a-t-il déjà parlé que vous aviez une maladie chronique du système nerveux (e.g., neuropathie, syndrome du tunnel carpien, dystonie focale) pouvant nuire à votre capacité de ressentir les objets avec vos mains ou une autre partie du corps en particulier? Si oui, veuillez spécifier la ou les régions atteintes :	OUI • NON •
Est-ce que votre métier ou passe-temps dans le passé ou présentement nécessitait l'utilisation de vos mains en performant des mouvements répétitifs ou l'utilisation d'outils à moteur? (e.g., ordinateur, perceuse, tricot...) Si oui, Quel type : _____ Heures/jour : _____ Nombre d'année : _____	OUI • NON •
<i>Has your doctor ever said that you have a chronic condition (e.g., heart or respiratory diseases, diabetes, arthritis, multiple sclerosis, paralysis, stroke, Parkinson, dermatological condition) that could seriously interfere with your ability to perform physical activities or household tasks?</i>	YES • NO •
<i>Has your doctor ever said that you have a chronic condition (e.g., neuropathy, carpal tunnel syndrome, focal dystonia) that could interfere with your ability to feel objects with your hands or other body parts in particular?</i> <i>If yes, please specify the regions affected:</i>	YES • NO •
Does your previous or current occupation or leisure require you to use your hands by performing any repetitive movements or to use power tools? (e.g., computer, drill, knitting...) If yes, What type: _____ Hours/day: _____ Number of years: _____	YES • NO •

APPENDIX II
HEALTH QUESTIONNAIRE FOR TMS



uOttawa

L'Université canadienne
Canada's university

Faculté des sciences de la santé
École des sciences de la réadaptation

Faculty of Health Sciences
School of Rehabilitation Sciences

HEALTH QUESTIONNAIRE FOR TRANSCRANIAL MAGNETIC STIMULATION APPLICATIONS

IMPORTANT NOTICE

The present study involves the use of a magnetic stimulator to induce micro-current in the brain through a coil applied on the scalp. Although the technique is known to be safe and virtually painless, we need to screen our subjects to exclude those who might be at risk. This is why we ask you to fill this health questionnaire, as a potential participant.

Have you consulted a physician recently (i.e., in the last 12 months)?

- Yes
- No

If No, when was your last visit? _____ months/years

Have you ever been diagnosed with any of the following conditions?

- Epilepsy
- Migraine
- Traumatic brain injury
- Depression
- Stroke or TIA (Transient Ischemic Attack)
- Heart Conditions (angina, hearth failure)
- Hypertension (high blood pressure)
- Sciatica or disc problems
- Arthritis
- Diabetes
- Any other conditions?
 - Yes please specify: _____
 - No,

Are you presently (in the last month) taking any prescribed medication?

- Yes please specify: _____
- No,

Do you have any metal implants in your body?

- Yes please specify where : _____
- No,

Do you a have a "pace-maker" for cardiac stimulation?

- Yes
- No,

Are you presently receiving any form of medical treatment?

- Yes please specify the reason: _____
- No,

For women, are you pregnant or do you think you might be?

- Yes
- No

Do you considered yourself in good health?

- Yes please, specify: _____
- No,

Do you have any other health condition of which we should be made aware?

- Yes if ye please specify: _____
- No,

I acknowledge that I have answered this questionnaire to the best of my knowledge and that my answers truly reflect my health status.

Signature

Date

**APPENDIX III
CERTIFICATE OF ETHICS APPROVAL**



Université d'Ottawa University of Ottawa

Le 22 juin 2007

François Tremblay
Programme de physiothérapie
Université d'Ottawa
451 chemin Smyth, pièce 3071
Ottawa, ON K1H 8M5

Patricia Oliver

Objet: Age & Laterality Differences in Tactile Pattern Recognition (Dossier H 05-06-01)

Chers Monsieur Tremblay et Madame Oliver,

Vous trouverez ci-joint une attestation d'approbation éthique du Comité d'éthique de la recherche (CÉR) en Sciences de la Santé et Sciences pour votre projet de recherche mentionné en rubrique. Le Comité d'éthique a accepté votre demande de prolongation d'approbation éthique.

Au cours de votre étude, toute modification au protocole ou aux formulaires ne peut être introduite sans l'approbation préalable écrite du CÉR. Vous devez aussi aviser, dans les plus brefs délais, le CÉR de tout événement ou expérience indésirables vécus par les participants.

Cette attestation d'approbation déontologique est valide jusqu'au 22 juin 2008. Veuillez soumettre un rapport annuel en juin 2008 à la Responsable de l'éthique en recherche pour soit fermer le dossier ou faire demande d'extension. Ce rapport se trouve à l'adresse suivante : <http://www.uottawa.ca/services/research/rpe/rehs/tra/index.html>.

Une copie de cette approbation sera soumise aux Services de la Recherche, si nécessaire.

Si vous avez des questions, n'hésitez pas à me contacter au poste 1787.

Veuillez agréer mes sentiments les meilleurs

Catherine Paquet
Responsable de l'éthique en recherche
Pour le Daniel Lagarec, Président du CÉR

Université d'Ottawa
145, rue Jean Jacques
Ottawa, Ontario K1N 6N5
Téléphone : (416) 547-5800
Téléfax : (416) 547-5801
Courriel : ethique@uottawa.ca

**APPENDIX IV
HANDENESS QUESTIONNAIRE**

Handedness Questionnaire

Edinburgh Handedness Inventory

Please indicate your preferences in the use of hands in the following activities by putting a check in the appropriate column. Where the preference is so strong that you would never try to use the other hand, unless absolutely forced to, put 2 checks. If in any case you are really indifferent put a check in both columns.

Some of the activities listed below require the use of both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try and answer all of the questions, and only leave a blank if you have no experience at all with the object or task.

	Left	Right
1. Writing	☐ ☐	☐ ☐
2. Drawing	☐ ☐	☐ ☐
3. Throwing	☐ ☐	☐ ☐
4. Scissors	☐ ☐	☐ ☐
5. Toothbrush	☐ ☐	☐ ☐
6. Knife (without fork)	☐ ☐	☐ ☐
7. Spoon	☐ ☐	☐ ☐
8. Broom (upper hand)	☐ ☐	☐ ☐
9. Striking Match (match)	☐ ☐	☐ ☐
10. Opening box (lid)	☐ ☐	☐ ☐
TOTAL(count X's in both columns)		

Scoring:

Add up the checks in both left and right columns.

Whichever number is greater, would be considered your handedness.

APPENDIX V
PAPER PRESENTED AT THE XVIIth ISEK CONGRESS
NIAGARA FALLS, CANADA
JUNE 2008

SELECTIVE INCREASE IN CORTICOSPINAL EXCITABILITY WITH TACTILE EXPLORATION

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INTRODUCTION

Active contraction is known to lead to facilitation of motor responses evoked from transcranial magnetic stimulation (TMS) of the motor cortex. This facilitation of motor evoked potentials (MEPs) is thought to reflect an increase in excitability both at the spinal and cortical level (ie, number and size of descending volleys). While MEP facilitation could be elicited with simple finger movements, several studies have shown that the magnitude of this facilitation could be modulated in a task-dependant manner. For instance, Bonnard et al showed that when the precision demands increased for the thumb-index grip force, corticospinal (CS) excitability also increased selectively in either the 1st dorsal interossei (FDI) or the abductor pollicis brevis (APB), but not in both. Sale et al (2005) reported similar findings showing a selective increase in MEP facilitation in the FDI during a scissor action as compared to isolated contraction or a power grip.

In the present study, we sought to determine whether engaging the fingers in tactile exploration would enhance CS excitability in intrinsic hand muscles when compared to simple motor tasks.

METHODS

Eighteen healthy young participants volunteered to participate in this study (age, 24 ± 2 yrs, 9 males, 9 females).

Corticomotor excitability of the hand motor representation was assessed under two task conditions: 1) Tactile Exploration (TE) wherein subjects were asked to explore raised letters (6 upper case characters, 6-mm high) with the tip of the index finger for tactile recognition; and 2) Button Pressure (BP), wherein subjects depressed a button with the index finger. Five subjects were tested under an additional condition, ie, scanning a smooth surface identical in size to the surface used for tactile recognition using a similar exploratory movement. In all conditions, TMS pulses (Magstim 200, figure-of-8 coil) were delivered @ 2500 ms in the course of the 5000 ms trials (intensity, 110% MT) over the contralateral motor cortex (hot spot for FDI muscle). Twelve trials were recorded in each condition. Variations in MEP amplitude and latency recorded in the FDI were subject to a repeated measure analysis of variance (ANOVA) to determine the effects of task conditions and hand dominance.

RESULTS AND DISCUSSION

The ANOVA revealed a large effect of "TASK" ($F=31.4$, $p<0.001$) on MEP amplitude, but no laterality effect of "Hand (R vs.L)" ($F=0.3$, $p=0.62$). As shown in Figure 1, the large effect of "TASK" was

background EMG level produced in the two tasks (TE and BP) on the corresponding MEP amplitude was further examined with ANOVA and showed no significant effect ($F < 2.8$, $p > 0.1$). Thus, MEP facilitation was independent of the level of EMG produced in the two tasks.

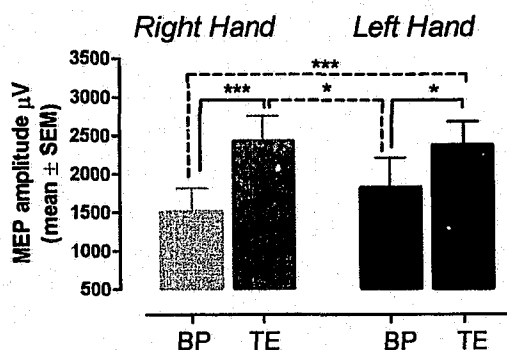


Figure 1. Mean variations in MEP amplitude under the task conditions.
*significance levels from the Tukey's test.

Active finger scanning without tactile letter recognition led to MEP facilitation comparable to that seen with the BP task ($n=5$, Scan: Right, 1235 μV ; Left, 1290 μV).

The present results confirm and extend previous observations on the influence of task conditions on CS excitability of intrinsic hand muscles (Muir & Lemon 1983; Bonnard & al 2007). The novel finding was that engaging the index finger in TE for sensing raised letters produced a selectively larger facilitation in the FDI than the other tasks (ie, either BP or finger scanning). This selective increase in CS excitability associated with tactile sensing likely reflects influences exerted at the cortical level. Tactile letter recognition requires fine precise control over the finger, as it scans the contour to allow for recognition. Such dextrous tasks are known

to lead to greater activation in the motor cortex as opposed to tasks requiring no dexterity or precision (Bonnard et al 2007). Thus, when compared to BP, the level of precision required for the TE might have led to a greater engagement of the motor cortex in controlling the index finger to optimize sensory acquisition. The large attentional demand associated with the TE task may have also exerted top-down influences to further enhance CS excitability under the TE condition. This conclusion is supported by the fact that finger scanning without tactile recognition led to facilitation levels comparable to the BP task. In this regard, our results are entirely consistent with recent TMS studies showing that attention greatly enhanced sensory responsiveness to tactile inputs in the CS system (Rosenkranz & Rothwell 2004, Stefan et al 2004).

SUMMARY/CONCLUSIONS

Corticomotor excitability is greatly enhanced when the index finger is used to explore and recognize tactile forms as compared to tasks involving finger movements to produce minimal force.

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