THE HONG KONG POLYTECHNIC UNIVERSITY
DEPARTMENT OF REHABILITATION SCIENCES

VIBROTACTILE IMAGERY: NEURAL CORRELATES OF OLDER ADULTS AND PATIENTS SUFFERED FROM STROKE

BY
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A THESIS SUBMITTED TO THE RESEARCH OFFICE IN PARTIAL FULFILMEN OF THE REQUIREMENTS OF THE DEGREE OF MASTER OF PHILOSOPHY

HONG KONG

MAY 2006

CERTIFICATE OF ORIGINALITY

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_____ (Signed)

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DEDICATION

I dedicate this work to my parents and Libin LI, who have supported me through out the Master study.

OUTPUTS RELATED TO THE STUDY

REFEREED JOURNAL ARTICLES

Journals Submitted Under Review

Chow, W. S. K., Chan, C. C. H., Liu, K. P. Y., Lee, T. M. C., Li, L. S. W., & Hui-Chan, C. W. Y. (Under review). "Imagery network" of vibrotactile Imagery: An ERP study, *Neuroscience Letters.*

Chow, K. W. S., Chan, C. C. H., Liu, K. P. Y., Li, L. S. W., & Hui-Chan C. W. Y. (Under review a). The sensory recovery of stroke patients in the intensive rehabilitation stage. *Stroke.*

CONFERENCE PRESENTATION AND PUBLICATIONS

Paper Accepted for Platform Presentation

August 2004 Chow, W. S. K, Chan, C. C. H. & Hui-Chan, C. W. Y. (2004). Mental imagery of vibration sense – an event related potentials study, *XXVIII International Congress of Psychology, Beijing, China*.

Feb 2006 Chow, W. S. K., Chan, C. C. H., Liu, K. P. Y., Li, L. S. W. & Hui-Chan, C. W. Y. (2006). Event-related potentials of vibrotactile imagery – a potential treatment for patients with sensory impairments, *The Forth Congress for NeuroRehabilitation, Hong Kong, China*.

Feb 2006 Chan, C. C. H., Chow, W. S. K., Liu, K. P. Y., Li, L. S. W. & Hui-Chan, C. W. Y. (2006). Case studies on vibrotactile imagery among post-stroke patients. *The Forth Congress for NeuroRehabilitation, Hong Kong, China*.

Paper Accepted for Poster Presentation

June 2005 Chow, W. S. K., Chan, C. C. H., Liu, K. P. Y., Hui-Chan, C. W. Y. Luo, Y. J. & Sung, Y. Y. C. (2005). Imagery of vibrotactile

sensation – An event-related potential study, *Human Brain Mapping 11th Annual Meeting, Toronto, Canada*.

Feb 2006 Chow, W. S. K., Chan, C. C. H., Liu, K. P. Y., Li, L. S. W. & Hui-Chan, C. W. Y. (2006). Sensory profile of the post-stroke patients before and after intensive rehabilitation. *The Forth Congress for NeuroRehabilitation, Hong Kong, China*.

Abstract of dissertation entitled:
Vibrotactile imagery: Neural correlates of older adults and patients suffered from stroke by Kari Wai Sum Chow for the degree of Master of Philosophy at The Hong Kong Polytechnic University in May 2006.

ABSTRACT

The present study examined the neural processes associated with the imagery of vibrotactile sensation of older adults. It was hypothesized that vibrotactile imagery was composed of an image generation process and an image maintenance process. These two processes would elicit event-related potential in the frontal parietal and central areas of the brain. It was further hypothesized that the image maintenance process was task and modality specific, and hence would elicit event-related potential in the sensorimotor areas. To further verify these hypotheses, event-related potentials of a few patients who suffered from a stroke and resulted in different brain lesions were recruited. The results obtained from these patients were compared with those from the older adult group.

Twelve normal older adults and three post-stroke patients participated in both the imagery and control tasks. The imagery task required the subjects to imagine a vibrotactile sensation for 4000 ms primed by a 250 ms vibrotactile stimulus. Another stimulus was then delivered right after the imagery of the first stimulus, and the subjects were required to differentiate between the two stimuli.

Under the control condition, the subjects were required to passively detect the vibrotactile sensation without imagining it. The event related potential was recorded using a 32-array of silver-silver chloride electrodes placed in an extended International 10-20 system. The accuracy and response time was also recording during the recording.

Among the normal older adult, an ERP component was observed within the 150 – 200 ms time window (N170) which had its maximum in the frontal central area for both the imagery and control conditions. This suggests probable attention and detection of the vibrotactile stimuli a short while after the stimulus was delivered to the subjects. The second ERP component was found to be within the 280 – 390 ms time window (P300) of which the amplitudes for the imagery condition were less positive-going than the control condition in all sites, especially the frontal and central area. There were two ERPs appeared around the 480 – 620 ms and 640 – 970 ms which suggest possible N400 and P600 components. The N400 component was found less negative-going at the parietal and occipital sites, whilst the P600 component was less positive-going at the frontal and central sites in the control condition. These P300, N400 and P600 components, with the dipoles modelled and located at the frontal and parietal areas, indicate a continual processes from generation of vibrotactile images

which was dominated by the P300 and N400 components to maintenance of the images in the working memory which was dominated by the P600 component. These observations and processes are consistent with the “imagery network” described in the literature.

The lesions of in the cerebellum, thalamus, and frontal and temporal lobes in the three post-stroke patients were found to separately modulate different neural processes associated with imagery of vibrotactile sensation. Stronger modulation effects P600 were observed in the patient who had lesions over the frontal and temporal areas, which are consistent from the findings based on normal older adults. Future research should use neuroimaging techniques to identify the neural substrates associated with vibrotactile imagery and test the efficacy of using mental imagery to promote recovery of somatosensory deficits in post-stroke patients.

ACKNOWLEDGEMENTS

I would like to express my greatest gratitude to Prof. Chetwyn Chan, my chief supervisor, for his kind support and excellent supervision during the course of my MPhil study. I have been constantly inspired by his trenchant critiques and rich experience in research study. My thanks should go to Prof. Christina Hui-Chan, Dr. Karen Liu for serving as the co-supervisors of my study and their valuable inputs to this study. I also wish to extend my gratitude to Dr. Kevin Kwong, Mr. Man Cheung, and Dr. Kin Hung Ting for their professional technical support of my study. In addition, I wish to extend special thanks to Dr. Leonard Li, Ms Christina Yau and the staff in the Occupational Therapy Department of the Tung Wah Hospital for their kind assistance during my research. Thanks should also go to my labmates, colleagues and friends, from whose wisdom and knowledge I benefited greatly during the course of my studies. This study was partially supported by the Area of Strategic Development grant awarded to Prof. Christina Hui-Chan.

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CHAPTER I

INTRODUCTION

Background and Justification

Sensory impairment has been commonly found in patients who have suffered from a stroke. Previous studies indicate that the sensory impairments following a stroke can reach as high as 80% (Kim & Choi-Kwon, 1996). Recently, a similar study was conducted among post-stroke patients in Hong Kong. The results indicated that 50% of the patients manifested sensory impairments that had not shown improvements despite three weeks of intensive physical rehabilitation (Chow, Chan, Liu, Li, & Hui-Chan, under review a). Though impairments to the sensory functions have been found to be quite common, little attention has been given to investigating the possible mechanisms and techniques for restoring sensory deficits subsequent to a stroke. Mental imagery has been reported to be useful for promoting functional regain among post-stroke patients. The regain of function ranged from lower limb to upper limb functions, as well as performance in complicated daily tasks (e.g. Liu, Chan, Lee, & Hui-Chan, 2004a, 2004b). Nevertheless, no studies have explored the effect of mental imagery on promoting the regain of the somatosensory functions through the practice of mental imagery. It is therefore logical to gain a better understanding of the neural mechanisms behind the imagery of somatosensory sensation before designing an imagery protocol for promoting recovery of somatosensory sensation for post-stroke patients.

The neural mechanism behind the imagery of visual stimuli has been studied by different researchers. Recent studies indicate an imagery network believed to be mediated by the frontal parietal region (see Mechelli, Price, Friston, & Ishai, 2004,

for a review). The functional role of the imagery network has been further proposed to be generating and maintaining the visual images, and the associated executive control, attention, and working memory (e.g. Kosslyn et al., 2004). Though the identification of the imagery network was based on visual imagery, it is hypothesized that the generic process can be equally applied to other types of mental imagery. A review of the literature indicated that no study has been conducted to explore whether the "imagery network" would exist in the imagery of somatosensory sensation such as vibrotactile sensation. It would therefore be interesting to develop a study to further examine this aspect. Another issue regarding the imagery of somatosensory sensation is that many of the previous studies used verbal or visual stimuli in the imagery task. It is intuitive to argue that these stimuli could have confounded the imagery process of somatosensory sensation, which is not necessarily associated with verbal or visual processes. The present study is intended to minimize the confounding variables by using a basic somatosensory sensation — vibrotactile sensation. More importantly, the priming stimuli and the task would not involve either verbal or visual processes.

Statement of Purpose

The purpose of this study was to reveal the neural processes associated with imagining vibrotactile sensation. We used event-related potential (ERP), which has a high temporal resolution, to differentiate the neural processes associated with the imagery. The ERPs obtained from the imagery condition were compared with those of the passive stimulation condition.

After obtaining the data of the normal subject group, the same paradigm was tested on individual patients who had suffered from a stroke. The purpose was to

further explore the extent to which the selected brain lesions would modulate the imagery of vibrotactile sensation.

Hypotheses of the Study

We hypothesized that imagery of vibrotactile sensation is composed of an imagery generation process that involves access to the working memory. This process occurs early and primarily involves frontal activities. The other process is maintenance of the vibrotactile images that are task specific. This process occurs later and involves activities at the sensorimotor areas.

Organization of Chapters

This report consists of six chapters including the present one. Chapter II provides a review of the literature on sensory impairments encountered by post-stroke patients. The effectiveness of mental imagery in rehabilitation and the lack of understanding of its mechanism are described. The model of mental imagery and the current knowledge about the neural mechanisms of visual and tactile imagery are therefore reviewed. Finally, the discussion is directed to the reasons for using vibration stimulus as the imagery modality. Chapter III first describes the subject selection criteria for normal older subjects and the stroke patient group. The same experimental design used to study the neural processes of tactile imagery in both groups of subjects is presented. In Chapter IV, the results of the study, including ERP results and behavioral results, are reported. Chapter V first analyzes and discusses the results generated by the normal older subjects. Then the results of the post-stroke patients are analyzed and compared with those of the normal group. Chapter VI provides an overall conclusion to this research study.

CHAPTER II

LITERATURE REVIEW

Introduction

This chapter begins by suggesting the importance of studying mental imagery and its neural correlates to the rehabilitation of post-stroke patients. A model of visual imagery is presented and discussed and the recently proposed "imagery network", which is believed to be a generic process common to all types of imagery, is described. A number of previous studies on tactile imagery are also reviewed. It is argued that most of these studies have been confounded by their designs and use of different stimuli, and hence have produced divergent findings on the neural substrates associated with the imagery of vibrotactile sensation. Finally in this chapter, the reasons for the use of event-related potential (ERP) and vibration stimuli for studying priming imagery in this research are further explained.

Stroke Survivors and Their Sensory Impairments

Stroke is defined by the World Health Organization as an acute neurological dysfunction of vascular origin (World Health Organization, 2001) and is the most common disabling neurological disease in adults (Pedretti, 2001). In Hong Kong, the majority (86%) of stroke sufferers survived the event, as measured in the period 2000 - 2002. The increase in life expectancy amongst the public also means that more and more of these stroke survivors will be living with their disabilities for a prolonged period (Hong Kong Hospital Authority, 2002).

Sensory impairment after a stroke is determined by the extent to which the brain has been impaired: this depends on the size and location of the lesion (U. S.

Department of Health and Human Services, 1995). It has been reported that the degree of sensory impairment can reach 80% among those who have suffered from acute unilateral stroke (Kim & Choi-Kwon, 1996). Recently, a similar study was conducted among post-stroke patients in Hong Kong which indicated that 50% of patients exhibited sensory impairments which had not improved despite three weeks of intensive rehabilitation (Chow et al., under review a). These impairments covered both the basic tactile sensation (vibration, pinprick, temperature, and light touch) and the discriminative sensation (two-point discrimination (2-PD), point localization, texture discrimination, position sense, and stereognosis). These findings are alarming because somatosensory senses are of the utmost importance if patients are to regain independent functioning after a stroke. Furthermore, impaired tactile sensation has been found to impede motor function recovery, which itself is a predictor of the functional outcome of post-stroke patients (Rose, Bakal, Fung, Farn, & Weaver, 1994).

Problems Associated with Current Methods of Sensory Rehabilitation

Regain of motor function is the main focus of stroke rehabilitation (e.g. Carey, 1995; Dannenbaum & Jones, 1993). Although, as shown above, impairments to sensory functions are common among post-stroke patients, little attention has been paid to investigating the possible mechanisms and techniques for restoring such deficits.

The literature indicates that sensory re-education is a commonly employed technique in the clinical field for promoting sensory recovery in post-stroke patients (Trombly, 1995). The general belief is that exposure to different sensory experiences will enable patients to benefit from cortical re-organization, helping to improve the

recapture of lost functions (Carey, Matyas, & Oke, 1993; Yekutiel & Guttman, 1993). The process of re-education may involve patients being asked to visualize specific sensory modalities. This would require them to see and feel the sensation, and then associate it with a texture or object (Carey, 1995; Trombly, 1995). To reinforce the relearning, patients may be asked to repeatedly rehearse what is being felt in the hands. These processes are repeated and upgraded (e.g. from gross to fine texture, and from large to small objects) to include different sensations and objects.

These techniques suffer from two main problems. The first is that there are no studies describing the neural mechanisms underlying such sensory re-education, that is to say the association between what is felt and the regaining of tactile sensations. While the technique is intuitively plausible, the processes by which patients regain sensory functions by re-learning sensations are still unclear. The second issue is the lack of systematic empirical studies of the effectiveness of the method in post-stroke rehabilitation. This study attempts to address these gaps by using mental imagery to theorize the phenomenon of sensory re-education. Of all the possibilities, we selected an experimental design and psychophysiological methods to investigate the initial mechanism involved in sensory relearning: the imagery of tactile sensation.

Mental Imagery and Rehabilitation

Mental imagery can be defined as voluntary perception of non-existing objects or external stimuli (Kosslyn, 1994; Yoo, Freeman, McCarthy, & Jolesz, 2003). In visual terms, mental imagery can be thought of as reversing the process of perception. In other words, mental imagery is a top-down process while perception is a bottom-up process such as, for example, seeing the shape, color, and size of an

animal. This involves reception of stimuli at the retina and primary visual cortex; these features are then processed at the sub-cortical and cortical level before the animal is consciously recognized by the person. In imagery, the corresponding top-down process might be that involved in generating an image of the animal from memory. The image is then maintained in the brain for processing functions such as inspection and transformation.

The application of mental imagery is a fairly new idea in the area of stroke rehabilitation. Over the past few years, the Applied Cognitive Neuroscience Laboratory of The Hong Kong Polytechnic University has conducted a range of clinical studies on the use of mental imagery protocols for training post-stroke patients who are relearning complicated daily functions. The studies have shown that mental imagery can be effective in this context (Liu, Chan, Lee, Li, & Hui-Chan, 2002, Liu et al., 2004a, 2004b). Its effect is not confined to improvements on training task performance, but has also improved the sustainability of the skills and their generalization to performance in tasks not included in the training (Liu, Chan, & Hui-Chan, 2000, Liu et al., 2002). Kwan (2003) has further demonstrated that such learnt skills and performance could be generalized to performance of tasks carried out in a different environment. These findings demonstrate the therapeutic value of mental imagery in stroke rehabilitation. Its effects may be mediated by the overlap of the neural substrates activated during imagery and actual task performance (e.g. Yoo et al., 2003).

Model of Mental Imagery

Mental imagery is a major area of study in psychology and cognitive neuroscience (see Kosslyn & Thompson, 2003 for a review). In the past 25 years, the

primary focus has been on investigation of the model of visual imagery and the elucidation of the corresponding neural mechanism. In this section, the context for the description of mental imagery is primarily based on research on visual imagery. Nevertheless, the models and mechanisms can equally be applied to other types, such as vibrotactile imagery or tactile sensation. The essence of mental imagery is that the neural substrates it uses overlap with those in the execution of the sensory process. However, it is important to note that while there are similarities between imagery and execution, they are not identical (see Ganis, Thompson, & Kosslyn, 2004). Because of this, it is useful to begin a description of mental imagery by elucidating the neural processes associated with actual perceptual experiences, such as visual perception.

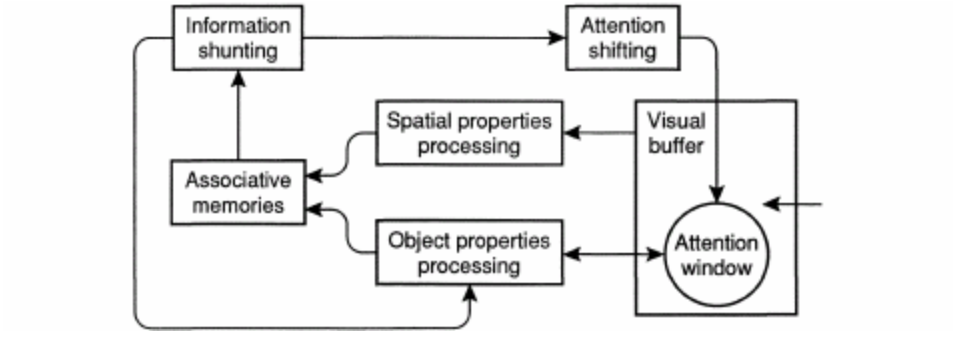
When an individual perceives an external image, the perceptual process begins with the image being projected onto the retina and pre-processed by the retinotopically organized visual areas in the occipital lobe (Kalat, 2004). Information received in the visual area is selected (by means of attentional processes) and further processed by other systems, such as the object-properties system (which specializes in processing object-like characteristics such as shape and color) and the spatial-properties system (which deals with spatial-related characteristics such as location and orientation) (Kosslyn, 1994, Figure 2.1). The object-properties system is implemented by a pathway running ventrolaterally from the occipital lobe to the inferior temporal lobe, and the spatial-properties system by a pathway running dorsally from the occipital lobe to the posterior parietal lobe.

Information from these two systems then reaches the associative memory, where multimodal knowledge about objects can be stored. It is proposed that short-term associative memory is mediated by the dorsolateral prefrontal cortex, whereas

long-term associative memory is mediated by the classical “association cortex” in the occipital/temporal/parietal junction area. Depending on the nature of the task, however, visual perception does not stop at this level. According to Kosslyn’s model, an information shunting system, mediated by the prefrontal cortices, accesses the knowledge stored in the associative memory. This is a top-down process used when an individual intends to derive more information from the image, and is guided by the previous knowledge stored in memory. For example, when someone sees a wing-like shape, he or she may derive a hypothesis that this image corresponds to an airplane. A further hypothesis may be determined by whether the image carries a tail or a wheel, prompting the individual to focus on either the end or bottom of the image.

Figure 2.1

Major subsystems used in perception and mental imagery. (Adapted from Kosslyn, S. M., *Image and Brain.* Cambridge, MA: Harvard University Press; 1994)



In summary, visual perception involves sensory processes initiated at the sense organ, that is, the retina. The image formed is then processed in different cortical regions which basically involve attention, and access to both long-term and work memory. Visual imagery, however, is thought to take a different route. Nevertheless,

as one can see, the faculties involved are by and large similar to those in visual perception. According to Kosslyn's model, the process begins in the shunting system where the long-term associative memory is accessed in order to retrieve the stored representation of an object. This information is sent to the object- and spatial-properties processing systems which activate a representation of the visual properties of an object. The model further hypothesizes that this process is identical to the priming effects created by top-down hypothesis testing in perception. More importantly, the priming effects are strong enough to activate a backward process (bottom-up), by which an image representation can be formed. These processes enable the object and spatial relations of visual images to be inspected and identified by the same mechanisms used to inspect them during perception. Support for this idea is found in the evidence that people can reinterpret patterns in mental images just as they do with perceived images, provided that capacity limitations are not exceeded (Chambers & Reisberg, 1992; Peterson, Kihlstrom, Rose, & Glisky, 1992; Reisberg & Chambers, 1991; Reisberg & Logie, 1993; Rouw, Kosslyn, & Hamel, 1997)

This visual imagery model has been tested by a range of different studies. In general, there are two converging threads of evidence in support of it: (1) visual imagery and perception share some processes and structures (Farah, 1984; Kosslyn, 1994; Kosslyn, Ganis, & Thompson, 2001; Kosslyn & Thompson, 2003) but not all (e.g. Mazard, Tzourio-Mazoyer, Crivello, Mazoyer, & Mellet, 2004; Mechelli et al., 2004); and (2) visual imagery is not a unitary nor undifferentiated faculty, but involves different sensory processes — and hence their neural substrates — depending on the nature and context of the images (Farah, 1984; Handy et al., 2004;

Mechelli et al., 2004). In fact, the imaging process involves image generation, maintenance, and transformation.

Mental images are first generated when imagery begins. The generation process can be separated into distinct operations, namely the activation of representations in long-term memory and the subsequent display on visual short-term memory (Bruyer & Scailquin, 2000; Kosslyn, Cave, Provost, & Von Gierke, 1988). Image maintenance is then continued, allowing inspection, copying, and matching to occur. These processes are similar to those described in Baddeley's (2003) updated working memory model. This is not surprising because the generation of images relies on reactivation of the representation stored in episodic memory, which resembles the retrieval process described in memory (Buckner & Wheeler, 2001). Along similar lines, the maintenance of images requires a platform within which images are held. This process is very close, if not identical, to visuo-spatial working memory (Bruyer & Scailquin, 2000; Kosslyn, 1994). Indeed, the experience of mental imagery can be seen as the outcome of an interaction between the retrieval of visual representations from episodic memory and the maintenance and transformation properties of working memory. It may be revealed, at least in part, by the presence of frontal activation.

The "Imagery Network" — Neuro-activations and Activities

The neural correlates of each of the imagery processes have been investigated more intensively in recent years as a result of advances in neuro-imaging techniques. The neural substrates associated with mental image generation and maintenance are the prefrontal and the ventral occipito-temporal regions (Ishai, Haxby, & Ungerleider, 2002). Mechelli et al. (2004) further report that the occipito-temporal,

parietal, and frontal regions are involved in visual imagery of faces, houses, and chairs. They suggest that when no actual stimulus was presented, the mental images generated from long-term memory were stored in the occipito-temporal region. Other areas found to be associated with the two processes were the precuneus, the superior parietal, and the ventral occipito-temporal regions (Mechelli et al., 2004; Rama, Sala, Gillen, Pekar, & Courtney, 2001). Mechelli et al. (2004) also propose the existence of intrinsic connections linking the precuneus, the superior parietal, and the ventral occipito-temporal regions, forming an "imagery network" which is generic (i.e. used in different types of imagery). Their results on visual imagery suggest that this "imagery network" comprises an attentional mechanism, arising in the parietal cortex, and a content-sensitive mechanism, originating in the prefrontal cortex. The network is thought to be involved in mental image generation and maintenance. The prefrontal involvement is probably required to access long-term memory and formation of visual images and the parietal for image generation and maintenance.

Apart from the "imagery network", which explains the attentional mechanism, the process of access and retrieval from episodic memory has been further supported by the activation of the precuneus during different modalities of imagery (Buckner, Raichle, Miezin, & Petersen, 1996; Fletcher et al., 1995; Ishai, Ungerleider, & Haxby, 2000, Ishai et al., 2002; Mellet, Petit, Mazoyer, Denis, & Tzourio, 1998). However, due to limitations in the temporal resolution of fMRI, it is not clear which specific neural substrates are involved in each of the generation and maintenance processes activated during imagery.

Different spatial and non-spatial imagery tasks have been found to activate the parietal area (Ishai et al., 2002; Mellet et al., 2000). Mazard et al. (2004) studied

nine imagery tasks (including both spatial- and object-like images) and revealed activations in the bilateral parietal lobe as well as several foci in the frontal area, across all the tasks. Frontal lobe activations have also been commonly found in tasks involving working memory (Haxby, Petit, Ungerleider, & Courtney, 2000) and retrieval from episodic memory (Buckner & Wheeler, 2001; Nyberg et al., 2001). The prefrontal cortex has been found to take part in working memory function, such as operation and maintenance, regardless of the modality of the stimulus (Romo, Brody, Hernandez, & Lemus, 1999; Stoeckel et al., 2003). Activations of the bilateral parietal lobes have been associated with the decoding of the spatial relation during imagery, and also attention in general (Mazard et al., 2004). Other areas, including the left superior part of the temporal pole, the insula, the anterior cingulated cortex, and the cerebellar vermis, have all been found to be simultaneously activated during the generation of object- and spatial-like images.

Specific Sensory Processes — Imagery of Vibrotactile Sensation

It is more difficult to identify the neural substrates which are specific to sensory processes, compared to the generic “imagery network.” This is because the study of such processes has often been confounded by the tasks or stimuli used to elicit the responses, as a number of studies on tactile imagery have found. For instance, Uhl et al. (1994) reported activations in the contralateral central, parietal, and right posterior temporal sites, and the bilateral occipital area, when subjects visually imagined texture sensations. The authors further proposed that the temporal lobe was the neural substrate related to imagining texture. Fallgatter, Mueller, and Strik (1997) used words which described specific tactile sensations to elicit subjects’ imagery. They found that the global field power was located in the posterior part of

the left hemisphere, which was thought to be associated with imagery. A closer look at these studies leads us to argue that the specific modality used for eliciting tactile imagery might have confounded the results. In Uhl et al.'s study (1994), the subjects were asked to visually imagine different tactile patterns after hearing a verbal prompt. The prompts were numbers which had been associated with specific texture patterns prior to the experiment: the temporal lobe is largely related to language processing. A similar explanation might also apply to the Fallgatter et al. study (1997). Similar differences (i.e. caused by retrieval strategies) have also been found in studies of visual imagery. According to Handy et al. (2004), although the same content of imagery was encouraged, the activation when imagery was elicited by nouns was left-lateralized, while that provoked by pictures was bilateral. Therefore, to avoid any interferences originating from retrieval strategies, the current study used imagery induced by the vibrotactile sense.

Only a few studies have employed direct imagery of a tactile sensation. Yoo et al. (2003) used a brush stroke (on the right palm, at a rate of ~ 2 Hz) to produce a gentle moving-touch sensation and asked subjects to imagine the same sensation when prompted. The results revealed activations at the contralateral primary and secondary somatosensory areas, which overlapped with those involved in actual tactile stimuli. Other neural substrates engaged were the left inferior parietal lobe (BA 40), left medial frontal gyrus (BA 6), and dorsolateral prefrontal areas in the left middle frontal gyrus (BA 9/46), which are thought to be responsible for the imagery process. There was no activation in the primary visual cortex and related areas, in contrary to the findings of Uhl et al. (1994). These observations further highlight the problems with the use of different modality for eliciting tactile imagery.

However, these problems do not yet seem to be settled, given that a study of tactile imagery of a tactile object, in which no visual imagery of the object was encouraged by the researcher, has shown some overlap with the neural substrate and particularly the object-responsive region (Prather, Votaw, & Sathian, 2004). Therefore, two possibilities arise: firstly, the neural substrate found is specific to the imagery of tactile objects and secondly, the results actually demonstrate a cross-modality "imagery network." The latter proposition is supported by the fact that the prefrontal area has been repeatedly shown to be involved in the maintenance of sensory working memory, retrieval of sensory information from the posterior cortex, and encoding of the stimulus, while the parietal lobe is activated when attention is required to coordinate vision (retinocentric), audition (head-centered), and touch (somatotopy) in external space and the location of the body in that space in order to take further motor action.

Therefore, this study investigated whether or not imagery of vibrotactile sense utilizes the same "imagery network" and content-specific associative memory (such as primary and secondary somatosensory cortex for vibration), using a vibration-induced imagery paradigm. This differs from Mechelli et al. (2004) insofar as the focus is on neural correlates during each of the imagery processes. To achieve this, event-related imagery was used.

Perception of Vibrotactile Sensation

In a recent study conducted in the Applied Cognitive Neuroscience Laboratory at The Hong Kong Polytechnic University, which focused on the recovery of sensori-motor sensation in post-stroke patients, none of the 60 patients studied scored below the normal range on the test of vibrotactile sensation (Chow et

al., under review a). The test involved applying vibrations at the tips of the patients' fingers using 30 Hz and 256 Hz tuning forks. The patients were asked to describe whether the sensation could be accurately felt. The results indicated all the subjects had intact vibration sensations in their fingers. Despite this, however, it is interesting to note that impairments were found to other sensations such as light touch and temperature, point localization, and texture discrimination.

Vibrotactile sensation is a basic component of cutaneous sense. Unlike moving touch and form perception, vibration can be perceived in a static form on the skin. There are four cutaneous mechanoreceptive afferent neuron types innervating the glabrous skin involved in the detection of vibration. They are the slowing adapting (SA1) afferents, which end in Merkel cells; rapidly adapting (RA) afferents, which end in Meissner corpuscles; Pacinian (PC) afferents, which end in Pacinian corpuscles; and slowly adapting type 2 (SA2) afferents, which are thought to end in Ruffini endings. Only the PC afferent can detect high frequency (100 – 1000 Hz) vibrations, while the RA, SA1 and SA2 afferents are responsible for signaling low frequency (below 100 Hz) vibrations, and the SA1 is mainly responsible for the detection of form and texture (Johnson & Yoshioka, 2002). The vibration signal is transferred through the dorsal column pathway to the somatosensory cortex. Previous neurophysiological studies have concluded that the vibrotactile sensation of high frequency (10 – 1000 Hz), mediated via the PC afferents, is perceived in the primary somatosensory cortex (SI) at the Brodmann's Area 3 and 1, which overlaps with other (higher) forms of tactile sensation such as form and texture. These sensations are mediated via the SA1 afferent (activate at the BA 3 only) (Paul, Merzenich & Goodman, 1972). As well as the SI, vibration has been found to activate the bilateral secondary somatosensory cortex (SII), the subcentral gyrus, the

precentral gyrus, the posterior insula, the posterior parietal regions, and the posterior cingulated gyrus (Francis et al., 2002; Stippich et al., 1999). It is plausible that training which is mediated by vibrotactile sensation — a lower form of sensation — could enhance the regaining of higher forms such as form and texture, which share common areas in the somatosensory cortex. The purpose of this study therefore is to investigate the neural processes associated with the imagination of vibrotactile sensation (as this is largely unimpaired among post-stroke patients) in two groups; one comprised of healthy older adults and the other of selected patients who had survived a recent stroke.

Event-Related Potential

In this study, as well as behavioral variables, event-related potential (ERP) was used to capture and analyze the processes associated with the imagery of vibrotactile sensation. ERP is a procedure which is capable of capturing neural activities occurring over msec, which is to say that it offers extremely good temporal resolution of neural activities (Yamamoto & Mukai, 1998). Furthermore, individual ERP are time-locked, with changes being related to a particular event. The technique provides summated electrical events produced by individual brain cells, giving rise to a broader view of neocortical activity that includes both superficial and deep sources at any orientation relative to the scalp.

ERP has been used by other studies looking at different cognitive functions, particularly those focused on attention and memory. Numerous such studies have suggested that attention modulates ERPs such as N250 and P300 (e.g. Kekoni, Hämäläinen, McCloud, Reinikainen, & Näätänen, 1996; Yamaguchi & Knight, 1991) while memory retrieval and maintenance processes elicit the more positive N400 and

P600 (e.g. Guillem, Rougier, & Claverie, 1999; Rugg & Doyle, 1994). Using the active oddball or discrimination methods, infrequent auditory deviant stimuli have been found to elicit a negative mismatch (MMN), N250 and P300 (Näätänen, 1992). Similar ERPs have been elicited for visual (Simson, Vaughan, & Ritter, 1977) and somatosensory stimuli (Kekoni et al., 1996). Wickens, Kramer, Vanasse, & Donchin (1983) demonstrates that the amplitude of P300 is related to the extent to which individuals attended to a stimulus while performing a secondary task. Because the latency of P300 can be extended to 800 ms depending on the complexity of the task, P600 is generally considered to be a delayed P300. The N400 is commonly found in complex recognition tasks. A more positive going N400 has been associated with the conscious recollection of stimuli which had been previously seen, such as faces, picture, words, and non-linguistic stimuli. This further suggests that N400 might relate to access to memory and/or context integration processes (Guillem et al., 1999; West & Holcomb, 2000).

The technique has also been used to study the neural processes of visual and motor imagery. Yamamoto and Mukai (1998) measured subjects' ERPs while they constructed images of alphabets. The results revealed that the imagery process had elicited a negative component at around 220 ms in the left frontal, central, and parietal areas. This probably indicated retrieval from working memory processes during generation of the mental image. Another study revealed that the imagery and execution of actual movements of the limbs elicited a similar N2 component. The manipulation of the target force and rate of force during the motor imagery was found to modulate the associated ERPs (Romero, Lacourse, Lawrence, Schandler, & Cohen, 2000). Therefore, we concluded that ERPs are a useful method for studying mental imagery and its neural correlate over time.

Objectives of the Study

The purpose of this study was to explore and reveal the neural processes associated with imagining a vibration, which is a basic form of tactile sensation. We used ERP, which has a high temporal resolution and thus is capable of differentiating the neural processes associated with the imagery. The task involved vibration stimuli transmitted through the skin, to minimize potential visual contamination of the imagery process. Brief vibrations of 250 ms duration each were used to elicit subjects' imagery process. The ERPs obtained from the imagery condition were compared with that from the passive stimulation condition. We hypothesized that tactile imagery would comprise two processes; imagery generation, involving access to the working memory, occurring earlier and including primarily frontal activities: and imagery maintenance, specific to the tactile modality, occurring later and involving the sensorimotor areas.

After obtaining data from a group of normal subjects, the same paradigm test was administered to patients with a stroke. This enabled us to study the effect of brain lesion on the processes of vibrotactile imagery.

The results of this study will shed light on 1) the processes associated with the "imagery network" and how it can be applied to tactile imagery; 2) the processes of tactile-specific imagery and the generalizability of Kosslyn's model of visual imagery to tactile imagery; 3) how the "imagery network" and sensory processes are affected by the brain lesions in the post-stroke patients; 4) the likelihood that post-stroke patients would benefit from imagery interventions; and 5) temporal information about the processes of tactile imagery.

CHAPTER III

METHOD

Introduction

This chapter describes the methods used to conduct the study. There were two parts to the research. The first aimed to investigate the neural processes associated with imagery of vibrotactile sensation in a group of normal older adult subjects. The second set out to examine the effects of brain lesions in post-stroke patients on these neural processes. Both phases used the same experimental designs and data collection procedures, which will therefore be described only once in this chapter.

Subjects

Normal older subjects

The study adopted a convenience sampling methodology (Portney & Watkins, 2000), in which appropriate subjects were contacted by the experimenter. The individuals approached were non-academic supporting staff in the Hung Hom area, near The Hong Kong Polytechnic University. The selection criteria for the subjects were:

1) no history of sensory or motor deficits;
2) no signs or history of other neurological or psychiatric diseases;
3) no reported active medical problem such as diabetes;
4) had received at least 3 years of education;
5) similar vibration threshold as tested by the vibrometer (described below);
6) of right hand dominance.

Ethics approval was obtained from both the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University and the Faculty of Medicine, The University of Hong Kong (Appendix I). Contact was made with a total of 13 potential subjects, one of whom declined to participate. Each was screened according to the selection criteria and the purpose of the research was explained. Informed consent was obtained (for consent forms see Appendices II and III). All subjects were remunerated HK$ 200 after completion of the experiment.

The sample size of this part of the study was decided by reference to previous studies (e.g. Lacourse, Cohen, Lawrence, & Romero, 1999; Yahagi & Kasai, 1999; Yamamoto & Mukai, 1998). A power analysis was also conducted in which the mean differences between the imagery and perception conditions at the P600 of Cz in another study were used to estimate the number of subjects required for this study (Chow et al., under review b). A sample size of 12 gave a power of 0.80 [alpha = 0.003 (for 14 channels), beta = 0.20] and an effect size of 1.57 (Machin, Campbel, Fayers, & Pinol, 1997).

Post-stroke subjects

Similarly, a purposive sampling method was used to recruit patients with pre-determined medical and demographic characteristics (Portney & Watkins, 2000). The criteria were chosen to match those of the normal older subjects:

1) aged 40 – 70, male or female;

2) had suffered infarction or hemorrhage stroke;

3) in active rehabilitation phase of recovery (about 1 – 2 months post-stroke);

4) cognitive function within the normal range as defined by the Mini Mental State Examination (MMSE);

4) intact light touch sensation, tested by monofilament;

5) intact vibrotactile sensation, tested by 30 Hz and 256 Hz tuning forks;

6) had received at least 3 years of education.

The exclusion criteria were:

1) presented with significant aphasia and communication problems;

2) premorbid history of sensory or motor deficits;

3) presented with psychiatric symptoms such as depression and schizophrenia;

4) suffered from transient ischemic attack;

6) evidenced with peripheral neuropathy by history;

7) lesions in the brain could not be identified with Computerized Tomography (CT) and/or Magnetic Resonance Imaging (MRI).

Patients who had received a diagnosis of stroke and been admitted to the stroke ward of Tung Wah Hospital were screened for participation in the study.

Justification of the selection criteria

The selection criteria were intended to control for possible confounding variables. The first set of criteria set out to maximize the homogeneity of the subjects in terms of their diagnostic group, age, educational level, phase of stroke, and previous medical history. The second set intended to maximize the likelihood that the subjects would be able to perform the imagery tasks. This required them to have the ability to detect and discriminate between different vibration sensations. Furthermore, the subjects had to be able to learn the experimental paradigm and communicate effectively with the experimenter. The orientation, attention, and

repetition items of the MMSE were intended to identify subjects who could achieve these goals.

Imagery and Control Tasks

The imagery trials adopted a match-to-target design, in which subjects were required to imagine the vibrotactile sensation after the "target" vibration had been given, and then match the second vibration stimulus with the "target". These trials were designed to prime the imagery more effectively. The effectiveness of mental imagery has been shown to be better when there is a minimal pause between imagery and actual stimulation (Driskell, Copper, & Moran, 1994). Therefore, imagery was required immediately after the first vibration stimulus. A period of 250 ms was chosen as previous studies have demonstrated that stimuli 250 ms apart can be detected successfully (Eimer & Driver, 2000; Kekoni et al., 1996). To further help to ensure subjects produced imagery after the first vibration stimulus, we chose 6 stimuli of different frequencies and intensities. This minimized the chance that the subjects would complete the matching task merely by recalling the stimuli from memory but without rehearsing them. The control task was designed to mimic the imagery tasks and at the same time to control for the confounding variable. A signal detection design was used to maintain a similar level of attention between imagery and control. Furthermore, to avoid contaminating the ERP with motor potentials, the subjects were instructed to press the computer key after the second sound signal.

The six vibratory stimuli were divided into two levels of frequency (150 and 300 Hz) by three levels of intensity (20, 50, 125 m/s^2) (Table 3.1). The three levels of intensity were each set at 1.5 Weber's fraction apart. The stimuli were generated by the experimental set-up described below.

Table 3.1

Intensity and frequency of vibrotactile stimuli.

1st pair	2nd pair	3rd pair
Frequency (Hz), Intensity (ms^2)		
150, 20	150, 50	150, 125
300, 20	300, 50	300, 125

Imagery task

In the imagery task, each trial comprised an image of the target (or 1st) stimulus followed by discrimination of the match (or 2nd) from the target (Figure 3.1). The duration of each trial was 10.5 seconds. The trial began with the subject hearing a 500 ms sound signal which was followed by a 500 ms waiting time (for preparation). The subject then received a 250 ms vibration stimulus, called the target stimulus. The target stimulus was randomly selected from the pool of the six stimuli and was very brief. Right after the signal diminished, the subject began to actively imagine what had been felt, for a period of 4000 ms. This was followed by presentation of the second 500 ms sound signal which indicated the beginning of the discrimination phase of the trial. Correspondingly, there was 500 ms waiting time before the delivery of another 250 ms vibration stimulus, called the match (or 2nd) stimulus. Unlike the target stimulus, the match stimulus was not randomly selected but had been chosen from either the same pair or its neighboring pair. In other words, if the target stimulus belonged to the 1st pair, the choice of match stimulus could only have come from the 2nd pair but if the target belonged to the 2nd pair, the match could have come from either the 1st or 2nd pairs. This design sought to increase the difficulty of the task while at the same time minimizing the chance that the subject

could simply guess the desired response. The subject was required to detect the match stimulus and compare it with the target stimulus which he or she had rehearsed earlier in the trial. He or she responded by pressing one of two key buttons on a keynote with the left hand. The key buttons were the “N” and “M” keys on a standard computer keyboard and were labeled “Yes” and “No” respectively. Pressing the “Yes” key indicated that the stimuli came from the same pairs, whilst pressing the “No” key indicated the opposite. The time limit for the subject to make a response was set at 4000 ms. The beginning of each trial was controlled manually by the experimenter. No feedback about accuracy was given. One task block contained 10 trials and each subject completed a total of 15 imagery blocks. The sequence of the blocks (together with the control blocks) was randomized and counterbalanced. Rest breaks were allocated between blocks and also given on the subject’s request.

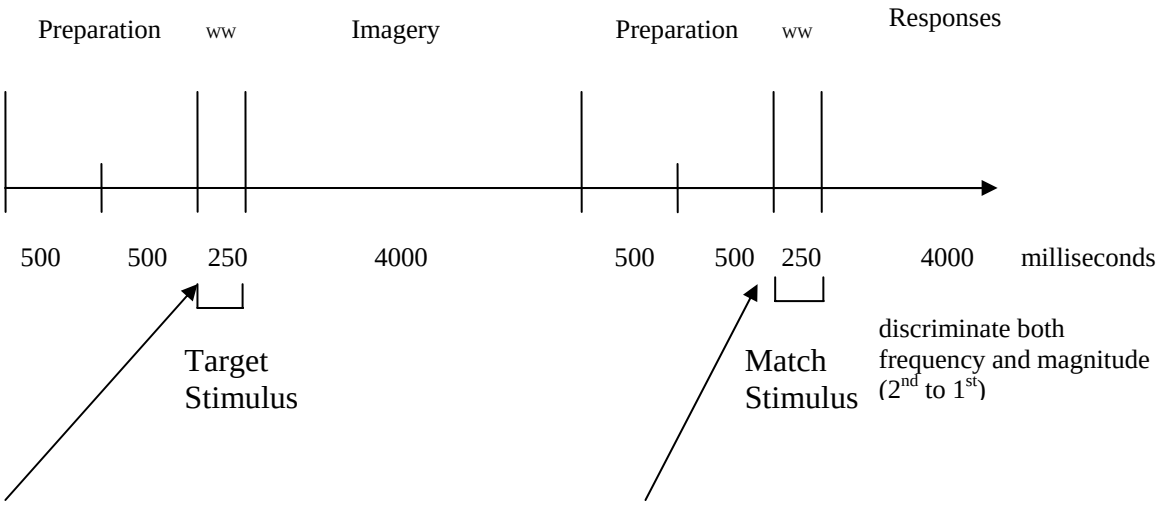
Control task

The control task only covered the first phase of the imagery task (Figure 3.2). It lasted for 9.75 seconds. Similar to the imagery task, the trial was prompted by a 500 ms sound signal followed by a 500 ms waiting time. A 250 ms vibration stimulus randomly selected from the available pool was then delivered. Different from the imagery task, the stimulus may (80%) or may not be presented (20%). After detecting the stimulus (or in the absence of one), the subject was instructed not to engage in imagery but to wait for 4000 ms for the next sound signal. After hearing the second 500 ms sound signal, the subject responded, again by pressing one of two keys to indicate whether or not the vibration stimulus had been delivered. The same “Yes” and “No” button as described above were to be pressed, a “Yes” response

indicating a vibration had been detected, and the “No” button the reverse. There were 10 trials in each control block and each subject completed a total of 10 blocks.

Figure 3.1

Design of the imagery trial.

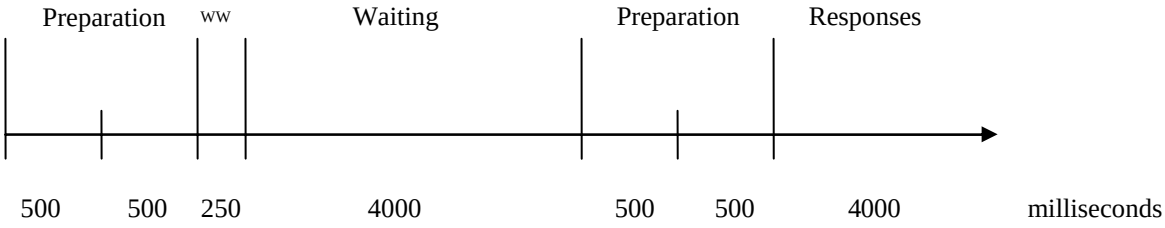


1st pair	2nd pair	3rd pair
Frequency (Hz), Intensity (ms^2)		
150, 20	150, 50	150, 125
300, 20	300, 50	300, 125

Note: “ww” represents the vibration stimulus.

Figure 3.2

Design of the control trial.



Note: “ww” represents the vibration stimulus.

Generation of Vibration Signals — Experimental Set Up

Vibrations of varied frequencies and intensities were generated using a vibration exciter (Bruel and Kjaer, 4809 Naerum, Denmark) and a signal generator (BK Precision type 3040). An acrylic plastic rod was attached to the table of the vibration exciter with its axis parallel to the direction of vibration. An accelerometer (Bruel and Kjaer, type 4381) was attached to the top of the rod. This was connected to the charge amplifier (Bruel and Kjaer, Type 2635) and a cathode ray oscilloscope (Philips PM 3350A) to enable monitoring of the frequency and magnitude intensity of the vibration. The area of mechanical contact to the subjects' skin was controlled at about 3 cm^2 using a plastic dome-shaped tip firmly attached to the top of the accelerometer (see Figure 3.3). The magnitude of the vibration was expressed in term of ms^{-2} acceleration. This was calibrated from the voltage displaced on the oscilloscope and multiplied by the value suggested in the technical manual of the charge amplifier (Technical Manual of Bruel and Kjaer, Type 2635).

Positioning of Subjects

Subjects were seated comfortably in front of the vibration exciter. The vibration stimulus was delivered to the first interrosseus muscle near the palmar base of the right index finger (Figure 3.4). This area was chosen because it has been shown to have the greatest density ratio of PC afferents (with temporal sensitivity 100 – 1000 Hz for vibration reception) compared to other mechanoreceptors (Johansson & Vallbo, 1979). The arm and hand were stabilized in a foam support which was mounted onto a vibration-isolated table. In order to ensure a uniform magnitude of vibration was applied, the height of the table supporting the arm was adjusted according to the reading from the cathode ray oscilloscope. Skin

temperature was monitored throughout the experiment at above 30 ºC. The subjects wore headphones which delivered pseudo-white masking noise (bandwidth 100 Hz to 15 kHz) throughout the experiment. This was to obscure any possible sounds related to the vibratory stimuli.

Figure 3.3

Diagram of the vibration generation apparatus. The left shows the vibration exciter[1], signal generator[2], signal generator[3] and cathode ray oscilloscope[4]. The right shows the position of the acrylic plastic rod[5], which was attached to the table of the vibration exciter[6] with its axis parallel to the direction of vibration. An accelerometer was attached to the top of the rod. Mechanical contact with the skin was controlled at about 3 cm^2 using a plastic dome shaped tip firmly attached on the top of the accelerometer.

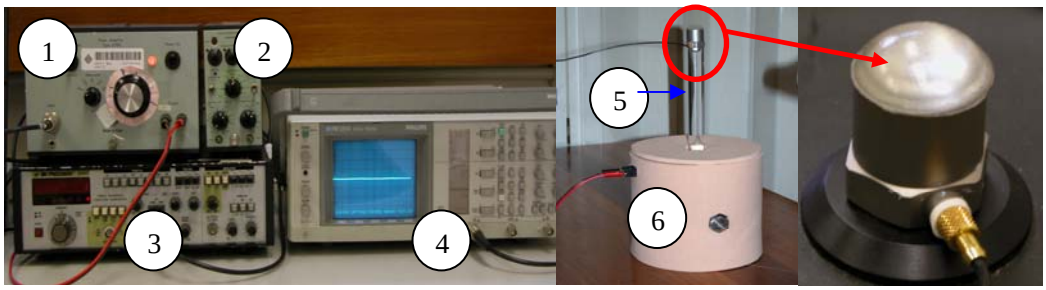


Figure 3.4

The seating position of the subject. The vibration was delivered to the first interrosseus muscle near the palmar base of the right index finger.

Acquisition of Event-Related Potential (ERP)

The electroencephalogram (EEG) of the subjects was recorded using a 32-array of silver-silver chloride electrodes placed in an extended International 10-20 System (Jasper, 1995). The NuAmps Digital DC EEG Amplifier (NeuroScan Labs, Sterling, VA) was used for data capture. Vertical electro-oculograms (EOG) were recorded to monitor eye movements. The EEG was referenced to the right mastoid process, and a ground electrode was placed on the forehead. The signals were amplified with a band-pass filter of 0.1 – 100 Hz, and sampled at a rate of 1024 Hz. Electrode impedance was kept at $\leq$ 5 KOhm.

Noise Reduction of ERP Data

When EEG signals were captured in this experiment, there were non-biological and biological artifacts. The non-biological artifact can originate from other electrical devices at the data collection site, such as computer monitors,

overhead lighting, power cables, and power strips. In this study, attempts were made to clear all the electrical appliances from the subjects, and the NuAmps Digital DC EEG Amplifier, to minimize the noise from the regular 50 Hz main electrical current.

Biological artifacts may include the electromyographic (EMG) activities that occurred near the recording sites arising from gross head/body movement, eye movements, or eye blinking of the subjects. Reduction of these types of artifacts can be tackled with a prophylactic method. In this study, biological artifacts were minimized by instructions given to subjects on sitting posture, on avoiding large body movements, and on relaxing as much as possible. The subjects were instructed to fix their eyes on a near object, avoid excessive movements during the resting period, and close their eyes when they underwent the experimental and control trials. Because of reduced visual input, closing the eyes could elicit slow-frequency eye movements, and increased alpha activity. Noises associated with these eye movements were reduced by conducting the artifact rejection and averaging process. Epochs with voltage exceeding -100 to +100 μV were rejected. The method proposed by Semlitsch, Anderer, Schuster, and Presslich (1986), and Picton et al. (2000) was used for removing the ocular artifacts associated with eye blinks. The method combines regression analysis and averaging, and assumes that the potentials associated with ocular artifacts are the linear function of the EOG amplitude. It also assumes that the ocular artifacts contain only EOG signals but not other EEG signals.

The process of removing the ocular artifacts, using the method just described, starts with averaging the signals captured from the ocular channel, which exceeded 10% of the maximum eye movement potentials. From this average, the transmission coefficients can be computed by estimating the covariance of the averaged potentials of the ocular channel with other EEG channels:

$$b = \text{cov}(EOG, EEG) / \text{var}(EOG)$$

where b is the transmission coefficient, and cov and var are the covariance and variance statistics. The transmission coefficients were computed separately for all EEG channels.

Then EOG is subtracted from the EEG channels on a sweep-by-sweep, point-by-point basis in the following manner:

$$\text{corrected EEG} = \text{original EEG} - b \cdot EOG$$

As these transmission coefficients might change over time, and the VEOG channel might also capture potentials associated with eye-blinking activities, the possible distortions brought about by these factors when computing the EOG transmission coefficients can be minimized by conducting a low pass filtering or by averaging the recordings, using the onset of the eye movement for synchronization. One drawback to using the combined regression analysis and averaging was that the subtraction of transformed (or scaled) waveform (by multiplying the EOG recordings with the transmission coefficients) from the scalp EEG recordings could have removed a portion of the frontal EEG signals as well as the EOG.

A new approach to eliminating eye artifacts in multiple electrode data uses a source component analysis (Berg & Scherg, 1991, 1994). This method can provide a better estimation of the eye activity (Jung et al., 2000). However, the implementation of this method required the use of six or more peri-ocular electrodes for monitoring the EOG to obtain an adequate source component for noise reduction. As the older

subjects recruited in this study had experienced difficulties with the peri-ocular electrodes, this method was not adopted in the present study.

ERP Data Analysis Procedures

Experimental blocks with a vividness score of less than 4.0 or an attention score of less than 5.0 were excluded from the analysis (see the instrumentation section below for details). The continuous EEG was filtered with a zero phase shift band-pass filter of 0.5 – 30 Hz (24 dB/Oct), and then corrected for ocular movements. The regression technique built in the Scan 4.3 software was selected for the ocular movement correction (Semlitsch et al., 1986). The epochs that captured the correct responses were extracted. The extracted epochs with a voltage larger than 100 μV or smaller than -100 μV were rejected before the averaging. The averaged epochs covering the periods 100 ms before and 1300 ms after the presentation of the target (or 1st) vibration stimuli were selected for further statistical analysis. All the averaged ERPs were baseline corrected against the pre-stimulus interval (-100 ms).

Modeling of ERP sources

Maps of scale voltage were obtained (Perrin, Pernier, Bertrand, & Echallier, 1989) for the ERP components in the imagery-minus-control condition. Estimation of the dipolar sources, based on the ERP components, was carried out with the Brain Electrical Source Analysis (BESA version 5.0). The residual variance (RV) between the model and the observed spatial-temporal component distribution was minimized by the iterative changes in the location and orientation of the dipole sources (Scherg, 1990). The energy criterion was set at 15% for reducing the possible interactions among the dipoles identified, and the separation criterion was set at 10% for

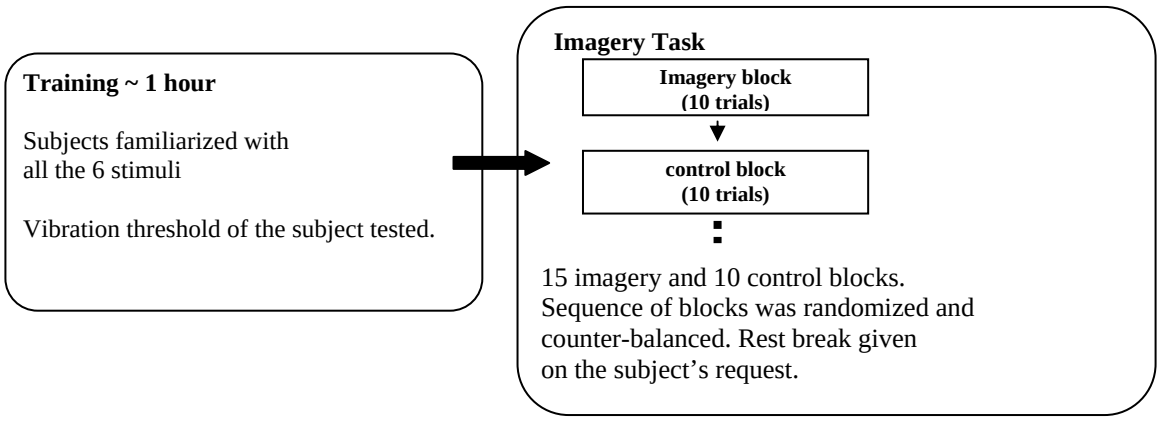
optimizing the separation of the source waveforms across time. In the computation processes, BESA assumes a fourshell elliptical head model. Single dipole or pairs were fit sequentially over a specific latency range to correspond to the distinctive components in the waveform.

Data Collection Procedures

The experimenter who had screened the subjects also conducted all the behavioral testing and ERP measurements. The procedures of an ERP session are summarized in Figure 3.5. Before beginning the experiments, the subjects completed a test of the vibration threshold of the right hand, using the experimental vibration exciter and accelerometer (see Figure 3.4). Each also completed a battery of tests designed to assess the basic cutaneous sensation on the thumb, third, and fifth fingers of both hands. Details of this assessment can be found in the next section. Each subject completed one hour of pre-experimental training intended to develop familiarization with the stimuli. He or she then completed a total of 15 blocks of imagery and 10 blocks of control tasks. After finishing one block, the subjects reported: 1) the vividness of the vibrotactile images which had been generated, 2) the ability to attend to the task. Depending on the progress the subject was making, the tasks and ERP measurement were completed within one or two half-day sessions. In the latter schedule, the subjects completed the familiarization process and 25 imagery task blocks (including control blocks) in one day, undertaking the remainder of the experiment the day after. This arrangement was necessary because most of the older subjects, and particularly the post-stroke patients, were unable to tolerate an experimental session lasting longer than 3 hours. The sensory assessments were conducted within three days of the task sessions (either before or after).

Figure 3.5

Summary of the ERP session.



Instrumentation

Imagery and attention questionnaire

The purpose of designing this customized questionnaire was to monitor the extent to which the subjects perceived their performance on the imagery tasks. Pervious study has shown that both the imagery vividness and attentional level of the subjects modulated the event-related potentials captured during the imagery tasks (Finnigan, Humphreys, Dennis, & Geffen, 2002). They were two single-items with each of them measured the perceived imagery ability and attentional level. The subjects were required to give responses to the two items after completing one task block. The same procedure was repeated in each block. The wording of the vividness of imagery item was referenced to that in the kinaesthetic imagery scale of the movement imagery questionnaire (Hall & Martin, 1997). The item was: "Please rate the ease/difficulty with which you were able to do this mental task", rating on a 7-point Likert scale with "1" indicating very easy to imagine the vibrotactile sensation and "7" indicating very hard to imagine the vibration sensation. The attentional level

item was: “Please rate the attentional level during the imagery tasks” on a 11-point Likert scale with “0” indicating the lowest level of attention and “10” indicating the highest level of attention.

Sensory testing

The sensory testing was used to test the integrity of the subjects’ tactile sensation, particularly for the stroke survivors. It was important to ensure that the post-stroke subjects, who were known to have brain lesions, did not present with problems in perceiving tactile sensation including vibration. The test used in this part of the study was adopted from the neurological examinations developed by Kim and Choi-Kwon (1996). The protocol covered basic sensations such as pinprick, temperature, touch, and vibration: this examines the ability to receive sensory stimuli. These modalities were tested on the thumb, third, and fifth fingers of both hands, since these fingers activate a larger area of the topographically organized primary somatosensory cortex, and thus can reveal any small brain lesion caused by stroke. Other multi-modal discrimination senses were also tested; texture discrimination (TD), position sense (PS), stereognosis (ST), point localization (PL), and two point discrimination (2-PD). This element of the test focused on the subject’s ability to manipulate the sensory information obtained, and was tested on different parts of both the left and right hands depending on the task requirements. The subjects were blindfolded throughout to avoid the possibility that they could use visual information to assist in performing the tests.

The testing of the vibration sensation used two tuning forks at 30 and 256 Hz. The ability to detect both vibrations indicates no damage to any of the four mechanoreceptors. Failure to detect the 256 Hz vibration indicates damage to the

high frequency perception, which is modulated by the Pacinian afferent (Johnson & Yoshioka, 2002). Each of the tests was administered separately to the subjects. The fork was struck against a rubber surface and then held tangentially against the pad of one finger while still vibrating. The sequence of fingers was randomized. The subjects were asked to determine whether or not there was a vibration.

The testing of light touch sensation used a Semmes-Weinstein Monofilament (North Coast Medical Inc, California). Four monofilaments ranging in diameter from 0.06 to 1.14 mm were employed. Each was embedded in a plastic rode with a handle. The free end of each filament was 38 mm long. The monofilament corresponding to a normal touch sensation was tested on each finger first. If the subject failed to feel the touch, a thicker monofilament was used next. The inter-stimulus interval was 3 – 8 s (Mackinnon & Dellon, 1988). The sequence of testing on each finger was randomized. The monofilament was pressed at a 90° angle against the skin until it bowed and held there for 1.5 s. As soon as the patient perceived the pressure of the stimulus, he or she responded by saying the word “touch”. If he or she did not respond to the first application, a minimum of two further attempts were made.

Temperature sensation was tested using an aluminum rod apparatus set at either 10 °C or 50 °C. These two temperatures were chosen because they can be successfully distinguished by older adults (Dyck et al., 1993). The two rods were touched against the finger pad consecutively at 3 s intervals. During each strike, the rods were moved back and forth (3 cm) along the shaft of the fingers. The subject responded by identifying either the first or the second rod as hotter, or alternatively that no difference had been perceived.

The testing of pinprick (or pain, sharp/dull) sensation used a gauge needle according to the procedures described in Horch, Hardy, Jimenez, and Jabaley (1992).

Again, each finger was tested in a pre-determined random sequence. The needle was propelled at a perpendicular angle into the skin at a ramp speed. At low intensity, the stimulus is perceived as dull; as it is increased, there will come to a point at which it is perceived as painful. The depth to which the needle had to go to be perceived as pain was about 2 mm. The subjects were asked to indicate when they first felt pain. If the subject did not respond to the first application, a minimum of two further trials was administered.

Constant 2-PD was measured using the two-point esthesiometer known as the Disk-Criminator (largest distance between two points 8 mm and smallest 2 mm). Each finger was tested separately and the test sequence was randomized. The two prongs were held transverse (at right angles) to the longitudinal axis of the skin surface being tested. The experimenter asked the subject to say “one” if they felt the touch as one point and “two” if they felt it as two. The test began with a distance of 4 mm; if the subject failed to discriminate at this level then it went to 5 mm, otherwise to 3 mm. The threshold for 2-PD was defined as the point at which 70% accuracy was achieved by the subject.

The TD test used was based on that developed by Carey et al. (1993) with some modifications. Thirteen metal molds with ridged surfaces were produced. The finely graded surfaces were marked by ridges at set spatial periods ranging from 1500 to 3000 μm (each period increased by 50, 100, or 150 μm), with a constant ratio of ridge to groove. The patients were required to compare a selection of these surfaces (i.e. with different spatial periods) against a 1500 μm control surface, indicating which was the rougher texture. Using a predetermined random sequence, three different sets of six plates were administered, each housing six sets of textured surfaces, so that the experiment covered the entire range. Differences in the surface

spatial periods were expressed as percentage, ranging from 3.33 to 100 [Percentage Spatial Increase = (X - 1500) / 1500 x 100]. Responses were recorded as correct or incorrect for each set of surfaces. The TD threshold was defined as the point at which the patients were 66% accurate in their responses.

The PS test quantified the ability to indicate wrist position following an imposed movement. A total of eight predetermined wrist angles (both flexion-extension and abduction-adduction) were tested. The position of the wrist was determined by a semiconductor laser device attached to the dorsum of the hand aligned to the third finger. The laser beam emitted from the device was shot onto a perpendicular white surface located 30 cm in front of the wrist (measured from the base of the metacarpal bones with the forearm and wrist lay in a horizontal position). The wrist joint position was θ, where $\tan \theta = x / 30$ cm (x is the vertical distance between the laser beam spot on the white surface and the baseline). The subject was blindfold throughout the entire testing procedure. The forearm of the subject was rested onto a table surface with the wrist placed on the edge of the table freeing the hand from any support. The examiner first moved the subject's wrist from the neutral position (horizontal and in alignment) to one of the eight different angles: 45°, 30° and 15° in flexion (downward); 15°, 30° and 45° in extension (upward); and 15° abduction (hand in prone, toward midline), or 15° adduction (hand in prone, away from midline). The examiner instructed the subject to remember the new wrist position and then moved the wrist to the original neutral position. The subject was then required to reproduce the position of the wrist which they felt and remembered. The point produced by the laser device at the time when the subject reproduced the position was recorded. The same procedure was repeated for all the angles, and the left and right hands. The differences between all the tested angles and the angles

reproduced by the subject were averaged to form the index of joint position sensation deficit.

For the ST test, 12 objects (bottle cap, box, cotton, eraser, pencil, extension plug, key, screw, spoon, coin, safety pin, and watch) which differed in size, shape, weight, and texture were first named by the subjects before being placed on their hand. The subjects were then asked to close their hand (or the examiner would do this for them) so as to feel them carefully, and then to respond with the names of the objects or alternatively with a description of their use.

For PL, the method described in Corkin, Milner and Rasmussen (1970) was used. Point discrimination was defined as the ability on localizing touch sensation by differentiating whether two successive touch stimulations (well above the pressure threshold) were localized at the same or different points on the palm. An eight-spoked pattern of dots was stamped on each palm. The distance between the dots was 3 mm in each of the four 3 mm long diagonals. The subject was told that his or her palm would be touched twice in succession with a blunt probe, and that he or she should say “same” if both stimuli were at exactly the same point and “different” if they were at different points. Each stimulus lasted less than 1 s, with an interval of approximately 1 s elapsing between the two comparison stimuli. The first of the two was always at the center point, and the second at each point along the eight spokes, coming in a different order but always alternating four stimuli outward from the center with four inward. The order of testing was constant for all subjects. For each direction, the farthest point from the center reported as the same as the center was taken as the score. The general error of localization was defined as the mean distance from the center of these eight points with the maximum threshold arbitrarily set at 30 mm.

On the basic sensory test, the subjects were graded as normal if they could report the stimulus correctly; otherwise, they were graded as abnormal. The only exception to this was the light touch sensation where the subjects were graded as normal, diminished light touch, diminished protective sensation, or loss of protective sensation, as stipulated in the industrial guidelines (see appendix IV). For the discriminative senses, the patients' deficits were graded as slight, moderate, or severe for each. The lower limit was based on the performance of normal control subjects. The upper limit for each test was determined by the maximum deficits (ST, 0; TD, 100% spatial increase; PL, 30 mm; 2-PD, > 8 mm; PS, 26°) manifested by the patients. The deficit was considered slight when it was less than 34%, moderate when 34% to 66%, and severe when above 66% of the maximum.

Statistical Analysis

The results for the subjects in the normal and stroke groups were analyzed separately. For the normal subjects, to avoid loss of statistical power, a total of 14 electrodes were selected for analysis: five in the right hemisphere (F4, C4, P4, O2, T8), five in the left (F3, C3, P3, O1, T7), and four in the midline (Fz, Cz, Pz, Oz). These sites are believed to be associated with imagery and somatosensory stimulation (Yoo et al., 2003; Uhl et al., 1994) The ERPs of the imagery and control conditions were compared. A 2 x 4 repeated measure ANOVA was conducted to test the differences in amplitude and latency between Condition (imagery versus control) and Site (4 midline electrodes). This procedure was rerun for a 2 x 2 x 5 design between Condition, Lateralization (left and right), and Site (5 lateral electrodes). Huyhn-Feldt values were used to correct for violations of sphericity, and post-hoc tests were Bonferroni corrected.

For the post-stroke patients, the grand average of the ERPs was obtained in the same way as for the normal older subjects. The comparisons of the ERPs obtained from individual post-stroke patients and from the grand averages derived from the norm group provided information on the extent to which brain lesions as a result of the stroke would modulate the imagery process. The approach we adopted for the comparison was derived from that used in Marchand, D'Arcy and Connolly (2002). The basic idea is to compute group distribution parameters (norm values) for the imagery-related ERPs based on the data collected from the norm group. The values of the ERPs obtained for each of the post-stroke patients are then compared with grand average values and the individual differences accommodated by incorporating the within-group variability in terms of confidence intervals. The type I error of post-hoc comparisons was adjusted with the Bonferroni method ($p = 0.050 / 14$ electrodes).

The ERPs of the subtracted imagery-control waveform were used. Point-by-point t-test (imagery minus control) was computed on the ERPs within the components' time windows for each subject (norm group and the three post-stroke patients). The t-values produced from the point-by-point t-tests within each time window were averaged. The same procedure was repeated for all 14 electrodes for each subject. In other words, each subject had a total of 14 mean t-scores for each component, hereafter referred to as the derivative scores. The mean (and SD) of the derivative scores were computed for the norm group and the 99.7% confidence intervals built for each. The 99.7% confidence interval is a conservative one which takes account of both within-group variability and multiple post-hoc comparisons. Significant differences in ERP components between post-stroke patients and the norm group were defined as occurring where the derivative scores of the former fell

outside the upper and lower limits of the 99.7% confidence intervals of the latter.

CHAPTER IV

RESULTS

Introduction

This chapter is divided into four parts. The first presents the demographic characteristics, sensory test performances, and the results of the imagery experiment participated in by the normal older subjects (norm group). The second presents the same results obtained from the three post-stroke subjects. The results of the post-stroke subjects will then be compared to that of the norm group.

Demographic Characteristics of Subjects (Norm Group)

Twelve healthy older adults (6 males, 6 females, mean age = 56.8, SD = 7.1) participated in the study after giving their informed consent (Table 4.1). The majority of the subjects were retired. The occupations of the rest of the subjects varied from blue-collar worker to health care professional. All of them had received at least a primary school education.

Table 4.1

Demographic characteristics of the norm group (N = 12).

Characteristics	Counts
Mean age (SD)	56.8 years (7.1)
Gender	
Male	6
Female	6
Occupations	
Retired	7
Unskilled manual laborer (e.g., cleaner)	3
Skilled technical worker (e.g., facility maintenance worker)	2
Professional (e.g., nurse)	1
Educational Level	
Primary	5
Secondary	6
Tertiary	2

ERPs of Norm Group (Imagery versus Control Tasks)

The mean response time of the normal subjects in the matching task was 1456 ms (SD = 199), and the mean accuracy rate was 67.0% (SD = 5.2). On average, the mean correct trials were 101 out of a total of 150. Because no subject reported an imagery vividness more than 4 or an attention score less than 5, the epochs of all subjects were included in the subsequent analysis.

The morphology of the ERPs during the first 1300 ms, between the imagery and control conditions, was similar (see Figure 4.1). The grand-averaged ERPs were

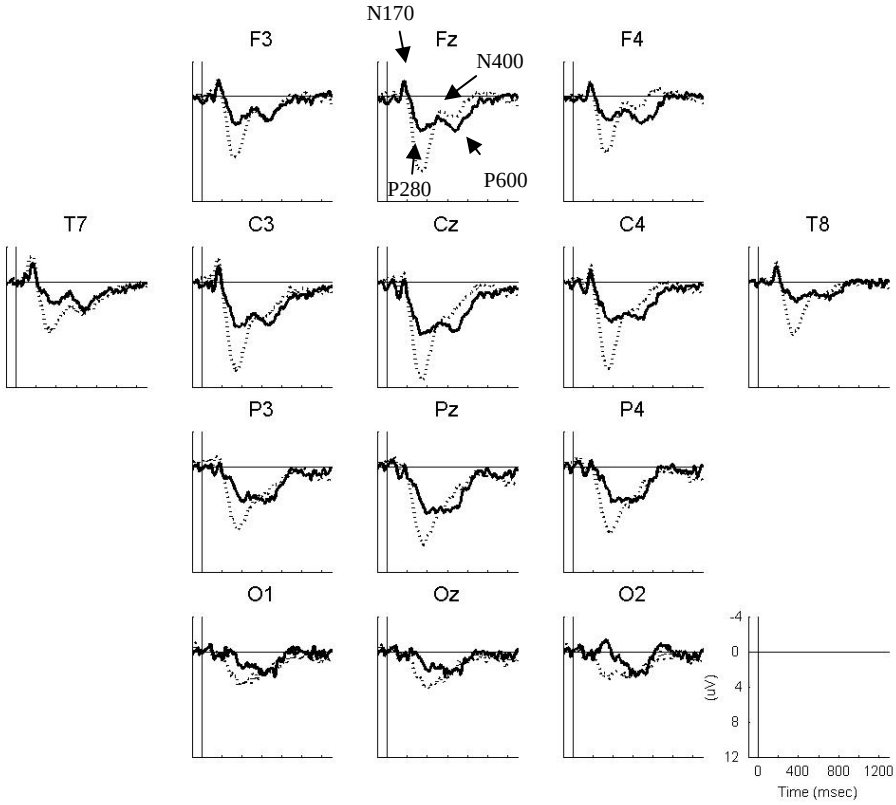
reliably identified as composed of four peaks: N170 (150 – 200 ms), P300 (280 – 390 ms), N400 (480 – 620 ms), and P600 (640 – 970 ms). These peaks were identified in all sites except O1, Oz, and O2 in the imagery condition. In the control condition, the P300 component was found in all the electrodes, while the N170, N400, and P600 components were less prominent than in that of the imagery condition at the parietal and occipital areas. The naming of the peaks was according to their latencies and polarities.

The amplitude of the ERPs identified was defined as the average amplitude across the time window constructed for the ERPs. Peak amplitudes were not used here because the latency of a peak was relatively more difficult to identify across electrodes and subjects. In addition, the mean amplitude was more stable than the amplitude at a fixed latency. According to previous studies, a time window can be derived from the peak latency of grand mean waveforms or from the components of interest (Picton et al., 2000). In the case of the latter, the time windows are defined arbitrarily even though no clear peaks can be identified. The objectivity and the reliability of the determination of the time could be assured in the following ways. First, the grand-averaged ERPs of the control condition were subtracted from those of the imagery condition. The largest amplitude differences found in the subtracted waveforms formed the basis of peak identification. The latencies of these peaks were then obtained. The same procedure was repeated for each electrode site. The latencies of the peak amplitude obtained from all the sites were collated. The mean and standard deviation of the latencies were computed. For the N170 and N400 components, the window was constructed by using one standard deviation above and below the mean latency. In the P300 and P600 components, the window was constructed by using two standard deviations above and below the mean latency. The

window set for N170 was 158 – 193 ms, for P300 it was 259 – 382 ms, for N400 it was 488 – 614 ms, and for P600 it was 640 – 942 ms. These windows were used for the rest of the statistical analyses presented in the latter part of this chapter.

Figure 4.1

Grand-averaged ERPs, corresponding to imagery of vibratory stimulation (solid line), and its control condition (dotted line), at 14 electrodes from -100 ms to 1300 ms. There were recognizable differences in the P300, N400, and P600 components.



The N170 component

The N170 component in both the control and the imagery conditions had a maximum at the frontal central sites as shown in Figure 4.1. The amplitude of the

control condition was very similar to that of the imagery condition. Since N170 cannot be identified at O1, O2, and Oz, the comparisons of their amplitudes and latency included only electrodes in the frontal, central, parietal, and temporal areas. The results revealed a significant main effect of Site on modulating the amplitudes of N170 (F (2, 24) = 3.64, p = 0.006). Follow-up analysis showed that amplitudes at Fz were larger than Pz (p = 0.038) in the control condition. Other comparisons were not statistically significant. In the latency comparisons, only the main effect of lateralization was found significant (F (1, 11) = 9.50, p = 0.010). Post-hoc analyses revealed that the latency at C3 and T7 was significantly shorter than that at C4 and T8 (p = 0.002 and p < 0.001 respectively) in the control condition. Other comparisons were not statistically significant.

The P300 component

The P300 component in both the control and the imagery conditions had a left central frontal maximum, as shown in Figure 4.1. The amplitudes of the control condition were more positive than those of the imagery condition in nearly all the sites, especially the right frontal and central areas. The ANOVA results revealed significant differences in the amplitudes (but not the latency) of P300. In the Condition x Site (midline) comparisons, the Condition (F (1, 11) = 35.41, p < 0.001), Site main effects (F (3, 33) = 22.84, p < 0.001), and the Condition x Site interaction effect (F (1, 58, 17.4) = 4.82, p = 0.006) were significant. In the Condition x Lateralization x Site (lateral) comparisons, only the Condition (F (1, 12) = 41.69, p < 0.001), Site (F (2.72, 29.94) = 22.27, p < 0.001), and Condition x Site interaction effects (F (2.58, 28.41) = 4.03, p = 0.020) were statistically significant. The results

of post-hoc analyses of both ANOVAs for testing the midline and lateral sites are summarized in Table 4.2.

Table 4.2

The pair-wise post-hoc analyses of the P300.

Main effect	Condition	Sites	p level	Sites	p level
Condition	(Imagery <	F3	< 0.001	P4	< 0.001
	Control)	F4	< 0.001	Pz	< 0.001
		Fz	< 0.001	O1	< 0.001
		C3	< 0.001	O2	0.008
		C4	< 0.001	Oz	0.020
		Cz	< 0.001	T7	< 0.001
		P3	< 0.001	T8	< 0.001
Lateralization	Imagery	C4 < C3	0.015		
	Control	-			
Site	Control	F3 > O1	0.001	C4 > O1	< 0.001
		F4 > C4	0.004	C4 > T7	< 0.001
		F4 > O2	0.009	Cz > Pz	0.008
		Fz > Oz	< 0.001	Cz > Oz	< 0.001
		C3 > P3	0.001	Cz > Fz	0.031
		C3 > O1	0.001	P3 > O1	< 0.001
		C3 > T7	< 0.001	T7 > O1	0.004
		C4 > P4	0.007		
	Imagery	Cz > Oz	0.003	C4 > T7	0.002
		C3 > O1	0.011	Pz < Oz	0.002
		C3 > T7	0.004	P3 > O1	0.011

Note: the “<” or “>” sign compares the actual voltage of the amplitudes.

The N400 component

Both the control and imagery conditions had bilateral central-frontal maximum (the most negative) topographies, as shown in Figure 4.1. As N400 was not found at the parietal and occipital sites in the control condition, the comparisons of the latency included only the frontal, central, and temporal sites. A 2 x 2 repeated measure ANOVA was conducted to test the differences in latency between Condition (imagery versus control) and Site (Fz and Cz). This procedure was rerun for a 2 x 2 x 3 design between Condition, Lateralization (left and right), and Site (frontal, central, and temporal electrodes). In all the ANOVA comparisons, only the Condition x Site (lateral) interaction effect (F (1, 11) = 3.63, p = 0.044) was significant. Other main and interaction effects were not statistically significant in both the midline and lateral site comparisons. Further, the post-hoc analyses revealed that the latency of C4 in the control condition was longer than that in the imagery condition (p = 0.023).

The amplitude differences, frontal, central, parietal, temporal, and occipital sites were included for testing as in the analysis of the latency. In the Condition x Site (midline) comparisons, only the Site main effect was significant (F (1.98, 21.77) = 7.59, p = 0.003). In the Condition x Lateralization x Site (lateral) comparisons, only the Site main effect (F (2.22, 24.42) = 7.54, p < 0.001) was found to be statistically significant. The post-hoc analyses are shown in Table 4.3.

Table 4.3

The pair-wise post-hoc analyses of the N400.

Main effect	Condition	Sites	p level	Sites	p level
Site	Control	Cz > Fz	0.017	P3 > T7	0.004
		C4 > T8	0.009	Pz > Fz	0.046
		C3 > F3	0.015	Pz > Oz	0.003
		C3 > O1	0.046		
	Imagery	Cz > Fz	0.039		

Note: the "<" or ">" sign compares the actual voltage of the amplitudes.

The P600 component

The amplitude of the P600 component in the control condition had a bilateral central-parietal-temporal maximum (most positive), while that of the imagery condition had a bilateral central-parietal maximum. Since the P600 component was not found in the parietal and occipital sites, the ANOVA conducted for latency was performed for the frontal, central, and temporal sites. According to the results, only the Lateralization x Site (F (1.43, 15.7) = 5.16, p = 0.027), and the Condition x Site interaction effects were significant (F (1.89, 20.78) = 3.47, p = 0.053). In the control condition, the latency of C4 was shorter than that of the T8 (p = 0.043). In the imagery condition, the latency of T8 was longer than that of the C4 and F4 (p = 0.019 and 0.012 respectively).

Regarding the amplitude differences, the frontal, central, parietal, temporal, and occipital sites were included for testing. In the Condition x Site (midline) comparisons, the Condition main effect (F (1, 11) = 5.512, p = 0.039), the Site main effect (F (1.92, 21.09) = 4.49, p = 0.031), and the Condition x Site interaction effects

(F (2.34, 25.77) = 4.27, p < 0.021) were all statistically significant. In the Condition x Lateralization x Site (lateral) comparisons, the Lateralization main effect (F (1, 11) = 5.97, p = 0.033), the Site main effect (F (3.03, 33.29) = 9.57, p < 0.001), and the Lateralization x Site interaction effects (F (2.43, 26.68) = 4.31, p = 0.018) were found to be statistically significant. Other effects including the Condition main effect (F (1, 11) = 3.81, p = 0.077), the Condition x Site interaction effects (F (1.98, 21.23) = 2.43, p = 0.077), and the Condition x Lateralization x Site interaction effects (F (1.57, 17.24) = 3.18, p = 0.077) only reached a marginal significance. The post-hoc analyses are shown in Table 4.4. In the between-condition differences, more significant results were found in the frontal and central sites with the amplitudes elicited in the imagery condition being more positive than those elicited in the control condition.

Table 4.4

The pair-wise post-hoc analyses of the P600.

Main effect	Condition	Sites	p level	Sites	p level
Condition	(Control < Imagery)	Fz	0.018	C4	0.005
		Cz	0.014		
Lateralization	Imagery	P3 > P4	0.011		
	Control	T7 > T8	0.005		
Site	Imagery	C3 > F3	0.015	C4 > T8	0.009
		C3 > O1	0.046	P3 > O1	0.029
		C3 > T7	0.004		
	Control	-			

Note: the "<" or ">" sign compares the actual voltage of the amplitudes.

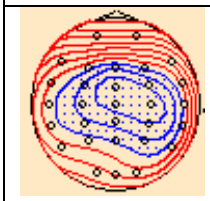
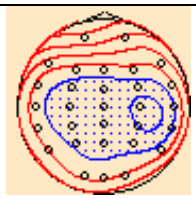
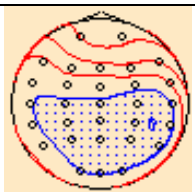
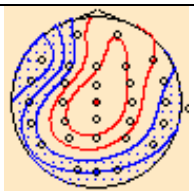
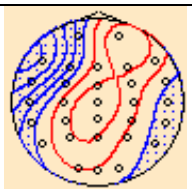
Component topography

Figure 4.2 shows the voltage topographies of the three major components obtained for the first 280 – 810 ms of the imagery-minus-control waveform. Since there were no significant differences in the amplitude and latency found in the N170 component between the imagery and control conditions, its topographies were not analyzed. A change in topography was first observed from a more right central negativity in the 370 – 470 ms interval to a more bilateral parietal negativity in the 488 – 610 ms interval (N400). Another change in topography was observed from the parietal negativity to a frontal-central-parietal positivity in both the 610 – 700 ms and 700 – 810 ms intervals. The three intervals — that is, 280 – 370 ms (P300), 480 – 610 ms (N400), and 700 – 810 ms (P600) — which carried the distinct topographies and had the largest differences in between-condition amplitudes, were

then used in the dipole localization.

Figure 4.2

Spline-interpolated voltage maps of ERPs components in the imagery – control condition.

280 – 370 ms P300	370 – 470 ms	480 – 610 ms N400	610 – 700 ms	700 – 810 ms P600
				

Note: Voltage = 0.6 μV / line

Red line = positive

Blue line = negative

Dipole modeling

Inverse dipole modeling of the components in the time range 158 – 941 ms was carried out on the imagery minus control grand average waveforms using the BESA algorithm. The 158 – 280 ms and 810 – 941 ms intervals were included to further test the validity of the results. Table 4.5 shows the results of the dipole analysis. The multi-dipole models derived accounted for more than 91.22% of the variance of the scalp voltage topography within the 158 – 941 ms interval. This was to check if the dipoles found presented the distinct components of an entire epoch (Russo, Martı´nez, Sereno, Pitzalis, & Hillyard, 2001). Table 4.5 shows the residual variance values and dipole coordinates in each of the P300, N400, and P600 components. Figure 4.3 displays the dipole localizations and the time course of each source activity.

Figure 4.3

BESA dipole models fitted to the imagery minus control grand averaged waveforms. The graphs on the left side show source activities across time for each of the modeled dipoles. Dipoles 1 and 2 (blue and red) correspond to the P300 component, dipole 3 (brown) to the N400 component, and dipoles 4 and 5 (green and pink) to the P600 component.

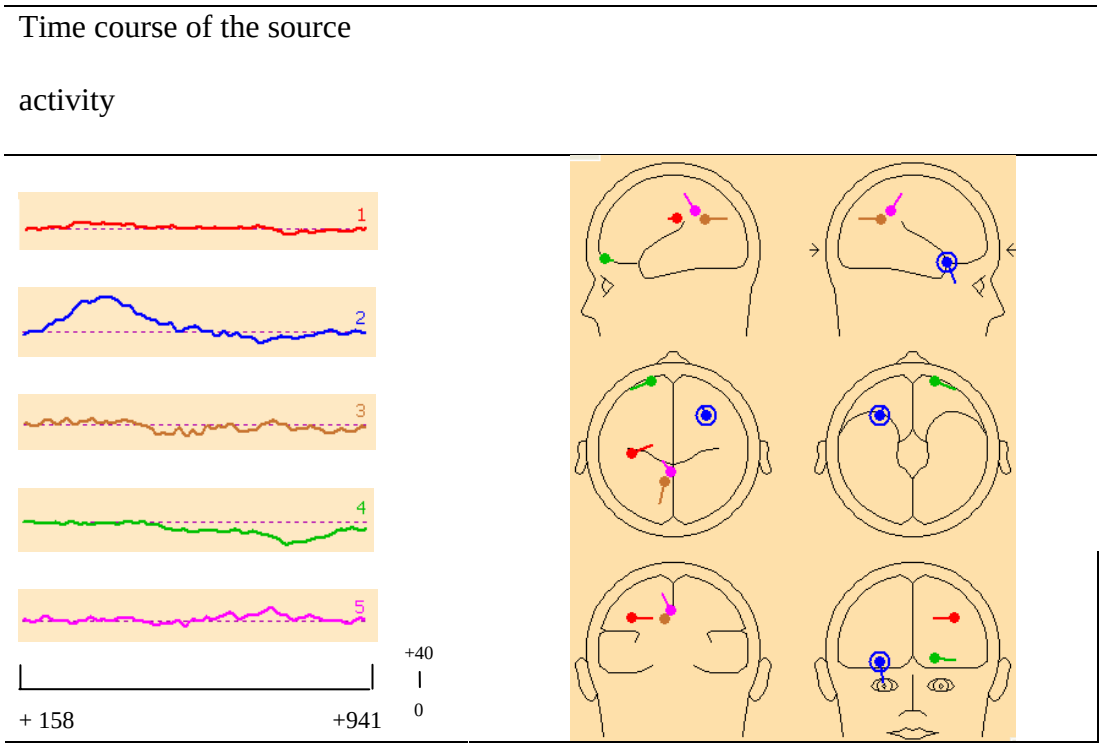


Table 4.5

Locations and orientations of BESA fitted dipoles expressed in Talairach coordinates.

Components	RV	Names	X	Y	Z
P300	8.98%	Dipole 1 (blue) – Right inferior	32	22	-9
(280 – 390 ms)		frontal gyrus			
		Dipole 2 (red) – Left parietal	-41	-25	33
		lobe, postcentral gyrus			
N400	9.56%	Dipole 3 (brown) – Left parietal	-8	-57	27
(477 – 612 ms)		lobe, precuneus			
P600	5.00%	Dipole 4 (green) – Left superior	-22	61	-1
(699 – 809 ms)		frontal gyrus			
		Dipole 5 (pink) – Left parietal	-3	-46	37
		lobe, precuneus			
The entire epoch	8.78%				
158 – 941 ms					

Note: Values are in mm. Residual variance (RV) is the percentage of variability not explained by the model.

Somatosensory Ability of the Norm Group

All subjects completed a series of sensory assessments of their basic tactile sensation (vibration, pain, temperature perception, and light touch sensation) and discriminative tactile sensation (2-PD, stereognosis, point localization, position sense, and texture discrimination). All the basic tactile senses of the normal subjects were intact in both hands. There were no significant differences in discriminative sense between the right and left hands. The tests results are summarized in Table 4.6.

The post-stroke patients' deficits on the discriminative sense were graded as slight, moderate, or severe, according to the results in the norm group (see Chapter III for the method of grading). Their results are presented with their demographic data in the next session.

Backgrounds and Demographic Characteristics of Post-stroke Patients

Three post-stroke patients participated in this part of the study. The recruitment of patients with specific brain lesions after stroke was difficult to conduct. This was because the majority of the post-stroke patients who were screened did not satisfy the selection criteria of the study. Their clinical conditions and backgrounds are described below.

Table 4.6

Results of the discriminative sensory tests.

Sensory assessment (units)	Right		Left	
	Mean	SD	Mean	SD
2-PD (mm)	4.02	0.86	4.23	0.82
Stereognosis (items)	12.00	0.00	12.00	0.00
Point localization (mm)	3.75	0.66	3.51	0.72
Position sense (degree)	8.20	3.30	7.42	2.90
Texture discrimination (% of spatial increase)	35.58	9.58	40.51	8.61

Patient 1 LKS (70 years old, female): LKS was right handed and suffered from right cerebral thrombosis in the cerebellum. She was retired, and was living in an old age home before admission to the hospital. She was admitted after the sudden

onset of slurring of speech and weakness over the left side of her body. She was admitted to Tung Wah Hospital (TWH) for rehabilitation 5 days after the onset. The imagery protocol was completed in the 3rd week after onset of stroke. On examination, she had ataxia over her left hand. Her MMSE score was 29/30. Basic and discriminative tactile sensations were found to be diminished in the left arm (see Table 4.7). The grip strengths of both hands were 13 lbs, and the pinch grip was 3 lbs and 5 lbs on the right and left hands respectively.

Table 4.7

Results of the sensory tests of the post-stroke patients.

Sensory Test (units)	Patient LKS		Patient CCT		Patient CKF	
	Right	Left	Right	Left	Right	Left
Vibration	Normal	Normal	Normal	Normal	Normal	Normal
Pinprick	Normal	Normal	Normal	Normal	Normal	Normal
Temperature	Normal	Normal	Normal	Normal	Normal	Normal
Light touch	Normal	DLT	Normal	Normal	Normal	Normal
2-PD (mm)	Severe	Severe	Normal	Normal	Normal	Normal
ST (items)	Normal	Slight	Normal	Normal	Normal	Severe
PL (mm)	Normal	Slight	Normal	Normal	Normal	Normal
PS (degree)	Slight	Moderate	Normal	Normal	Normal	Normal
TD	Slight	Moderate	Normal	Normal	Moderate	Severe

Note: ST = Stereognosis

PL = Point localization

PS = Position sense

TD = Texture discrimination

DLT = Diminished light touch

Patient 2 CCT (57 years old, male): CCT was right handed and suffered from a right thalamic infarct over the anterior nucleus of the right thalamus. He was a hardware worker before admission. CCT was first admitted to an acute hospital after the sudden onset of weakness in both lower limbs. Six days later, he was admitted to TWH for rehabilitation. The sensory tests and imagery protocol were conducted on

the 11th day, post-stroke. On examination, his MMSE score was 27/30. His basic tactile sensation was normal, and discriminative tactile sensations were found to be normal in both the affected and unaffected hands (see Table 4.7). The grip strengths of the right and left hands were 40 lbs and 30 lbs respectively.

Patient 3 CKF (70 years old, male): CKF was right handed and suffered from a right middle cerebral artery infarct. The CT brain scan suggested an ill-defined hypodense area at the right temporal and frontal region, suggesting a recent ischemic infarct. CKF was retired. He was admitted to hospital due to a sudden onset of dizziness, weakness in the left side of the body, and an inability to walk. He was transferred to TWH for rehabilitation on the 6th day post-stroke. The sensory tests and imagery protocol were completed on the 11th day after the onset of the stroke. On examination, his MMSE score was 27/30. The basic tactile sensation was found to be intact. However, the discriminative sensation was found to range from normal in the 2-PD to severely damaged in the stereognosis (see Table 4.7). The grip strength of the left and right hands was 0 lb and 27 lbs respectively.

ERPs of Post-stroke Patients (Imagery versus Control tasks)

ERPs of Patient LKS

The mean response time of the matching task was 2150 ms (SD = 254), and the accuracy rate was 62%. The grand-averaged ERPs of this patient are shown in Figure 4.4. A glance at the morphology suggests a general latency shift (about 50 ms) to the right when compared with the norm group. To facilitate comparisons between the patients and the norm group, it was decided to use the same labels for the four

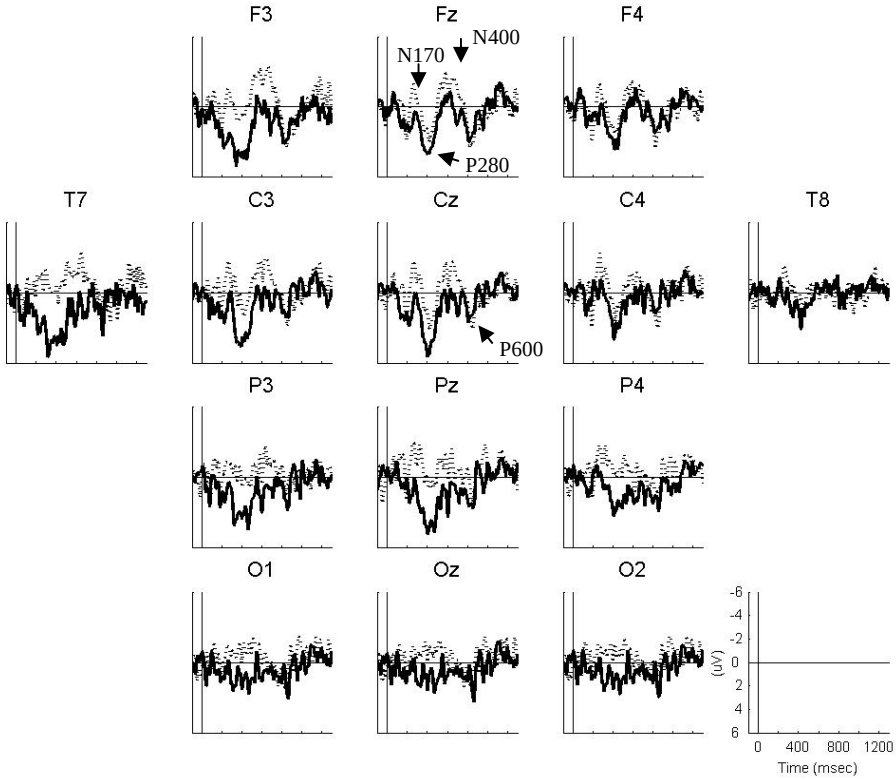
identified peaks; that is, N170, P300, N400, and P600. The same was applied to Patient CCT and Patient CKF.

The three peaks found in the norm group appeared in the ERPs of LKS. In the control condition, the mean latency of the first peak (N170) across all sites was 237.6 ms (SD = 48.0), the second peak (P300) was 392.2 ms (SD = 53.0), the third peak (N400) was 618.4 ms (SD = 63.0), and the fourth peak was 808.9 ms (SD = 96.0). In the imagery condition, the mean latencies for the first, second, third, and fourth peaks were 261.4 ms (SD = 31.0), 412.5 ms (SD = 25.0), 603.4 ms (SD = 55.0), and 849.7 ms (SD = 51.0) respectively. The differences in amplitude between the imagery and control conditions were found to be greater between the first 300 ms over the left frontal, central, and temporal areas than other areas. In the control condition, the P600 (at around 800 ms) appeared to have attenuated at the bilateral parietal and occipital areas.

The windows were constructed for the four peaks. Unlike in the norm group, the peaks were difficult to identify in the subtracted ERP waveforms (imagery minus control). Consequently, it was determined that the windows were decided based on the latencies revealed from the imagery and control conditions. The average of the imagery and control conditions formed the mean and standard deviations of the latencies of the four peaks. The windows constructed for the first to the third peaks took one standard deviation, while that for the forth peak took two standard deviations. The windows for analyzing the ERPs of LKS were N170 (223 – 281 ms), P300 (370 – 442 ms), N400 (552 – 670 ms), and P600 (682 – 976 ms).

Figure 4.4

The grand-averaged ERPs of Patient LKS. The dotted line represents the control condition, and the solid line represents the imagery condition.



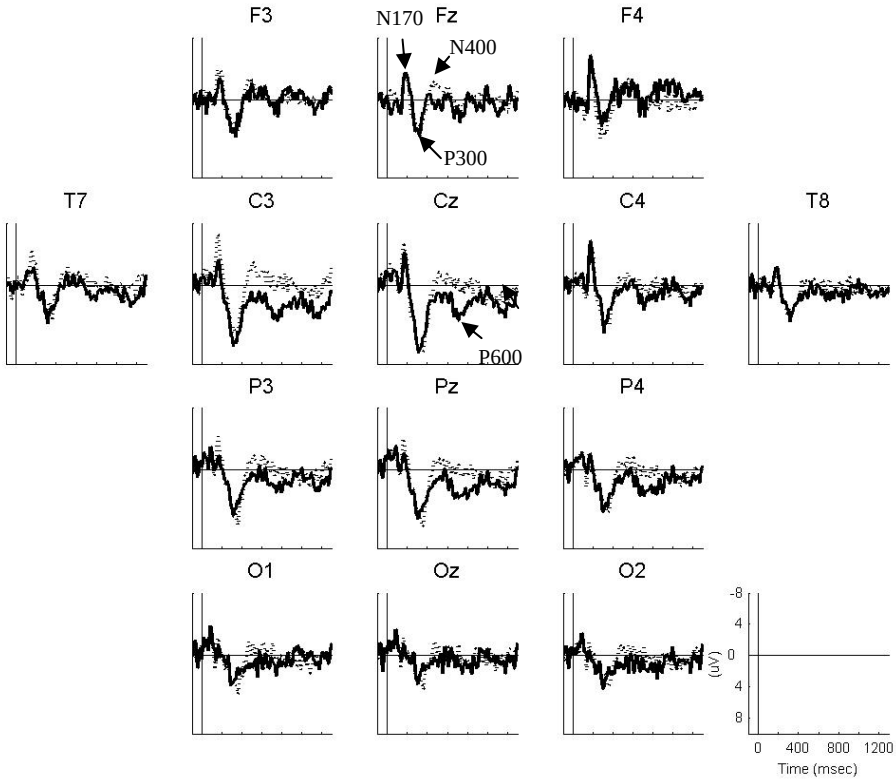
ERPs of Patient CCT

The reaction time and accuracy of the matching task were 1548 ms (SD = 634.0) and 65% respectively. The grand-averaged ERPs of Patient CCT are shown in Figure 4.5. In the ERP of this patient, distinct N170, P280, N400, and P600 were found, and are similar to the morphology of those of the normal older subjects. The mean latencies of N170, P300, N400, and P600 during the control condition were 164.4 ms (SD = 26.5), 309.1 ms (SD = 15.4), 554.8 ms (SD = 60.5), and 746.7 ms (SD = 59.6). During imagery, the mean latency of N170 was 169 ms (SD = 13.4), while P300 was 330.6 ms (SD = 32.6), N400 was 515.7 ms (SD = 33.1), and P600 was 880.3 ms (SD = 113.5). The amplitude differences between conditions, however,

were not as great as those of the norm group. A more prominent difference was found in the N400 and the P600 of the left central and parietal areas. The method for identifying the windows of the peaks for the subsequent analyses was the same as that used for Patient LKS. That is, the window representing N170 was 147 – 187 ms, that representing P280 was 296 – 344 ms, that representing N400 was 488 – 582 ms, and that representing P600 was 727 – 900 ms.

Figure 4.5

The grand-averaged ERPs of Patient CCT. The dotted line represents the control condition and the solid line represents the imagery condition.

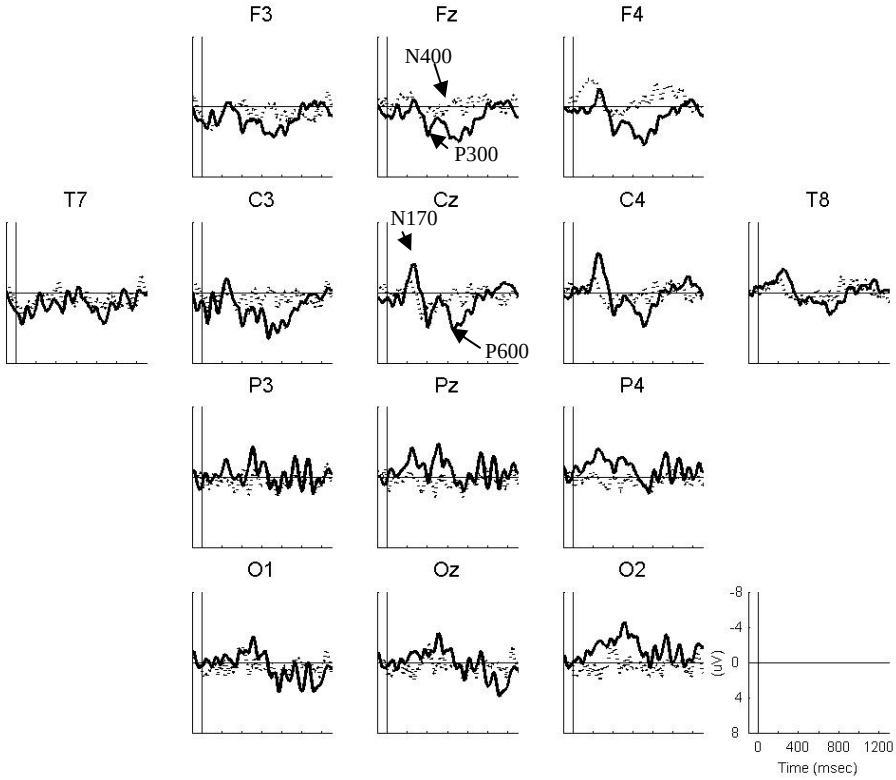


ERPs of Patient CKF

The accuracy of the matching task was 52%. Since Patient CKF had difficulty pressing on the keyboard with his left hand, his responses for the matching task were made verbally. By the end of each trial, Patient CKF told the researcher his responses as soon as he identified whether or not the second stimulus matched with the first stimulus. The researcher recorded the responses made by Patient CKF. The grand-averaged ERPs of Patient CKF are shown in Figure 4.6. Similar to Patient LKS, there appears to be a 50 ms latency shift to the right in all the ERP components. During the control condition, the mean latency (across electrodes) of N170 was 247.8 ms (SD = 32.0), while that of P300 was 339.8 ms (SD = 122.0), that of N400 was 518.8 ms (SD = 54.2), and that of P600 was 744.9 ms (SD = 74.1). For the imagery condition, the mean latency of N170 was 169.2 (SD = 13.4), while that of P300 was 394.6 ms (SD = 99.8), that of N400 was 492.6 (SD = 93.9), and that of P600 was 753.3 ms (SD = 77.6). The method for identifying the windows of the peaks for the subsequent analyses was the same as that used for Patient LKS. That is, 196 – 271 ms for N170, 256 – 478 ms for P300, 432 – 580 ms for N400, and 597 – 900 ms for P600.

Figure 4.6

The grand-averaged ERPs of Patient CKF. The dotted line represents the control condition and the solid line represents the imagery condition.



Comparisons of ERPs between the Post-stroke Patients and the Norm Group

Tables 4.8 to 4.11 are summaries of the comparisons of the derivative scores between each of the three post-stroke patients (LKS, CCT, and CKF) and the norm group.

For Patient LKS, all his derivative scores of the N170 and P300 components were more positive than those of the norm group (confidence intervals (CIs)). There were observable differences in the derivative scores of the N400 and P600 components. In the N400 component, the differences appear at scattered locations, including the occipital sites (O1, O2, and Oz), F3 and T7. The ERP differences between the imagery and control conditions elicited in LKS's N400 component were

more positive than those of the norm group. Regarding the P600 component, only the derivation score of O2 was higher than the upper CI of the norm group, except the T7. In other words, the differences in the ERPs in the P600 component were more positive than those of the norm group.

For Patient CCT, there were observable differences in the derivative scores of the P300 component. The derivative scores of the N170 component of CCT appear more positive than those of the norm group at the left hemisphere, except the occipital sites (F3, C3, P3, and T7). In other words, the ERP differences between the imagery and control conditions elicited by Patient CCT in the N170 component were larger than those of the norm group. For the P300, the between-condition differences were not similar to those of the norm group at all sites, except F4, Pz, Oz, and O1. For the N400 component, only the P4 derivative score was higher than that of the norm group. The between-condition differences in the P600 component were more positive than those of the norm group, and larger differences were observed in C3, O2, and T7.

Regarding Patient CKF, the between-condition differences in the N170 component were found in all the sites except F3, Pz, P3, O1, and T7. For the P300 component, the between-condition differences were more positive than those of the norm group at all sites, except a few of the sites in the parietal (Pz and P4), occipital (Oz), and temporal areas (T7). The derivative scores of the N400 component were more negative than those of the norm group only at Pz and O2. For the P600 component, the differences in the derivative scores between CKF and the norm group were found mainly at the frontal area (Fz, F3, and F4). Other sites included C3, O2, and T8. That is, the between-condition differences in amplitudes were more positive in CKF than in the norm group.

Table 4.8

Comparisons of the N170 derivative scores of LKS, CCT, and CKF with those of the norm group.

N170	Norm Group				LKS	CCT	CKF
158 – 193 ms	Mean	SD	CI lower	CI upper	223 – 281 ms	147 – 187 ms	196 – 271 ms
FZ	-0.30	1.43	-1.59	1.00	*2.21	0.24	*1.03
CZ	0.28	1.27	-0.87	1.42	*2.63	1.13	*-1.15
PZ	0.16	1.20	-0.93	1.24	*2.55	1.16	-1.58
OZ	-0.23	1.17	-1.29	0.83	*1.08	0.54	*-1.36
F3	-0.05	0.97	-0.93	0.83	*3.02	*0.99	0.10
C3	0.38	1.17	-0.67	1.44	*2.42	*2.34	*-0.76
P3	0.40	1.19	-0.68	1.47	*1.79	*1.54	-0.57
O1	-0.04	1.06	-0.99	0.92	*1.31	0.69	-0.91
F4	0.07	1.13	-0.96	1.09	*1.78	-0.67	*1.18
C4	0.37	1.49	-0.98	1.71	*2.01	-0.17	*-2.22
P4	-0.09	1.13	-1.12	0.93	*1.33	-0.34	*-2.14
O2	-0.32	1.10	-1.31	0.68	*1.24	0.58	*-2.33
T7	0.51	0.76	-0.18	1.20	*2.64	*1.54	0.10
T8	0.68	1.41	-0.59	1.95	1.87	-0.52	*-1.67

Note: * denotes derivative scores of the patient falling outside the 99.7% CIs of the norm group.

Table 4.9

Comparisons of the P300 derivative scores of LKS, CCT, and CKF with those of the norm group.

P300	Norm Group				LKS	CCT	CKF
259 – 382 ms	Mean	SD	CI lower	CI upper	363 – 442 ms	296 – 344 ms	256 – 478 ms
FZ	-3.10	2.06	-4.97	-1.23	*1.31	*0.47	*0.82
CZ	-3.00	2.25	-5.04	-0.96	*2.14	*0.08	*-0.47
PZ	-2.52	2.39	-4.68	-0.35	*2.85	-0.12	-1.27
OZ	-1.53	1.99	-3.33	0.27	*1.97	-0.15	-0.68
F3	-2.64	2.21	-4.63	-0.64	*2.79	*0.38	*1.03
C3	-3.00	2.57	-5.33	-0.68	*2.07	*1.12	*0.42
P3	-2.39	2.35	-4.51	-0.27	*2.44	*0.19	*0.26
O1	-1.43	1.41	-2.70	-0.15	*2.11	-0.09	*-0.45
F4	-2.76	1.72	-4.32	-1.20	*1.12	-1.77	*0.60
C4	-3.32	2.18	-5.29	-1.35	*1.57	*-0.04	*-0.79
P4	-2.49	2.09	-4.38	-0.60	*2.97	*0.00	-1.94
O2	-1.91	1.77	-3.52	-0.31	*2.06	*0.29	*-1.84
T7	-2.28	1.93	-4.02	-0.53	*2.95	*0.57	1.05
T8	-2.74	1.66	-4.25	-1.24	*0.87	*0.67	*-0.82

Note: * denotes derivative scores of the patient falling outside the 99.7% CIs of the norm group.

Table 4.10

Comparisons of the N400 derivative scores of LKS, CCT, and CKF with those of the norm group.

N400	Norm Group				LKS	CCT	CKF
488 – 614 ms	Mean	SD	CI lower	CI upper	552 – 670 ms	488 – 582 ms	432 – 580 ms
FZ	0.56	1.83	-1.10	2.21	1.17	1.01	1.46
CZ	0.48	1.76	-1.11	2.07	1.79	0.04	0.24
PZ	0.33	1.74	-1.24	1.90	1.74	-1.96	*-2.06
OZ	-0.65	1.70	-2.19	0.89	*1.15	-1.45	-1.55
F3	-0.12	1.69	-1.65	1.41	*2.13	0.71	0.84
C3	0.17	1.85	-1.51	1.84	1.83	0.95	0.94
P3	0.23	1.84	-1.43	1.90	1.89	-0.56	-0.99
O1	-0.46	1.35	-1.68	0.77	*1.20	-1.24	-1.30
F4	0.34	2.18	-1.63	2.32	0.72	1.29	1.85
C4	0.22	1.67	-1.29	1.73	1.45	0.19	0.41
P4	-0.09	1.87	-1.78	1.61	1.36	*-1.82	-1.73
O2	-0.61	1.55	-2.01	0.79	*1.06	-2.70	*-2.83
T7	-0.59	1.44	-1.90	0.71	*2.57	0.37	-0.15
T8	-0.23	1.46	-1.55	1.09	0.00	0.21	0.55

Note: * denotes derivative scores of the patient falling outside the 99.7% CIs of the norm group.

Table 4.11

Comparisons of the P600 derivative scores of LKS, CCT, and CKF with those of the norm group.

P600	Norm Group				LKS	CCT	CKF
577 – 942 ms	Mean	SD	CI lower	CI upper	682 – 976 ms	640 – 987 ms	597 – 900 ms
FZ	0.77	1.13	-0.26	1.79	0.39	0.56	*2.93
CZ	1.06	1.33	-0.15	2.26	0.41	1.91	1.73
PZ	0.63	1.48	-0.71	1.97	1.08	1.89	-0.46
OZ	-0.09	1.03	-1.02	0.85	0.58	0.34	-0.43
F3	0.03	1.22	-1.07	1.14	0.52	-0.15	*1.80
C3	0.68	1.61	-0.77	2.13	0.12	*2.76	*2.21
P3	0.56	1.39	-0.70	1.82	0.70	1.22	-0.32
O1	-0.10	0.94	-0.95	0.75	0.59	0.34	0.17
F4	0.65	1.52	-0.72	2.02	0.28	-1.08	*3.50
C4	0.77	0.99	-0.13	1.67	-0.06	1.13	1.50
P4	0.28	1.40	-0.99	1.55	0.89	1.51	-0.41
O2	-0.20	0.88	-0.99	0.60	*0.75	*0.82	*-1.46
T7	-0.30	1.17	-1.35	0.75	0.45	*0.78	0.54
T8	0.10	1.09	-0.89	1.09	-0.43	0.88	*1.41

Note: * denotes derivative scores of the patient falling outside the 99.7% CIs of the norm group.

CHAPTER V

DISCUSSION

Introduction

This chapter begins with a discussion of the significance of the findings of the event-related potentials revealed in the older adults of the normal group. The different event-related potentials shed light on the plausible neural processes associated with the imagery of vibrotactile sensation. The event-related potentials of each of the three patients are then discussed in the light of those obtained from their normal counterparts. Emphasis is put on relating the differences to specific lesions in each of these patients.

The Neural Processes Associated with Vibrotactile Imagery

The comparisons of the event-related potentials obtained from this experiment between the control and imagery conditions suggest that the imagery of vibrotactile sensation probably involves four distinct components: the N170, P300, N400, and P600. These components have been reliably revealed in a similar study conducted in a group of younger subjects by the Applied Cognitive Neuroscience Laboratory of The Hong Kong Polytechnic University (Chow et al., under review b).

The N170 component

The N170 is the first ERP component identified in both the imagery and control conditions. The results indicate no significant differences in both the latency and amplitude between the two experimental conditions. As both conditions showed, the N170 component had a frontal-central maximum (Figure 4.1), it similar to the

N250 component (or N200, N2b) revealed in other active oddball or discrimination tasks involving the use of vibration or electrical stimulation (Ito, Shibasaki, & Kimura, 1992; Kekoni et al., 1996; Kida, Nishihira, & Hatta, 2003). The N250 component was previously related to the attentional process in which subjects attended to the stimulus presented to them. The relatively shorter latency of N170 (when compared with N200 or N250) obtained in this study might be due to the relatively easy task involved by the subjects; that is, detection of the vibrotactile stimuli instead of discrimination of the stimuli as used in other studies (Kekoni et al., 1996). The latency of N170 is also found consistent with the 250 ms presentation time of the prompt stimuli presented to the subjects in both imagery and control conditions. The N170 component was elicited before the prompt stimuli ended, suggesting the subjects attended to the stimuli, and processed them accordingly. The results of no significant between-condition differences were found in the N170 component, further supporting the notion that this attentional process was required in both the imagery and control conditions. The frontal-central distribution of the N170 component is similar to that of the tactile N250 component revealed in other studies (Kekoni et al., 1996). This distribution is in agreement with human intracranial recordings in which the N250 component was elicited from the human frontal cortex, and specifically from the cingulated gyrus (Baudena, Halgren, Heit, & Clarke, 1995; Clarke, Halgren, & Chauve, 1999; Kropotov et al., 1995).

In conclusion, the N170 component, similar to the N250 component found in other discrimination tasks, suggests that the subjects attended to the brief vibrotactile stimuli (250 ms) common to both the imagery and control conditions.

The P300 component

The stimulus presented for prompting the subjects to begin imagery of the stimuli lasted for 250 ms. The first component that appears to associate with the imagery process was within the 280 – 390 ms time window. In the imagery condition, the subjects were required to detect and interpret the brief stimuli, and rehearse what they felt for 4000 ms. In the control condition, the subjects were instructed to detect but not to actively interpret the stimuli, and not to rehearse what they felt for 4000 ms. In other words, the subjects in the control condition only passively perceived the stimuli. If the N170 component is related to the attentional process, the P300 component, which follows the N170 component, probably is related to the encoding of the specific information contained in the brief vibrotactile stimuli.

The results from previous studies on P300 suggest that the P300 component is an endogenous component and accompanies the context updating within the working memory stores (Donchin & Coles, 1988). The amplitude of the component was found in proportion to the amount of attentional resources devoted to a given task (Kramer & Strayer, 1988; Schubert, Johannes, & Koch, 1998; Wickens et al., 1983). The P300, elicited in the imagery condition in this study was substantially more negative than the control condition, especially at the right frontal and central sites. The differences in its amplitudes between the imagery and control conditions showed a central-parietal maximum (see Figure 4.2).

The first interpretation of the modulation effects on the P300 component in the imagery condition can be that, after attending to the stimulus, the subjects were to encode the stimulus-specific information, that is, frequency and intensity to identify and discriminate a particular vibrotactile stimulus for subsequent rehearsal. The attentional resources invested in processing the stimulus-specific information probably was more than those invested in the control condition. The encoding

process was completed before the prompt stimulus diminished in 250 ms. This process was absent in the control condition. Another interpretation of the P300 modulation effect can be that, after the vibrotactile stimulus diminished in 250 ms, subjects in the imagery condition were required to base on the stimulus-specific information, and retrieve from long-term memory the relevant sensory images for undergoing the mental rehearsal. The associations between the stimulus-specific information and sensory images had been reinforced during the training prior to the experimental task. It is postulated that the P300 component could indicate the beginning of the process of retrieving the mental images from long-term memory. The actual retrieval process, however, would associate more with the N400 rather than P300 component (to be discussed below). Similar results have been found in another study on imagery of auditory stimuli primed by visual stimuli (Wu, Mai, Chan, Zheng, & Luo, under review).

The P300 component modulation effects have been reported in previous studies. In Kida et al.'s study (2003), they used an oddball paradigm to design a mental counting task. The results revealed a P170-N250-P300 complex elicited by the detection of deviant stimuli requiring the active attention of the subjects. The authors further explained that the P300 peak amplitudes were modulated when subjects discriminated the deviant from the standard stimuli, and updated the number in the working memory stores. Kida et al.'s study (2003) did not involve intense imagery processes, but their findings further support our postulation that the P300 component is likely to relate to the encoding and discrimination of the stimuli-specific information, and the beginning of the retrieval of vibrotactile image processes.

The results of the dipole analysis on the P300 component further support our postulation on its modulation effect. The two diploes modeled for the P300 component were located at the right inferior frontal gyrus and postcentral gyrus of the left parietal lobe. The frontal lobe was previously reported to have a connection to the task/category specific region that stores the visual memory of objects in imagery (Mechelli et al., 2004). This suggests that generation of images for imagination possibly associate with the P300 component.

The N400 component

At the time when the subjects attended to the brief stimuli which lasted for 250 ms, they were required to generate the images of specific vibrotactile sensations which they had learnt prior to the study. This process would involve subjects retrieving from their long-term memory with specific frequency and intensity characteristics with which they were familiar. If this process began during the P300 component, the first negative-going component identified within the 488 – 614 ms time window would be the continuation of such process. The results indicate that there were significant interaction effects of Condition x Site in the differences in the latency, and significant main effect of Site on the amplitude of the N400 component. It was found that the amplitude of N400 was the least negative-going at the frontal sites, which is suggestive of an access to memory process. Mecklinger (1998) reported that the N400 component intensified at the frontal areas was associated with access to memory for identifying non-linguistic symbolic stimuli. Other studies found that a less negative-going N400 component was elicited when the retrieval process was context specific and required effort (Guillem et al., 1999; Jacoby, 1991; Rugg, & Dolce, 1994). The functional role of the N400 component was consistent

with the processes involved in the task in which subjects recognized and rehearsed the vibration stimuli, which were briefly presented for 250 ms and had only a 16.7% rate of occurrence.

Dipole analysis based on the imagery minus control waveforms suggests that the dipole modeled for the N400 component coincided with the precuneus of the left parietal lobe. Activations at the precuneus were found to associate with memory retrieval during visual imagery (e.g., Mechelli et al., 2004), and during kinesthetic motor imagery (Tetsuya, Kando, & Morihiro, 2000). Shallice et al. (1994) suggested that activity in the precuneus reflects the use of imagery during retrieval, and supports the idea that the precuneus is related to retrieval of sensory information in the vibrotactile imagery. Besides, Mechelli et al. (2004) found the pattern of activation in the precuneus remarkably similar to that in the superior parietal cortex. It showed greater activation during imagery relative to imagery control, but did not express any task-specific pattern of activation. Previous studies have shown that the precuneus was implicated in retrieval from episodic memory, irrespective of the modality or format, for example, during picture recall and auditory word recall (see Buckner et al., 1996). In summary, the dipole and the topography of the N400 might probably support its functional role as the memory retrieval processes.

The P600 component

After the subjects detected and identified the stimuli, the task required them to generate the images of the vibrotactile sensation and maintain and rehearse the images until the end of 4000 ms. This process would involve the subjects generating and maintaining the images for an exact period of time in their working memory. The second positive-going component identified within the 640 – 942 ms window

appears to associate with the image generation and maintenance process. There were significant differences found in the amplitude of the P600 component between the imagery and control conditions at the bilateral frontal and left central sites. Dipole analysis modeled the P600 component in the left superior frontal gyrus, and the precuneus in the left parietal lobe. There are topographical overlaps between the dipoles modeled for the N400 and P600 components, or the precuneus in the left parietal lobe, suggesting the continuation of the neural processes associated with these two ERPs.

Guillem et al. (1999) reported that the P600 component was found to associate with complicated information processing and working memory maintenance. It has also been reported to reflect the processes associated with working memory (Donchin & Coles, 1988; Kok, 2001; McCarthy, Luby, Gore, & Goldman-Rakic, 1997). Several studies also revealed that the P600 was elicited by a cued recall task (Allan & Rugg, 1997; Johnson, Kreiter, Zhu, & Russo, 1998). The equivalent dipoles found in the frontal and parietal lobe appear to coincide with the neural activations associated with the “imagery network”. Recent neuroimaging studies on imagery have revealed the functional role of the so-called “imagery network” which connects the frontal and parietal areas (Kosslyn et al., 2004; Mechelli et al., 2004). According to these authors, the “imagery network” was common to different types of visual imagery. The functional role of this network was hypothesized to cover the attentional processes, the retrieval of memory for the generation of images, and the execution of planned actions in imagery. The frontal involvement was related to a content-related process in which the long-term memory of the sensation is retrieved from a content-specific area.

The significant modulation effect on the P600 component at the central sites suggest that the sensori-motor areas were involved in a generation of images of vibrotactile sensation, in particular the primary somatosensory cortex (SI). The activation of SI was found in the fMRI study of imagery in tactile stimuli (Yoo et al., 2003), and in tasks requiring working memory (Romo et al., 1999). This assertion that SI is involved in working memory is most strongly supported by other studies on topographic tactile learning conducted by Harris, Harris, and Diamond (2001). In their study, subjects were required to compare the frequency of two vibrations presented to the same fingertip or to different fingertips. The vibration was separated by a retention interval of variable length. For intervals shorter than 1 s, subjects were accurate when both vibrations were delivered to the same fingertip, but were less accurate when the two vibrations were delivered to different fingertips. For intervals of 1 to 2 s, subjects' performance was the same when the vibration was applied on the same finger or to the corresponding fingers of the opposite hands, but the performance was poor when the vibration was delivered to two fingers (in either hand) farther apart from one another, such as 2^{nd} and 5^{th} fingers. These results suggest that working memory specific to tactile sensation resides within a topographic framework. The results are further supported by the work of Recanzone and colleagues (Recanzone, Schreiner, & Merzenich, 1992; Wang, Merzenich, Sameshima, & Jenkins, 1995). In the studies, the intensity of training on detecting different vibrotactile stimuli modulated the number of cortical neurons at the somatosensory cortex that responded to the learned stimuli. This suggested a functional role of the somatosensory cortex in memory of tactile sensation, and that images were probably organized in a topographical manner.

In spite of the access and retrieval from long-term memory for vibrotactile images, the significant P600 component during the imagery condition also suggests a process of integrating and maintaining those images. Hence, the involvement of the central sites further indicates that these images were somatosensory in nature. Our findings probably are analogues to the visual buffer proposed by Kosslyn (1994) for visual images. This is echoed by the study of Yoo et al. (2003), which showed that the imagery of a brushing stimulus applied to the hand also activates the primary somatosensory cortex.

Unique Characteristics of Vibrotactile Imagery in Post-stroke Patients

There are limitations to our discussion of the results obtained from the three post-stroke patients, that is, LKS, CCT, and CKF. The fact that each of the patients had their own pathology and brain lesions did not warrant amalgamation of the data. The low power of the analyses also largely impedes the validity of the conclusion drawn, if any.

Patient LKS

Because LKS suffered from a right cerebellum infarct, it was expected that the lesion would partly modulate the imagery process. The reason was that the cerebellum was found to participate in a number of important cognitive and sensory functions, instead of merely motor execution control (Gottwald, Wilde, Mihajlovic, & Mehdorn, 2004). Schmahmann and Pandya (1997) identified anatomically that the cerebellum received input from different sensory systems via the cerebellocortical loop. An MRI study further revealed that activations in the cerebellum were in conjunction with other somatosensory cortical activations during cutaneous discriminative tasks (Gao, Parsons, Bower, Xiong, & Li, 1996). It is therefore

intuitive that lesions in the cerebellum are attributable to sensory deficit (as argued in Lang & Bastian, 2001). Further supporting this view, the results of the sensory tests suggested that LKS had detectable deficits in the discriminative tactile sensation.

There were significant differences in the N170 at all the sites when compared with the normal counterparts. This suggests that the processes involved in attending and detecting the vibrotactile stimulus appear to differ between LKS and his normal counterpart. These findings were consistent with previous studies that lesion in the cerebellum caused deficits in attentional processes such as working memory and divided attention (Gottwald et al., 2004). Further analysis also revealed that patients with right-side lesion were in general more impaired than those with left-side lesions. Recent studies further shed light on the mechanism of the cortical-cerebellum on modulating attention. Tesche and Karhu (1997) used magnetoencephalograph (MEG) to study short-latency somatosensory-evoked responses from median nerve stimulation in the human cerebellum. Their results suggested that in normal subjects, all cerebella responses peaked in the same time frame as the thalamic neuronal population. These responses peaked in the primary somatosensory cortex. In contrast, for patients with cerebellum infarct, the results indicated abnormal activations in the contralateral primary somatosensory cortex, also found in the present study. This primary sensory acquisition function might lead to subsequent deficits in the attention and target orientation and detection, and alter activation in other cortical areas. In fact, in our study, apart from the central sites, the differences in activation can be seen in all other areas of the brain. Apart form the modulation effect via the SI, the second interpretation of our findings can be based on the fact that the cerebellum itself was linked to different areas of the brain for the attention function. It was suggested that the cerebellum was part of the attention network that

augmented, sustained and split the attention of the visual and motor stimuli (Allen, Buxton, Wong, & Courchesne, 1997; Rees, Frith, & Lavie, 1997). Such an attention network was found to connect to the frontal parietal cortex in sustained attention (Buchel & Friston, 1997), the right posterior parietal cortex in shift attention (Coull & Nobre, 1998; Nobre et al., 1997), and the occipito-temporal cortex in attention to motion (Beauchamp, Cox, & De Yoe, 1997). However, due to the limited information obtained in our study, the interpretation needs verification by future studies.

The amplitudes of the P300, N400, and P600 components of LKS were found to be significantly different from those of the normal group at various sites. The P300 component was more positive than that of the norm at all sites, the N400 component was more positive-going in the bilateral occipital sites and the left frontal and temporal areas, while the P600 was more positive-going at only the right occipital site. These differences might indicate that the lesions in the cerebellum were modulated by the neural processes underlying retrieval sensory images from the long-term memory, and the generation and maintenance of these images in the working memory. The behavioral results indicate that LKS's accuracy and reaction time was about 10% lower and 600 ms slower than the norm group. The findings were consistent with those revealed in Gottwald et al.'s study (2004) that people with cerebella lesions generally had poorer performance in the tasks (reaction time and accuracy) related to working memory and divided attention. Cerebella function was previously found to modulate the imagery processes. For instance, in Naito et al.'s study (2002), subjects mentally rehearsed motor actions (kinesthetic imagery), and kinesthetic illusions, prompted by vibration stimulations applied on the body parts. Imagery processes were found to associate with activations in right cerebellum,

left cingulated motor area, supplementary motor area, and dorsal premotor area. The results obtained from LKS indicate that the lesion in the cerebellum appears to affect more the P300 and N400 components at the frontal and temporal sites, but less the P600 component. Such observations suggest that the cerebellum is likely to mediate the generation of sensory images from the long-term memory rather than maintenance and manipulation of sensory images in the working memory. Whishaw (2003) revealed that the learning of a skilled movement led to an increase in areas of activations in the frontal and temporal lobes, and cerebellum. As there is a general lack of information on the neural networks linked between the cerebellum and other neural substrates mediating mental imagery, future studies are called for to investigate further the neural mechanisms associated with this aspect.

Patient CCT

The brain scan of CCT indicated an infarct at the anterior nucleus of the right thalamus. The anterior nucleus is part of the association nuclei, with reciprocal connections to the area of the cortical cortex that involves emotion (the limbic lobe), and to the pulvinar nucleus (within the association nuclei), reciprocally with the parietal, temporal, and occipital lobes (Lundy-Ekman, 1998). The anterior nucleus has the function of processing emotion-related information and integrating different types of sensations, that is tactile and visual information. The tactile information received from sensory organs conveyed to the cerebral cortex is not via the anterior nucleus. In the present study, the subjects were blindfolded when they performed in the sensory tests in order to avoid the contamination of the tactile information by any possible visual inputs. Therefore, the lesion in the thalamus should not affect the basic and discriminative tactile sensation, as revealed in the results.

The ERPs of CCT were largely comparable with those of the normal group. This was supported by the similar topographies between CCT and the normal group (Figures 4.1 and 4.5). The differences observed in CCT's ERPs were that the amplitude of the N170 component was relatively more positive-going than that of the normal group over the left hemisphere (F3, C3, P3, and T7). The anterior nucleus was found to relate to spatial memory encoding and acquisition of acoustic cues in animal models (Jenkins, Dias, Amin, Brown, & Aggleton, 2002; Warburton, Baird, Morgan, Muir, & Aggleton, 2001). These functions do not seem to be related to the N170 component in this study. It is plausible, however, that the modulating effects would have been exerted via the pulvinar nucleus, which links the anterior nucleus to the other cortical areas responsible for attention to vibrotactile sensation. Recent research reported that the pulvinar nucleus modulated tactile attention function as in other cortical areas, such as the intraparetial and superior temporal area (Bender & Youakim, 2001). Besides, fMRI studies confirmed the involvement of parietal and frontal sites in attention, and extended these findings to show that the specific impact of a warning cue preceding a target by a short interval activated the left hemisphere (Coull, Frith, Buchel, & Nobre, 2000; Coull, Nobre, & Frith, 2001; Nobre, 2001), and the thalamus (Kinomura, Larsson, Gulyas, & Roland, 1996).

Yoo et al. (2003) conducted a fMRI study on tactile imagery using a light brush stroking paradigm on the dorsum of the hand. The results indicated that the imagery processes activated the ventral posteromedial nucleus of the thalamus (Yoo et al., 2003). The posterior nucleus of the thalamus receives somatosensory information from the face, and relays it to the somatosensory cortex. It means that generation of vibrotactile images might involve neural activities in different cortical areas. In the present study, because CCT had a lesion in the anterior nucleus of the

right thalamus, the negative effects, if any, were expected to impede the generation of the sensory images process. In other words, the effects due to the lesions would affect the N170 and P300 components, which probably extended to N400 and P600. The results suggest lesions at the anterior nucleus in the right thalamus did not seem to impede the imagery process. Small modulating effects were found in the N400 (only at P4) and P600 (only at O2, C3, T7) component. Besides, the observations that the lesions of anterior nucleus of the right thalamus exerted less negative effect on the imagery specific processes seems to agree with the behavioral results that the reaction time and the accuracy of CCT were comparable with those of the norm group.

Patient CKF

Patient CKF had lesions in the right middle cerebral artery. Clinical signs presented by CKF suggest that the damages were in both the superior and inferior division of the artery (Warlow et al., 2001). The results of CT scan showed infarctions of both the gray and white matters of the right frontal and temporal areas.

The lesions affected CKF's motor functions in the left hand. As a result, he had difficulty in making responses by pressing on the computer keyboard. CKF completed the matching task by giving a "yes" response if the two stimuli matched with each other, and a "no" response if the two stimuli did not match with each other. The verbal responses were recorded by the researcher. There was no reaction time recorded for CKF. The use of verbal responses would not contaminate the imagery and control tasks because ERP signals were only recorded at the time when the first stimulus was presented (for the first 1000 ms in a total of 4000 ms), while the verbal responses were made after the presentation of the second stimulus

The accuracy of CKF on the matching task was 51%, which was lower than that of the norm group (67%), LKS (62%), and CCT (61%). This suggests that lesions in the right frontal and temporal areas could have exerted stronger effects on compromising the processes involved in the imagery of vibrotactile stimuli. Severe deficits in stereognosis and texture discrimination could have made the identification of stimulus-specific information more difficult, even though CKF had an intact basic tactile sensation.

The amplitudes of the N170 component were found more negative in the right hemisphere (e.g., F4, C4, P4, O2, and T8) when CKF engaged in imagery of vibrotactile stimuli. Our observations are partly consistent with those reported by Giaquinto and Fraioli (2003). In their study, the patients with middle cerebral artery infarct were involved in discriminating electrical stimuli using an oddball paradigm. The results indicated that, only three out of a total of 20 patients elicited a N140 component. In contrast to the results of this study, the N140 amplitudes obtained were less negative over the affected hemisphere. Giaguinto and Fraioli (2003) further interpreted that the N140 component was related to stimulus detection and spatial attention to the tactile stimuli.

Lesions in the right frontal and temporal areas appear to affect the P300 component. The between-condition differences of CKF in the amplitude of P300 were more positive than his normal counterpart at all sites, except a few areas in the parietal and occipital areas. As the modulation effects of imagery were at the right frontal area among the subjects in the normal group, it is reasonable to expect a significant compromise of the between-condition differences in the P300 component in CKF. Our observations are consistent with those revealed in Gummow, Dustman, and Keaney's study (1986). They suggested the overall amplitudes were less positive

and intercorrelations between brain regions were reduced in patients with a middle cerebral artery infarct if the lesions were localized in the right hemisphere. They further attributed the less positive amplitude to the decreased intercommunication between the cortical and subcortical brain structures, and thus led to reduced cognitive efficiency.

The between-condition differences in the N400 amplitudes of CKF were found to be more negative-going than the norm group at Pz and O2. D'Arcy, Connolly and Eskes (2000) reported that the amplitudes of the N400 component were modulated by lesions in the brain. In their study, the subjects were post-stroke patients who were exposed to picture stimuli followed by digitized spoken words that were either congruent or incongruent with the pictures. The N400 component elicited in the congruent situations was found to be less negative than those elicited in the incongruent situations. The differences in the N400 amplitudes between the two situations were found to be more significant among those post-stroke patients who possessed a language deficit. Similar N400 effects were revealed by Mecklinger (1998). In their study, non-linguistic stimuli were used and the results further suggest that the neural processes associated with N400 might not be stimulus specific. Along this line of thinking, the more negative differences observed in the N400 component of CKF could have been due to the brain lesions in the right middle cerebral artery. Since image generation was previously found to be composed of two sequential processes: retrieval of the sensory images from the long term memory and generating sensory images in working memory (Bruyer, & Scailquin, 2000; Kosslyn, 1994), and the compromise of the N400 component because the right middle cerebral artery lesions could have impeded CKF in engaging in at least part of these two processes. This could account for CKF's lower accurate rate on the

discrimination task when compared with the normal group. Similarly, lesions in the right frontal and temporal areas could also account for the more positive-going between-condition differences in the P600 component, observed in these areas in CKF, than subjects in the norm group.

CHAPTER VI

CONCLUSION

The present study used event-related potential to study the neural mechanisms associated with imagery of vibrotactile sensation. Twelve healthy older subjects performed the imagery and control task. The results indicated that the N170 component was not different between the imagery and control conditions in terms of the latency and amplitude, which might indicate that the attention and target detection process is common in both the tasks. The amplitude and latency of the P300, N400 and P600 components elicited during the imagery task was somewhat different from the control group. These ERPs components are found related to stimulus encoding (P300), image generation (P300, N400, and P600), and image maintenance (P600). The image generation and maintenance processes appear to coincide with the "imagery network" described in the literature, which had dipoles localized at the frontal and parietal lobe. The maximum at the central area of the P300 and P600 components further suggest that the imagery involved somatosensory information.

The same imagery and control tasks were repeated for three post-stroke patients who had defined lesions in the brain. The results reveal that lesions in the cerebellum, the thalamus, and the right frontal and temporal areas possibly modulated imagery of the vibrotactile sensation. The modulation effects seem to be the largest in the lesions over the right frontal and temporal areas. These findings shed light on the neural substrates related to vibrotactile imagery. Our findings also further support the model of mental imagery proposed by Kosslyn and Thompson (2003).

Limitations of the Study

Due to the time and resource constraints of the present study, there are several limitations that affect the interpretation and generalization of our results. The first limitation is the comparatively low spatial resolution of the ERPs. This low spatial resolution prevents us from drawing a more confirmative conclusion about the sources of the ERPs underlying the imagery process. For instance, it would be difficult to differentiate the ERPs elicited between the primary and secondary somatosensory cortices, which have differential roles in the processing of vibrotactile sensation. By the same token, the identification and differentiation of the neural substrates underlying various cognitive processes has become more controversial. The second limitation is found in the recruitment of post-stroke patients and the vibrotactile imagery task. A review of the literature indicated that there is a lack of previous lesion studies describing the imagery abilities and deficits of individuals who have suffered from a stroke. As a result, all the assessments on tactile sensation and imagery abilities were customized and developed in the present study. Because subject recruitment was based on the specific type and site of the brain lesions, only three patients eventually fulfilled the selection criteria and so participated in the study. The small sample size did not allow us to use powerful statistical analysis, and thus largely hampered the powerof the results of comparisons of the ERPs between individual patients and the normal group. Finally, the task used in the present study was a fairly difficult one. The ratelimiting steps involved recognizing the frequency and intensity of the brief priming vibrotactile stimuli, and retrieving the same sensory experience from the subjects' long-term memory. This required the subjects to possess relatively high levels of vigilance, memory, and attention functions, and further decreased the chance of recruiting appropriate

subjects for the study. This limitation lowered the power of our interpretations of the ERPs, and the generalization of the results to a wider group of older subjects and post-stroke patients.

Implications for Future Study

Research on tactile imagery is scarce. Our study is the first of its kind to use ERPs to explore the neural processes associated with the imagery of vibrotactile sensation. Mental imagery induced by vibration stimulus elicited the N170 component that appears to denote the target detection and attentional process. The imagery that follows is composed of least two processes. The first is the generation of vibrotactile images, and the second is the maintenance of the images. The P300, N400 and P600 components elicited over the frontal parietal and central areas further revealed the functional role of these neural substrates in the imagery of vibrotactile sensation. These findings will be useful for designing more in-depth studies on vibrotactile imagery in the future. The results obtained from the three case studies provide a basis for developing clinical protocols for using imagery to promote sensory restoration among patients who have deficits in tactile sensations.

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APPENDIX I

Letters of Ethics Approval

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Department of Rehabilitation Sciences

MEMO

To : Prof. Chetwyn Chan, Associate Head, Dept. of RS

From : Prof. Gabriel Ng, Chairman, DRC, RS

Ref : RS 9/10 **in :** _____ **Your Ref :** _____ **in :** _____

Tel No. : 6721 **Fax No. :** _____

E-mail : _____ **Date :** 4 May, 2004

Re: Application for ethical review of research proposal

Project Title: Mental imagery of vibrotactile sensation in patient suffered from stroke

Thank you very much for your application for ethical review of the above research proposal. I am pleased to inform you that the proposal has been reviewed and approved by the Departmental Research Committee, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University. Please note that the validity of this ethics approval ceases upon the completion of the proposed project.

Please inform me should there be any subsequent changes in your protocol.

Prof. Gabriel Ng
Chairman
Departmental Research Committee
Department of Rehabilitation Sciences

GN/MLyl

Ethics

香港大學 香港大學及醫管局港島西醫院聯網研究倫理委員會
University of Hong Kong Institutional Review Board of the University of Hong Kong/
Hospital Authority Hong Kong West Cluster (HKU/HA HKW IRB)
Address: Rm 901, Administration Block, QMH Tel 2855 3351 2855 3923 2855 4086 Fax 2855 4735

Prof. Chetwyn Chen
Dept. of Rehabilitation Sciences
Hong Kong Polytechnic University
16-06-2004

Dear Prof. Chen,

IRB Reference Number: **UW 04-171 T/493**

The HKU/HA HKW IRB is authorized by the Cluster Chief Executive [and the University of Hong Kong, Faculty of Medicine] to review and monitor clinical research. It serves to ensure that research complies with the Declaration of Helsinki and acts in accordance to ICH GCP guidelines, local regulations and HA [and the University] policy. It has the authority to approve, require modifications in (to secure approval), or disapprove research. This Committee has power to terminate/suspend a research at any time if there is evidence to indicate that the above principles and requirements have been violated.

Professor C L Lai, Chairman of the HKU/HA HKW IRB has reviewed/approved, as appropriate, your submission on the date shown below by an expedited process. You are required to adhere to the conditions listed.

Date of expedited review (Date/Month/Year)	:	16-06-2004
Protocol title	:	Mental imagery of vibrotactile sensation in patients suffered from stroke
Study site(s)	:	As stated in application form
Document(s) approved	:	01. Clinical research ethics approval application form
	:	02. Research protocol
	:	03. Informed consent form - English and Chinese
Document(s) reviewed	:	04. Approval letter from RC/HKPU dated 4 May, 2004
	:	05. Short CV of principal investigator

Conditions : 1. Do not deviate from, or make changes to the study protocol without prior written IRB approval, except when it is necessary to eliminate immediate hazards to research subjects or when the change involves only logistical or administrative issues.

2. Report the following to HKU/HA HKW IRB: (i) study protocol or consent document change (use 'HKU/HA HKW IRB RE001F7'), (ii) serious adverse event (use 'HKU/HA HKW IRB RE001F8'). (iii) study progress (use 'HKU/HA HKW IRB RE001F9a')* (iv) new information that may be relevant to a subject's willingness to continue participation in the study.

3. Report first study progress to HKU/HA HKW IRB at a 12-monthly interval until study closure.

(Mr. Chris Yip)
Secretary
HKU/HA HKW IRB

APPENDIX II

The Hong Kong Polytechnic University
Department of Rehabilitation Sciences

Research Project Informed Consent Form for Post-stroke Patients

Project title: Mental imagery of vibrotactile sensation in patients suffered from stroke

Investigator(s):
Prof. Chetwyn C. H. Chan, Prof. Christina W. Y. Hui-Chan, Dr. Karen P. Y. Liu, Dr. Leonard Li, Ms. Christina S. F. Yau, Ms. Kari, W. S. Chow

Design of the study:

The purpose of the study is to investigate the neural mechanism associated with vibrotactile imagery in a group of stroke patients.

In this project, during your rehabilitation stage in the hospital, you are invited to participate in a four-hour vibrotactile imagery program. In the 1st two hours, you are required to memorize and discriminate different vibrotactile stimulations. Then your are required to undergo the an electroencephalogram acquisition session in the later 2 hours, during which you are required to imagine the vibration sense and response to a sensory discrimination task by pressing a key on the computer keyboard. Besides, assessments on your sensory and cognitive function will be carried out. This study will inform the feasibility of utilizing vibrotactile imagery as a sensory rehabilitation regime for patients who suffer from stroke. The study carries no risk to you.

Consent:

I, _____, have been explained the details of this study. I voluntarily consent to participate in this study. I understand that I can withdraw from this study at any time without giving reasons, and my withdrawal will not affect the treatment I receive in the hospital. I also understand that my personal information will not be disclosed to people who are not related to this study and my name or photograph will not appear on any publications resulted from this study.

I can contact the investigator, Ms. Kari Chow at telephone 27664377 or Prof. Chetwyn Chan at telephone 27666727 for any questions about this study. If I have complaints related to the investigator(s), I can contact Mrs. Michelle Leung, secretary of Departmental Research Committee, at 27665397. I know I will be given a signed copy of this consent form.

Signature (subject): Date:

Signature (witness): Date:

香港理工大學 - 康復治療學系

中風病人研究計劃同意書

研究題目

研究中風病人之康復治療 -- 感知覺意象治療

研究人員

陳智軒教授、許雲影教授、廖佩儀博士、李常威博士、丘世芬小姐、周惠心小姐

研究內容

本研究目的在於探究中風病人進行感知覺的意象訓練時，大腦活動的機制。

這個研究是在你的康復階段中進行, 你會被邀請參加一個約 4 小時的感知覺意象課程。在首兩個小時, 你需要記憶和分辨不同的觸覺震動信號, 在後兩個小時, 我們會錄取你的腦電圖, 在錄取期間你需要意象及分辨不同的觸覺震動信號, 然後按電腦鍵盤表示你的選擇。另外, 你亦需接受有關感覺和認知能力之檢查。研究結果將會有助確定感知覺意象治療對中風病人感覺復康的作用。整個研究過程不會對參加者構成任何危險。

同意書

本人 _____ 明白此項研究之細節，並聲明自願參加此項研究。 我明白可以隨時在不需作出解釋之情況下退下出此項研究，而不會影響本人在醫院所接受的治療。我明白本人之個人資料將不會向本研究以外人仕公開，並且我的姓名或照片將不會出現於任何研究報告之內。

本人可致電 27664377 向研究員周惠心小姐，或致電 27666727 向陳智軒博士查詢本研究事項，若果我對研究員有任可投訴，可以致電 27665397 與梁小姐接洽。我將授予簽署同意書副本一份。

簽署(參加者): 日期:

簽署(見證人): 日期:

APPENDIX III

The Hong Kong Polytechnic University
Department of Rehabilitation Sciences
Research Project Informed Consent Form for Normal Subjects

Project title: Mental imagery of vibrotactile sensation in patients suffered from stroke

Investigator(s):
Prof. Chetwyn C. H. Chan, Prof. Christina W. Y. Hui-Chan, Dr. Karen P. Y. Liu, Dr. Leonard Li, Ms. Christina S. F. Yau, Ms. Kari, W. S. Chow

Design of the study:

In this project, you are invited to participate in a four-hour vibrotactile imagery program. In the 1st two hours, you are required to memorize and discriminate different vibration stimulations. Then your are required to undergo the an electroencephalogram acquisition session in the later 2 hours, during which you are required to imagine the vibration sense and response to a sensory discrimination task by pressing a key on the computer keyboard. Before the experiment, screening assessments on your sensory and cognitive function will be carried out. This study will inform the feasibility of utilizing vibrotactile imagery as a sensory rehabilitation regime for patients suffer from stroke. After finishing the experiment, you will be given Hong Kong dollar 200 to compensation your time. The study carries no risk to you.

Consent:

I, _____, have been explained the details of this study. I voluntarily consent to participate in this study. I understand that I can withdraw from this study at any time without giving reasons, and my withdrawal will not lead to any punishment or prejudice against me. I am aware of any potential risk in joining this study. I also understand that my personal information will not be disclosed to people who are not related to this study and my name or photograph will not appear on any publications resulted from this study.

I can contact the investigator, Ms. Kari Chow at telephone 27664377 or Prof. Chetwyn Chan at telephone 27666727 for any questions about this study. If I have complaints related to the investigator(s), I can contact Mrs. Michelle Leung, secretary of Departmental Research Committee, at 27665397. I know I will be given a signed copy of this consent form.

Signature (subject): Date:

Signature (witness): Date:

香港理工大學 - 康復治療學系

長者研究計劃同意書

研究題目

研究中風病人之康復治療 -- 感知覺意象治療

研究人員

陳智軒教授、許雲影教授、廖佩儀博士、李常威博士、丘世芬小姐、周惠心小姐

研究內容

本研究目的在研究及比較正常人和中風病人在感知覺的意象訓練時，大腦的變化情況及機制。

參加者將會接受約 4 小時的感知覺學習課程，期間參加者會配帶腦電圖的儀器及對電腦程序的指出作出反應，反應包括接收震動器在參加者掌心發出的震動信號及意象該震動信號。同時, 參加者亦接受有關感覺及認知能力之檢查。研究結果將會有助確定感知覺意象治療對中風病人感覺復康的作用。整個研究過程不會對參加者構成任何危險。參加者在需要盡力完成實驗的要求，而整個實驗完結後將會獲得$200 之酬勞。

同意書

本人 _____ 明白此項研究之細節，並聲明自願參加此項研究。 我明白可以隨時在不需作出解釋之情況下退下出此項研究，而將不會受到處罰或歧視。我悉知參與本研究可能帶來之影響及願意對此承擔一切責任。我明白本人之個人資料將不會向本研究以外人仕公開，並且我的姓名或照片將不會出現於任何研究報告之內。

本人可致電 27664377 向研究員周惠心小姐，或致電 27666727 向陳智軒博士查詢本研究事項，若果我對研究員有任可投訴，可以致電 27665397 與梁小姐接洽。我將授予簽署同意書副本一份。

簽署(參加者): 日期:

簽署(見證人): 日期:

APPENDIX IV

Industrial Guidelines of Monofilaments

Figure 5—Touch-Test™ Sensory Evaluator Chart

Product Number	Evaluator Size	Target Force*	Representation	Hand & Dorsal Foot Thresholds	Plantar Thresholds
NC12775-01	1.65	0.008			
NC12775-02	2.36	0.02	Green	Normal	Normal
NC12775-03	2.44	0.04			
NC12775-04	2.83	0.07			
NC12775-05	3.22	0.16	Blue	Diminished Light Touch	
NC12775-06	3.61	0.4			
NC12775-07	3.84	0.6			
NC12775-08	4.08	1	Purple	Diminished Protective Sensation	Diminished Light Touch
NC12775-09	4.17	1.4			
NC12775-10	4.31	2			
NC12775-11	4.56	4			Diminished Protective Sensation
NC12775-12	4.74	6			
NC12775-13	4.93	8			
NC12775-14	5.07	10			
NC12775-15	5.18	15	Red	Loss of Protective Sensation	
NC12775-16	5.46	26			Loss of Protective Sensation
NC12775-17	5.88	60			
NC12775-18	6.10	100			
NC12775-19	6.45	180			
NC12775-20	6.65	300			

* Individually calibrated within a 5% standard deviation.

Touch-Test™ Sensory Evaluators and Accessories:

Product Number	Description
NC12775	Touch-Test™ 20 Piece Full Kit
NC12774	Touch-Test™ Complete Foot Kit (6 Piece Kit, Screening Forms, Colored Pencils)
NC12773	Touch-Test™ 6 Piece Foot Kit (2.83, 3.61, 4.31, 4.56, 5.07, 6.65)
NC12771	Touch-Test™ Complete Hand Kit (5 Piece Kit, Screening Forms, Colored Pencils)
NC12772	Touch-Test™ 5 Piece Hand Kit (2.83, 3.61, 4.31, 4.56, 6.65)
NC12775-14	Touch-Test™ Sensory Evaluator 5.07 (10 grams of force*)
▲ See NC12775-01 thru NC12775-20 for Individual Replacement Touch-Test™ Sensory Evaluators ▲	
NC12749	Foot Screening Forms (pad of 100)
NC12750-1	Hand Screening Forms (pad of 100)
NC12776	Colored Pencils Set
NC12780	Touch-Test™ Training Video-FREE

CE