National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

## NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

## AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

# UTILIZATION OF MAGNIFIED VISUAL FEEDBACK IN THE MAINTENANCE OF FINGER POSITION

A Thesis
Submitted to the
Faculty of Graduate Studies and Research

In Partial Fulfillment
Of the Requirements for the Degree of
Masters of Science

submitted by:
KONSTANTINON VASILAKOS
Department of Physiology
McGill University, Montreal

©Konstantinon Vasilakos, 1996

April 4, 1996

National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

*Your file Votre référence*

*Our file Notre référence*

**The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.**

**L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.**

**The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.**

**L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.**

ISBN 0-612-12285-9

Canada

Γιά τούς γονείς μου

Αντρέας καί Βασιλική

# ABSTRACT

This study investigates the interaction between increased gain in the visual feedback loop and motor control of the periphery. Subjects were asked to maintain a constant finger position while utilizing magnified visual feedback. The accuracy of each trial was quantified by taking the standard deviation (trial-error) of the finger position. Trials performed under magnification have lower trial-errors than trials without magnification. The change in trial-error between trials with and without magnification proves greater than the difference between trials at any two magnifications. In contrast, the differences between individual subjects is often greater than the difference between performances at individual magnifications. At higher magnifications performance seems to be limited by the tremor. Trial-error is approximately 2 times the tremor-intensity. When applied to microsurgery these results are in accord with earlier research including results suggesting that the level of magnification used in microsurgery is not the most significant factor in achieving good results,[1] and that tremor is the limiting factor in microsurgical tasks.[2]

# RÉSUMÉ

Cette étude porte sur le rapport entre l'augmentation de l'amplification dans le feedback visuel et le contrôle moteur périphérique. Nous avons demandé aux sujets de maintenir leur index dans une position fixe sous des conditions de feedback visuel amplifié. La précision de chaque essai fut estimée en mesurant la l'écart-type de la position de l'index. Les essais sous amplification ont un degré plus faible de l'écart-type qu'en absence d'amplification. Cette différence est supérieure à celle entre deux essais effectués à deux niveaux d'amplification donnés. Par contre, les variations d'un sujet à l'autre dominent souvent les écarts entre les performances individuelles à deux niveaux d'amplification différents. Sous forte amplification, la performance est limiteé par le tremblement. Le niveau de l'écart-type est environ le double du degré du tremblement. Dans le domaine de la microchirurgie, ces résultats confirment les conclusions de travaux précédents montrant que le degré d'amplification visuelle ne joue pas un rôle primordial dans l'obtention de résultats probants,[1] le niveau de tremblement étant le principal facteur limitant la précision des interventions microchirurgicales.[2]

# ACKNOWLEDGMENTS

I would like to take this opportunity to thank Dr. Anne Beuter for her supervision of my research project and for her help and support over the last few years. Her gracious charity, her much abused patience and her unending support have helped me through some of the most difficult times in my life. I am indebted to her and am eternally grateful.

Dr. Leon Glass has also played a critical role in my academic growth over the past five years. My thanks go to him for taking a risk and betting on the dark horse, as well as for having the understanding of how the night crew sometimes works. As well I am indebted Leon for his willingness to edit my wordy indirect manuscripts and for much support over the years.

As well I would like to thank various members of the Center for Nonlinear Dynamics for their contribution over the years. Thanks to Doctors Michael Guevara and Jacques Bélair for being on my thesis committee and for many useful discussions. Thanks to Professors John Outerbridge and Daniel Kaplan for assistance on many technical aspects, and a special thanks to Professor Michael Mackey for some early guidance in my academic career.

Thanks to Doctors François Bellarance and Roch Roy for taking the time to look at my data and suggest some statistical analyses, and to Chris Lemay for the early work on the program to operate the display.

I would also take this moment to personally thank my fellow graduate student Gil Bub, with whom I have shared an office and many a conversation. Gil is truly an amazing individual, someone who strives and succeeds, yet cares, understands and empathizes.

Of course, I should also acknowledge all the other individuals who have enriched my life here both at McGill and at UQAM, starting with Arkady Kunysz for helping me in many computer (as well as social) endevours, Adam Sherman for helping me with programming the PC, Harald Henschke for being a good number one, Claude Lacoursiére for the wonderful left wing ideology, and Anne de Geoffroy pour la belle patience avec un petit enfant.

Finally, the love, understanding, and support my parents have always given me have proven to be a source of strength for me over the years.

# Contents

# Chapter 1

# INTRODUCTION

## 1.1 OVERVIEW

The effects of visual feedback on motor control of extremities, in particular during microdisplacements, is a topic of interest to physiologists and clinicians attempting to eludicate the pathways of motor control,[3] to microsurgeons interested in improving their skill and accuracy,[4] and to theoreticians interested in the various properties of negative feedback present in this loop.[5] One relatively unexplored aspect of this field is the effective utilization of magnified visual feedback.

Effective motor performance involves proper integration of several factors including visual inputs,[5,6] proprioceptive stimuli,[7,8] control strategies[9,10] and coordination. Inherent limitations to carrying out fine tasks include tremor,[2,11] delays in the sensory and motor pathways,[12,13] and inaccurate interpretations of sensory information.[14–16] Proper understanding of the control systems involved will provide valuable insight on maximizing performance.

The effective utilization of visual feedback is extremely important in microsurgery. To this end, microsurgeons generally use some form of magnifying device to increase accuracy.[4] Studies investigating the optimal magnification for improving performance usually rely on

indirect qualitative methods.[1,17,18] Only one study has actually measured the accuracy of microsurgeons.[4]

This study investigates the interaction between increased gain in the visual feedback loop and several aspects of motor control. This is accomplished by analyzing the performance of subjects attempting to maintain a constant finger position while utilizing visual feedback with high magnification.

## 1.2 Literature Review

### 1.2.1 Neural Structures

One may classify the structures of the brain into four separate functional groups: sensory, motor, cognitive, and circuitry.[19] Sensory information from afferent nerves is processed primarily in the parietal and occipital lobes. Initial cortical processing of proprioceptive information occurs in the primary somatosensory cortex of the parietal lobe (the post-central gyrus), while the remainder of the parietal cortex subserves complex aspects of orientation in space and time. The occipital lobe is more intimately related to vision. Initial processing of optic nerve signals is completed by the primary visual cortex of the occipital lobe (the walls of calcarine sulcus). The remainder of the occipital lobe (termed the visual association cortex) deals with higher visual functions.[19]

The frontal lobe and the cerebellum are involved in the production of efferent motor signals. The frontal lobe, which may be subdivided into the primary motor cortex (precentral gyrus) and the premotor area is primarily involved in the initiation of voluntary movement. The cerebellum is a complex structure closely involved with the coordination of voluntary movements.[19]

Strategies and learning which may aid the subject in completing a motor task occur as well. The primary center for these processes is the parietal lobe. This lobe is involved with both learning and memory.[19]

Finally, each structure of the brain is interconnected with other structures. The integration of the signals (both afferent and efferent) occurs primarily in the thalamus and the basal ganglia. All sensory pathways relay through the thalamus, while descending pathways (including motor pathways) provide input to the thalamus. It is believed that the thalamus then provides feedback to the higher structures.[19]

Although it is possible to section areas of the brain into functionally separate structures, effective motor performance involves proper integration of several factors including visual inputs, proprioceptive stimuli, control strategies and manual skill. The resultant performance must deal with errors in control resulting from misinterpretation of sensory information, poor motor skill, and inherent drift and tremor.

### 1.2.2 Origin and Influence of Tremor

Physiological tremor refers to the relatively rapid involuntary variations of position or force occurring several times a second throughout the body.[20] These small, unintentional, irregularities are most often described by their frequency content, whose range is bounded between 3 and 15 Hz.[2,11,21-26]

The origin of physiological tremor has been a subject of debate for many years. Early research suggested that physiological tremor resulted from ballistocardiac forces generated each cardiac cycle,[27] but this study was performed on limbs at rest. Marsden *et al.* demonstrated convincingly that although limbs at rest do exhibit oscillations predominantly cardiac in origin, physiologic tremor is the product of other factors.[22] For a finger held stretched out in posture, the ballistocardiac impulse contributes to between 2 and 10% of the total tremor power.

By perturbing the finger with a step-function, Lippold demonstrated that physiological tremor appears to be produced by an under-damped servo-system and postulated that the origin of tremor is the stretch reflex arc.[28] The stretch reflex acts to maintain limbs in a given posture. By slightly perturbing fingers held in posture, Lippold showed that the resulting oscillations have the same origins and characteristics as physiological tremor. Furthermore, by recording EMG's, Lippold demonstrated that these oscillations are not due to mechanical die away resonance of the finger but rather by muscle activity. The conclusion was that the

stretch reflex arc produced the tremor.

Some doubt has been cast on this hypothesis by the findings that certain centers in the brain have a tendency to oscillate at 10 Hz, the frequency of physiological tremor.[24,29] Drugs which enhance tremor result in the oscillations in these structures becoming much more prominent.[30]

Several examples of tremor persisting despite deafferentation have been documented. These findings further contradict the hypothesis of generation of tremor by the stretch reflex arc as a peak is still found in the power spectrum around 9 Hz, although the peak is smaller and less sharply defined.[25]

### 1.2.3 Vision and Tremor

The arguments that physiological tremor is a product of the peripheral structures are strong, as the experiments of Lippold have demonstrated.[28] There is strong evidence for the involvement of the central nervous system (CNS) in the generation of pathological tremors (i.e. parkinsonian tremor[31]), but evidence that central structures can influence physiological tremor has not been consistent.

In 1967, Sutton and Sykes noted an effect on tremor mediated through vision. Tremor was recorded in subjects attempting to maintain a constant torque on a joystick. In half the trials the force generated by the subject was displayed as feedback. In these trials a peak appeared in the spectrum of the tremor at 9 Hz. Removal of visual feedback abolished this peak.[20]

In the same year, Merton *et al.*[21] conducted a similar task implementing a time delay in the feedback to the visual monitor. This added delay resulted in a shift in the frequency of the peak in the tremor spectrum of the subject performing the task. Many of the conclusions regarding visual feedback's influence upon tremor of the extremities formed in these studies

was later refuted by the work of Stevens and Taylor in 1974.[11] By altering the gain of the visual feedback to subjects, they demonstrated that although changes in the power spectrum of the tremor did occur, the changes were uncorrelated to mean force of exertion or to visual feedback gain. The earlier examples by Sutton and Sykes and Merton were then ruled exceptions as those earlier studies were performed on very few subjects.

### 1.2.4 Vision and Perception

While the influence of vision on tremor is now considered to be intermittent and inconsistent, the influence of tremor on vision or more particularly, the effect of noise on visual perception, is still an unresolved question. Many questions remain unanswered on how the eye extracts a clear signals from the sea of noise,[32] but considerable work has been completed on many psycho-perceptive aspects of vision.[14,15,33,34] Increasing the magnification of visual feedback will naturally increase the noise content in that feedback. Accordingly visual robustness in the presence of noise is an important issue. Much of the work has been geared towards delineating the degree to which the visual system can operate in the presence of noise.[14,15] It has been determined that when a signal (or movement) is immersed in noise, threshold detection of the signal occurs most efficiently when the signal has a different frequency than the noise.[14] Physiological tremor has a frequency range of 3-15 Hz and a magnitude generally under 1 mm.[11,26] Slow movements have frequency characteristics considerably below this range, but fast movements may easily reach these higher frequencies.[35]

### 1.2.5 Proprioception

Sensory information is provided by cutaneous, joint, and muscle receptors, which respond to both passive and active movement.[7] This information is utilized by higher centers in detecting and determining degree of motion. Application of vibration to muscles and their

tendons can produce illusory "movement".[7]

As early as 1954, the motor response of subjects without visual feedback was measured.[36] This early experiment studied the accuracy of positioning responses in the absence of visual feedback as displacement and force information was varied. The subjects were asked to move a rod to one of six different distances, against one of four different loads. Proprioception is more attuned to discerning different distances than different forces. As well, the work discovered that in the absence of visual feedback, subjects tended to overshoot short target movements and undershoot long target movements.[36]

A more recent study by Bevan *et. al.* compared the ability of subjects to discern joint angle versus angular distance covered, again without visual feedback. The right elbows of normal human subjects were passively extended from either predictable or unpredictable starting angles. The subjects were instructed to open the right hand to indicate that the elbow was passing through a target joint angle or a target angular distance. The subjects were not given visual information about the location of the elbow, and had to rely on proprioceptive input to perform the task. The subjects were more accurate in covering specific distances, than stopping at particular joint angles. As well, subjects tended to overshoot when they were closer to the target, and undershoot when they were farther away.[8]

Nearly all joint afferents innervating the metacarpo-phalangeal joints of the hand are recruited or have discharge accelerated during passive movements.[37] However, the overall capacity of the joint receptors to signal static angular position is limited.[7] Proprioceptive acuity for passive movement remains when joints (and the surrounding skin) are anesthetized, suggesting that the information provided by joint and skin receptors may be redundant. Most importantly, all proprioceptive information is interpreted by the CNS against a background of information from other sources; vision of the limb will abolish illusionary movement caused

by vibration.

### 1.2.6 Visuomotor Control

Inherent in all of the experiments investigating the influence of vision on the periphery is the utilization of visual feedback to control displacements or micro-displacements. Perhaps the first such study was a 1965 study involving a compensatory tracking task. In this study, the subject's vertical finger position was displayed on an oscilloscope, and the subject was asked to maintain the position as close as possible to a second beam which did not move.[38]

A similar setup was used to study the effects of delays in the visuomotor control system, Once more, the subject's vertical finger position was displayed as a line on an oscilloscope, and the subject was asked to maintain the line as close as possible to a second reference line which did not move. The feedback to the subject was then delayed between 0 and 1500 ms. Glass *et al.* demonstrated that subjects tended to enter into a pattern of irregular low frequency finger oscillations.[5,13]

It was proposed that the system was governed by stable negative feedback dynamics.[5,39] Negative feedback systems with single control loops can be destabilized by increasing the gain and/or delay to produce regular oscillations with periods between two and four times the delay.[40] The irregularity of the oscillations in the experiment suggest a more complex process possibly involving more than one loop.[5,39,41]

Multiple negative feedback loops can, in certain circumstances, lead to deterministic chaotic dynamics in which there is aperiodic dynamics with sensitive dependence on the initial conditions.[5,39] However, although chaotic dynamics can be found in multiple negative feedback systems, this is a comparatively rare phenomenon.[42]

The task of maintaining a constant finger position also involves occasional rapid corrective movements. The ability to perform these rapid accurate corrections indicates that

feed-forward is also important in this system.[13] The interaction of the feed-forward loops with the multiple feedback loops may also be contributing to the complex dynamics in this setup.[13,39,41]

The appearance and disappearance of the low-frequency oscillations suggests that the relative weighting of various control mechanisms regulating finger position may be varying during the course of these experiments.[13] An alternative possibility is that various feedback loops are selectively activated or deactivated depending on the current and past states of the system.[41]

When the same experiment was performed in patients with Parkinson's disease, only half the subjects responded as controls while the other half failed to enter into the pattern of irregular low frequency oscillations.[43] The subjects who did not react as controls had a rest tremor that was generally higher than patients who did act as controls.

The influence of stochastic elements in this task was investigated.[16,44] In 1993, Beuter *et al.* performed a modeling study in which the inclusion of noise in the modeling equations is seen to contribute qualitatively to a more accurate reproduction of experimental traces.[44] In the same year, Vasilakos and Beuter hypothesized that pathological tremor may act as noise in the visual feedback and influence the behavior of subjects performing the task.[16] To examine this hypothesis, noise of varying amplitude was included in the visual feedback of normal subjects attempting the task. Increased noise in the feedback curtails and destroys the oscillations normally produced by the inclusion of the time delay. Numerical simulations also indicated that increased noise in the feedback would result in the curtailment of oscillations normally caused by an increased delay.[16]

These studies were based on the hypothesis that the visuomotor control system operates by negative feedback. It is commonly assumed though that the initial phase of movement is open-loop, while the terminal phase is closed-loop with visual feedback playing an important

role.[6] Investigators of other systems have also found that early short-term motor programs may indeed be based on open-loop control mechanisms.[45]

The terminal closed-loop phase in visually guided movements is composed of discrete corrections,[6] or sub-movements.[46] Slow finger movements in man are not smooth, but rather characterized by steps or discontinuities, often recurring at intervals of 100-125 ms (8-10 Hz).[3]

### 1.2.7 Microsurgery

In order to increase accuracy during surgery on small blood vessels, nerves, and other microstructures, surgeons usually use some form of magnifying device.[4] Magnifications range from 2.5× to 8× for surgical loupes, and up to 40× for operating microscopes.[47] Physiological tremor can cause significant error in the accurate placement of sutures.[2] This error is caused both by the movement of the hand and by the surgeon receiving possibly misleading visual feedback.

Early work studied the physics of the motor system along with the ergonomics of microsurgery with the intent of improving microsurgical skill. Various suggestions were made, including type of equipment to use as well as optimal hand position to reduce physiological tremor during surgery.[48]

Harwell and Ferguson investigated the usage of biofeedback techniques to reduce physiological tremor during microsurgery. Subjects were asked to either hold a 1 mm wire loop steady under 40 times magnification or to move an aneurysm clip from one position to another. The average distance the loop or clip moved each second was measured using a simple analog device and taken to quantify the magnitude of tremor. The level of tremor was then provided to the subject on a meter. With practice, the subjects quickly learned the proper posture and positioning of the hands for a reduced tremor score.[2]

Other investigators have investigated whether the level of magnification has a significant effect.[1,4,17,18] Early studies were limited to investigating post-operative health of patients, comparing loupe-assisted surgeries to microscope-assisted surgeries.

Strow analyzed the post-operative vision of patients who had undergone cataract surgery. The major criterion for success of the surgery was the patients' vision three months after surgery. Strow concluded that the microscope seemed to produce better visual results. A major weakness of the study though was the lack of statistical analysis.[17]

McManamny performed a similar study, analyzing the post-operative recovery of 31 patients who had undergone repair of complete divisions of median and ulnar nerves. This study involved a detailed assessment of both sensory and motor recovery in the patients. Once more the study failed to include a valid statistical analysis. The conclusion of the study was that the type of magnification assistance used in peripheral nerve repair is not as significant in achieving good results as other factors such as skill of surgeon.[1]

Rock *et al.* completed a randomized clinical trial comparing the efficacy of the loupe and microscope in reversing sterilization in patients. Their measure of success was the pregnancy rate following surgery. It was found that the difference between groups was not significant.[18]

Finally in 1993, Rooks *et al.* actually measured the accuracy of surgeons performing a microsurgical task. This group compared the precision of suture placements in microscope- and loupe-assisted anastomoses. Experienced surgeons were asked to perform four microvascular anastomoses each, two with surgical loupes (range of 3.5 - 4× magnification) and two under a surgical microscope (range of 8× to 30× magnification). The surgery was performed on 2 mm Gortex prostheses and the accuracy and variability of the sutures was measured. The mean suture puncture to prosthesis edge measurement for the microscope-assisted group was significantly closer to the edge (P value $< 0.0001$ using the Mann-Whitney U test). Furthermore, the variability from the mean for the microscope-assisted group was significantly

lower than that of the loupe-assisted group (P of 0.0123 using the Mann-Whitney U test). The authors recommended that the higher power magnification of the microscope should be used whenever available to increase the precision of microsurgery.[4]

### 1.2.8 Conclusions

The influence of visual feedback upon the periphery has been a subject of study for many decades. The avenues of research have been directed in several directions. Earlier work considered the influence vision had upon physiological tremor in the extremities.[20] Later studies were interested in improving performance of fine motor control during tasks such as microsurgery.[4] Another direction was primarily interested in investigating the control functions involved in the system.[41] Yet other research has been interested in the cognitive processes involved in interpreting the visual feedback.[34] Throughout all this time, considerable research has gone into the investigation of the motor output itself in the extremities, often in visually guided tasks.[3]

In this study, we investigate the utilization of magnified visual feedback in the maintenance of finger position. The subject's finger position was recorded under several different conditions of magnification. This experiment replicates some of the early work on the influence of vision upon physiological tremor and help confirm the results of Stephens and Taylor, that changes in power of the tremor are uncorrelated to magnification level.[11]

Although the task in this experiment is simple, previous work has demonstrated that quite complicated dynamics arise when an artificial delay is included in the feedback loop.[5] As inherent delays exist in the system, an increase in magnification should elicit similar dynamics. Analysis of the recordings should indicate whether similar behaviour occurs and shall give us insight into the control mechanisms used in the loop.

This task is strongly related to microsurgery with the subject using magnified visual

feedback to increase precision. To date, there has been only a single study analyzing accuracy under different levels of magnification.[4] This study will attempt to answer the question of which magnification is most effective in improving performance.

# Chapter 2

# MATERIALS and METHODS

The goal of the study is to investigate the effect of increased magnification on visually guided motor control. To accomplish this task, an experiment has been designed in which magnification of the visual feedback can be generated.

## 2.1 PROCEDURE

### 2.1.1 Population

The subjects were eight males and seven females between the ages of 20 and 45 and each subject gave informed consent. The subjects were screened to ensure all subjects were free of motor or visual dysfunction. Use of visual aids (such as glasses) was mandatory for those subjects who possess such aids. Each subject had the experiment explained to him or her and was familiarized with the equipment.

### 2.1.2 Experimental Apparatus

Experiments were performed using an apparatus similar to previous work.[5,13,16,39,43,44]

**A) Chair and Laser** The subjects sat in a chair with arm rests such that their eyes were 80 cm from the screen. Their dominant hand and arm were immobilized and a brace

was placed on their index finger so movement could only be conducted at the metacarpo-phalangeal joint. A flat surface was placed on the top of the brace and an infrared semiconductor laser (Matsushita Electric Works, Osaka, Japan) located 10 cm from the joint. The laser was positioned to record in the vertical plane (the flexion-extension joint angle).

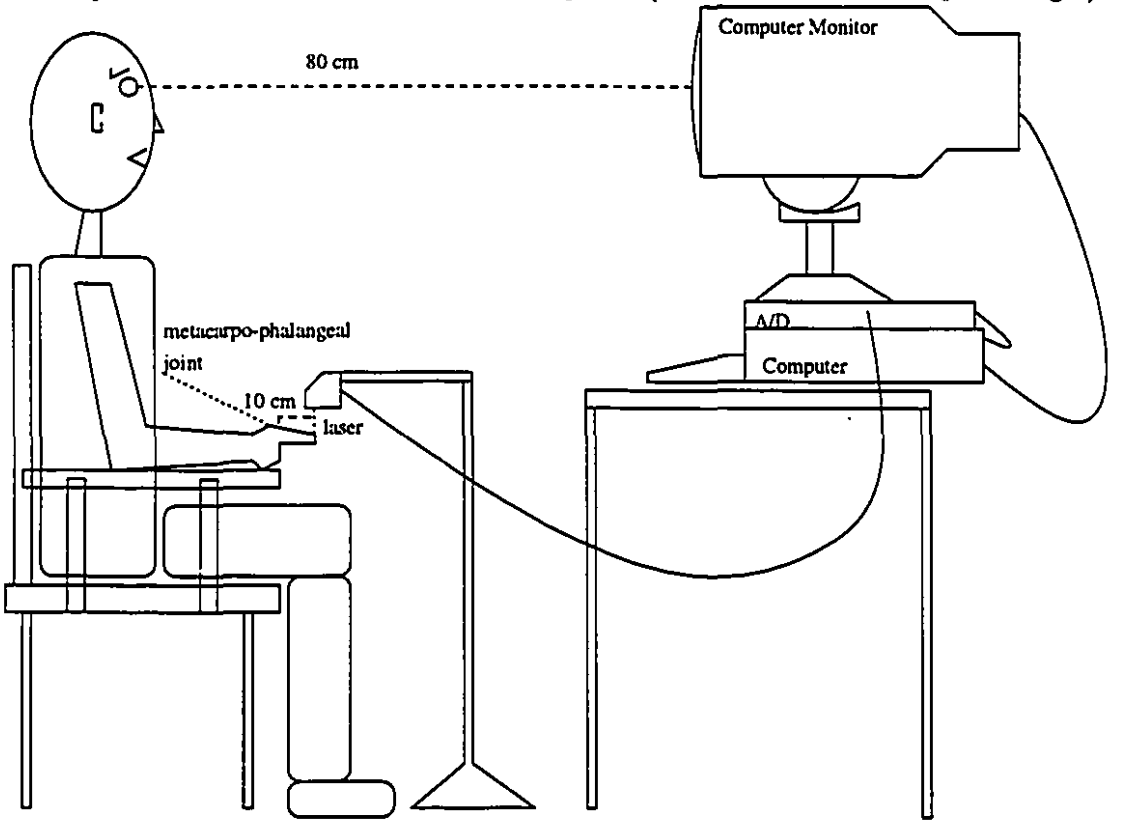


Figure 2.1: Diagram of the experimental setup.

**B) Display** The computer in front of the subject ran the program to operate the display. As the refresh rate of the screen was 70 Hz, the program was limited to run at this speed. This program accessed the first A/D board (Axotape, Axon Instruments, Foster City, California) reading the voltage output of the laser. This voltage was then scaled to represent distance displaced from the reference line. A horizontal line representing finger position was displayed on the screen.

Several manipulations occurred at the digital level. First, different visual magnifications

were set. Under the default setting, a finger movement of 1 mm would result in the movement of the line of 1 mm. Total top to bottom distance of the display was 160 mm.

Secondly, if the finger position was such that the displayed line would coincide with the reference line, a line of a different colour would be drawn. If the finger position was too high or too low to be displayed on the screen, a line would be drawn at respectively the top or bottom of the screen.

Finally, the program exports the screen position displayed at 70 Hz. In this way, it was known at all times what visual feedback the subject received.

### 2.1.3 Data Acquisition

The infrared semi-conductor laser was placed 10 cm from the metacarpo-phalangeal joint in the flexion-extension axis. The laser had a resolution of 35 $\mu$m, its specifications may be found elsewhere.[49] The signal coming from the laser was digitized by two A/D boards (Axotape and Brainwave (Data-Wave Technologies, Longmont, Colorado) ). The first board was utilized by the computer running the display. This computer then output a signal corresponding to the feedback displayed to the second board. The second board was connected to a computer operating data acquisition software (Brainwave). Both signals were recorded at 200 Hz for a duration of 40 seconds.

### 2.1.4 Experimental Procedure

Written informed consent was obtained from the subjects before the experiment was begun. A verbal explanation of the experimental goals, set-up and procedure was then given as the subjects were installed into the equipment. The subjects were then allowed to familiarize themselves with the task at each level of magnification. Once the subject felt comfortable, the trials commenced.

Magnifications of 1×, 4×, 10×, 20×, and 40× were used. These magnifications cover the range of the surgical loupe (2.5× to 8×) and the operating microscope (8× to 40×).[4,47] There were two trials at each magnification. The trials were presented in a varied order. The order was such that the subject completed one trial at each magnification within the first five trials. The subject then repeated the pattern in reverse order. The trials were presented in four groups with either two or three trials per group. After each group, one trial was conducted with visual feedback removed to control for changes in attention and concentration. After this trial, the subjects were removed from the equipment and given a 10 minute break.

For each trial, the subjects were allowed to accustomize themselves to the conditions of the trial. Once the subjects felt that performance would not be improved by further practice, they signaled and recording commenced. The recordings lasted 40 seconds. With the completion of each trial, the subject was then instructed to relax while the new condition was set up. In total, each subject completed 14 trials.

An experimental error occurred in a single trial. During subject 5's second trial at magnification 20, a malfunction resulted in a greatly amplified signal being displayed to the subject. We have subsequently removed both of subject 5's trials at magnification 20 from the study.

## 2.2 Experimental Design and Statistical Analysis

In the most simple analysis, a single factor (independent variable) exists in this experiment; the level of magnification. The dependent variable in this study is the subject's finger position during each trial. From the recordings of finger position, two measurements were derived, trial-error and tremor-intensity.

Trial-Error is a measure of subject's inaccuracy in his or her attempts to maintain his or her position on the target line. In the past, both means and standard deviations have been used to quantify accuracy and/or error in this field,[4] as well as in related fields.[9] Previous work with this experimental setup suggested that mean position does not always tend to zero as some subjects attempt to remain slightly above or below the target line.[50] The standard deviations are independent of the means, and we have defined the trial-error for each trial as the standard deviation of the trial, calculated as:

$$\texttt{Trial-Error} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}. \tag{2.1}$$

Tremor-Intensity is a measure of the involuntary movement present in each subject's trace. Physiological tremor is typically described by its frequency, a range bounded by 3 and 15 Hz.[2,11,21–26] Quantifying tremor intensity naturally proceeds by the analysis of the power in this frequency range. Previous authors have acknowledged this and have taken measures of intensity from the tremor power spectrum, in particular by using the magnitude of power in the 3 to 15 Hz range.[26,51] Our measure of tremor-intensity for each trial was the square root of the mean of the band-pass filtered power spectrum. The filter was such that only the power between 3 and 15 Hz remained. By an application of Parseval's Theorem, this measure has the units millimeters. [52,53, see appendix]

A one-way Analysis of Variance (ANOVA) was completed to estimate the effect of magnification upon both trial-error and tremor-intensity.

To demonstrate more clearly the effects of magnification, the null hypothesis that the measures (trial-error or tremor-intensity) are randomly distributed with equal probability at each level of magnification was tested. This was accomplished by tabulating the total number of trials at each magnification which were superior to the other magnifications for each subject and then totaling across all subjects. A comparison was then made against the expected distribution.

In our statistical analysis, two levels of significance were considered. P values less than 0.05 were deemed significant, while P values less than 0.005 were considered highly significant. This second level of significance is important in tests where multiple comparisons were used as multiple comparisons increase the probability of type I errors.[54]

All data processing and statistical tests were completed on Splus (Statistical Sciences, Seattle, Washington).

# Chapter 3

# RESULTS

## 3.1 Statistical Results

### 3.1.1 Time Series and Power Spectra

*Time Series:* The effects of magnifying the feedback signal on the finger position control task is illustrated for two different subjects at magnifications of 1×, and 10× in figure 3.1. There are irregular high frequency fluctuations in finger position. Superimposed on these high frequency oscillations are lower frequency excursions from the baseline. There is marked difference between the magnitude of the fluctuations in the two subjects, but in both subjects the deviations from baseline appear to decrease with the increased magnification.

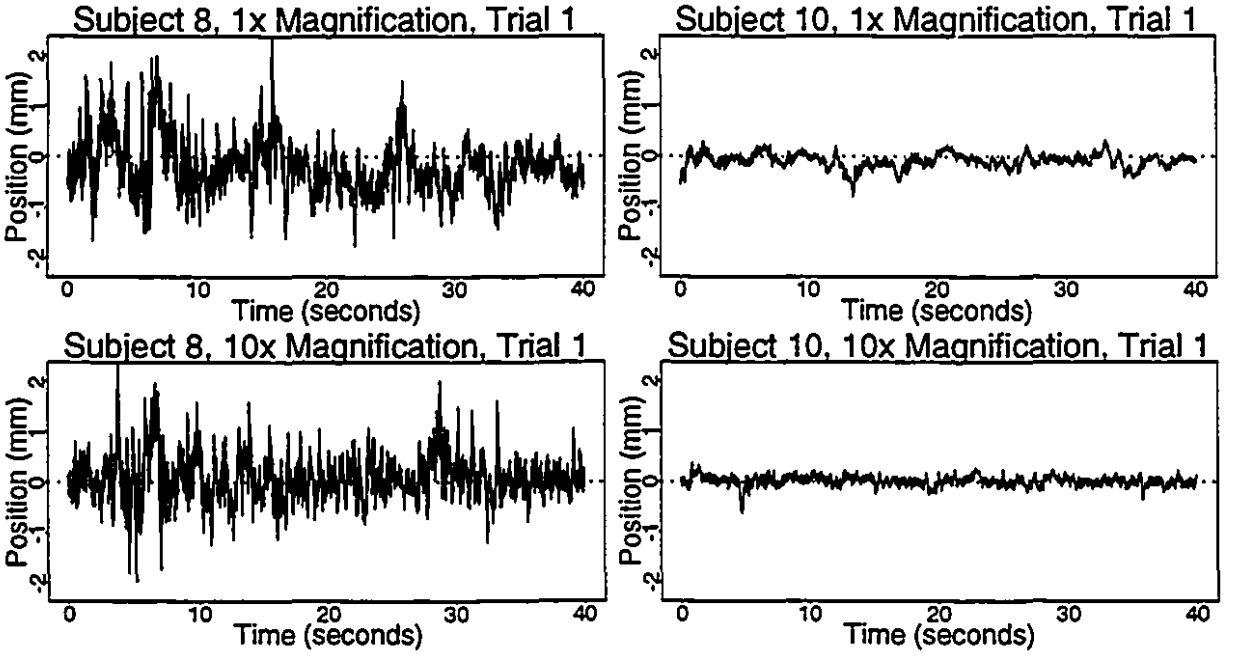


Figure 3.1: Data from Subjects 8 and 10 at magnifications 1 and 10, the first trial at each magnification.

***Power Spectra:*** Quantitative measures of the fluctuations are provided by the trial-error, which we have defined as the standard deviation of the displacements around the mean, and the tremor-intensity, defined here as the power between 3 and 15 Hz (see Materials and Methods). The power spectra of the data in figure 3.1 are illustrated in figure 3.2. The power spectra show that in the range of physiological tremor, there are small inconsistent differences in a given subject at different magnifications. However, at lower frequencies, there is more power in the data at magnification 1× than at 10×. There is also considerable variability between subjects in the magnitude of the tremor and their ability to carry out the task.

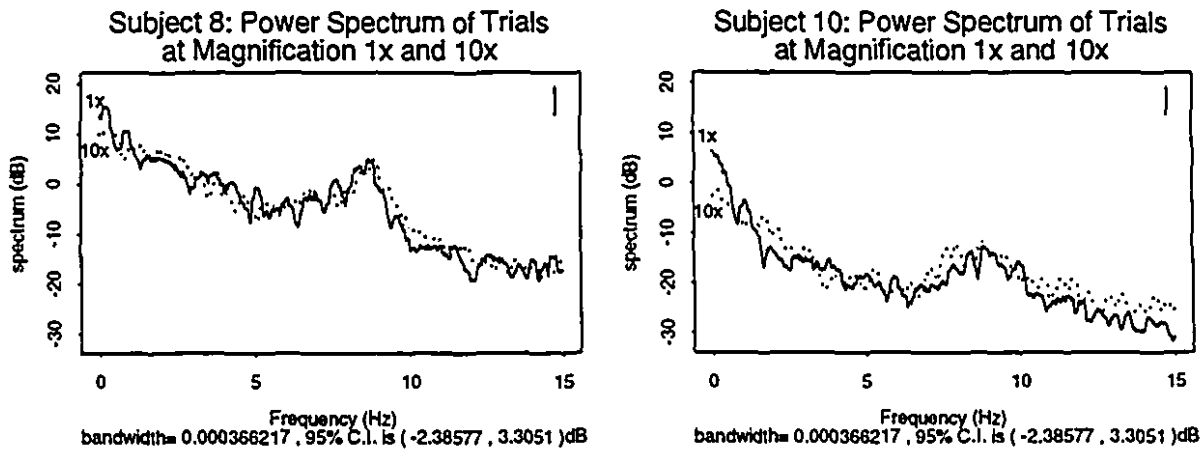


Figure 3.2: Power Spectra of Trials in figure 3.1. The bandwidth and 95% confidence interval are printed below each figure, while an error bar displaying the size of these quantities appears in the top right of each figure.

***Subject Variability:*** To more clearly illustrate the variability both between and within subjects, box-plots of the trial-error and tremor-intensity by subject appear in figure 3.3.

Each box represents the middle half of the data, while the white line represents the median of the data. The 'X' at each magnification is the mean of the data, while the whiskers are the spread of one standard deviation. Outliers are presented as lines.

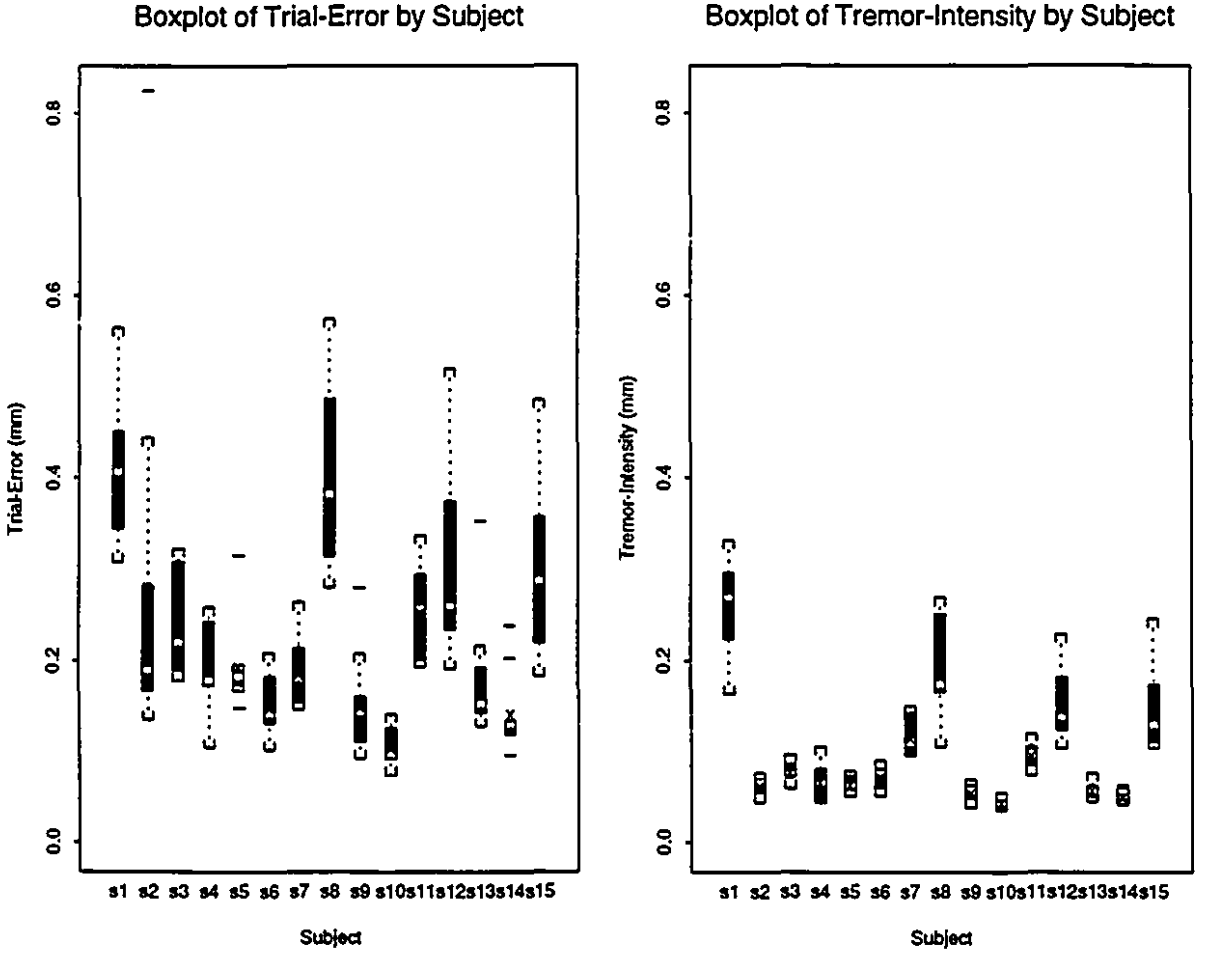


Figure 3.3: Box-plots of Trial-Error and Tremor-Intensity by Subject. The dark box represents the middle half of the data at each level, while the white band marks the location of the median. One standard deviation is displayed by the whiskers of the box, while the mean of the data is labeled with an 'X'. Finally, outliers are displayed as straight lines.

Ignoring the single outlying point, both trial-error and tremor-intensity vary considerably from subject to subject. As well, for most subjects there is considerable variation within subjects, although less so for trial-intensity. To handle to this large variation, subjects were treated as an independent variable and included as a factor in our analysis of variance.

### 3.1.2 Trial 1 vs. Trial 2

There are several different factors that can lead to changes during the course of this experiment. If the subjects learn to perform better as the experiment continues, one would expect the error would be decreased in Trial 2 compared with Trial 1. On the other hand, the task requires concentration and muscle control. If the subject tires over the course of the experiment, or loses concentration, then the performance would be expected to degrade.

In order to help assess these factors, and others that might lead to systematic variations, in each subject two trials were conducted at each magnification, once in the first half of the experiment and again in the second half of the experiment. The trial-error and tremor-intensity of trial 2 plotted as a function of trial 1 is shown in figure 3.4.

The coefficients of correlation for trial 1 versus trial 2 are:

| | Correlation Coefficient |
|---|---|
| Trial-Error | 0.689 |
| Tremor-Intensity | 0.821 |

The least-squares best-fit lines to the scatter-plots of trial 1 vs. trial 2 (figure 3.4) were calculated. The slopes (with 95 % confidence interval) of these lines are:

| | Slope | Confidence Interval |
|---|---|---|
| Trial-Error | 0.930 | (0.847, 1.009) |
| Tremor-Intensity | 0.898 | (0.827, 0.969) |

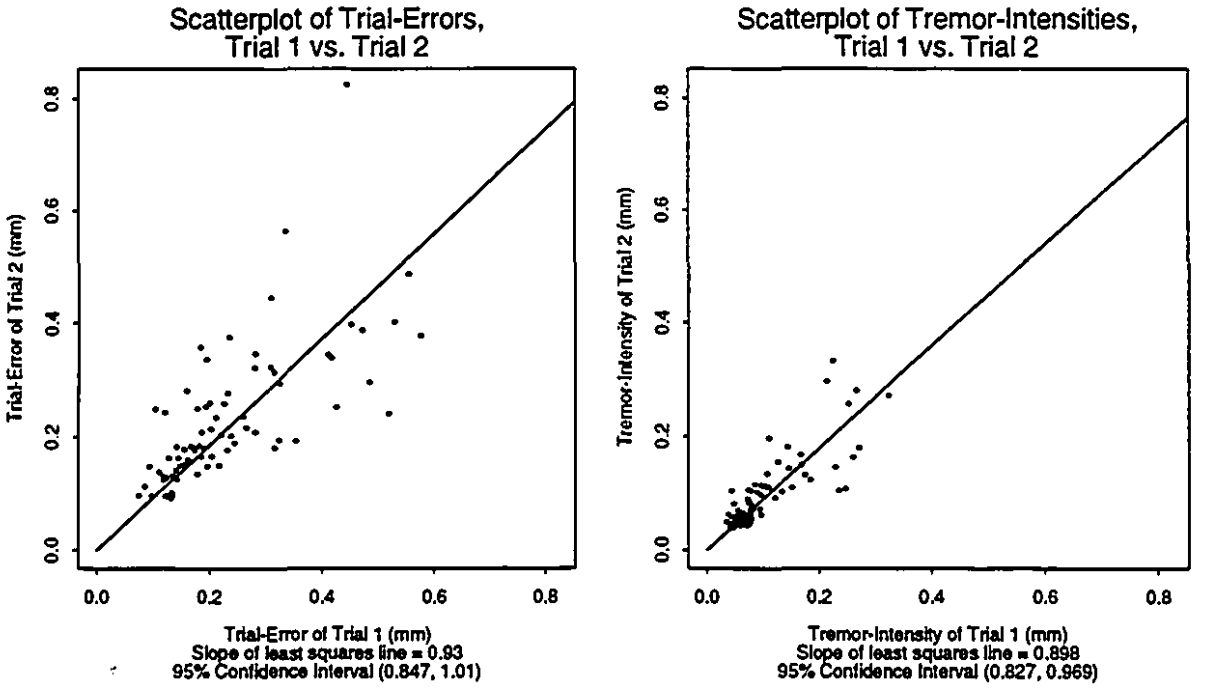


Figure 3.4: Trial-Error and Tremor-Intensity of Trial 1 vs. Trial 2, the least-squares best-fit line for each scatterplot. Below each panel, the slope of the least-squares line (with its 95% confidence interval) appears.

The results are interesting for several reasons. First there is often considerable variation between the trial-error and tremor-intensity in both trials, so that the correlation coefficients, 0.689 and 0.821 respectively, are well below 1. The slope of the best-fit line for trial-error is not significantly different from one, but the slope of the best-fit line to the tremor-intensity scatterplot is less than one, suggesting that tremor-intensity may decrease in the second trial. However, this trend is not consistent in the data. The trial-error in trial 1 is better than trial 2 in 35 cases out of 74 trials, while the tremor-intensity is higher in the first trial 41 times out of 74 trials. In comparison to random binomial distribution, the probability of these results to occur by chance are 72% and 21% respectively. These results are presented in the table below:

$$\mathcal{H}_0 : \Pr\left(\mathcal{F}_\mathcal{E}(trial_1) > \mathcal{F}_\mathcal{E}(trial_2)\right) = 0.5.$$

$$\mathcal{H}_1 : \Pr\left(\mathcal{F}_\mathcal{E}(trial_1) > \mathcal{F}_\mathcal{E}(trial_2)\right) > 0.5.$$

| | Trial 1 > Trial 2 | P-value |
|---|---|---|
| Trial-Error | 35 | 0.7193 |
| Tremor-Intensity | 41 | 0.2080 |

This small difference, is not sufficiently great to correspond to usual measures of statistical significance and in the remainder of the analysis we group the results of trial 1 and 2 together.

### 3.1.3 Analysis of Variance and Other Inferences

***Transforming the Data:*** Classical methods of statistical inference depend heavily on the assumption that the data has a nearly normal distribution. As can be seen from the probability histograms plotted in figure 3.5, this assumption is not justified in our case. The histograms were binned over 20 values, and a density was estimated (solid line). A normal density with the same mean and standard deviation as the data is superimposed with a dotted line. Histograms of the untransformed data appear in the top two panels, while results from the logarithmically transformed data appear in the bottom two panels.

It has been recommended that for measures consisting of variances, standard deviations, root mean squares, and the like, that a logarithmic transform be used to make the data more normal.[55] The measures we have chosen for our data fall into this category and we have utilized this transform. A Chi-square Goodness of Fit test with 14 degrees of freedom was used to check if the data and/or the transformed data was normally distributed.

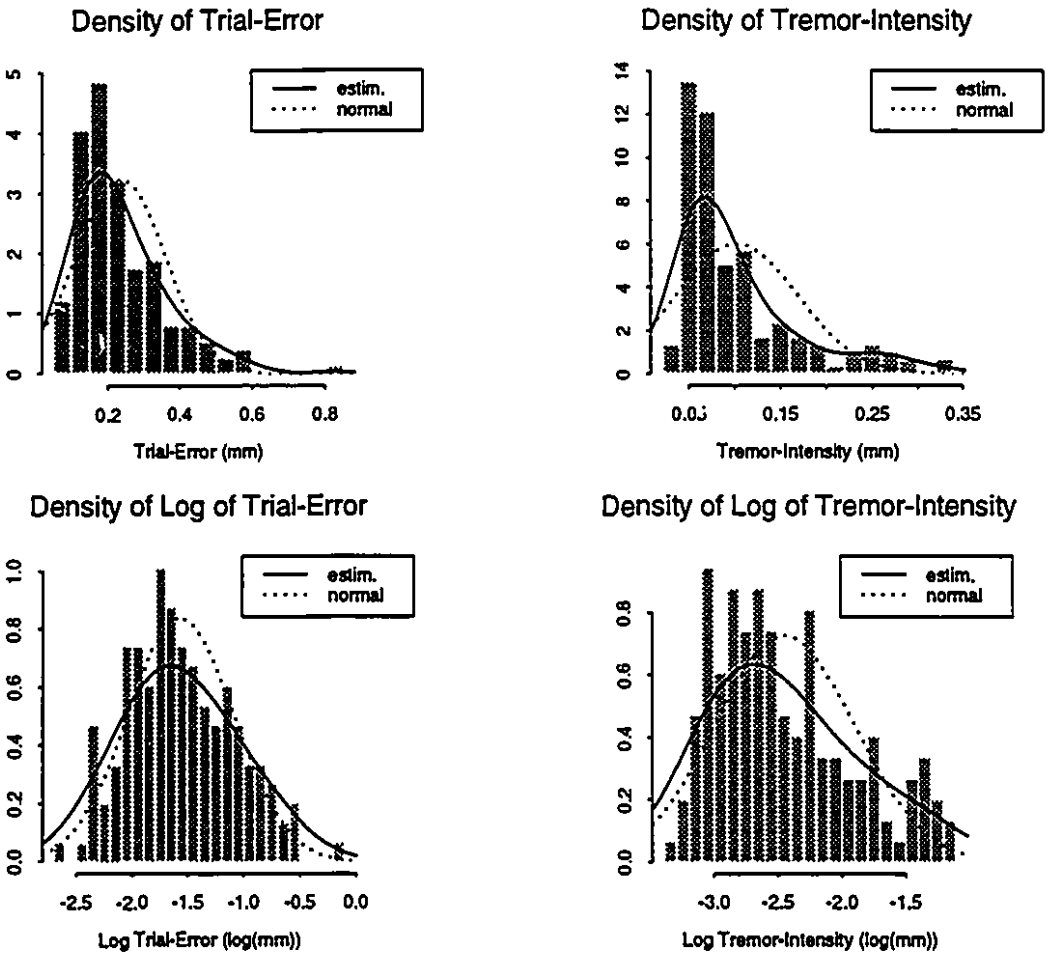


Figure 3.5: Probability Histograms of Trial-Errors and Tremor-Intensities. trial-error on the right, tremor-intensity on the left, the top two panels are raw data, the bottom two are logarithmically transformed data. On each histogram, the solid line is the estimated density of the data, while the dotted line is a normal density with the same mean and variance as the data.

| | $\chi^2$ | P-value |
|---|---|---|
| Trial-Error | 44.973 | $< 10^{-4}$ |
| Log Trial-Error | 13.149 | 0.5149 |
| Tremor-Intensity | 122.608 | $< 10^{-16}$ |
| Log Tremor-Intensity | 33.014 | 0.0029 |

With the logarithmic transform, the values of the trial-error are approximated by the normal distribution as determined by the Chi-square Goodness of Fit test. Although the

tremor-intensity following the logarithmic transformation is still significantly non-normal, this distribution is considerably closer to a normal distribution and we will rely on the robustness of the Analysis of Variance (ANOVA) model and the F test.[56]

***Analysis of Variance:*** The two variables of interest in this study are magnification and subject. A two-way ANOVA can be used to statistically determine which of these factors have significant effects on the results. As we are limited to 150 degrees of freedom, only the first order effects were analyzed. A second order model was examined but the interaction between factors was not significant and the results have not been included. This is equivalent to using the following statistical model:

$$\begin{aligned} \texttt{Trial-Error} &= \mathcal{F}_E^s(sub_i) + \mathcal{F}_E^m(mag_j) + \varepsilon_{P_{i,j}}, \\ \texttt{Tremor-Intensity} &= \mathcal{G}_I^s(sub_i) + \mathcal{G}_I^m(mag_j) + \varepsilon_{T_{i,j}}, \end{aligned}$$

where:

| | |
|---|---|
| $\mathcal{F}_E^{s\,or\,m}$ | = function relating trial-error to subject or magnification, |
| $\mathcal{G}_I^{s\,or\,m}$ | = function relating tremor-intensity to subject or magnification, |
| $\varepsilon_{P_{i,j}}$ | = Gaussian distributed error term for trial-error of subject$_i$ at trial$_j$, |
| $\varepsilon_{T_{i,j}}$ | = Gaussian distributed error term for tremor-intensity of subject$_i$ at trial$_j$, |
| $sub_i$ | subject $\in$ [s1, s2, s3, s4, s5, s6, s7, s8, s9, s10, s11, s12, s13, s14, s15], |
| $mag_j$ | = magnification at trial$_j$ $\in$[1, 4, 10, 20, 40]. |

When applied to all the data, the ANOVA table is as follows, note the analysis of data was performed on the log transformed data.

**Analysis of Variance, Log Trial-Error**

| *treatment* | *Df* | *Sum of Squares* | *Mean Square* | *F Value* | *Pr(F)* |
|---|---|---|---|---|---|
| subject | 14 | 21.6803 | 1.5486 | 28.5052 | $< 10^{-11}$ |
| magnification | 4 | 4.2310 | 1.0577 | 19.4701 | $< 10^{-11}$ |
| Residuals | 129 | 7.0081 | 0.0543 | - | - |

Both subject and magnification are highly significant factors in the logarithm of trial-error.

**Analysis of Variance, Log Tremor-Intensity**

| *treatment* | *Df* | *Sum of Squares* | *Mean Square* | *F Value* | *Pr(F)* |
|---|---|---|---|---|---|
| subject | 14 | 38.5006 | 2.7501 | 65.2312 | $< 10^{-16}$ |
| magnification | 4 | 0.2559 | 0.0640 | 1.5173 | 0.2009 |
| Residuals | 129 | 5.4384 | 0.0422 | - | - |

The level of magnification is not a significant factor in the magnitude of tremor-intensity.

Reviewing the aptness of our Analysis of Variance model leads us to consider the residuals of both models. Foremost in this consideration is the test of whether the error terms are actually Gaussian distributed . Probability histograms and quantile-quantile plots of the residuals from the two ANOVA's (not shown) indicate that the residuals are distributed in a near-normal fashion. To further check this assumption, Chi-square Goodness of Fit tests were completed on both distributions, and appear below. Neither population of error terms is significantly non-normal.

| | $\chi^2$ | P-value |
|---|---|---|
| Trial-Error Residuals | 12.338 | 0.5792 |
| Tremor-Intensity Residuals | 7.676 | 0.9055 |

Constancy of error variance is a second assumption which must be investigated. If the error terms have the same variance, then their distributions at each level of each factor will be similar. Use of the Bartlett Test for Equality of Variances[56] indicates that the variance of at least one set of trial-error residuals is significantly different when considering subject levels. The Bartlett test yields non-significant results for equality of residual variance by magnification for trial-error, and for the residuals of both factors for tremor-intensity.

When error variances are unequal, the F test for the equality of means with the ANOVA model is only slightly affected if all factor level sample sizes are approximately equal.[56] As this is the case in our experimental design, we can accept the unequal error variance for trial-error residuals for the subjects. Moreover, the logarithmic transform promotes homogeneity of variance,[55] and thus the results of the ANOVA are valid with only a slight increase in the significance level.

### 3.1.4 Trial-Error, Tremor-Intensity and Magnification

Figure 3.6 presents box-plots of the trial-error and tremor-intensity of all 15 subjects at each magnification. Each box represents the middle half of the data, while the white line represents the median of the data. The 'X' at each magnification is the mean of the data, while the whiskers are the spread of one standard deviation. Outliers are presented as lines.

The range of trial-error values at each magnification decreases as the magnification is increased. This improvement is matched by a decrease in the means (marked by an 'X' in figure 3.6) with the increasing magnification. This trend is much less noticeable when one examines the median value, or only considers the middle half of the data. Although an improvement in these values does occur between magnifications one and ten, the differences between medians and the spread of the middle half of the data seems marginal at best when 10 and 40 are compared.

Box-plots of the tremor-intensity indicate that although differences do exist between the means, medians, standard deviations and spread of the results at different magnifications, no consistent trend is present. This is in accord with the results of the ANOVA, which indicated that the level of magnification is not a significant factor in determining tremor-intensity.

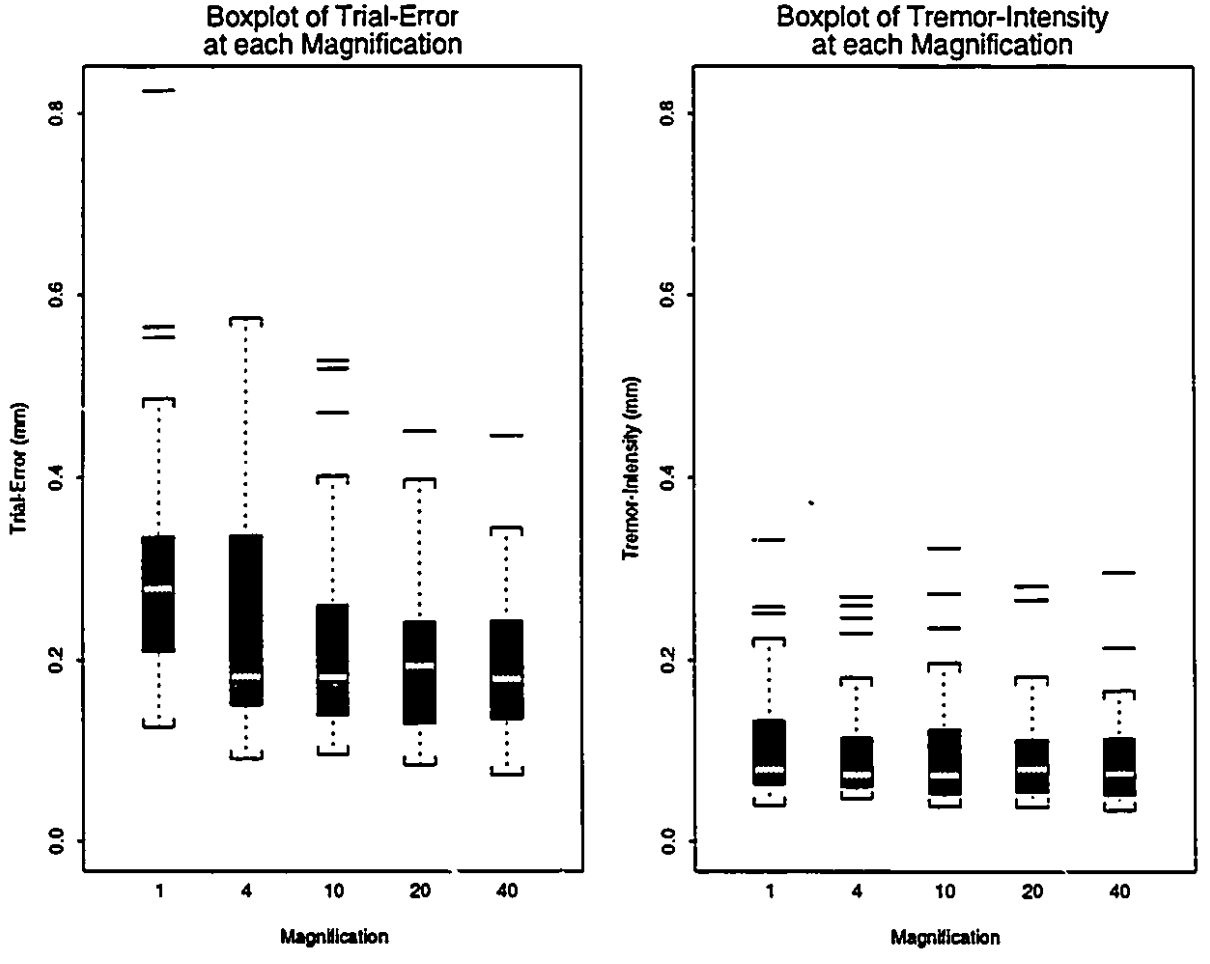


Figure 3.6: Box-plots of Trial-Error and Tremor-Intensity. The dark box represents the middle half of the data at each level, while the white band marks the location of the median. One standard deviation is displayed by the whiskers of the box, while the mean of the data is labeled with an 'X'. Finally, outliers are displayed as straight lines.

***Effects of Magnification:*** One of the two significant factors affecting trial-error is trial magnification. To investigate the effect of magnification, independent of subject, the following hypothesis was tested,

$$\mathcal{H}_0 : \Pr\left(\mathcal{F}_E^m(magnification_x) < \mathcal{F}_E^m(magnification_y)\right) = 0.5,$$

where,

$$\text{magnification}_{x,y} \in [1, 4, 10, 20, 40],$$

and,

$$\text{magnification}_x \neq \text{magnification}_y.$$

This hypothesis can be tested by counting the number of trial-errors at magnification$_x$ less than the number of trial-errors at magnification$_y$ for each subject. When these results are totaled across all subjects, they are distributed normally with a mean of 30 and a standard deviation of 5. As both of subject 5's trials at magnification 20 were removed, the sum of comparisons of trials with magnification 20 are normally distributed with a mean of 28 and a standard deviation of 4.83. The results of all pairwise comparisons are displayed in the table below, with the total number of trial-errors at magnification$_x$ less than the trial-error at magnification$_y$ displayed below the diagonal, and the probability of such a result displayed above the diagonal.

Trial-Error at Magnification$_x$ < Trial-Error at Magnification$_y$

| $mag_x$ \ $mag_y$ | 1× | 4× | 10× | 20× | 40× |
|---|---|---|---|---|---|
| 1× | - | 0.00135 | 0.00000 | 0.00000 | 0.00001 |
| 4× | 45 | - | 0.21186 | 0.01139 | 0.01390 |
| 10× | 53 | 34 | - | 0.15031 | 0.11507 |
| 20× | 50 | 39 | 33 | - | 0.20281 |
| 40× | 52 | 41 | 36 | 32 | - |

The effect of magnification is greatest at low levels. The trial-errors at 1× are significantly higher (at the 0.005 level of probability) than the trial-errors at all other magnifications. The trial-error at 4× was significantly worse (at the 0.05 level of probability) than the trial-errors at 20× and 40×, but were not significantly different from the trial-errors at 10×. Finally, this test was unable to discern between the trial-errors at 10×, 20×, and 40×.

To highlight the constancy of tremor throughout the experiment despite changes in magnification, the same test was conducted on tremor-intensities.

Tremor-Intensity at magnification$_x$ < Tremor-Intensity at magnification$_y$

| $mag_x$ \ $mag_y$ | 1× | 4× | 10× | 20× | 40× |
|---|---|---|---|---|---|
| 1× | - | 0.15866 | 0.02275 | 0.15031 | 0.00820 |
| 4× | 35 | - | 0.34458 | 0.26728 | 0.11507 |
| 10× | 40 | 32 | - | 0.58200 | 0.21186 |
| 20× | 35 | 33 | 29 | - | 0.50000 |
| 40× | 42 | 36 | 34 | 30 | - |

Tremor-Intensity does not seem to differ greatly as the magnification is changed. Two significant results (at the 0.05 probability level) occurred; when trials at magnification 1× are compared with trials at magnifications 20× and 40×. Neither result was significant at the 0.005 level of probability.

***Regressions:*** The effect of magnification seems greatest at low levels. Trial-Error clearly improves as the magnification is increased from 1× to 4×. This improvement levels off after a magnification of 10× is reached. At this level, trial-error seems to be bounded by tremor-intensity. Figure 3.7 displays scatterplots of trial-error versus tremor-intensity at each level of magnification. Drawn on each plot is the least squares best-fit line forced through the origin. The slope of the regression line for each scatterplot is written in each panel, along with the 95% confidence interval for the slope.

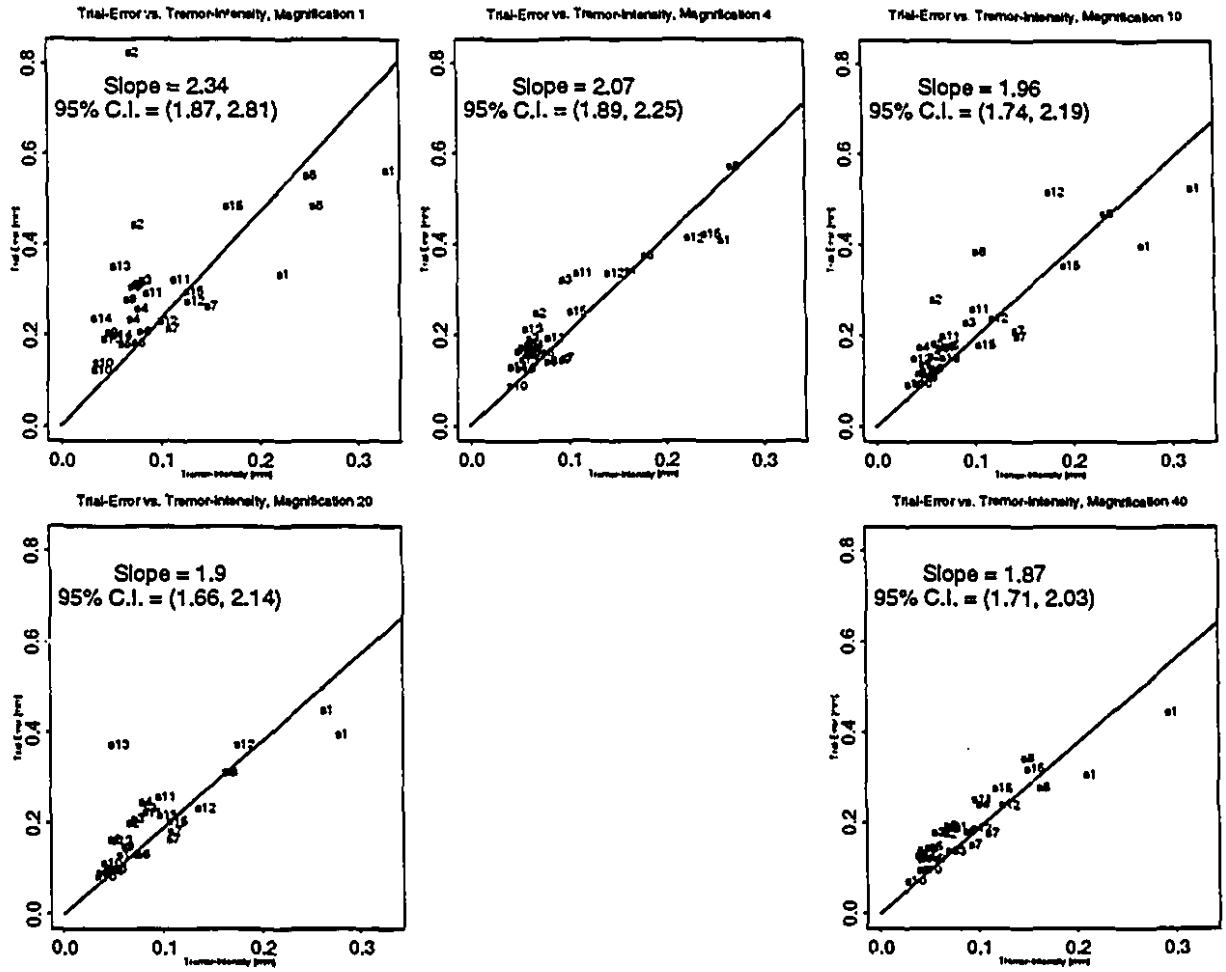


Figure 3.7: Scatterplots of Trial-Error vs. Tremor-Intensity by level of Magnification. The least squares regression line forced through the origin is drawn on each plot while the slopes of each line (and 95% confidence intervals) are printed in each panel. Note that each subject's number is plotted.

The slope of the regression line at magnification 1× is 2.34, clearly outside the confidence intervals of the four other regression lines. Moreover, the fit of the regression line to the scatterplots improves considerably as the magnification increases. Thus, at magnifications 10×, 20×, and 40×, the trial-error of each trial seems limited to approximately 2 times the intensity of the tremor.

The earlier analysis of variance indicated that subject was the strongest factor affecting trial-error. The degree to which trial-error is limited to tremor-intensity varies considerably from subject to subject. Figure 3.8 displays the scatterplots for all fifteen subjects. The least square regression line for each scatterplot is shown as well, and the slope of the regression line, along with the 95% confidence interval, appear in each panel.

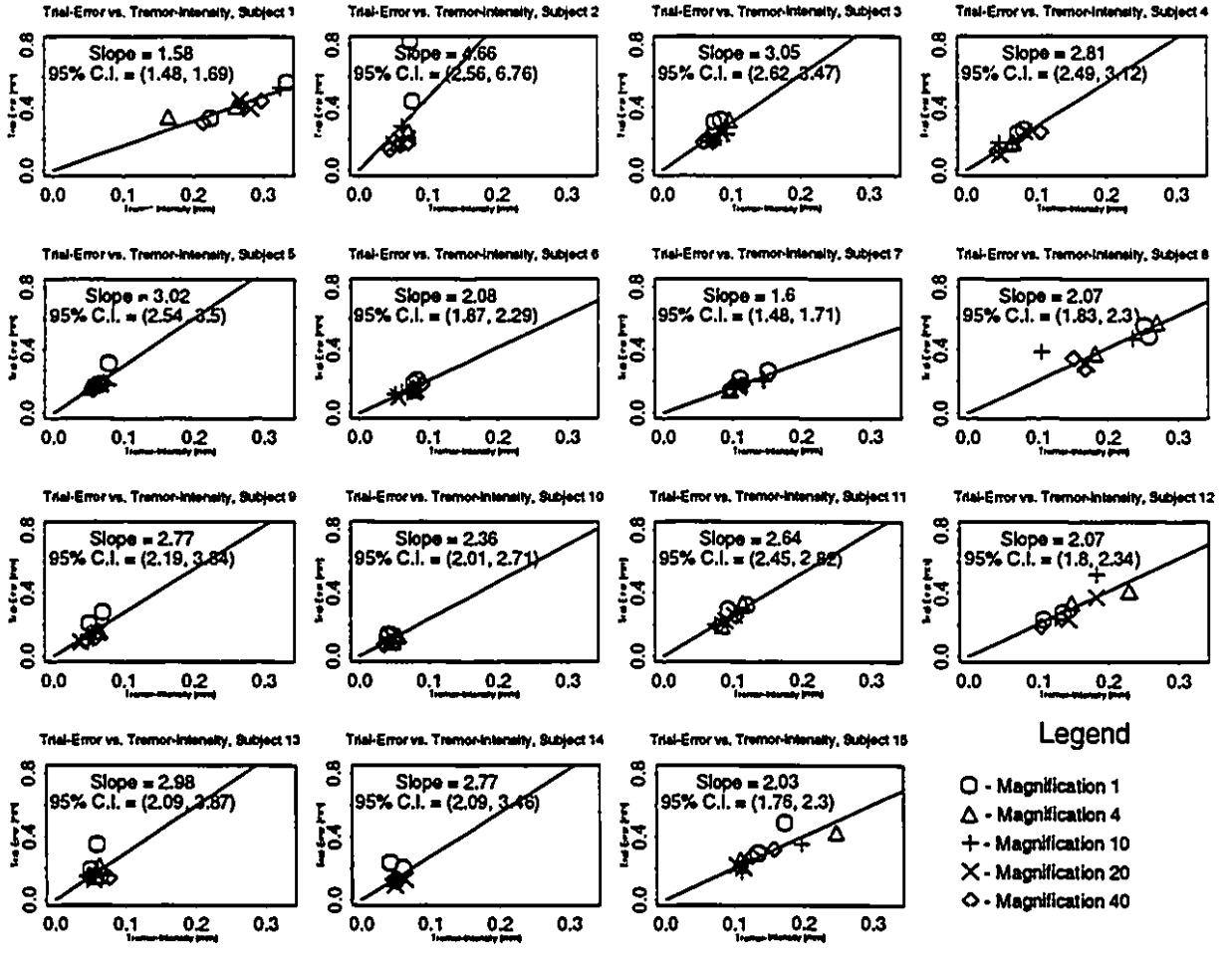


Figure 3.8: Trial-Error vs. Tremor-Intensity by Subject. The least-squares regression line forced through the origin is plotted on each panel, with the slope of the line (and corresponding 95% confidence interval) appearing in the panel. Note that each level of magnification is displayed as a different plotting symbol.

In each case the regression line fits the data nicely with an accurate estimate of the slope. Depending on the subject, trial-error is limited to 2 to 5 times the intensity of the tremor. Within subject, the limit is consistent with the occasional outlier trial.

# Chapter 4

# DISCUSSION

## 4.1 IMPLICATIONS

***Variability of the results.*** Considerable variability occurred in the results, both between subjects and within subjects. Variability in the tremor-intensities (figures 3.6 & 3.3) is not unexpected as experience with tremor recordings has shown that they are extremely variable and that single spectral analyses are unreliable.[11,57] Variability of performance (trial-error) between subjects (figure 3.3) is also not surprising as skill and coordination should differ between people. Differences of trial-error within subject (figure 3.3) was unexpected. This variability is understandable from the fact that at a given magnification trial-error is proportional to tremor-intensity. As tremor-intensity varied from trial to trial, a corresponding variation was seen in trial-error. The ratio of trial-error to tremor-intensity proves to be much more constant. Within subjects, the standard error of the ratio was consistently under 20% and generally under 10% of the ratio.

***Does tremor-intensity change with magnification?*** The earlier work of Stephens and Taylor demonstrated that changes in the gain of the visual loop does not affect tremor in-

tensity or the tremor spectrum in a consistent fashion.[11] The analysis of variance in our study did not show that magnification was a significant factor in determining tremor-intensity. But, when trials were compared across magnification, significant differences ( at the 0.05 prol - ability level) were found in two out of ten possible comparisons. Both of these instances were with trials at magnification 1×, and neither result was significant at the more stringent 0.005 probability level.

Several differences in methodology exist between the two studies. Although both studies involved the maintenance of posture, Stephens and Taylor's setup involved the maintenance of a certain finger force. The force exerted by the finger was measured instead of finger position and the degree of accuracy demanded from the subject was of an order of magnitude lower than our study.

Tremor refers to the small unintentional irregularities in force or posture.[11] Our measure for tremor-intensity is derived from the power spectrum and encompasses the range of 3-15 Hz.[see Methods] Similar definitions have been used previously by other authors,[26,51] and assume that only involuntary motion related to tremor occur at frequencies above 3 Hz. Although voluntary motion such as corrections are generally of a much lower frequency, these movements can and do reach frequencies of 6-8 Hz.[35] Thus it is not entirely surprising that inaccurate trials with extra corrections and large standard deviations (trial-error) would have larger tremor-intensities. Moreover, the statistical test used in this case involved multiple comparisons, which in turn increases the likelihood of a type I error (false-positive).[54] As neither significant difference was highly significant, and as both occurred in comparisons against trials with magnification of 1×, these two significant differences should be viewed with caution. This study does confirm the earlier results of Stephens and Taylor; changes in the gain of the visual system does not affect the tremor-intensity of the finger in a consistent fashion.

***Does performance improve with magnification?*** In examining how increased magnification affects trial-error, two aspects are readily apparent. First, the utilization of magnification reduces trial-error and improves performance. Trials conducted with no magnification (1×) consistently had higher trial-errors than trials completed with magnification. This difference is highly significant at the level of 0.005. This improvement with increased magnification continues when one compares trials at magnification 4× to trials at magnifications 20× and 40×. This improvement is significant at a level of 0.05.

The second point of note is that the performance does not continue to improve as magnification is increased further. The number of trials at magnification 10× with a lower trial-error than trials at magnification 4× is not significantly different from chance. As well, when one compares the trials at magnifications 10×, 20×, and 40×, the results are indistinguishable from chance. Thus, performance improves when magnification is initially used, or when one goes from 4× to 40×, but the performance does not change significantly when the magnification goes from 4× to 10×, or from 10× to 20× or 40×. This result is in accord with the work of McManamny who suggested that the type of magnification assistance used (surgical loupe versus microscope) in the microsurgical repair of peripheral nerve damage was not the most important factor in achieving good results; rather other factors such as the skill of the surgeon were more important.[1]

Indeed, these other factors have been the focus of two earlier research papers on microsurgery. Patkin's early work was a treatise on the ergonomics of microsurgery, suggesting in particular various equipment and techniques to increase skill and reduce physiological tremor.[48] Other work actually considered tremor as the major limitation in microsurgery.[2] By using a biofeedback machine measuring tremor, the authors of this work demonstrated that subjects quickly learned the best wrist, hand, and finger positions to reduce tremor.

Tremor proves to be the limiting factor in our study. The ratio of trial-error to tremor-intensity

demonstrates this fact. The initial use of magnification reduced the ratio of trial-error to tremor-intensity, but the ratios do not change significantly as one moves from magnification 10× to 40× (see figure 3.7). The fit of the least squares regression line passing through the origin improves with increased magnification as evidenced by the decrease in the size of the 95% confidence interval. In our study, increased magnification limited trial-error to approximately 2 times the tremor-intensity.

Along with these earlier authors, we must conclude that level of magnification is not the most important factor in determining performance in microsurgical-like tasks. Rather, once sufficient magnification is used to see the target, tremor becomes the limiting factor. This is in accord with the work of Rock *et al.* who concluded that level of magnification was not important in pregnancy success following tubal anastomosis, but still recommended using the microscope when performing certain types of anastomoses which require greater magnification.[18]

## 4.2 LIMITATIONS

***Is this task related to microsurgery?*** The degree to which our task is related to microsurgery is debatable. In this study, the task involved the maintenance of a stationary posture; microsurgery on the other hand involves motion, in particular while suturing. Still, considerable parallels can be drawn between the two situations. The speed of movements under magnification is slow; it has been recommended that the operator not draw sutures faster than 0.5 mm/sec.[48] As velocity is decreased, the organization of motor output in slow finger movements more closely resembles the kinematics of position holding,[3] linked by the mechanisms generating physiological tremor.[25] Hence, analysis of the maintenance of posture under magnification will shed some light on effective microsurgical technique.

Indeed, Harwell and Ferguson began their study of the interaction of tremor in micro-

surgery by analyzing a similar maintenance of position task.[2] These authors investigated the performance of several subjects trying to hold a wire loop steady under visual magnification. The results were analyzed in the context of microsurgery. The authors followed the obvious extension to the experiment by later asking subjects to perform a dynamic task under magnification. We therefore conclude that although our study lacked a dynamic component, the task we examined is related to microsurgery.

***Aptness of the ANOVA Model.*** The choice of our ANOVA model involved several assumptions. First, only two factors were included in the model, subject and magnification. Both presentation order and carry-over effect were ignored in this analysis. As the order of presentation was changed with each new subject, it was assumed that the effect of the order would be negated. The carry-over refers to the possibility that for any particular trial, the strategy adopted for the previous trial might be carried over to the trial in progress. The experimental protocol included a practice period at the start of each trial. This period lasted until the subject reported that they felt comfortable at the new magnification level. We have therefore assumed that any carry-over would be negligible and have not included it in our analysis.

A second assumption of our model was that the factors did not interact. This is equivalent to stating that the effect of one factor is independent of the effect of the other factor. In practice, we know this assumption to be false; the effect of magnification on each subject varies with the subject. Two-way ANOVA's with second order interactions were completed, but these indicated that the second order effects were not significant and have not been included. We have assumed that any higher order interactions are small and could be safely ignored.

The use of the ANOVA also assumes that the data is normally distributed and that

the error terms have a constant variance. A logarithmic transform was utilized to improve normality of the data. Even with the transform, the tremor-intensity values were still non-normal. The F test is robust to departures from normality.[56] As the departure from normality is not extreme in form, the use of a parametric model is justified.

The assumption of constancy of the error variances was violated in our ANOVA models. To guard against this, equal sample sizes were used. Along with making the experiment more simple to perform, equal sample sizes ensures robustness of the F test against unequal error variances.[56] Moreover, the logarithmic transform promotes homogeneity of variance,[55] and thus the results of the ANOVA are valid with only a slight increase in the significance level.

***Limitations of the equipment.*** Utilization of the infrared semi-conductor laser and the A/D acquisition systems provided a resolution of finger position of 35 $\mu$m. This position was then displayed as a horizontal line on the computer monitor in front of the subject. Several limitations are inherent in this display. First, the total height of the display was 160 mm. If the finger was sufficiently displaced to move the line off the screen, the line instead remained at the edge of the screen. Thus, if the subject was too high to be on-screen, he or she would only receive information of being off the top of the screen, but no information as to how far off the screen. In all the data analyzed, only one trial existed where the subject went off-screen, and in this instance the subject went off-screen for a total of 0.2 seconds. This short period was not deemed sufficiently long to have influenced the subject and no special treatment was conducted in this case.

For practical purposes, the screen height reduced the range of motion of the finger to 160 mm divided by the magnification. As the highest magnification was 40×, this restricted the range to 4 mm. Screen-height therefore forced two constraints on the experiment. First the

highest magnification which could be analyzed was 40×. Use of any higher magnification would risk having the subject go off-screen. Second, no kinematic paradigms could be examined. As any movement of greater than 2 mm in either direction would lead to the subject going off-screen at magnification 40×, we were restricted to having the subject hold their finger still.

Second, the refresh rate of the screen was 70 Hz, restricting the program to run at this speed. As well, the phosphorus decay time was considerable. Although the frequency of tremor is well below the Nyquist frequency of the screen, problems did occur. In particular, as the magnification was increased, the line began to jump around. The after-images would persist long enough for the eye to perceive two or three lines. This resulted in essentially a noisier display to the subject.

Third, the screen is comprised of 450 vertical lines. Although finger position was measured with an accuracy of 20 $\mu$m, the display had a resolution of 450 pixels. At a magnification of 40×, this corresponds to a resolution of 9 $\mu$m, but at a magnification of 1×, the resolution was reduced to 350 $\mu$m. To some degree, the inaccuracy of the trials at 1× was due to the lack of resolution of the display, rather than the lack of accuracy on the part of the subject.

## 4.3 Future Work

***Improve experimental setup.*** Several obvious improvements can and should be made to the experiment. First, a new method of display should be implemented. One possible method involves the use of a laser and a mirror galvanometer to display a point of light on a wall. The angle of the mirror can be changed in proportion to finger displacement, resulting in an elegant way to display finger position. This method would be free of the problems of the computer monitor including the presence of after-images. As well, we would no longer be restricted to a total display width of 160 mm.

***Investige hypermagnification.*** If the obstacle of limited display height is removed, higher magnifications could be examined. The effects of hypermagnification would be interesting from a theoretical point of view. It has been theorized that a sufficient increase in magnification within the visual loop should lead to the destabilization of the loop controlling finger position.

In a similar experimental setup, Glass *et al.* included an external delay in the visual feedback.[5] These authors then demonstrated that subjects tended to enter into a pattern of large irregular low frequency finger oscillations.[5,13] It was theorized that the onset of the oscillations corresponded with a bifurcation in the equations governing the system. This bifurcation was brought on by the increased time delay.[5,44]

As the system contains an inherent delay of the order 100 msec,[6] a similar bifurcation should be caused by the increase in the gain of the visual feedback. Presumably this bifurcation would once more result in large irregular oscillations. Oscillations of this sort were not noted in this experiment. Nor did they appear in a study manipulating the gain in a similar setup.[50] If the limit of display height was removed, a more careful study could be made for this phenomenon.

***Examine a dynamical task.*** In addition to limiting the range of magnification used in the experiment, the screen height made any paradigm involving movement impractical. An experiment involving a kinetic task would more closely resemble microsurgery. To better analyze the effects of magnification in microsurgical situations, and to shed some light on the control strategies involved in such tasks, an experiment involving movement could be set up.

***Investigate control strategies.*** Although considerable effort has been invested in the study of rapid discrete movements,[9,46,58] little attention has been paid to the control of slow

finger movements. One recent work analyzed slow finger movements with regard to kinematics and EMG activity of the finger muscles.[3] The authors hypothesized that a biphasic motor output structure may be involved in the control of slow finger movements. Although important work, this study does not investigate any control loops or strategies.

Study of this system with external delay included in the visual feedback has led to the proposal of possible control loop models.[16,44] Although quite simple in nature, these models take advantage of their nonlinear character to produce some of the dynamics present in the system. But these model fail to grasp the whole range of dynamics present in the system and are not always robust.

Another approach which may prove fruitful is to utilize a random walk analysis. Other researchers have applied this approach in their analysis of the human postural control system.[10,59] This analysis has allowed the identification of separate open-loop and closed-loop control mechanisms. The approach has also given clues to possible methods of modeling the system.[45] In the future, it may prove useful to examine the finger control system in this context. Some work has already been completed in this direction,[60] but a closer examination may identify multiple control strategies in the system. Better understanding of the control strategies would enable the proposal of more accurate models. Armed with this knowledge it may be possible to combine the best aspects of nonlinear dynamics with more realistic motor control theories to analyze these systems.

# Appendix A

# Parseval's Theorem

Let us define our notation as:

| | | |
|---|---|---|
| $t$ | - | time, |
| $\omega$ | - | angular frequency, |
| $x(t)$ | - | series in the time domain, |
| $X(\omega)$ | - | series in the frequency domain, |
| $\mathcal{F}$ | - | Fourier Transform, |
| $\mathcal{P}$ | - | Power, |

with the power at $\omega$ as:

$$\mathcal{P}(\omega) = |X(\omega)|^2 .$$

Now, the Fourier transform can be defined as,[61]

$$\begin{aligned} X(\omega) &= \mathcal{F}(x(t)), \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} x(t) e^{-\imath\omega t} dt, \end{aligned}$$

with the inverse as,

$$\begin{aligned} x(t) &= \mathcal{F}^{-1}(X(\omega)), \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} X(\omega) e^{\imath\omega t} d\omega. \end{aligned}$$

Simply stated, Parseval's theorem relates the power of the two representations of the same signal, namely,

$$\int_{-\infty}^{\infty} x(t)^2 dt = \int_{-\infty}^{\infty} |X(\omega)|^2 \, d\omega.$$

In the discrete system, this theorem is reformulated as:

$$\sum_{t=-\infty}^{\infty} x(t)^2 \delta t = \sum_{\omega=-\infty}^{\infty} |X(\omega)|^2 \, \delta\omega.$$

For the finite series,

$$\frac{1}{n}\sum_{t=1}^{n} x(t)^2 = \frac{1}{n}\sum_{\omega=1}^{n} \mathcal{P}(\omega).$$

Thus the mean square value of the series in the time domain is equal to the mean value of the power spectrum.[52,53]

Moreover the root mean square power,

$$\begin{aligned} RMS &= \sqrt{\frac{1}{n}\sum_{t=1}^{n} x(t)^2}, \\ &= \sqrt{\frac{1}{n}\sum_{\omega=1}^{n} \mathcal{P}(\omega)}. \end{aligned}$$

Thus the square root of the mean of the power spectrum is equal to the root mean square power. Recall that for standard deviations (STD),

$$\begin{aligned} STD &= \sqrt{\frac{1}{n}\sum_{t=1}^{n} (x(t) - \overline{x})^2}, \\ &= \sqrt{\frac{1}{n}\left(\sum_{t=1}^{n} x(t)^2 - n\overline{x}^2\right)}. \end{aligned}$$

For a zero mean series ($\overline{x} = 0$),

$$
\begin{aligned}
STD &= \sqrt{\frac{1}{n}\left(\sum_{t=1}^{n} x(t)^2 - n\bar{x}^2\right)}, \\
&= \sqrt{\frac{1}{n}\sum_{t=1}^{n} x(t)^2}, \\
&= RMS, \\
&= \sqrt{\frac{1}{n}\sum_{\omega=1}^{n} \mathcal{P}(\omega)}.
\end{aligned}
$$

Equivalently, a series whose DC component is equal to zero has a mean of zero. Thus any series which is high pass filtered (or band pass filtered) has a mean of zero. Hence its RMS power is equal to its standard deviation, which is equal to square-root of the mean of the power spectrum.

Tremor is being defined as the power of the signal between 3 and 15 Hz. Using the above, we can define the intensity of the tremor as:

$$
Tremor - Intensity = \sqrt{\frac{1}{n}\sum_{\omega=3Hz}^{15Hz} \mathcal{P}(\omega)}.
$$

If we define $y(t)$ as the series band pass filtered such that all power at frequencies outside of 3 to 15 Hz is set to zero, tremor intensity is equal to the RMS of the new series, i.e.,

$$
Tremor\ Intensity = \sqrt{\frac{1}{n}\sum_{t=1}^{n} y(t)^2},
$$

where,

$$
y(t) = filtered\ x(t).
$$

Similarly, the standard deviation of the original series is equivalent to the square-root of the mean value of the power spectrum of the demeaned series. Where,

$$\begin{aligned} \textit{Demeaned series} &= x(t) - \overline{x}, \\ \textit{Demeaned Fourier series} &= \mathcal{F}\left(x(t) - \overline{x}\right), \end{aligned}$$

then,

$$\begin{aligned} \mathcal{P}\left(x(t) - \overline{x}\right) &= \left|\mathcal{F}\left(x(t) - \overline{x}\right)\right|^2, \\ \sqrt{\frac{1}{n}\sum_{\omega=1}^{n} \mathcal{P}\left(x(t) - \overline{x}\right)} &= \sqrt{\frac{1}{n}\sum_{t=1}^{n} \left(x(t) - \overline{x}\right)^2}, \\ &= STD\ of\ x(t). \end{aligned}$$

The standard deviation of the series is equal to the square root of the mean power of the demeaned series. As an example, consider subject 11's first trial at magnification 20, displayed in figure A.1. The raw data appears in the top left panel, while the power spectrum of the demeaned data appears in the top right. The standard deviation of the raw data is 0.2593 mm, while the square-root of the mean value of the power spectrum is 0.2544 mm, a difference of less than 0.005 mm.

The lower left panel contains the bandpass filtered data (corners at 3 and 15 Hz). This trace represents our operational definition of tremor in this study. To the right of this panel, appears the power spectrum of the filtered data, note the corners at 3 and 15 Hz. The standard deviation of the filtered data is 0.0978 mm which is equal to the square-root of the mean power of the spectrum.

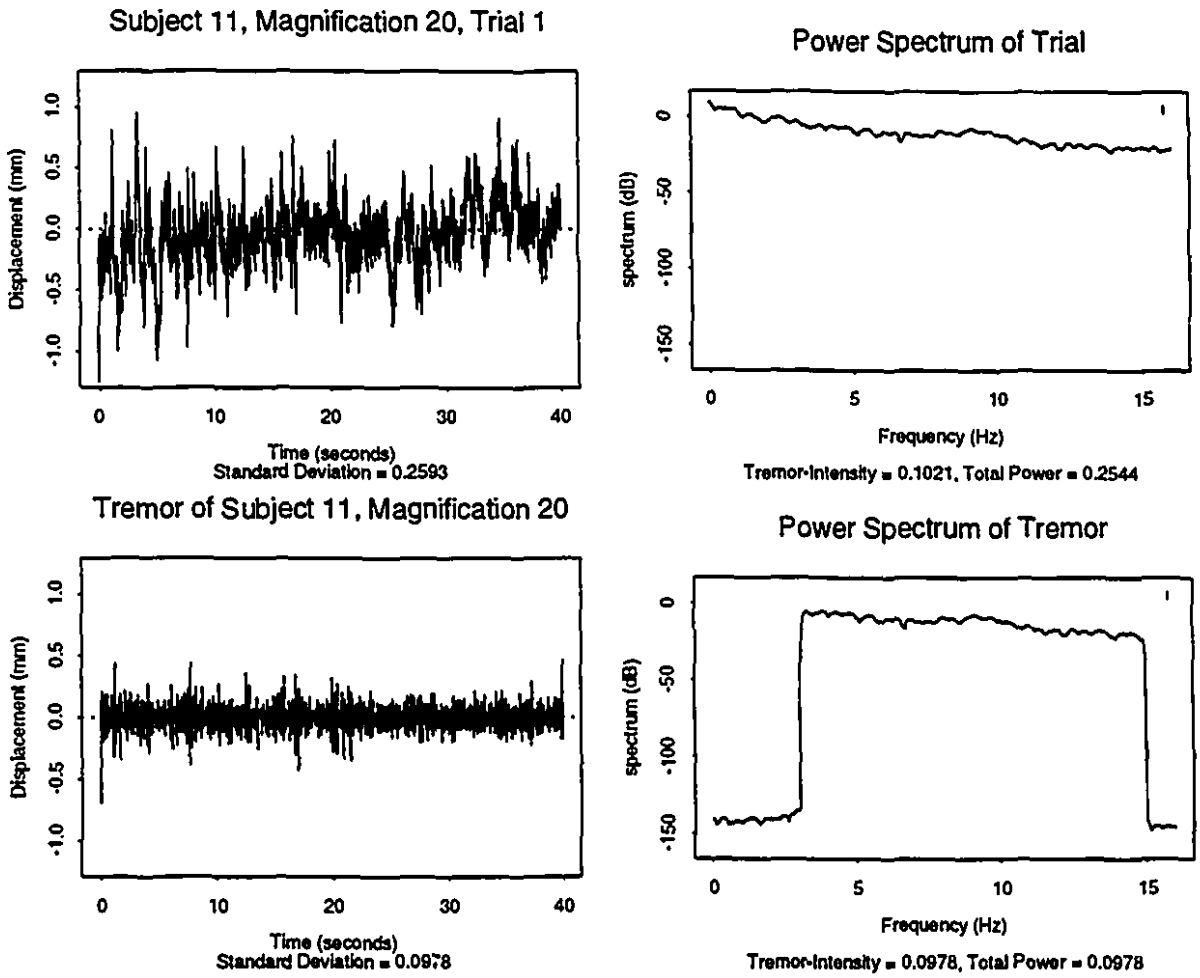


Figure A.1: An application of Parseval's Theorem. The top left panel contains raw data from subject 11, the standard deviation of the trace appears below the panel. The top right trace contains the power spectrum of the demeaned data, with the total power in the spectrum printed below. The bottom left panel contains the raw data bandpass filtered at 3 and 15 Hz; our operational definition of tremor. Once more the standard deviation appears below the panel. The bottom right panel displays the power spectrum of the tremor, with the total power printed below.

# Bibliography


[1] D.S. McManamny. Comparison of microscope and loupe magnification: assistance for the repair of median and ulnar nerves. *British Journal of Plastic Surgery*, 36:367–372, 1983.

[2] R. C. Harwell and R. L. Fergurson. Physiological tremor and microsurgery. *Microsurgery*, 4:187–192, 1983.

[3] A. B. Vallbo and J. Wessberg. Organization of motor output in slow finger movements in man. *Journal of Physiology (London)*, 496:673–691, 1993.

[4] M. D. Rooks, J. Slappey, and K. Zusmanis. Precision of suture placcement with microscope and loupe-assisted anastomes. *Microsurgery*, 14:547–550, 1993.

[5] L. Glass, A. Beuter, and D. Larocque. Time delays, oscillations, and chaos in physiological control systems. *Mathematical Biosciences*, 90:111–125, 1988.

[6] G. K. Kerr. *Approaches to the Study of Motor Control and Learning*, volume 2 of *The Handbook of Physiology*, chapter 9: Visuomotor control in goal-directed movements, pages 253–287. Elsevier Science Publishers, 1992.

[7] S. C. Gandevia and D. Burke. Does the nervous system depend on kinesthetic information to control natural limb movements. *Behavioural and Brain Sciences*. 15:614–632, 1992.

[8] L. Bevan, P. Cordo, L. Carlton, and M. Carlton. Proprioceptive coordination of movement sequences: discrimination of joint angle versus angular distance. *Journal of Neurophysiology*, 71:1862–1872, 1994.

[9] D. E. Meyer, J. E. K. Smith, S. Kornblum, R. A. Abrams, and C. E. Wright. *Attention and Performance XIII*, chapter 6: Speed-accuracy tradeoffs in aimed movements: towards a theory of rapid voluntary action., pages 173–226. Erlbaum, Hillsdale, NJ, 1990.

[10] J. J. Collins and C. J. De Luca. The effects of visual input on open-loop and closed-loop postural control mechanisms. *Experimental Brain Research*, 103:151–163, 1995.

[11] J. A. Stephens and A. Taylor. The effect of visual feedback on physiological muscle tremor. *Electroencephalography and Clinical Neurophysiology*, 36:457–464, 1974.

[12] R. C. Miall, D. J. Weir, and J. F. Stein. Manual tracking of visual targets by trained monkeys. *Behavioural Brain Research*, 20:185–201, 1986.

[13] A. Beuter, D. Larocque, and L. Glass. Complex oscillations in a human motor system. *Journal of Motor Behaviour*, 21:277–289, 1989.

[14] G. J. Anderson. Detection of three-dimensional surfaces from optic flow: the effects of noise. *Perception and Psychophysics*, 54:321–33, 1993.

[15] D. R. Badcock and K. Sullivan. Resistance to positional noise scales with target size. *Vision Research*, 34:1327–1330, 1994.

[16] K. Vasilakos and A. Beuter. Effects of noise on delayed visual feedback. *Journal of Theoretical Biology*, 165:389–407, 1993.

[17] W. F. Strow. Computer analysis of 637 patients done with loupe and 102 patients done with microscope. *Advances in Opthalmology*, 37:122–126, 1978.

[18] J. A. Rock, C.A. Bergquist, A. W. Kimball, H. A. Zacur, and T. M. King. Comparison of the operating microscope and loupe for microsurgical tubal anastomosis: a randomized cilincal trial. *Fertility and Sterility*, 41:229–232, 1984.

[19] J. G. Chusid. *Correlative Neuroanatomy and Functional Neurology*. Lange Medical Publications, Los Altos, California, 1973.

[20] G. G. Sutton and K. Sykes. The effect of withdrawal of visual presentation of errors upon the frequency spectrum of tremor in a manual task. *Journal of Physiology (London)*, 190:281–293, 1967.

[21] P. A. Merton, H. B. Morton, and C. Rashbass. Visual feedback in hand tremor. *Nature (London)*, 216:583–584, 1967.

[22] C. D. Marsden, J. C. Meadows, G. W. Lange, and R. S. Watson. The role of the ballistocardiac impulse in the genesis of physiological tremor. *Brain*, 92:647–662, 1969.

[23] S. M. Padsha and R. B. Stein. *Control of Posture and Locomotion*, chapter : The bases of tremor during a maintained posture, pages 415–419. Plenum Press, New York, 1973.

[24] R. B. Stein and M. N. Oğuztöreli. Tremor and other oscillations in neuromuscular systems. *Biological Cybernetics*, 22:147–157, 1976.

[25] C. D. Marsden. *Movement Disorders: Tremor*, chapter 4: Origins of normal and pathological tremor, pages 37–84. MacMillan Press, 1984.

[26] M. Lakie, E. G. Walsh, E. G. Arblaster, F. Villagra, and R. C. Roberts. Limb temperature and human tremors. *Journal of Neurology, Neurosurgery, and Psychiatry*, 57:35–42, 1994.

[27] J. Brumlik. On the nature of normal tremor. *Neurology (Minneapolis)*, 12:159–179, 1962.

[28] O. C. J. Lippold. Oscillations in the stretch reflex arc and the origin of the rhythmical 8-12 c/s component of physiological tremor. *Journal of Physiology (London)*, 206:359–382, 1970.

[29] D. M. Armstrong. Functional significance of connections of the inferior olive. *Physiology Review*, 54:358–417, 1974.

[30] R. Llinás and R. A. Volkind. The olivo-cerebellar system: functional properties as revealed by harmaline-induced tremor. *Experimental Brain Research*, 18:69–87, 1973.

[31] M. P. Deiber, P. Pollak, R. Passingham, P. Landais, C. Gervason, L. Cinotti, K. Friston, R. Frackowiak, F. Mauguière, and A. L. Benabid. Thalamic stimulation and suppression of parkinsonian tremor. *Brain*, 116:267–279, 1993.

[32] F. Flam. Physicists take a hard look at vision. *Science (Research News)*, 261:982–984, 1993.

[33] P. M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47:381–391, 1954.

[34] K. Nakayama and G. H. Silverman. Temporal and spatial characteristics of the upper displacement limit for motion in random dots. *Vision Research*, 24(4):293–299, 1984.

[35] E. Logigian, H. Hefter, K. Reiners, and H-J Freund. Does tremor pace repetitive volunatry motor behavior in Parkinson's disease. *Annals of Neurology*, 30:172–179, 1991.

[36] B. Weiss. The role of proprioceptive feedback in positioning responses. *Journal of Experimental Psychiatry*, 47:215–224, 1954.

[37] D. Burke, C. Gandevia, and G. Macefield. Response to passive movement of receptors in joint, skin and muscle of the human hand. *Journal of Physiology (London)*, 402:347–361, 1988.

[38] R. A. Chase, J. K. Cullen, S. A. Sullivan, and A. K. Ommaya. Modification of intention tremor in man. *Nature*, 206:485–487, 1965.

[39] A. Beuter, J. Milton, C. Labrie, and L. Glass. Complex motor dynamics and control in multi-looped negative feedback systems. *Proceedings IEEE International Conference on Systems, Man and Cybernetics*, pages 899–902, 1989.

[40] L. Glass and M. C. Mackey. *From Clocks to Chaos: The Rhythms of Life.* Princeton University Press, Princeton, 1988.

[41] J. G. Milton, A. Longtin, A. Beuter, M. C. Mackey, and L. Glass. Complex dynamics and bifurcations in neurology. *Journal of Theoretical Biology*, 138:129-147, 1991.

[42] L. Glass and C. P. Malta. Chaos in multilooped negative feedback systems. *Journal of Theoretical Biology*, 145:217–233, 1990.

[43] A. Beuter, J. G. Milton, C. Labrie, L. Glass, and S. Gauthier. Effects of delayed visual feedback on motor control in patients with Parkinson's disease. *Experimental Neurology*, 110:228–235, 1990.

[44] A. Beuter, J. Bélair, and C. Labrie. Feedback and delays in neurological diseases: a modeling study using dynamical systems. *Bulletin of Mathematical Biology*, 55:525–541, 1993.

[45] J. J. Collins and C. J. De Luca. Open-loop and closed-loop control of posture: A random-walk analysis of center-of-pressure trajectories. *Experimental Brain Research*, 95:308–318, 1993.

[46] R. J. Jagacinski, D. W. Repperger, M. S. Moran, S. L. Ward, and B. Glass. Fitts' Law and the microstructure of rapid discrete movements. *Journal of Experimental Psychology: Human Perception and Performance*, 6:309–320, 1980.

[47] A. M. Belker. Principles of microsurgery. *Urologic Clinics of North America*, 21:487–505, 1994.

[48] M. Patkin. Ergonomics and the operating microscope. *Advances in Ophthalmology*, 37:53–63, 1978.

[49] A. Beuter, A. de Geoffroy, and P. Cordo. The measurement of tremor using simple laser systems. *Journal of Neuroscience Methods*, 53:47–54, 1994.

[50] A. Beuter, H. Haverkamp, L. Glass, and L. Carrière. Effects of manipulating visual feedback parameters on eye and finger movements,. *International Journal of Neuroscience*, in print, 1995.

[51] M. Lakie, K. Krymann, F. Villagra, and P. Jakeman. The effect of alcohol on physiological tremor. *Experimental Physiology*, 79:273–276, 1994.

[52] T. W. Körner. *Fourier Analysis.* Cambridge University Press, Cambridge, 1984.

[53] E. O. Brigham. *The Fast Fourier Transform and its Applications.* Prentice Hall, Englewood Cliffs N.J., 1988.

[54] R. G. Petersen. *Design and Analysis of Experiments.* Marcel Dekker, Inc., New York, 1985.

[55] H. R. Lindman. *Analysis of Variance in Experimental Design.* Springer Texts in Statistics. Springer-Verlag, Berlin, 1992.

[56] J. Neter, W. Wasserman, and M. H. Kutner. *Applied Linear Statistical Models; Regression, Analysis of Variance and Experimental Designs.* Irwin, Homewood, Il, third edition, 1990.

[57] A. Beuter and K. Vasilakos. Tremor: Is Parkinson's disease a dynamical disease? *Chaos*, 5:35–42, 1995.

[58] N. Walker. Spatial and temporal characteristics of rapid cursor-positioning movements with electromechanical mice in human-computer interactions. *Human Factors*, 35:431–458, 1993.

[59] J. J. Collins and C. J. De Luca. Random walking during quiet standing. *Physical Review Letters*, 73:764–767, 1993.

[60] J. Bélair and A. Beuter. Feedback control of limb position: a random walk approach. In *IEEE Engineering in medicine and biology, 17th annual conference*, page 78 (abstract), 1995.

[61] M. B. Priestley. *Spectral Analysis and Time Series*, volume 1 & 2 of *Probability and Mathematical Statistics*. Academic Press, London, 1981.