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EXAMINATION OF THE EFFECT OF DIFFERENT TRAINING METRICS ON PERFORMANCE OF A MINIMALLY INVASIVE SURGERY TRANSFER TASK

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A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

by

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ABSTRACT

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The purpose of this experiment was to determine if there existed techniques to more efficiently train prospective surgeons the skills necessary to capably perform minimally invasive surgical procedures. Also, we wanted to know if trainees could be pushed to cognitively define a laparoscopic environment with a novel hand-eye relationship. To explore these questions, a simulation was setup wherein subjects would perform a laparoscopic transfer task and receive active feedback during training. Different subjects would receive different metrics as feedback and a comparison would be made between subjects with respect to standard metrics. Results of this experiment show that all subjects adapt to a laparoscopic environment and that they do so at

different rates and to different proficiencies. The difference was shown to be statistically significant. It was concluded that the techniques we utilized were effective enough to claim as useful techniques to utilize in current training systems.

Keywords: Minimally Invasive Surgery, MIS, Laparoscopy, Training, Metrics, Motor Adaptation, Motor Error, Laparoscopic Simulation

CHAPTER 1 INTRODUCTION AND MOTIVATION

1.1 Invasive versus Non-invasive Surgery

Medical surgery is a procedure involving a surgeon directly manipulating the physical systems of the body of an ailing human patient. Usually, these procedures are performed because the patient's condition is unusual or may become life threatening in the future. There are a number of ways a surgical procedure may be classified (i.e. purpose, procedure type, body part, etc.). In most of these categories, there may be multiple classifications. However, most surgical procedures will fall under one of two classifications of invasiveness, open/invasive or Minimally Invasive Surgery (MIS).

For most of its existence, the practice of invasive surgery has been a dominant branch of medical treatment. Invasive surgery, the classic procedure of actually creating an open incision in a patient's body and manipulating the internal tissues through this incision, has been in practice for decades and is continually advancing in knowledge and technology. The practice is still very much utilized today as many procedures require the direct nature of this brand of surgery, such as many organ transplant procedures.

Invasive surgery also subjects the patient to extreme physical trauma. Although the patient is anesthetized during an open procedure, it will lead to painful recovery periods and extended hospital stays. These last points can encompass a number of effects. Patient morbidity,

systemic immune preservation, pain and chance of infection are all elements associated with any surgical procedure. It has been shown that all of these effects are observed in worse amounts when a surgical procedure is open rather than laparoscopic (Braga, et al., 2002).

Patient morbidity, as it relates to surgery, is defined as the rate of patients undergoing the same surgical procedure, maintaining a general state of disease or bad health even after the procedure has been completed. This effect can be linked to the preservation of a patient's immune response during and after a surgical procedure. When suffering the trauma of invasive surgery, the human body will lose a lot of nutrients and resources reserved for immune responses by delivering inflammatory responses to the site of the procedure. This site is comparatively larger than an MIS treatment site and a greater amount of tissue is physically manipulated, resulting in a greater immune response. This can result in the body spending large amounts of time to regenerating resources afterwards (Schwenk, et al., 2000). In the time that it takes for patients to recover their immune responses, they are left at greater risk of infection or perhaps even recurrence as in the case of cancer patients. This postoperative recovery period following invasive surgery also leaves the patient in a state of fatigue, pain and with a general suppression of immune system proliferation (Veldkamp, et al., 2005). These effects are what lead to increased, arduous postoperative recovery periods for patients who have undergone an invasive surgical procedure.

Because of these effects, greater awareness for patient safety is creating a desire for more skilled surgeons and more effective training to yield such individuals. As mentioned, some types of procedures require invasive surgery therefore individuals wishing to become surgeons must undergo thorough training. Indeed, entire curriculums and course tracks at medical schools are dedicated to the training and screening of individuals to produce capable and practiced surgeons

to perform invasive surgical procedures in a standard Operating Room (OR). The training and continuing practice that these students require for proficiency in procedures of this type of surgery is time consuming and costly (Chmarra, et al., 2007), considering it takes money to maintain the systems.

The other classification for a surgical procedure concerning invasiveness is MIS. In this brand of surgery, rather than making large, open incisions in a patient to work at the area of interest, the surgical team will simply insert a set of tools into the treatment site through puncture holes formed by devices called trocars. The tools are designed with long, rigid shafts meant to insert into the patient's body while allowing the surgeon to manipulate the tool from outside the body. This way, the surgeon can operate inside the patient's body without having to make a large incision and affording space for his hands to move at the treatment site. The trocars are designed to limit friction as the tool shifts into or out of the body; however, the physical interaction between a laparoscopic tool and a trocar limits movement about the entry point to four degrees of mechanical freedom. The tool can move back and forth, up and down, in and out of the patient's body and can rotate on the long axis of its shaft.

Of course, since the tools are functioning inside the body without any direct line of sight available to the surgeon, access to the visual inside the body has to be gained through one of the tools inserted into the body. This tool is a specialized camera called a laparoscope and consists of a lens system which passes the information to a camera mounted near the handle of the tool. The laparoscope can be manipulated outside the body just as the other tools used in the surgery. Its purpose is to feed an image of the interior of the patient's body to a simple monitor or screen which the surgeon watches to perform the required steps and motions to complete the surgery. Therefore, the surgeon must perceive the environment (laparoscopic tools inside the patient's

body) on the monitor and move his hands in appropriate ways to move the tips of the tools inside the patient's body to perform the desired actions.

1.2 Advantages and Disadvantages of MIS

The first reported MIS procedure for a cholecystectomy was performed in 1987 (Aggarwal, et al., 2004). With this came observations concerning the advantages of this type of procedure over traditional, open surgery (Aggarwal, et al., 2004):

1. Smaller Incisions:

   Since the incisions used in this type of surgery only need to be large enough to insert tools with a diameter of only millimeters, the trauma caused to the patient's body is smaller than that caused when invasive surgery is used.

2. Decreased Postoperative Pain:

   Because of smaller incisions, the patient will experience less pain during recovery.

3. Shorter Time in the Hospital:

   Through the nature of MIS, patients experience less pain and less complications resulting from the procedure so these individuals do not need to remain in the hospital for extended periods of time. This also means less money spent on the patient's part.

The above advantages are good reasons to elect for MIS if the patient's condition allows for it, as this type of procedure is conducive to the overall comfort and wellbeing of the patient involved. There also seems to be no obvious drawbacks for the patient to using this method as long as MIS is feasible as an option.

However, this is not to say that MIS is more convenient than invasive surgery in every aspect. Specifically, training in MIS can be complicated and even impossible for some individuals to undertake. This is due to the unique nature of the kinematics of MIS and the image information provided about the space. They transform the laparoscopic space such that the movement of the tool as observed on the monitor does not match the movement of the tool tip in the laparoscopic space, controlled by the surgeons hands outside the space. The major obstacles of MIS are (Chmarra, et al., 2007):

1. Fulcrum Effect:

   Because tools are inserted into a patient through small holes in the patient's superficial tissues, those tools will move on a pivot located at the point of insertion of the tool. Therefore, when a surgeon moves his hand outside the body in a certain direction, the tool tip inside the patient will move in the opposite direction.

2. Inversion of Environment:

   Typically, when laparoscopic procedures are performed, the surgeon is operating in a space within the patient's body while a laparoscope is inserted into the same space from a direction offline with the surgeon's natural line of sight. The surgeon may be looking directly down at the patient but the laparoscope may be looking into the patient from the left or right of the surgeon, at varying angles. The offset angle the laparoscope is positioned in can be called the Angle of Offset (AO). This compounds the effect produced by the fulcrum effect. Not only does the tool tip move in opposite directions when responding to the surgeon's hand movements, but the AO of the laparoscope forces the surgeon watching the monitor to observe movements of the

tool tip on the monitor that are not reflective of the true, physical movements of his hands and the tool tip inside the patient.

3. Depth Perception:

   During traditional surgery, depth perception is vital for understanding how to interact with the structures of the body relevant to the procedure. However, because a surgeon performing MIS is watching a monitor with a 2-D feed from a laparoscope, the third dimension and depth perception is eliminated. This is an unfortunate drawback to the nature of MIS and is one of the biggest adaptations trainees make before they can step into the OR.

4. Tool Effects:

   The tools used by the surgeon also affect the process of MIS. In traditional surgery, the surgeon is able to use the highest amount of dexterity possible through direct line of sight, direct interaction with the treatment site and better manual control of the tools used. In MIS, the surgeon's dexterity is greatly reduced. Due to the lengthy shafts of the tools used, the tool tip will vibrate with a frequency proportional to the baseline shaking of the surgeon's hand and to the depth the tool is inserted into the treatment site. If the tool is inserted father in, the vibration of the tool tip will generally increase. Also, the size of the tool will dampen force feedback (how well a surgeon can feel a tool tip touching something in the body). A surgeon will be able to detect physical contact reliably with practice; however the overall effect is lessened due to the length of the tool.

The above complications are all obstacles that a training curriculum in MIS intends to help prospective MIS surgeons overcome and adapt to so they can become effective surgeons in

the OR. Most current training systems used today can range from very simple box trainers to more complex virtual reality systems and can present a wide variety of tasks meant to mimic surgical procedures a trainee will encounter in the OR. These tasks can be simple transfer tasks, where a trainee simply moves an object around the simulator space with a tool, or more complex, dexterous tasks such as sewing sutures with a pair of laparoscopic tools. The development of these training systems can be rather involved as factors that must be considered are task design, assessment, efficiency and meeting the end objective of the training (Dankelman, 2008).

1.3 Designing a Training System

Task design and meeting the end objective of the training are closely related as the trainee will end the training having learned the MIS skills specifically used to complete the training task. What needs to be considered between these two factors is generating a task that will teach a trainee the skills that would be used in a real laparoscopic procedure. If a training task achieves this, then the training is said to have content validity. Content validity is generally defined as the amount an aspect of a training task differs from clinical reality (Cesanek, et al., 2008).

Other brands of validity that a training task should demonstrate are face and construct validity. The former is the extent to which a task actually represents the surgical procedure it is meant to mimic and the latter is a measurement of how well the task can differentiate experts and novices (Aggarwal, et al., 2004). If a task can demonstrate these brands of validity, it is a useful task. However, it should be mentioned that when assessing a training task for these brands of validity, face and construct should take priority as they are very easy to truly observe within the

scope of the experiment alone. Assessing content validity requires also examining trainees in the OR after they have left training.

Efficiency is also important for developing a task as lowering the cost of development and time to train produces trained, competent surgeons quicker than if cost and time to train remained increased.

The last factor that describes an MIS training system is the assessment factor. For every task a trainee performs in simulation, that trainee must be assessed to determine if the proper skills necessary to perform MIS have been learned through the training. In older training schemes, assessment would be unstructured and even subjective if a trainee was being scored by an observer (Grantcharov, et al., 2001). In recent years, MIS training has become more objective with the advent of skill based metrics calculated automatically by the simulator system. In many current training curriculums, the metrics commonly used to objectively assess a trainee are completion time, path length and error score.

These metrics, or variations thereof, are also used in many research experiments designed to determine if certain training models are useful or valid ways to train prospective surgeons (Clevin, et al., 2008). Completion time is simply how long it takes to perform a task and path length is how much distance the tool tip(s) or other parts of the tool/trainee's hand move during the task. Error score is a little more subject to interpretation because a universal definition for what an error in MIS is has not yet been presented. Usually error score consists of the number of excessive collisions during the task plus any mistakes or infractions committed relevant to the specific task being performed. This still leaves room for some subjective interpretation such as how much force used in a collision is "excessive". Generally, these metrics are good for discriminating between experts and novices but do not indicate how or where during task

performance a novice has a problem navigating the simulation space. Also, these metrics are not completely descriptive of how well a trainee understands the transformed space presented by MIS simulators (Cotin, et al., 2002). However, these metrics are widely utilized in current training systems because they are validated as good indicators of construct validity of a task (Van Sickle, et al., 2005).

The standard metrics listed above are not the only metrics that have been suggested or even used in experiments exploring different aspects of MIS training and adaptation. There exist other metrics that may be more descriptive or otherwise informative about a trainee's performance during a laparoscopic training task. In 2001, the Metrics for Objective Assessment of Surgical Skills Workshop met to try and develop a completely standard way to develop training and assessment for surgical training curriculums. In doing so they compiled a list of some metrics suggested as valid outcome measures. They are presented in Table 1. Note that the metrics listed are not all encompassing and do not represent every way to assess MIS trainees.

Table 1.1: Validated Outcome Measures as Presented by the Metrics for Objective Assessment of Surgical Skills Workshop (Satava, et al., 2003)

Economy of Motion (EOM) Ratio between trainee path length and ideal path length
Purposefulness of Motion The degree to which a committed motion works to complete a task
Absence of Motion Time trainees commit no tool motion during a task
Sequence of Steps How well a subject follows specific steps toward completing a task
State Analysis Whether or not the subject is moving the tool at all
Force Measurements Force exerted on a system by trainees as they complete a task

Errors Missed targets, tissue tearing, bleeding, organ perforation, burning of wrong tissue, etc.
Recovery from Error How well a trainee compensates for any errors committed
Response Latency How long it takes subjects to compensate for errors
Final Product What is the state of the system once the task has been completed
Global Assessment of Performance Overall performance of the task completed

The listed metrics in Table 1 are not suggested as feedback metrics to a trainee and are suggested only as metrics used to indicate performance after the fact. Many other experiments do not even account for the effect of feedback on performance and only use metrics, such as the standard ones, in analysis for comparison after the experiment has finished. This comparison could be between experts and subjects or between a group of subject's early and late performances (Bell, et a., 2007, Clevin, et al., 2008, Feldman, et al., 2009). The metrics used in these types of analyses are typically the standard ones but have also included smoothness of motion (SOM), depth perception (DP), economy of motion, tissue manipulation, accuracy of motion and a myriad of other actions interpreted as errors or excess movements depending on the task specifically being performed and the definitions of the investigator performing the experiment.

Commonly proposed metrics, but not used much for training, are smoothness of motion (the rate of change of acceleration of the tools used), depth perception (how far into a space a tool is inserted) and response orientation (the angle change of tool position over time). These metrics, as well as those listed in Table 1, have been reported to indicate a difference in

performance between experts and novice MIS performers (Cotin, et al., 2002, Stylopoulos, et al., 2004). Still, these metrics are technical quantities indicating overall performance but do not relate to the subject performing a task, how the laparoscopic training space is transformed, or what type of hand-eye relationship is required to successfully navigate that space. In the case of depth perception, smoothness of motion and response orientation, only absolute values are reported and only sometimes actively during training as in the case of the CELTS training system reviewed by Stylopoulos, et al. Because these quantities are sometimes technical and not entirely meaningful to an individual without a scientific background, they typically are used by investigators simply looking at aspects of training such as construct validity rather than by investigators actually looking into the training of the individual.

As for other commonly used training systems such as those developed by *Reachin*, *SimSurgery*, *Mentice*, *Select-IT VEST Systems*, *Surgical Science*, *Immersion*, *Simbionix* and *Xitact*, the metrics used are almost always the standard ones and are only occasionally used as active feedback (Schijven, et al., 2003). Time to completion or path length used to perform certain steps of a task are common manifestations of the standard metrics, as are errors interpreted as excess tissue manipulation or incorrect tool use. Metrics used in these systems that may not represent any of the standard metrics are things like accuracy of tool position, state of the simulation space upon task completion or simple confirmation as to whether or not the task was successfully completed.

What is more, these training systems afford a great amount of customization at the discretion of the training administrator. This flexibility is good for setting personal training goals or thresholds for performance in terms of completion time or path length, but this also works against the standardization of MIS training in general. This leaves the meaning of the metrics

used in these systems specific to the task being performed, the administrator's standards and the trainee performing the task.

1.4 Proposed New Metrics

To compensate for the standard metrics, we have developed a group of novel metrics that we believe are descriptive of how well an individual understands the transformation that occurs between the simulation space and the monitor observed during the performance of an MIS simulation task. Moreover, through the presentation of these metrics, we try to indicate where in the execution of a training task a trainee may have difficulty performing. When considering the definition of these metrics, the task to keep in mind is a simple transfer task where the individual performing the task is moving the MIS tool from one point to another within the simulation suite. The development and specific use of these metrics will be discussed in detail in succeeding chapters. These new metrics are defined here:

1. Initial Direction of Movement (IDM):

   This metric describes the direction of tool movement for the first ten percent of a motion. It is meant to indicate the initial, instinctive direction an individual moves the tool when trying to move from one point to another within the simulation suite.

2. Direction of Movement at Max Velocity (DMM):

   This metric describes the direction of tool movement when the individual is moving the tool at maximum velocity during the movement. This is meant to

indicate the direction the individual moves the tool when the individual has full confidence when moving from one point to another within the simulation suite.

3. Arc Area (AA):

   This metric describes the 2-D area the tool tip encompasses during the movement between two points within the simulation space. This metric is meant to describe the effect the weight of the tool has on the individual's ability to move the tool in a straight line during the movement. It is an indirect measure of swivel committed during the movement.

The above metrics are all reflections of the kinematic and dynamic effects one sees when performing MIS. The kinematic effects (reflected by IDM and DMM) are described as offsets between the directions the tool moves within the simulation suite, when controlled by a surgeon's hands at the handle, and the perceived directions the tool moves on the monitor being observed. The dynamic effects (reflected by AA) are described as the influence the weight and inertia of the tool have on an individual's ability to move the tool smoothly from point to point (Krakauer, et al., 1999).

1.5 Our Objectives

The purpose of this experiment is to test whether or not a new set of metrics, based on measurements used to quantify the learning of MIS skills, can help a trainee not only adapt quicker to a new, transformed laparoscopic environment, but to also see if there is a way to bring a trainee to truly understand how the environment is transformed. We wish to explore these questions to attempt to identify training protocols that may possibly train prospective MIS

surgeons with greater efficiency. This would result in more skilled surgeons entering the operating room, less time and funds spent training them and better care for potential patients in the OR.

To explore this question, an experiment was performed and will be detailed in the following chapters. The background information concerning this project has been covered and states the definitions of certain types of surgeries (open/invasive versus laparoscopic/minimally invasive) and the pros and cons of each concerning patient morbidity, pain, systemic immune preservation and chance of infection. Specifically, training within MIS is discussed and what current protocols may be lacking in terms of efficiency. That is, do current training-assessment techniques optimally develop a prospective surgeon to perform in the OR? Newly proposed metrics have been introduced (initial direction of movement, direction of movement at maximum velocity and arc area) and the objectives of the experiment have been made clear, to test if novice MIS performers can train more efficiently than with current techniques.

Chapter 2 discusses the background theory concerning the proposed new metrics. The concepts of motor control, motor adaptation and motor mapping are introduced and explained as it relates to manual control. A summary of these concepts as presented in published literature is made and described. The newly proposed metrics are related to this background theory and justifications for why these metrics are relevant are presented.

Chapter 3 details the experimental setup used for our experiment. All of the individual materials used to perform the experiment are presented and described technically. How all of these materials interact with one another and their purposes are also described to create an image of how the setup for the final experiment looked and was used.

Chapter 4 relates the experimental consideration for the metrics. Before the newly proposed metrics were actually developed, a series of pilot studies was performed to investigate the interaction of subjects with our experimental system. The genesis of the proposed metrics by observation of subjects through these pilot studies is summarized. Objective justification for how certain metrics were chosen over others is also presented.

Chapter 5 details the final experiment as it was performed. The hypothesis of this project is restated, the procedures and protocols used are described and results are reported. The hypothesis for this experiment is that our newly developed metrics will be able to train novice MIS performers faster and with greater effectiveness than do the current standards used in laparoscopic training regimens. The procedures that are described are the actual processes used to collect data from expert and novice MIS performers as well as a detailed description of how we utilized and manipulated that data. Different phases (training versus testing) will also be described. The results will report comparisons between novice subject groups. Results of the testing phase will also be reported.

Chapter 6 will be reserved for the discussion of the results. The discussion will detail conclusions, if any, that were drawn when analyzing the results as well as comment on the efficacy of the results and any strengths and shortcomings of the experiment as it was designed and performed. Suggestions for future work will also be presented.

CHAPTER 2 BACKGROUND THEORY

2.1 How Our Brains Keep Us on Target

Before discussing the details of the newly proposed metrics, it is important to provide a background on the fundamental principles that these metrics represent; specifically, motor mapping and adaptation.

It is something very simple most people take for granted every day. However, there are many specific processes that need to occur for a human individual to simply reach out and grab an object. Imagine a glass of water sitting in front of you on a table. If asked to reach out and pick up the glass then take a sip, almost any individual would be able to perform that process within a couple of seconds. It is a simple task, but there are many processes and systems that must be integrated together in order to pick up a glass of water and pull it to oneself from its original position. The process starts with the simple image of the glass sitting on the table. Ambient light reflects off the glass into the eye and stimulates the retinas of the eyes where a specific electrical signal is sent along the optic nerve to the occipital lobe of the brain where visual information is processed. This is the part of the brain that allows you to recognize and understand the objects filling the environment in your current field of vision. Now with the image of the glass present and the ultimate goal of taking a sip from the glass in mind, your brain is ready to tell you to reach out and grab it.

The second step is generally described as the visuomotor transformation that occurs to stimulate the muscles needed to reach out and grab the glass (Dvorkin, et al., 2008). As you reach out to grab the glass, your brain has already developed a 'plan' to grab the glass. When compared to other objects in the visual field, your brain can estimate precisely how close or far the glass is so you know how far you will move your hand. Also, through past experience, your brain has estimated the weight the glass of water may have so that when you do grab the glass you will be able to pick it up smoothly and not stall by not producing enough force to pick it up, or not produce too much force as to throw the glass or eject the water from the glass. This 'plan' the brain has set is a result of past experiences occurring in childhood and fine tuning in subsequent experiences occurring in the formative years (Breedveld, et al., 2001). As you reach for the glass, your brain continually stimulates the muscles in your arm to move your hand towards the glass while also monitoring the joint angles of the arm to make sure your hand is on the correct path towards the glass of water, making corrections for any deviations from the required trajectory (Brouwer, et al., 2006). This occurs continuously until your hand successfully grips the glass.

The last step, pulling the glass toward you, is accomplished in a similar fashion as the reach phase. The muscles in your arm will contract, in response to signals from your brain, with enough force to pick up the glass. If the weight of the glass has been misjudged, then the adjustment will be made here to successfully and smoothly pick the glass up from the table. The brain then signals the arm muscles to contract so as to pull the glass to your mouth for a sip of water. This process is also continuous as the brain signals your muscles to contract while making sure the joints of the arm are changing properly to smoothly draw the lip of the glass to your mouth. Once the glass is drawn, you can then take a sip of water. As can be seen, this is a very

involved set of processes that occur within seconds of deciding to pick up the glass. The reason this task is completed so quickly is because since infancy, an individual has been interacting manually with the environment every day. In those early years of life, the brain had developed a 'plan' to use at any future date if a small object needs to be picked up.

This 'plan' is called a motor map. A motor map is a strategy developed internally by the brain to interact with a specific environment. Every person develops a motor map to interact with our everyday environment. However, in MIS the environment is transformed. A laparoscopic environment is presented in such a way that real-world motion of the laparoscopic tool tip in the laparoscopic space does not match real-world motion of the hands of the individual manipulating the tool outside of the laparoscopic space. The perceived motion of the tool tip on the monitor also does not match the real-world motions committed. The factors that influence this transformation the most are the fulcrum effect of the tool-entry point set up, the 2-D image representing a 3-D environment and the AOO of the laparoscope. The cumulative effect of these factors is an offsetting rotation of the laparoscopic environment projected on a monitor screen while the trainee or surgeon still has to physically operate in a normal environment while only using the monitor image as visual feedback.

So an association must be made between the individuals moving hands, which control the actual motions of the tool tip in the laparoscopic space, and the perceived motions taking place on the monitor in the 'rotated' environment. This leads to serious complications when trying to navigate this new space such as increased time to complete tasks during adaptation because the perceived motions of the tool tip, on a monitor, do not match the motions individuals believe they will be committing in the laparoscopic space and with their hands. Since the environment has changed, that means the surgeon or trainee needs to develop a completely new

and unique motor map to successfully navigate the new, uniquely transformed space (Masia, et al., 2009).

Compounding on the novelty of the transformed space, the effort the brain has to make to develop a new motor map is significant in adaptation as new motor patterns of the hand-arm system of a surgeon need to be associated with resultant motions of the tool tip in the laparoscopic space and with how these motions present on a monitor observed by the surgeon.

As can be expected, this process takes time to learn. These new associations mostly concern the new kinematics of the laparoscopic environment as they are the earliest perceived difference and the most difficult to adapt. When actually performing a laparoscopic task, trainees will interact with the tool and environment, learning the unique dynamics and force interactions of the tools and objects in the laparoscopic space. All of this occurs continuously until a sufficient motor map is developed to effectively navigate the laparoscopic space.

2.2 How We Adapt

The process of an individual adapting to an environment where planned, natural motor commands of the hands produce unexpected resultant motions of a tool depending on what type of system that tool is a part of is an area of research many studies have tried to understand. Although many studies have focused on specific aspects of adaptation, most of them show that motor adaptation occurs through perceived errors in trajectory (Wei, et al., 2008; Brouwer, et al., 2006; Masia, et al., 2009). Examples of these can be how deviated a subject is from a straight line trajectory, how much overshoot or undershoot is committed when trying to reach to a point

or even how much ‘correction’ continuously takes place when trying to move along a straight line.

One aspect in understanding how humans adapt to perturbed environments in MIS is to understand the difference between implicit and explicit learning. Implicit learning describes the process of an individual adapting to a novel environment without forcing the subject to consciously realize the process of adaptation. Explicit learning describes a process forcing an individual to consider the specific perturbation in the environment to minimize errors before the individual interacts with that environment (Cameron, et al., 2010). For example, setting someone down to perform a laparoscopic task and allowing them to adapt at their own pace without providing feedback on the space is an implicit learning scheme. The individual simply learns to perform the task by practicing over and over until the proper motion is observed in performance. In an explicit learning scheme the individual is apprised of the nature of the transformation in the laparoscopic environment. The effects that alter the kinematics (fulcrum effect/tool effects) are explained as well as the effect the AO has on the monitor image. If the laparoscopic space is presented as rotated 90^0, the individual will know this beforehand so he may have a starting point for adaptation.

During MIS training, implicit learning is usually the dominant form. Trainees simply practice surgically relevant tasks a repeated number of times until they begin to demonstrate performance similar to expert standards. This process of task performance without specifically defining the transformed laparoscopic space to the trainee is preferable as it has also been shown that learning this way tends to establish endured learning while explicit learning demonstrates quicker but less retained learning (Cameron, et al., 2010).

However, the drawback with this type of training scheme is that in the OR a surgeon will potentially be presented with many different laparoscopic hand-eye relations based on properties dictated by the operation, the patient and even the team the surgeon will work with. For each unique situation (hand-eye relation), that surgeon will need to adapt a specific, appropriate motor map. If, during pre-operative training, a trainee is presented with just one environment, through implicit learning, it is likely that individual will only learn a hand-eye relation specific to that environment, developing a single motor map. This may not be useful for real OR conditions, where laparoscope-tool positions may not always be fixed in the same way as they were during training. It may also be difficult to generalize the principles from implicit learning and apply them to new laparoscopic environments.

If a trainee learns multiple environments, it would take a lot of time to develop motor maps for all of them and this increases costs and lowers efficiency during training. Also, there is no guarantee a real OR situation will present the exact same environment as one of the environments for which a trainee had developed a motor map. The new metrics we are presenting may offer a bridge between the implicit and explicit schemes for training and allow a trainee to explicitly understand the transformed space while implicitly adapting to it. One purpose of our proposed experiment is to show that while a trainee is implicitly adapting to a space, he or she will also learn to explicitly define the transformation of the simulation space internally.

Another important consideration for motor adaptation is how separate motor maps developed for unique environments are accessed and used by the Central Nervous System (CNS). It is known that once a motor map is developed and retained that it can be accessed and used again to navigate the same transformed environment at a later date (Brashers-Krug, et al.,

1996). However, it has been suggested that if an individual has developed a number of internal motor maps, then any number of those maps can be accessed to aid an individual to adapt to a unique environment for which the CNS has not yet developed a specific motor map (Flanagan, et al., 1999). This insight could be very useful for MIS training as learning different training tasks and hand-eye relationships can aid in learning new relationships in the OR later, where unexpected circumstances may force surgeons to work with a laparoscopic environment they had not encountered before. Or perhaps if an individual can internally define the transformed hand-eye relationship of a single environment, that definition can aid in later adaptation to multiple transformations.

Another interesting aspect of human motor adaptation is the rate at which we learn. That is how quickly a trainee adapts to a new laparoscopic environment and demonstrates a plateau of performance where continued attempts at a task will yield no further proficiency. In any new motor action, an individual needs to develop a strategy necessary to complete the action and as noted, if the environment is unusual, the strategy needs to account for that as well. When learning a new motion in our natural environment, it is usually a matter of imitation. When we are young, humans can learn motor skills very quickly in our natural environment and this shortens the learning time for learning motions later in life because we have developed a good foundation of motor action in our formative years.

However, learning how to perform specific motions in a transformed environment, such as an MIS space, is much more complex as a new motor map needs to be developed. The development of this new map is made over the learning curve that describes how the trainee adapts to the new laparoscopic environment over time. Typically, when learning a new MIS environment, the largest performance improvement takes place during the first few repetitions of

a task and as the trainee continually performs the task, quantified improvement using standard metrics (completion time, path length and error score) becomes less and less identifiable (Feldman, et al., 2009). We expect the same effect to occur with the new metrics we are proposing, however we also want to investigate whether or not the learning curve can be steepened if using them as feedback. We ask if subjects can reach a plateau of performance quicker with feedback from the new metrics.

2.3 Relating New Metrics to Theory

All of these different aspects of motor adaptation are usually linked to the minimization of motor error. In our natural environment, we learn specific motions by acting them out continually until the goal of the action is met consistently. This process can be short, such as gripping a glass of water, or it can be arduous, such as learning to sew sutures. If we add in the effect of transforming the hand-eye relation in the environment, adaptation becomes even more difficult. Current MIS training systems are not concerned with quickly minimizing the motor error associated with developing new motor maps as much as with simply pushing the trainee to eventually adapt to the space and develop the skills necessary to perform in the OR. Standard metrics used in most systems such as completion time, path length and error score are simply absolute values generalizing overall performance either at the end of a task or part of a task. They do not indicate the existence of motor error or relate how the laparoscopic space is transformed and how well a trainee is navigating that space.

The theory concerning how people adapt to novel hand-eye relations in transformed environments was the first stepping stone for developing new metrics. When investigators

explore motor adaptation, whether through generic experiments or experiments specifically involving MIS, one of the largest indicators used for assessment is motor error. Typically, this motor error is measured as some form of deviation from an ideal motion as in investigations performed by Krakauer, et al., 1999 (deviation from a straight line), Brouwer, et al. (accuracy when reaching to a point), 2006, Cameron, et al., 2010 (accuracy when reaching to a defined, invisible point) and Dvorkin, et al., 2008 (deviation from a straight line trajectory while the line changes continuously).

Large motor errors indicate little to no adaptation while smaller errors indicate better or more complete adaptation. If a subject in a given experiment is instructed to move a cursor or their hand in a straight line while interacting with a transformed eye-hand relation, the motor error is sometimes defined as the angular discrepancy between that straight line and the actual motion the subject produces. Here, angular discrepancy is the angle, measured in radians or degrees, measured between the two vectors representing the ideal motion and the actual motion committed by the subject. This discrepancy is what we wanted to describe to subjects with our new metrics by comparing novice data with an expert reference. Motor errors can be measured in other ways as well, such as the absolute distance between where the subject was meant to end their motion and where they actually ended their motion (accuracy), the area encompassed between the ideal trajectory and the committed trajectory (arc area) or even the percentage of the ideal path is committed by a subject (EOM). There is a good deal of subjectivity as to what a motor error is, depending on the investigator and what their goals may be. However, it is almost always defined as a physical deviation from an ideal.

The reason investigators use this difference between novice and ideal motion to describe motor error is because it is an objective way to measure accuracy committed by individuals when

they are trying to control the physical motion of some system (hand/finger, computer cursor or laparoscopic tool). It is almost impossible to measure a subject's intent as they move between points beyond perhaps the subject's own description. Using angles between vectors or distances between endpoints to describe a subject's accuracy is a complete way to describe a subject's performance relative to an ideal in terms of path taken. Consider once more the example of an individual simply moving a cursor across a screen. Under normal circumstances, with no reorientation of the screen environment, the individual will be able to move the cursor from one point to another in a fairly straight line. However if the screen environment is reoriented or rotated, say 90^0, such that intending to move the cursor straight left on the screen will result in the cursor moving straight up, the same individual will not move straight left on an initial attempt. This is because a motor map has not been developed for the newly transformed environment and the motor map in place for the normal scheme is interfering with performance. The result is as the development of this new motor map progresses, deviations from the ideal motion will persist but will be minimized by the subject with repetition of the task. Eventually, the individual will be able to faithfully move straight left in the rotated environment.

We want to describe these types of deviations with our metrics while taking things a step further and pushing subjects to understand why the discrepancy exists. That is, push them to understand the error is due mostly to the reoriented hand-eye relation of the transformed environment and to understand that transformation. The above paragraph gives an example of how rotated environments generate a difference in the directions of motion between the ideal and actual motions. The extension of this concept to arc area is simple. The same principle follows for this metric only the ideal value is 0 m^2, as moving from one point to another in a completely straight line will produce no arc. Any deviation from a straight line will add to the arc area. This

metric makes sense to use because if extra mass is added to one's hand, say in the form of a laparoscopic tool, the subject will need to learn to operate with that extra mass. Any deviations from a straight line or an intended motion under this circumstance will be accentuated because the subject will not have adapted to the extra weight yet.

From an investigator's standpoint, these metrics make sense because they are objective and accurate. However, since we will be using these metrics as feedback they need to make sense to subjects who may not be scientifically inclined. Thankfully, describing direction of movement in terms of angles in degrees is easily understandable since almost everyone has been familiar with the concept of angles since grade school. Describing arc area is simple as that involves reporting a positive, absolute value which is meant to quantify physical swivel that he subject would experience upon every trial. Since these metrics can be interpreted by both investigators and subjects, they are useful as feedback metrics for describing motion and any deviation from an ideal or frame a reference.

Before describing how these metrics were developed from theory to experimentation, the experimental setup used for the final experiment and for pilot studies will be introduced. The individual materials will be presented and a gradual depiction of the final experimental setup and how it was used will be made.

CHAPTER 3 EXPERIMENTAL SET UP

3.1 Laparoscopy Simulation Task Box

For this experiment, an experimental setup that emulated the training systems used to train prospective MIS surgeons needed to be developed. The first choice to make was whether or not to emulate a physical system or utilize a virtual reality system for our purposes. Both systems have advantages, the physical box systems more directly represent typical MIS procedures through tasks of physical manipulation while virtual reality systems have a greater diversity in task design and can incorporate internal software to generate metrics or quickly convert tasks to user specifications. In the current experiment there was no need for task diversity as only one was developed for this experiment, and given that virtual reality systems are very expensive, a physical task box was used to conduct the experiment. This task box was not developed specifically for this experiment but sufficient once a couple of simple modifications were made to it. The task box and its features are shown and described in Figure 3.1.

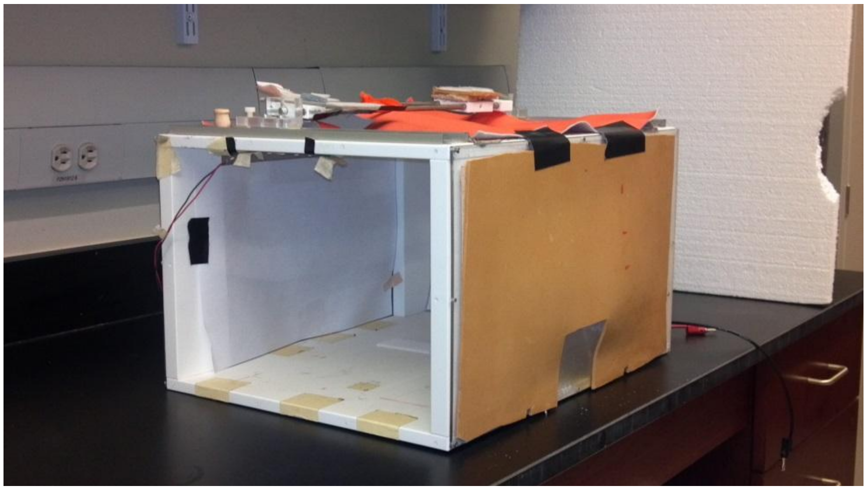

Figure 3.1: Orthographic View of the Task Box

A plastic MIS trainer (Figure 3.1) was used throughout the duration of the experiment. The dimensions were 45 x 26 x 25.5 centimeters. It was constructed by using sheets of plastic glued together to form the sides, leaving one side free for the investigator to observe the experiment and change the training task device, and the top open to allow for a more flexible cover to reposition the insertion point of the simulated laparoscope anywhere on the box's top surface.

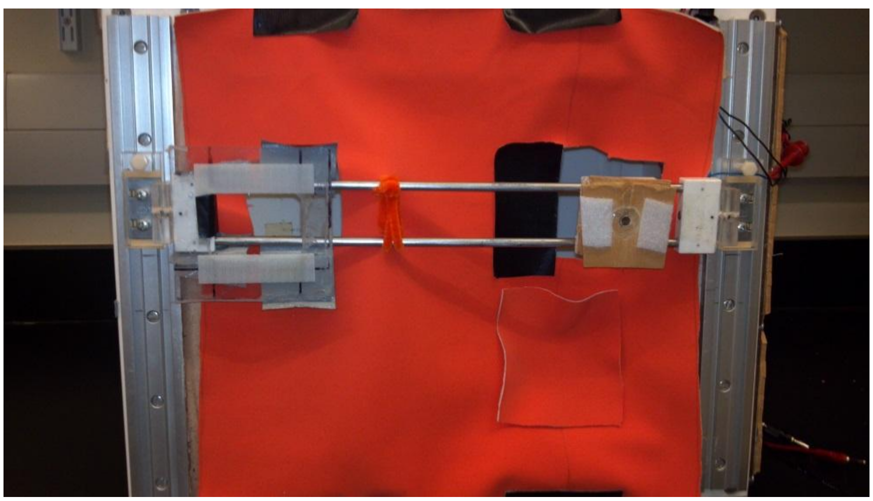

Figure 3.2: Top View of the Task Box

An orange, felt cover had been used to cover the open top wall of the box and contains two square-shaped holes on the left and right sides. The hole on the left side is to insert the

simulated laparoscope (which viewed the inside of the task box) and the hole on the right allowed the laparoscopic tool to operate within the space while being manipulated from outside the box. Also located on the top of this box is a rail and rubber insert to simulate the use of a port in the patient's body.

Flexible rubber was meant to simulate the elasticity of human tissue. Set in the center of this rubber, running through the thickness of it was an empty, plastic bobbin meant to reduce friction as subjects pushed and pulled the laparoscopic tools into and out of the task box.

On the left side of the box in Figure 3.2, a plastic, square frame was taped to the two struts right above the left hole cut into the felt covering. On this plastic frame a couple strips of hook-and-loop fasteners were adhered to help fix the simulated laparoscope once subjects were ready to begin performing in our training task.

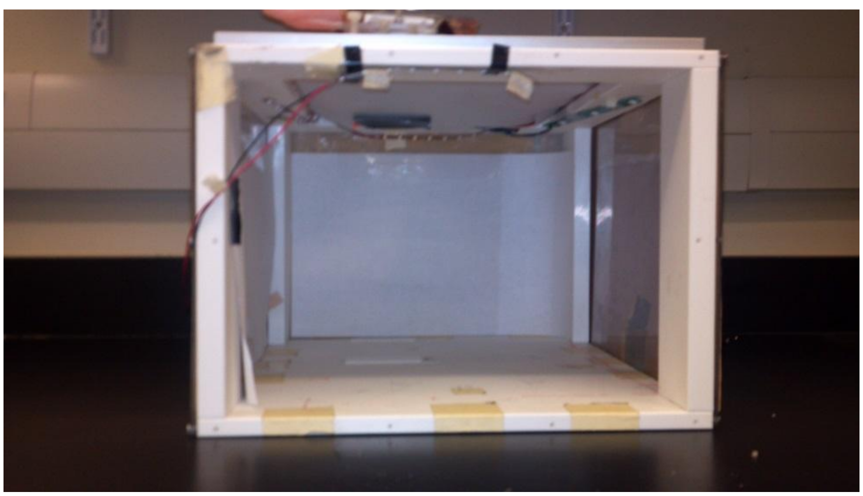

Figure 3.3: Side/Interior View of the Task Box

From the side, one can see into the task box as shown in Figure 3.3. This is the space where the laparoscopic tool operated to complete the training task and to give access whenever the interior needed to be fitted with a new training task device. The top of the inside of the simulation space was lined with strips of Light Emitting Diodes (LEDs) along all four sides of the box. These LED lights were powered by connecting them all to a small 15V power source.

They would illuminate the inside of the task box and give a subject a much clearer view on the monitor used during the training task.

3.2 Laparoscopic Simulation Tools

Once our task box was developed we needed to determine how the tools used for the task would be positioned. The laparoscopic tool used was a Stryker® 5mm Laparoscopic Dissector Tool and is shown below (Figure 3.4).

Figure 3.4: Stryker® 5mm Laparoscopic Dissectors (https://stryker.com/stellent/groups/public/documents/web_content/126639.pdf)

The basic function of the tool is a simple scissor-grip action at the handle resulting in the opening and closing of the small, curved grips at the end of the tool. The tool's shaft could also be rotated 360^0 in either direction along its axis. To note, if the grips were closed and held closed at the handle, the rotation feature of the tool would be somewhat impeded to assure less rotation of a griped object. However, rotation was still very possible and did not harm the tool in any way. The chord extending from the handle of the tool seen in Figure 4 is attached to the motion

sensor used for the experiment and was taped to one of the grips of the handle to ensure accurate data collection.

A 3-DMEd SimScope™ (Figure 3.5) was used to simulate a laparoscope.

Figure 3.5: 3-DMEd SimScope™
(http://www.3-dmed.com/SimScopes_Descriptions_%28CAM03%29.html)

The simulated laparoscope was fixed such that the right hemisphere of the box was visible through its camera. This visual was achieved by fixing the line of sight of the laparoscope approximately 30^0 from the plane of the top wall of the task box and placing the camera inside the task box at the top left frame. As stated earlier, the laparoscope was fixed in place by securing it to the plastic frame (via hook-and-loop fasteners) attached to the struts at the top of the task box and using a backstop to support the handle and weight of the laparoscope (Figure 3.6).

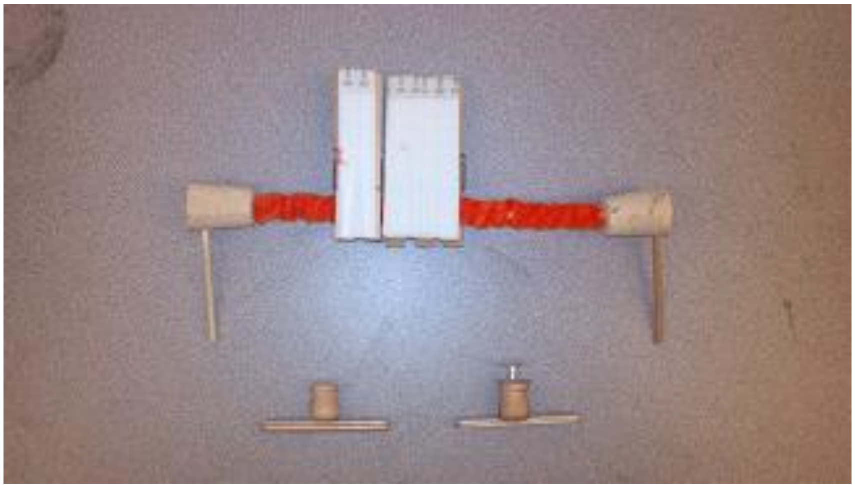

Figure 3.6: Backstop and Anchors used to Support the Laparoscope

The devices in Figure 3.6 were created through common craft store supplies. The anchors used to hold the backstop to the rail of the task box were constructed by adhering two miniature wooden slats together and then adhering a small wooden pot to insert the backstop's legs, measuring 7cm. Finally, a bobbin reel was glued to one of the wooden pots to strengthen the setting of the lower leg of the backstop, which supports most of the simulated laparoscope's weight. The backstop itself was constructed by inserting wooden dowels into a pair of corks at 90^0 angles within the plane of the backstop. The insertions were loose enough such that the long shaft of the backstop, measuring 21 cm, could rotate along its axis and also such that each leg of the backstop could rotate along their axes.

The long shaft of the backstop was also wrapped in pipe cleaners to increase the ability of the functional part of the backstop to bite onto the long shaft without freely rotating around it. The functional part of the backstop was developed using five normal sized clothespins. These clothespins were covered on one side with hook-and-loop fasteners which would eventually connect to the laparoscope shaft. The clothespins were then made to bite onto the long shaft of the backstop. Since the clothespins could be detached and reattached, the clothespins could be positioned anywhere, 360^0 around the long shaft. Combine this effect with the positioning

versatility of the legs of the backstop and many different orientations could be achieved to hold the laparoscope.

However, since only one orientation was needed to perform our task for all subjects, this versatility was useful only in that whenever subjects would bump the backstop while it was attached to the simulated laparoscope during our training task, the backstop-laparoscope system would give and this would reduce force applied to the anchors which were comparatively fragile and though connected to, were not entirely fastened to the rails of the task box. An image of this setup, the task box together with the laparoscopic tool and backstop-laparoscope system, is presented below (Figure 3.7).

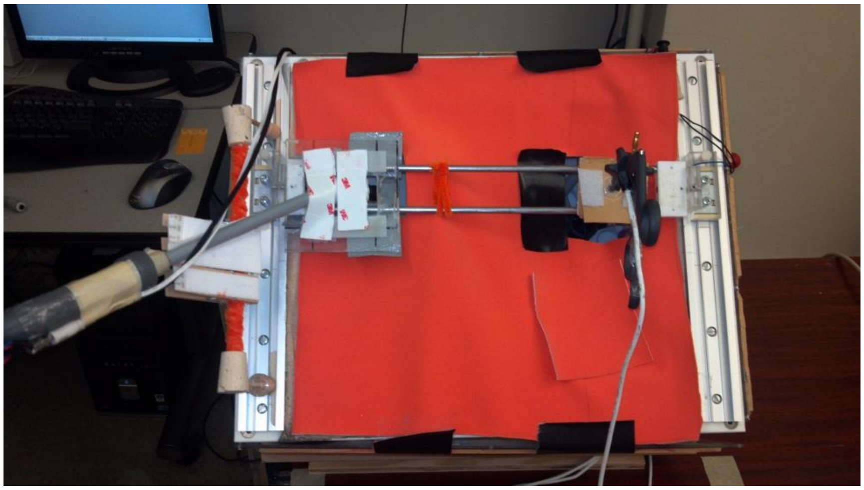

Figure 3.7: Task Box Setup with Laparoscopic Tool on Right and Backstop-Laparoscope System on the Left

During the experiment, subjects would manipulate the tool seen on the right while leaving the laparoscope seen on the left fixed.

One last adjustment was made to the task box rig before the experiment could begin. It was seen through pilot studies, described in the next chapter, that some motions committed by subjects were strained. That is not to say subjects had inherent difficulty with certain motions, what is meant is that the physical motion of the wrist to manipulate the tool used was unnatural,

inconvenient and generally uncomfortable. To remedy this, the task box was rotated forward approximately 45^0. Through this change, the ergonomics of the entire system became much more comfortable for the subjects. To achieve this, the task box was set on a simple wooden stand.

Figure 3.8: Side View of Stand

Figure 3.9: Front View of Stand

3.3 Detecting Collisions during Performance

One important metric that we investigated was errors during the task. Errors can be considered either dropping of the objects or collisions with excessive force in the simulation space. For our purposes drops were easily accounted for through a device attached to the motion capture system used for the experiment, which will be discussed further on. However, detecting collisions in the simulation space was a little more involved. To detect force exerted on objects in the simulation space by subjects through the laparoscopic tool, a simple accelerometer, a Triple Axis Accelerometer/ADXL 335, was used. Specifications for this device can be found in the Appendix (3.1). This device could detect acceleration in three dimensions and its leads were connected to a basic summing circuit. A diagram for the entire circuit used and a list of devices/components used are provided in the Appendix (3.2). An image of the summing circuit created is shown in Figure 3.10.

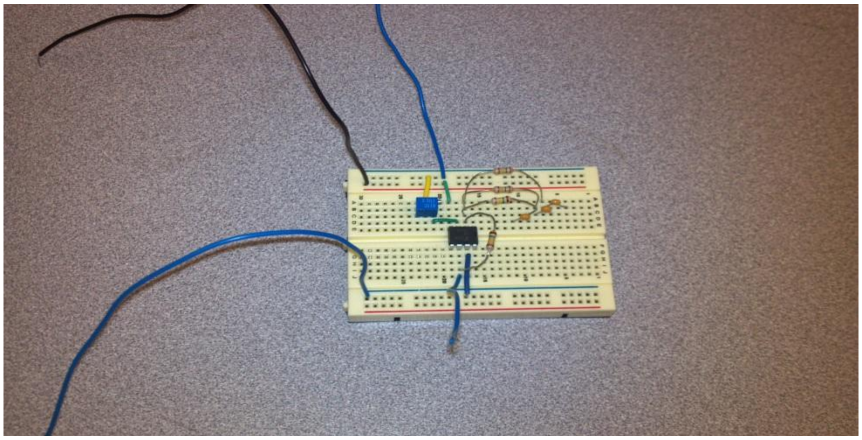

Figure 3.10: Summing Circuit used to Detect Task Tree Collisions

The circuit in Figure 3.10 detected collisions by summing the accelerations in all three dimensions sent by the accelerometer and connecting the output signal to a data acquisition board integrated into the motion system we used for the experiment. This circuit was powered by an Agilent E3630A Triple Output DC Power Supply. An NI USB-6009 DAQ was inserted between the power of the motion capture system used and the power lead of the accelerometer. Specifications on the power supply, DAQ and all other circuit devices/components can be found in the Appendix (3.3).

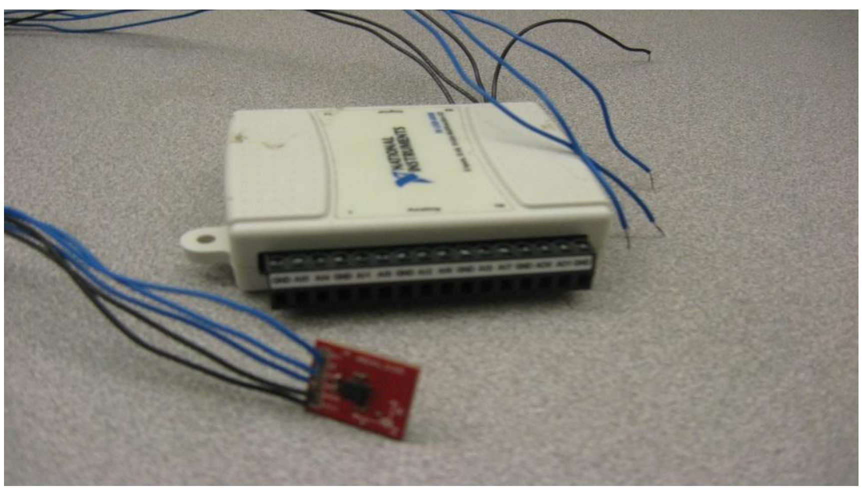

Figure 3.11: DAQ connected to Accelerometer for Detecting Collisions

3.4 Device Used to Track Tool Tip Motion

The final element of the experiment needed to complete the experimental setup was the inclusion of a system used to track motion of the tool used by subjects for our training task. We used *The Motion Monitor*® system developed by Innovative Sports Training Inc. (http://www.innsport.com/Home.aspx). For our purposes, we used only one of the four sensors which would feed position data to the system to collect motion data of the laparoscopic tool. This motion capture system used Ascension's "Flock of Birds" to collect position data. These sensors could also report the orientation of the sensor.

The sensor used captured position data in x, y and z coordinates based on a pre-determined origin point which stayed constant throughout the whole experiment. So each data sample had a corresponding sample number. The experimental setup was positioned relative to the origin point such that this x, y and z data was always positive. This origin point was determined by sampling various data points for the system. We designated where we wanted the origin by using a stylus connected to one of the other "flock of birds" sensors to point to the origin point. We then sampled data points with this stylus along hypothetical x, y and z axes running through the origin point to generate a virtual, three-dimensional coordinate space that the system would 'remember' and use each time a subject performed the MIS simulating training task we developed. This position data was accompanied by timestamp data linked to the capture frequency of the sensor.

The defined frame of reference the system 'remembers' while subjects are participating in the training task and data is being collected originates around the lower right-hand corner of the task box as depicted in Figure 3.13 below. It is located specifically near the table corner, on

the plane of the table top. If subjects stand in front of the experimental setup shown in Figure 3.14 below, facing the monitor screen, then the positive x-axis runs across and to the right of the subject, the positive y-axis runs away from the subject along the left side of the experimental setup and the positive z-axis runs vertically upwards. Figure 3.12 gives a better impression of this scheme.

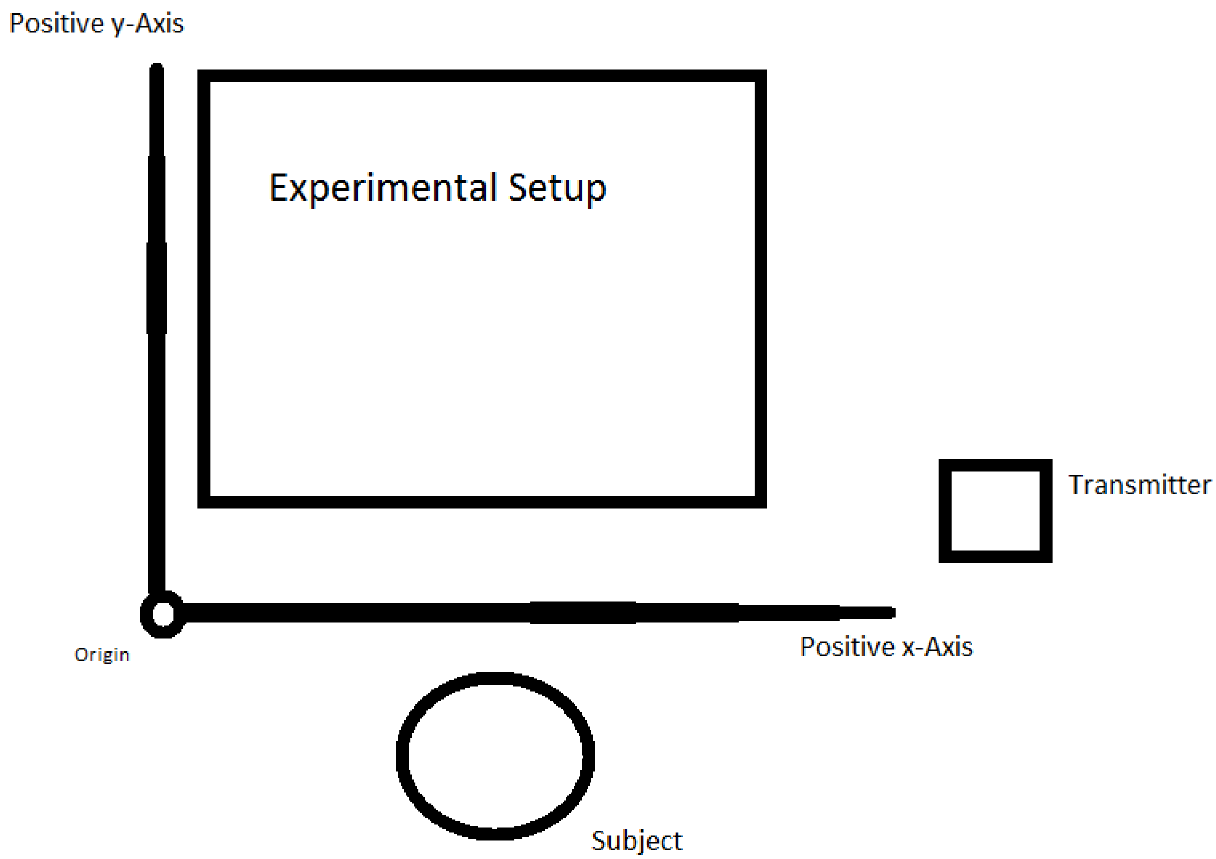

Figure 3.12: Bird's-eye View of the Frame of Reference for Motion Tracking

The experimental setup just described was how it existed as all subjects, novice and expert, performed the training task.

The only other device used to collect data on the system was the data acquisition board integrated in the motion detection system used to collect accelerometer data and to detect pushes of a button connected to it. This button, or "OK" button, would send a constant, approximate 5V

signal to the system's data acquisition board until it was depressed. As long as the "OK" button was depressed, the voltage signal sent to the data acquisition board would drop to approximately 0V. This button was used to indicate drops of objects or repeated trials during the experiment. These signals were synched to the position data collected by the motion monitor.

The entire setup after everything is connected is shown below from two different angles. In Figure 3.13, the side view of the system is shown and in Figure 3.14, the system from just to the left of where a subject would stand when performing our training task is shown.

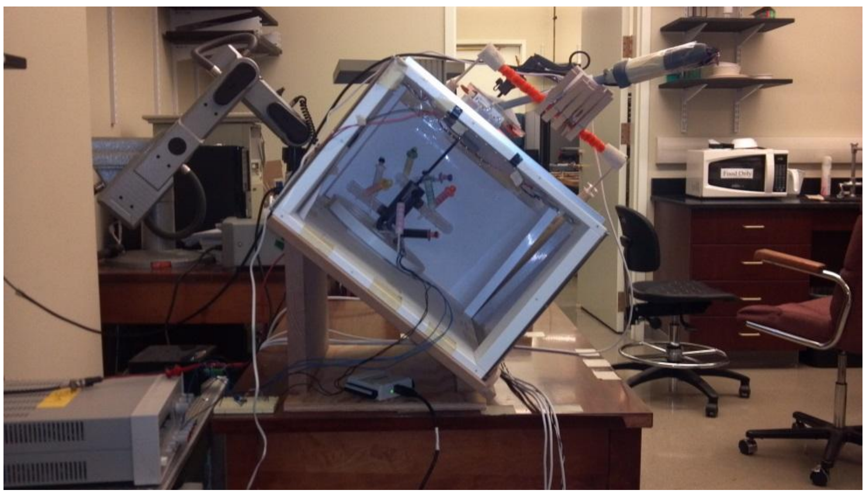

Figure 3.13: Side View of Laparoscopic Simulation Setup

The side view of the system shows all discussed elements of the experiment existing together as they did during the experiment when a subject performed our training task. The simulated laparoscope and laparoscopic tool are placed at the top of the box and ready to be used. The simulated laparoscope is feeding video to the monitor just off to the left side of Figure 3.13. The accelerometer and summing circuit are also present. The accelerometer is attached to the training task device in the simulation space and its leads are flowing out of the box to the DAQ and summing circuit, which are both connected to the power supply and the motion detection system.

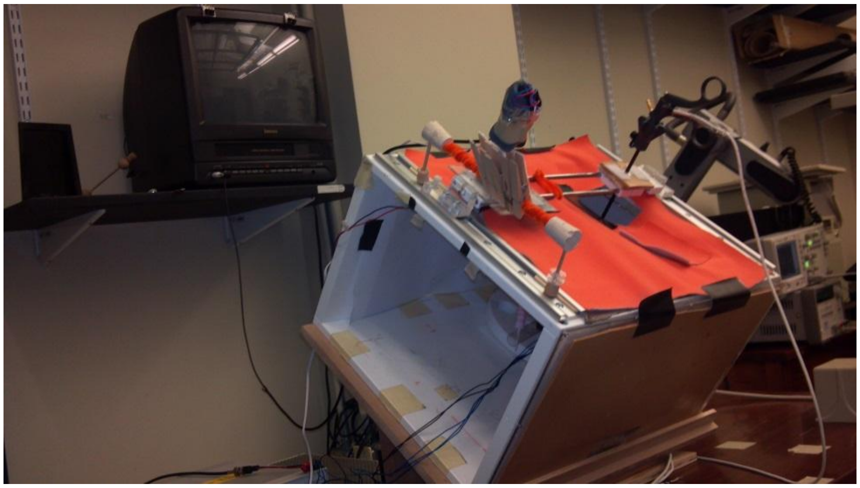

Figure 3.14: Same Setup as Figure 13 Seen from the Left of a Subject's Position during Performance

The above image is the same setup from Figure 3.13. However, here we show the monitor, a simple television screen, used to show a subject the image captured by the simulated laparoscope at the top of the task box. This monitor is positioned at approximately eye level for all subjects. Also seen at the bottom-right is the transmitter used by *The Motion Monitor*®. The transmitter is the device used by the motion system to actually receive coordinate data and is orientation specific (its position/orientation affects data collected). As mentioned, the motion system collects data based on a defined frame of reference. If the transmitter is oriented incorrectly, the data collected may be inverted or rotated. Figure 3.14 shows the general position of the transmitter throughout the experiment for all subjects. As long as the transmitter was in front of and to the right of the task box and oriented correctly (facing the right direction), the data received would be reliable.

Before describing how this experimental setup was used in the final experiment, the next chapter will cover experimental considerations for the newly developed metrics we have proposed. Specifically, how they were developed through observation and preliminary data collection.

CHAPTER 4 EXPERIMENTAL CONSIDERATION OF METRICS

4.1 Reintroduction of the Metrics

The metrics have been introduced and will be mentioned again here:

1. Initial Direction of Movement (IDM):

   This metric describes the direction of tool movement for the first ten percent of a motion. It is meant to indicate the initial, instinctive direction an individual moves the tool when trying to move from one point to another within the simulation space.

2. Direction of Movement at Max Velocity (DMM):

   This metric describes the direction of tool movement when the individual is moving the tool at maximum velocity during the movement. This is meant to indicate the direction the individual moves the tool when the individual has full confidence when moving from one point to another within the simulation space.

3. Arc Area (AA):

   This metric describes the 2-D area the tool tip encompasses during the movement between two points within the simulation space. This metric is meant to describe the effect the weight of the tool has on the individual's ability to move the tool in a straight line during the movement. It is an indirect measure of swivel committed during the movement.

As mentioned, these metrics are meant to reflect the kinematic and dynamic transformations that occur when operating within an MIS space. These metrics were developed starting with inspiration from studies such as Krakauer, et al., 1999 and Brouwer, et al., 2006. In those investigations, subject's adaptation to altered environments was measured through the minimization of motor errors during repeated, reaching tasks. The motor errors were measured as deviations from an ideal trajectory and absolute error in distance from a target. These metrics were used because they were a faithful way to measure how well a subject could navigate the new environment. Smaller motor errors indicate more adaptation and so the metrics they used became our starting point for developing new metrics. They were then modified through a series of pilot studies designed to expose how well individuals intuitively navigate a laparoscopic simulation space without or with limited, continuous visual feedback.

4.2 Relating MIS and Motor Errors

Many studies have investigated the process of motor adaptation (Asai, et al., 2010, Dvorkin, et al., 2008, Maitra, et al., 2010, Masia, et al., 2009, Mazzoni, et al., 2006, Wei, et al., 2008). One way to do that is to present an individual with an environment where real-world motions committed by the individual produce unexpected motions of a cursor or object, 'controlled' by the individual, projected on a two dimensional screen (Krakauer, et al., 1999, Brouwer, et al., 2006). The actual motions of the individual are also commonly carried out in a two dimensional plane. The effect is achieved through a virtual rotation of the screen. This is similar to a scenario if wherein a computer mouse was rotated and the resultant motions of the cursor on the computer screen would not match the motions of the mouse but would be offset,

corresponding to the degree of rotation of the mouse. The correspondence between the perceived errors and the offset can be thought of as a consistent kinematic relationship.

In MIS, this effect is achieved through the AO of the laparoscope and bridges a two dimensional observation on a monitor with three dimensional real-world motions of the tool in the laparoscopic space, controlled by the hands of the trainee/surgeon outside of the laparoscopic space. The common element in both these schemes is the production of a perceived difference between the expected motions and the observed motions where the difference (error) corresponds to the AO, introducing a consistent kinematic relationship. This error should be minimized through practice and repetition. However, in MIS training there are no explicit metrics used in standard training curriculums that describe this consistent kinematic relation to the trainee.

The standard metrics of time to completion, path length and error score do not directly inform a trainee about how effectively the new kinematic relationship is being understood. This effect relates to implicit learning in that with no generalization of the current laparoscopic space, it may be difficult for trainees to generalize any novel kinematic relations they may encounter in the OR, which can be varied by the type of operation and the patient body type. We expect explicit learning cues (using the metrics IDM & DMM) will help trainees realize the new kinematics of a novel laparoscopic space better and also help to generalize the kinematic relations of other spaces they may encounter later on. Specifically, the standard metrics do not describe the directions an individual commits to during a laparoscopic task and thus cannot describe the error or deviations from an ideal trajectory.

The same reasoning can be extended to the metric of arc area. None of the standard metrics can represent how the tool's mass might be affecting a subject's motion as well as arc

area. Path length is the most closely related to arc area but an absolute value indicating distance covered by a motion does not relate a deviation from an ideal path.

4.3 Investigating Many Metrics

Before we used the proposed metrics as feedback to assist with learning of a laparoscopic task by the user, there were a number of other metrics which were considered as feedback and investigated using a correlation study to determine how the metrics affected learning and how they related to each other. The metrics other than standard ones that were considered are listed & defined in Table 4.1.

Table 4.1: List of Metrics Considered as Feedback

Initial Direction of Movement (IDM) Direction of the velocity of the tool tip in the task box for the first ten percent of a motion
Direction of Movement at Max Velocity (DMM) Direction of the max velocity achieved of the tool tip in the task box during a motion
Arc Area (AA) Area encompassed between an ideal straight line trajectory and the arcing path of the tool tip in the laparoscopic space
Economy Of Motion (EOM) The ratio between how much distance a subject moved a tool tip during a task and the ideal distance between two points in a task
Maximum Speed (MS) The maximum speed a subject moved a tool tip during a motion
Initial Speed (IS) The speed with which a subject moved a tool during the first 10% of a motion
Smoothness of Motion (SOM) The time derivative of acceleration of a tool during a motion, an average. Represents how smoothly a subject moved the tool through a motion.
Depth Perception (DP)

How far the tool or laparoscope was inserted into the task box past the insertion point.

The metrics listed in Table 4.1 were considered for investigation because they all describe some physical aspect of performance during laparoscopic procedures and are all commonly used in investigations into MIS or motor adaptation. The descriptive nature of the proposed metrics (IDM, DMM & AA) has been explained. Economy of motion is closely related to path length and is used as an indicator of how efficient a motion is. Speed (whether describing maximum or initial) isn't used too often but is descriptive of motion and it is reasonable to expect greater speeds in motion will follow greater proficiency in performance. This is so because when speed increases, completion time decreases, and decreased completion time during performance indicates adaptation. If the metric changes during performance, then it may be used to indicate adaptation. Smoothness of motion (3^{rd} derivative of trajectory) is a fairly technical quantity that describes how smooth the path is that a subject takes to complete a laparoscopic motion. It gives a sense of how well an individual has adapted to the new dynamics of handling a tool. Depth perception is used because it judges how well a subject understands how far a tool may be inserted into a laparoscopic space.

The succeeding sections in this chapter cover a series of pilot studies performed to investigate these metrics and their relationship to motor error and subject performance over repeated trials. Finally, a correlation study used to determine if there was an objective justification for using the newly proposed metrics over others listed in Table 4.1 is presented.

4.4 Pilot Study: Basic Observations

The pilot studies conducted were gradual and compounding. We started small to see any basic effects and gradually added certain aspects to them to build up to our final experimental setup. The setup for all the pilot studies was very similar to the setup for the final experiment described in the previous chapter. Everything was present except for the specific laparoscope used (a smaller, simpler one was used), the laparoscopic tool, the accelerometer and the stand used to rotate the task box forward 45^0 so that it would lay flat on the table. Also, the fabric covering located at the top of the box with two holes cut into it was replaced by a covering with one, central hole cut into it, for subjects to manipulate the simple laparoscope through.

Briefly, we placed small structures in the task box for subjects to view through the laparoscope they were manipulating and they were to move the tip of the laparoscope (camera lens) back and forth between the structures in specific orders, with certain motions being repeated multiple times. They would perform this without visual feedback and in a 2-D environment. This was achieved by forcing the laparoscope to remain fixed just centimeters from the bottom of the task box so all they could see was a very small area. Between structures, all the laparoscope would see was white space (no visual cues). Subjects then performed these types of navigational operations in a 3-dimensional setting with visual feedback. For this the subject was able to move the laparoscope in every way physically possible so they could see almost every part of the task box. This way, they could see structures they were moving to before they reached them, unlike in the 2-D setup. The reason these studies were performed was to simply observe the effect a laparoscopic setup had on novice subjects performing a simple laparoscopic task, in this case using a laparoscope to navigate the laparoscopic simulation suite.

In this pilot work we explored what happens when a user moved a laparoscope from point to point in a 2-D or 3-D space. Even with visual cues, we observed that the participant could not maintain a straight path trajectory as they moved from point to point as evidenced by the sway of the structures on the monitor screen as a result of the sway of the laparoscope the participant was manipulating. Though subjects seemed to reach a target more accurately with visual feedback, we proved that even with visual cues, subjects committed motor errors in the reaching movements with the simple laparoscope.

When calculating the metrics listed in Table 4.1 for this pilot exploration, it was found that the metrics did change over the course of the study. As subjects completed more and more trials, completion time, path length, error score, smoothness of motion and arc area generally decreased. Maximum speed and initial speed generally increased and economy of motion approached a ratio of 1 with repeated trials. The angles describing direction of motion would change but not in any particular trend. Different subjects would start out making errors in different directions and would compensate to different degrees and in different directions when repeating trials. Depth of insertion of the laparoscope would change based on the dimensional setting the subject performed in. When operating in 2-D, the depth of the laparoscope was kept constant, leaving this metric unchanged. However, when operating in 3-D, the depth of the laparoscope would change depending on the direction the subject needed to move the laparoscope to reach the next structure (up or down) in the task box.

4.5 Investigating Correlation between Metrics and Performance

After the early pilot experiments, we wanted to get a get a better sense of how subjects interact with a typical laparoscopic environment where the laparoscope is static, not moving as in our earlier pilot studies. We also wanted to truly investigate the metrics listed in table 4.1 by observing how they changed when subjects handle a laparoscopic tool and to see how they changed with respect to each other by performing a simple correlation study; the purpose of which would be to help us determine which metrics would be most useful as feedback.

The experimental setup was adjusted somewhat. We added the laparoscopic dissectors and reintroduced the training laparoscope as they are seen in Figure 3.13. However, the task box remained flat on the table and a second felt covering (with one, central hole cut) remained. The basic principle remained the same for subjects. They were to use the laparoscopic dissectors to move a small cotton ball around the bottom of the task box between targets according to a 2-D diagram. This diagram can be seen in the Appendix (4.1). The reason we used a 2-D transfer task was to simplify the interpretation of the metrics before we moved into a 3-D transfer task for the final experiment. Subjects were to make motions as straight as possible to carry the cotton ball from one target to another where they would delicately place the cotton ball on the target, then immediately pick it up again to move it to the next target. So they would be moving from point to point and the metrics listed in Table 4.1 would be calculated for each individual motion between points.

Four (4) subjects participated in this correlation study and engaged with forty (40) diagrams, each with nine (9) targets making for eight (8) different motions per diagram. Metrics were only calculated for the first ten (10) and last ten (10) diagrams. The reason for this was

because the middle twenty (20) diagrams had special conditions added to them. These middle diagrams had markings on them around the targets that the subjects either had to avoid or follow between targets. Because of this, subjects would never take the straightest possible paths between targets for the middle diagrams and the metrics that might have been calculated would have beeen very dependent on the specific target reached. This would make the metrics calculated for the middle diagrams meaningless when compared to the metrics calculated for the first and last ten diagrams. Examples of these middle diagrams are also shown in the Appendix (4.1). We can still use the metrics recorded for the first and last ten diagrams to faithfully show change and correlation between metrics, even while omitting metrics for the middle diagrams, because the change is still apparent, we will just not witness the process of adaptation in this particular pilot study.

Presented below in Table 4.2 are the average values for all the metrics in Table 4.1, plus the standard metrics, calculated for the four subjects who participated in our correlation study for the first and last ten diagrams. Note that when counting the diagram number in the first column, the numbers skip from 10 to 31. This is because the middle twenty diagrams were not included in the correlation analysis.

Table 4.2: Metrics Calculated for Correlation Study

Diagram	CT (Sec)	PL (m)	EOM	Error	MS (m/s)	DMM (deg)	IS (m/s)	IDM (deg)	SOM (m/s^3)	DP (m)	AA (m^2)
1	1.52	.19	1.82	.34	1.02	15.5	.13	53.17	-1.28	.25	.03
2	1.79	.23	1.52	.5	2.47	74.68	.13	28.1	-.05	.26	.02
3	1.4	.88	1.84	.31	1.21	27.02	.18	30.07	-.44	.25	.03
4	1.5	.28	2.08	.34	1.48	26.42	.29	45.75	-3.37	.25	.03
5	1.24	.21	2.00	.25	1.19	23.38	.2	48.6	-.49	.25	.02
6	1.00	.19	1.51	.19	1.27	10.94	.25	37.57	-1.08	.25	.03
7	1.04	.21	1.52	.22	1.5	31.94	.21	82.96	-9.7	.26	.02
8	.97	.18	1.73	.28	1.5	17.14	.33	34.1	-13.1	.25	.03
9	1.00	.19	1.81	.25	1.39	16.53	.23	37.83	-5.35	.25	.03
10	1.00	.18	1.8	.28	1.56	36.82	.24	44.97	1.53	.25	.03
31	1.03	.13	1.14	.06	.79	3.38	.18	38.63	-14.7	.25	.04

32	.97	.17	1.27	.13	1.11	22.95	.14	31.63	-1.73	.25	.03
33	.92	.16	1.23	.09	1.25	23.66	.2	39.63	-2.57	.25	.03
34	.98	.15	1.37	.19	1.28	3.33	.16	18.54	-11.9	.25	.03
35	1.05	.18	1.4	.16	1.14	32.02	.2	30.74	-3.03	.25	.03
36	.82	.15	1.19	.06	1.18	3.92	.25	8.38	-13.3	.25	.04
37	.91	.17	1.35	.16	1.19	24.31	.13	26.48	2.36	.25	.03
38	.84	.16	1.31	.09	1.26	17.67	.22	19.78	-6.52	.25	.03
39	.89	.16	1.32	.06	1.31	3.29	.23	23.72	-13.3	.25	.03
40	.95	.2	1.59	.25	1.35	25.4	.18	38.56	.46	.25	.03

As can be seen, the metrics change mostly in the same fashion as was described for the earlier pilot studies between the first and last ten diagrams. Two differences that stood out were the general increase in smoothness of motion and the steady values for arc area. Overall, the data shows that when subjects use a tool with a static laparoscope, they do adapt to the new task and space. This change in the metrics also shows that subjects do not commit 'perfect motions' as improvement occurs between diagrams.

So we saw that metrics do change when operating a laparoscopic tool but we also wanted to know which metrics may be most informative for feedback. To do this, we performed a correlation analysis where we looked at how each individual metric was changing relative to the others. Was one metric value increasing while another was decreasing or do two given metrics change in the same direction during adaptation? More than just seeing how two metrics were changing relative to each other, we wanted to see how much they were changing. Do two metrics change during adaptation by the same amount? To answer these questions, a simple correlation function in MatLab was used. The specific algorithm used is provided in the Appendix (4.2). The function was used for each individual subject to produce Correlation Coefficients (CC) between each individual metric relative to the others. An example of the resulting coefficients is seen in Table 4.3.

Table 4.3: Sample Correlation Coefficients between Metrics Listed in Table 4.1

Metric	CT	PL	EOM	Err	Max Vel	Max Angle	Initial Vel	Initial Angle	SOM	DP	AA
CT	1	.37	.52	.94	-.8	-.72	-.47	.53	.63	.96	.1
PL	.37	1	.99	.08	.21	-.34	.49	.73	-.14	.14	.73
EOM	.52	.99	1	.23	.05	-.42	.38	.79	-.04	.29	.67
Err	.94	.08	.23	1	-.88	-.78	-.75	.22	.83	.99	0
Max Vel	-.8	.21	.05	-.88	1	.38	.66	-.25	-.58	-.86	.47
Max Angle	-.72	-.34	-.42	-.78	.38	1	.64	-.01	-.88	-.78	-.59
Initial Vel	-.47	.49	.38	-.75	.66	.64	1	.48	-.93	-.7	.14
Initial Angle	.53	.73	.79	.22	-.25	-.01	.48	1	-.31	.29	.08
SOM	.63	-.14	-.04	.83	-.58	-.88	-.93	-.31	1	.8	.2
DP	.96	.14	.29	.99	-.86	-.78	-.7	.29	.8	1	.54
AA	.1	.73	.67	0	.47	-.59	.14	.08	.2	.54	1

Looking closely, one can tell that the data array showing the correlation coefficients is symmetric and includes values between 0 and 1. A coefficient of 1 means two metrics change in the exact same way between trials and a coefficient of 0 means two metrics change in completely different ways. Positive coefficients mean two metrics change in the same direction (values increase or decrease together) and negative coefficients mean two metrics change in opposite directions (one value increases while the other decreases).

This analysis was performed for all four subjects involved in the most recent pilot study and metric pairs were classified based on what their correlation coefficient was. The ranges for coefficients dictating the categories were: 0 < CC < .2, .2 < CC <.4, .4 < CC < .6, .6 < CC < .8, .8 < CC < 1. Metric pairs from all four subjects were slotted into these categories and counted for number of occurrences. If a metric pair occurred many times in one category, that pair would or would not be considered for feedback in our final experiment depending on which category that metric pair was associated with. Metric pairs would occur four times across all coefficient

ranges, once for each subject in the study. If considering any three given metrics (3 possible metric pairs), this yields 12 different possible combinations to spread across the coefficient ranges.

4.6 Choosing Metric Sets from Observations

At this point we were ready to develop our metrics in kinematic and dynamic terms to describe the motor errors trainees new to laparoscopy commit. As described at the beginning of this chapter, metrics 1 & 2 quantify kinematic error and metric 3 quantifies dynamic error. These metrics were chosen because from the literature it was shown that when humans adapt to new hand-eye relationships in novel environments, they commit motor errors in the form of angular discrepancies. However, we also wanted an objective reason for using these metrics.

For our full study examining feedback using these metrics on training, it was decided that we would use three sets of metrics to use as feedback for novice subjects, with subjects split into groups based on these metrics sets. How to decide which metrics go into which set was the first issue dealt with. We decided to determine this by examining how correlated metrics were with each other. The reason a correlation study was used was because we believe metrics poorly correlated with each other will complement one another better and give a better overall description of performance. On the other hand, metrics that correlate too well with each other may be redundant and less effective in training.

Using the correlation analysis presented in the previous section of all the metrics listed in Table 4.1 for the subjects engaged in the pilot study using a laparoscopic tool (4 subjects), we decided the metric sets would be:

1. Standard, Averaged (Group 1):

   Performance was interpreted through completion time, path length and error score. These metrics were based on averages of groups of trials.

2. Novel (Group 2):

   Performance was interpreted through initial direction of movement, direction of movement at max velocity and arc area. These metrics were based on individual trials.

3. Standard, Individual (Group 3):

   Performance was interpreted through completion time, path length and error score. These metrics were based on individual trials.

The groups listed were developed through objective and subjective means. For Group 1, we wanted to use these metrics because they are the standard metrics used in most training curriculums. Objectively they complement each other poorly based on the correlation study we performed. When seen how well completion time, path length and error score correlated with each other, correlation coefficient greater than .8 for 8 of 12 possible combinations, we thought that they would represent redundancy well. For Group 2, we used metrics already described because they were sensible in terms of the theory behind motor adaptation but were also less well correlated with each other than the standard metrics. In 4 of 12 possible combinations, the novel metrics scored correlation coefficients less than .2. In 4 other possible combinations of the three novel metrics, a correlation coefficient of less than .6 was observed. Since the metrics in Group 2

were correlated less well with each other, it was hypothesized they may complement each other better than the standard metrics. This led us to develop our first two groups in the way described.

However, a third metric set was needed to round out the metric sets used for the final experiment. After some experimentation with the task developed for our final experiment, described in the next chapter, we found that it was impossible to avoid presenting feedback for Groups 1 & 2 in exact same ways. Group 1 was to be presented as averages of groups of trials, typical for training, and Group 2 was to be presented as averages of individual trials (as the actual value is trial specific, i.e., dependent on the specific motion committed). It was, therefore, decided to use the third metric set to provide a direct comparison between the standard metrics and the new metrics under the same conditions. To do this, the third set would consist of the same metrics as Group 1 (completion time, path length, error score) but would be presented in the same style as Group 2 (with feedback reported on a basis of individual trials).

Therefore, the actual experimental design asks two questions:

1. Does providing feedback with the new metrics as compared to the standard metrics improve learning?
2. When using standard metrics, does presenting them in terms of groups of trials or individual trials affect learning?

CHAPTER 5 FINAL EXPERIMENT

5.1 Introduction

For the main experiment, the actual experimental design asks two questions:

(1) Does providing feedback with the new metrics as compared to the standard metrics improve learning?

(2) When using the standard metrics, does precision of feedback, i.e., actual trial values versus average values across trials effect performance?

The evaluation of learning is twofold:

(1) Does learning take less time to reach the same proficiency as with the standard method. Although proficiency would ideally be defined by objective observations in the OR, for practical reasons we have chosen the assessment on the standard metrics as a proxy: completion time, path length and error score.

(2) Is the cognitive understanding improved after learning? The assumption here is that with an improved cognitive understanding, trainees would be better at coping with novel environments that they may have to adapt to in the OR for a given surgical operation on a particular patient.

This chapter first describes the methods and protocols used to conduct the experiment. The training and testing tasks are introduced and explained. The procedure followed to gain reference data from expert MIS performers and the purpose of which will then be described.

After that, the ways in which the metrics were calculated and how they were used as feedback for novice subjects will be shown. The last part of this section will describe how the novice subjects were recruited and how they went about engaging in the final experiment.

The remainder of the chapter will relay the results for the experiment. Summary statistics as well as a statistical analysis of the significance of the results will be presented. Progressions of the adaptation of the novice groups as they performed the training task will also be described. Lastly, the testing phase results will be presented.

5.2 Experimental Design

5.2.1 Laparoscopic Training Task

The majority of materials used to conduct this experiment were described in Chapter 3. In terms of creating a training task that would have face validity, we decided on a simple transfer task as many basic training tasks used in modern training curriculums for MIS use such tasks. Also, real OR procedures require MIS surgeons to move tools from one point to another to complete even the smallest of steps in a procedure.

The transfer task was simple. The experiment used five mechanically created 'trees' which had been utilized in previous studies (Vidwans, et al., 2012, Vasudevan, et al., 2012**)**. An image of one of these trees is shown below (Figure 5.1).

Figure 5.1: Task Tree used for Transfer Task

The tree shown in Figure 5.1 consists of a base, a hollow trunk, primary branches and secondary branches. The trunk was screwed into the center of the base. Primary branches extended outward from the trunk and were anchored there with small corks and adhesive epoxy. These primary branches were hollow and transparent. The secondary branches were the functional units of the tree and held the objects used in the transfer task. They were anchored to the primary branches by simply inserting the stem of the secondary branch through the walls of a primary branch. There were eight secondary branches on each tree and seven of them would hold an object for transfer during the experiment. One secondary branch would remain unoccupied. Also note that all secondary branches had associated with them a specific color. Each object also had a corresponding color so as to cue the subject once the training task was to be performed. The color of the object picked up would correspond to the branch of the same color to which the object should be inserted.

An example of one of the objects is shown in Figure 5.2.

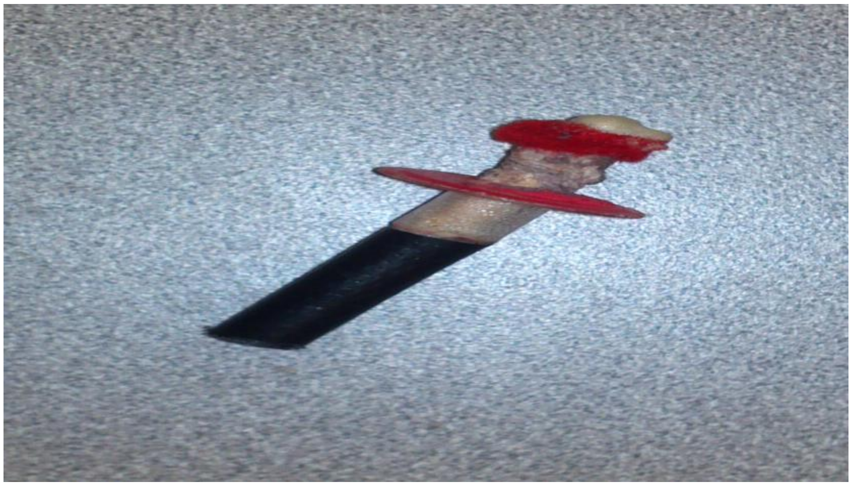

Figure 5.2: Object used for Transfer Task

The construction of the objects was similar to the construction of the backstop to hold the simulated laparoscope described in Chapter 3. Simple craft materials were again used to create the objects. A wooden dowel was cut down to approximately 5 cm. At about 3.5 cm along the length of the dowel, the rim of a bobbin reel was glued to the object and colored to match one of the secondary branches on the task trees. Then the remainder of the shaft exposed was wrapped with tape to keep the shaft of the object below the bobbin at a roughly constant diameter of .8 cm. The tip of the dowel was then capped with a small pipe cleaner to indicate an area where a subject could grip the object (between the colored bobbin reel and the cap). Lastly, to increase friction and dramatically reduce the chance a subject would drop an object; double sided tape was added to the area a subject would grip the object. This feature did not completely eliminate the chance of dropping the object because the tape used was malleable and not particularly adhesive. Seven objects were made altogether, each with a different color. The colors used were purple, blue, green, yellow, orange, red and black.

Before the transfer task could be performed by subjects, the seven objects created needed to be inserted into specific secondary branches on a task tree. The same objects were used for all five task trees. The trees were then set into the task box one at a time for subjects to work with.

To keep the task tree from slipping, since the box at this time had been rotated 45^0 forward, the bases of all the task trees were fitted with hook-and-loop strips. These strips were then attached to hook-and-loop strips already adhering to the bottom of the task box centered under the area where the laparoscopic tool was inserted into the task box. This effectively fixed the task trees with the trunk of the tree running parallel to the center of the trocar simulating device. This led to the effect that when the tool was inserted completely into the task box, it would run down the length of the trunk of the task tree and rest there until the transfer task was performed.

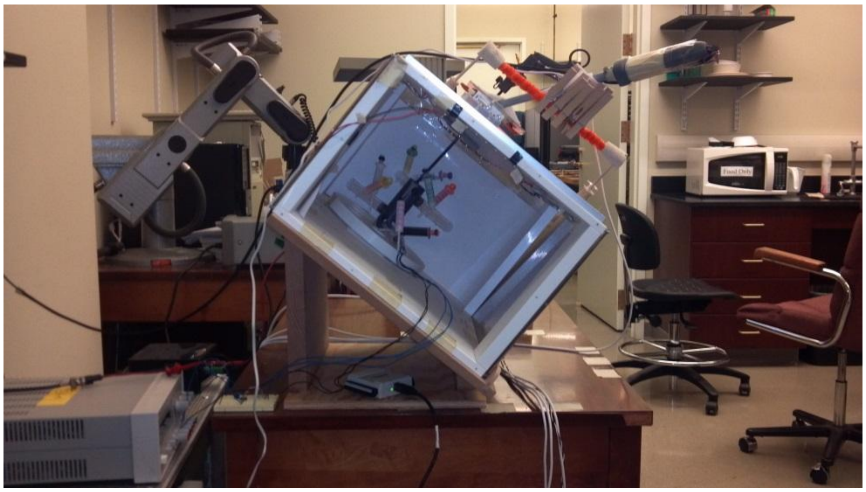

Figure 5.3: Side View of Laparoscopic Simulation Setup

Figure 5.3 above shows the final experimental setup used to conduct the experiment. The task tree, with objects present in the secondary branches, is fixed inside the task box. The accelerometer is attached to the base of the tree and leads stemming from it, which go to the summing circuit described in Chapter 3, can be seen. Also, the shaft of the laparoscopic tool can be seen extending from the top of the box down into the trunk of the task tree.

5.2.2 Training Task Procedure

The procedure for the training task implemented in the final experiment was similar to a typical, simple transfer task used in common box trainers. For a single tree all seven objects developed were inserted into specific secondary branches. The purple object was inserted into the blue secondary branch, the blue object was inserted into the green secondary branch, green into yellow, yellow into orange, orange into red, red into black and black into white. The reason for this scheme was so that whenever an object was transferred it would be transferred to a secondary branch matching the color of the object being transferred. The order of transfer of these objects was purple, blue, green, yellow, orange, red then black. The original setup of the objects in the secondary branches also meant that every object being transferred would be transferred to the secondary branch that housed the previously transferred object before it was transferred. This meant that once the objects were set into the secondary branches the subject performing the transfer task could do so without interference from the investigator unless an object needed to be reset.

As previously mentioned in Chapter 3, *The Motion Monitor*® system was used to collect data. Before the experiment started, calibration of the landmarks for the experimental frame of reference needed to be performed. The frame of reference for the unmoved transmitter was loaded from its initial determination and a position sensor attached to the laparoscopic tool, depicted in Figure 3.4, was used to digitize a "landmark" at the tip of the grips of the laparoscopic dissectors. This was achieved by simply pointing to the landmark with the stylus used to set up the frame of reference used by the transmitter. In essence, the sensor, attached to the handle of the laparoscopic tool, keeps track of the digitized landmark at the tip of the grips

and sends that data to the transmitter for storage on *The Motion Monitor*®. It is important to keep in mind that during the entire experiment, data collected and analyzed represented the position data in x, y and z of the tip of the grips of the laparoscopic tool used. We used this data because it represented the point where the subjects gripped the objects for transfer in the training task and that is the point that most faithfully and directly represents the tool's motion in the workspace.

Other parts of the experimental setup that needed to be initiated were the accelerometer and the laparoscope. The laparoscope was simply powered by *The Motion Monitor*® itself and connected to the powered monitor shown in Figure 3.14 with a video cable. The accelerometer was connected to the base of a given task tree by a small clip adhered to the base of the tree. This clip pinched onto the breakout board the accelerometer was set on. The accelerometer was powered and its leads connected to the summing circuit and ground. Once these parts were made ready, the system could faithfully track motion within the simulation task box.

Once the objects were set into the task tree within the task box, a given subject could begin to move the objects from branch to branch around the tree. To conduct the task, a subject would first grip an object with the laparoscopic dissectors between the colored plastic disc and the colored cap; the area covered with double sided tape. Once a solid grip was achieved, the subject was ready to pull the object out of its starting branch and transfer it into the target branch. Before the subject would do this however, data collection needed to be initiated. The motion system and its adjuncts were all ready so data collection could begin with the click of a button. Once an object was gripped by a subject, the button to begin data collection was clicked and the subject was given a verbal cue to begin transfer approximately one second after the start button was clicked. The reason for this delay between the click and start of an object's transfer was to allow enough data points to be taken at the start of a transfer. The nature of the data analysis

program used, required the beginning data in a transfer to be a certain amount. This was due to the fact that a simple Butterworth filter was used to process the data when generating metrics for feedback. If subjects moved too quickly after data collection was started, they would move through the first part of a motion too quickly and not enough data points that the filter would require to successfully process the data would be captured.

No outside advice or guidance was provided to any subject as they transferred the object from one branch to another. The only input given, and only for the first trial, was a simple reminder of the information stated before testing began, such as reiterating the rotation feature of the shaft of the tool or the allowance of using two hands to manipulate the laparoscopic dissectors. The transfer of a single object from a starting branch to a target branch was defined as one trial. Once a trial was completed successfully, data collection was stopped and the data collected was exported to a file to be processed through an analysis program to generate feedback metrics. These metrics and their generation will be discussed later on.

In some cases, particularly at the beginning, subjects would sometimes drop the object while the object was only partially inserted into the target branch, resulting in the object falling the rest of the way into the branch. When this happened the subjects were instructed to keep the tool as still as possible until data collection was ceased. Any motions of the tool after a drop of this nature would create erroneous data.

This was not the only type of drop that could take place during a trial. Of course, the subject could drop the object before even reaching the target branch. If this happened the subject was instructed to keep the tool as still as possible while the object was delicately placed back into its starting branch. Once that was done, the subject then restarted the trial while data collection continued recording. If a subject dropped the object three times the trial would end,

data collection would halt and the next trial would commence. At each drop, the “OK” button interfaced with *The Motion Monitor®* data acquisition board was pressed to indicate to the analysis program that a drop had occurred for error score consideration. A subject was also considered to experience a drop, if the object needed to be re-grasped to complete the task due to its rotation into a precarious position.

A second stopping condition was also used: if the subjects took approximately eight minutes to complete a single trial and had not dropped the object or otherwise restarted the trial more than twice, the trial ended and data collection stopped. This was chosen due to the limited capabilities of the data collection memory allocation.

However, limiting the amount of time a subject had to perform a single trial also kept the experiment time as a whole down to a reasonable length for each subject and also kept a subject from getting stuck on a single trial.

Once one of the above stopping conditions (successful object insertion, three drops or time limit exceeded) was met the trial ended and the next trial on the current task tree was started. This procedure continued for all seven objects placed on a task tree. Once seven trials were completed on a tree, the current task tree was switched out for the next task tree. The only difference between task trees was the actual orientation of the primary and secondary branches on the task tree. All aspects of the procedure concerning the transfer of objects from branch to branch remained the same.

5.3 Laparoscopic Testing Task

The purpose of this testing phase was to determine if the type of feedback subjects were presented with had any effect on their understanding of the spatial relationship between the hand, tool-tip and visual display, and on their ability to navigate the laparoscopic space.

During the testing phase, subjects were presented with ten visual displays of small, straight line motion of the laparoscopic tool tip in different directions in the workspace. The subjects were then to produce the actual motions of the tool tip in the task box that they believed would produce the displayed motions. The displayed motion was shown through images drawn on paper and were draped over the unpowered monitor screen. The paper images depicted the frame of the monitor screen as well as the edges of the walls of the task box that were visible when seeing the actual image captured by the laparoscope during training. However, instead of a task tree occupying the space, a small card had taken its place. This card was drawn in such a way as to give it dimension while still being a two dimensional image. On the card two small arrows were drawn originating at the approximate center of the card. These arrows were the displayed motions subjects were supposed to replicate. The subjects were also told whether an arrow was pointing within the plane of the card or pointing orthogonally relative to the plane of the card. In the experiment, five paper images were used, corresponding to ten displayed motions. An example of these images can be seen in the Appendix (5.1).

To allow the subjects to perform the movements, the simulation box was emptied of any task tree so the subject could freely move the laparoscopic tool inside the task box. Once the subject was ready, the subject took hold of the laparoscopic tool and waited for a verbal cue to begin producing a motion. Data recording was started and, once the verbal cue was heard, the

subjects immediately made a short, steady and as straight as possible motion with the tool tip in a direction the subject believed would produce the displayed motion depicted on the paper images. Once the subject had moved a few centimeters in a single direction, the data recording stopped and the subject's data was saved for later export and analysis.

5.4 Obtaining Reference Data

Another aspect of the experimental design is that typically during training, when feedback is provided it is usually compared to the results obtained by experts. So before training and testing novice subjects, data of expert MIS performers needed to be collected to create a reference line. So collection of this expert data was imperative before the bulk of the experiment could begin.

To collect expert data, our lab consulted with the Center for Human Simulation and Patient Safety (CHSPS) which is affiliated with the Medical Center of Virginia (MCV). Through the CHSPS we were able to contact 11 MIS attending surgeons to perform our laparoscopic training task. These surgeons were all classified as experts because they all had over 100 MIS OR procedures performed and were either gynecologic or abdominal surgeons. The specific procedure for performance for the experts was exactly as described in the previous section. The transfer of all objects for five trees (35 trials) was performed and the data collected. After all experts had completed the experiment, their performance was used to calculate the desired metric values specified for training goals for novices. For each trial performed by an expert, we found completion time, path length, error score, initial direction of movement, direction of movement

at max velocity, and arc area. It will be mentioned that the manner in which the data was manipulated is detailed in the Appendix (5.2) and will be explained generally in the next section.

These calculations were used to provide data for the feedback for the three different training conditions: Standard, Averaged (Group 1): The expert performance was interpreted through completion time, path length and error score. This analysis was averaged for each tree on which the experts performed, resulting in a single value for each metric for each tree. This group is a tree based group. Novel (Group 2): The expert performance was interpreted through initial direction of movement, direction of movement at max velocity and arc area. This analysis was not averaged for each tree. So a single value of each metric exists for each trial, or transfer, completed. This group is a trial based group. Standard, Individual (Group 3): The expert performance was interpreted through completion time, path length and error score. This analysis was not averaged for each tree. So a single value of each metric exists for each trial, or transfer, completed. This is a trial based group.

The next section will describe how the metrics used as feedback for these groups were calculated.

5.5 Generating Metrics

5.5.1 Organizing the Raw Data

This next section will detail how all of the metrics used in this experiment were calculated. As a reminder, data collected from subject's performances were of two types, position and signal. Position data was simple x, y and z coordinates with reference to a world

axis described earlier. This position data was taken continuously at 20 Hz and each discrete sample of coordinates was associated with a sample number starting at the number zero. Data from *The Motion Monitor*®'s Ok button were also recorded at this speed. The acceleration along the x, y and z axis was obtained from the accelerometer at 100 Hz. The position and button data were interpolated for the additional 4 samples at 100 Hz by being the same as the data values of the "first sample", which is the value sampled at 20 Hz.

5.5.2 Standard, Averaged (Group 1) & Standard, Individual (Group 3) Metrics

To calculate the standard metrics for Groups 1 and 3, the same techniques were used. The only difference between these groups was the manner in which we presented the feedback, so the actual calculations of the feedback metrics were the same. Metrics for each of these groups were calculated for individual trials but when reporting feedback to Group 1, expert metrics calculated for previous trials would be recalled and averaged for feedback whereas in feedback for Group 3, only the most current trial would be used.

Completion time was calculated very easily using the length of the raw data. Equation 1, where f_s is the sampling rate, was used to find out how long it took subjects to complete a trial.

$$\frac{\#\ of\ Samples}{f_s} \tag{1}$$

For path length, Equation 2 was used to find the trajectory resultant distances between all of the individual sample points collected at 20 Hz were calculated, those distances were added together to derive a total path length during a trial.

$$RES_T = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{2}$$

The error score was calculated using the number of drops and the number of excessive collisions. For each drop of an object by a subject or restart of a trial the “OK’ button attached to the data acquisition board was depressed for a short, sub-second interval. Our data analysis program ‘counted’ the number of times during a trial this button was pressed and summed them to report errors through drops or trial restarts. Collisions were determined to occur, if the accelerometer sent a signal exceeding .2V, corresponding to .2 G’s, to the data acquisition board and were counted toward the total errors during a trial. This threshold was chosen because we wanted to count errors without counting every small bump or brush the subjects committed on the task trees. Also, when looking at expert data, .2V would be low enough for them to commit errors for the first few trials they committed and high enough so that at final trials, many less collisions errors were interpreted. This gave good reason to use this threshold.

5.5.3 Novel (Group 2) Metrics

The novel metrics to be calculated were: direction of initial velocity, direction of maximum velocity and arc area per trial. For finding the directions of the initial direction of movement (IDM) of the tool tip at the start of a trial, Equation 4 was utilized only for the first 10% of the motion during a trial to find velocities between individual samples in each of the Cartesian directions (x, y and z). Those values were then used in a slightly altered version of Equation 2. Equation 4 was used to yield resultant velocity magnitudes (RES_V instead of RES_T) for all data points sampled within the first 10% of motion at the beginning of a trial.

$$V_{x,y,z} = \frac{R2-R1}{1/f_s} \tag{3}$$

$$RES_V = \sqrt{(V_x)^2 + (V_y)^2 + (V_z)^2} \tag{4}$$

To arrive at a single set of values describing direction of the velocity at the onset of motion, the values created using Equation 4 were averaged together. The values between individual data samples in each dimension, found earlier using Equation 3, were also averaged. Once we had average values of the velocity resultant and the velocity in each of the three dimensions (components), we used Equations 5 & 6 to yield elevation (θ) and azimuth (φ), respectively. This single set of two angles is what was used as the metric and as feedback.

NOTE: In equation 3 we were dividing sample point differences by the period of the capture frequency, so we needed to filter the results of each division to account for noise amplification. We did this by using a generic Butterworth filter with a cutoff frequency of 50 Hz. This cutoff frequency looked to produce the best noise cancellation.

$$\theta = \sin^{-1}\left({V_z}/{RES_V} \right) \tag{5}$$

$$\varphi = \tan^{-1}\left({V_y}/{V_x} \right) \tag{6}$$

The metric describing the direction of the velocity of the tool tip at maximum velocity during the phases of a trial was calculated the same way in which directions for initial velocity were calculated except for one difference. The directions were calculated at the single point where the tool tip achieved the maximum magnitude of the velocity during the course of motion during a trial. This was achieved by using Equations 3 & 4 (again finding the resultant of velocity components) over all of the data representing a trial and finding where the velocity of the tool tip peaked. The values of the velocity in each dimension at this specific point in the data were then used in Equations 5 & 6 along with the resultant velocity to determine the direction of

the tool tip at maximum velocity. This single set of two angles is what was used as the metric and as feedback.

The last metric calculated for the novel set of metrics was arc area describing the amount the tool tip deviated from a straight line trajectory during a trial. The basic theory behind this calculation is to find the perpendicular distances sample points were from a straight line representing the ideal trajectory during a trial. These distances would then be multiplied by small distance along the length of the ideal straight line trajectory to approximate small areas yielded by the tool tips trajectory. These series of areas would then be added to come to a final arc area for the trial. The algorithm is described in the succeeding paragraphs.

To calculate arc area, Equation 2 was used to determine the straight line resultant distance between the two points recorded at the beginning and end of a trial. Components in the x, y and z dimensions between these two points were also found. The resultant distance was then divided evenly along its length in terms of the number of samples recorded. How many times it was divided depended on the length of the data set associated with the specific phase of the trial.

Next, the values of the position data (x, y and z) of the first and last sample taken during the trial were each subtracted from all other samples in the data set of that trial with respect to dimension. This left us with two arrays of data, one where the first sample was subtracted from the data set and one where the last sample was subtracted from the data set.

The cross product was then found between corresponding rows in each array (i.e. 1st sample of array 1 vs. 1st sample of array 2, 2nd sample of array 1 vs. 2nd sample of array 2, etc.) This left us with a single array of x, y and z data once more. The reason the last couple of steps were made was to find a perpendicular term each sampled data point associated with the straight line between the first and last points sampled in a motion.

Equation 2 was then used once again to find the resultant of each sample of data in this new array. Note that this resultant does not represent an actual distance as it had in previous calculations, because this time Equation 2 was used with crossed values which represent an area by squaring the units.

After this we divided the resultants we found by the resultant of the components of the distance between the beginning and end samples of the original array. After performing this operation, we had numerical values representing the perpendicular distance of each sample of data, corresponding to each point in space the tool tip occupied during motion, from a straight line representing the ideal motion of the tool tip during the trial. These distances were then multiplied by the evenly spaced lengths along the straight line resultant between the beginning and end sample points calculated at the beginning of the analysis. Figure 5.4 shows a simplified schematic of the strategy for calculating arc area at this step. In it, “a” is multiplied by “b” to yield the area approximation and the small areas are divided by the black points representing sample points.

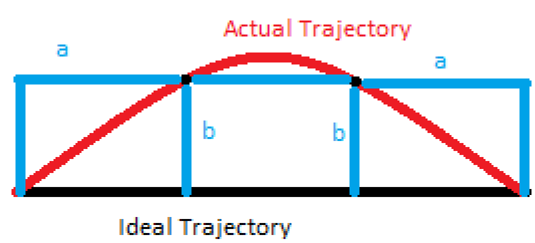

Figure 5.4: Diagram Approximating Arc Area Calculation

This gave multiple areas approximated along the trajectory of the tool and to get a single value for area encompassed by the tool we simply summed all of these mini areas.

5.5.4 Calculating Testing Phase Errors

To calculate the angles of motions, equations 2, 5 & 6 were used in a similar fashion for developing velocity metrics for subjects: yielding an elevation and an azimuth angle for direction of each trial. The difference being that position rather than velocity was considered in the calculations. The start and end points of the tool tip during each prompt of the testing phase were the only points considered in this analysis. This was feasible because the subjects were instructed to move in a single direction, once the motion was started. Once we had angles describing the subject's motions for all ten trials they were compared to ideal angles to determine the absolute error.

The ideal angles were derived from the paper images used. Each unique card and hypothetical motion was drawn against a standard facsimile representing the monitor screen as seen during the training phase. The comparison between subject performance and the ideal angles calculated from the paper images was a simple absolute difference between values for elevation and azimuth. These differences, or errors, were calculated for all subjects who performed in the testing task and were organized based on what types of feedback metrics subjects received.

5.6 Creating Feedback for Subjects

5.6.1 Organizing Feedback during Training

The form of the presentation of the metrics was standard across all groups, being a set of simple bar graphs. However, meaning of the bar graphs for the different groups is detailed and requires explanation.

For each trial, the transference of an object between branches was divided into three distinct, specific phases and metrics were calculated and presented for each phase. In the previous section, metric calculations were described for a whole trial: here they were calculated for each phase of a trial. The phases used were pick, transfer and place: the ‘pick’ phase consists of the motion used to pull an object out of a starting branch, a ‘transfer’ phase consists of a motion used to move an object from the immediate area of the starting branch to the immediate area of the target branch and the ‘place’ phase consists of the motion used to insert an object into a target branch. The reason for this division was conceptual. The phases each require a specific amount of dexterity and are rather distinct from each other. To convey as much meaning to a subject through the presentation of the metrics, we divided the trials as such to indicate to subjects how they may have performed at specific times in a trial and to guide where improvements are most needed.

All metrics were presented as feedback at the same time and in the same way.

5.6.2 Standard, Averaged (Group 1) Feedback

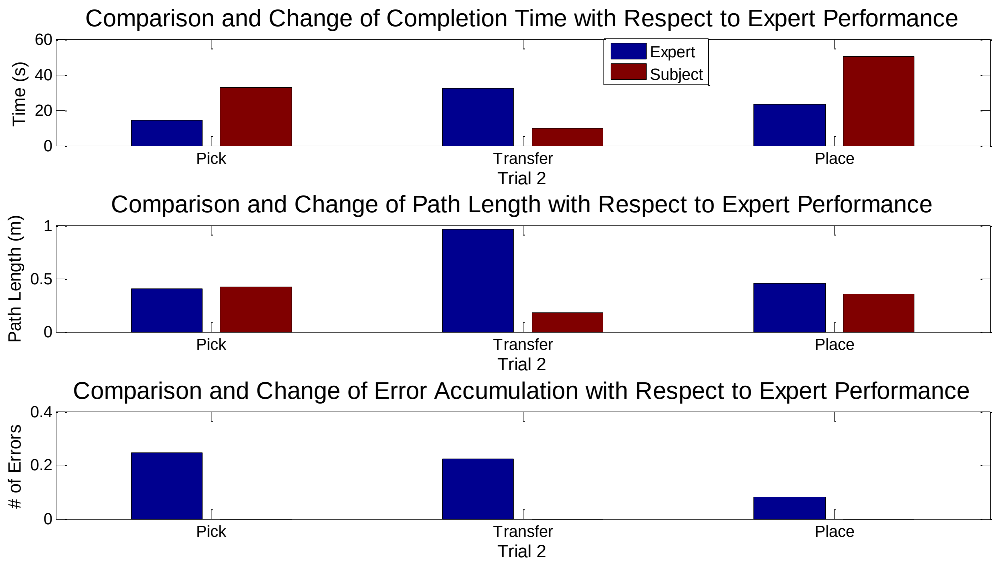

Figure 5.5: Typical feedback Presented to Novice Subjects in Group 1(Standard, Averaged Metrics)

Figure 5.5 above shows the typical feedback presented to a subject in Group 1. As a reminder, Group 1 is the Standard, Averaged Group which receives performance feedback in terms of completion time, path length and error score. As can be seen, there are subplots for each metric and each phase of the trial is represented within each subplot. The red bars represent the subject's performance metrics and the blue bars represent the expert's performance metrics, or a reference for performance. It should be noted that when a subject received feedback, the bars representing their performance metrics were calculated from data recorded by the subject for the single trial they had just performed. The reference bars, the expert's performance metrics, represent an average value of the metric for the tree the most current trial was part of. So through the course of receiving feedback during a tree, the subjects in Group 1 will see different performance metrics for their performance each time but the reference they are compared to will remain constant until the tree used was switched out for the next.

In addition, all the graphs shown to subjects, including the graph in Figure 5.5, were interactive. A subject could use the computer cursor as a cross-hair to click on specific regions on the graph to receive a small pop-up text box explaining briefly what had just been clicked. A full list of content contained within these text boxes as well as the code used to allow subjects to interact with the feedback graphics is included in the appendix (5.3). The regions on this graph that could be clicked were the title, plot axes, axes titles and the bars themselves. The subject was allowed two minutes to explore a graph each time they were presented with feedback. If subjects finished with a graph earlier, at their discretion, they could click out by clicking the left or right edge of the monitor the graph was presented on with the computer cursor. After a subject was done looking at a graph, the next trial for the current task tree was performed and the experiment continued.

5.6.3 Standard, Individual (Group 3) Feedback

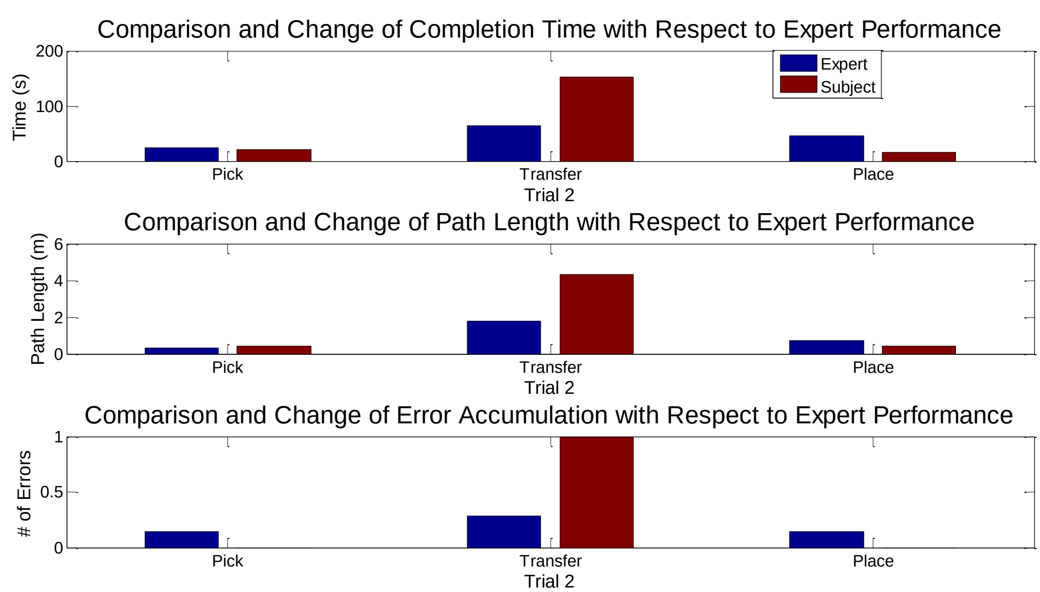

Figure 5.6: Typical Feedback Presented to Novice Subjects in Group 3 (Standard, Individual Metrics)

Figure 5.6 above is showing the metric feedback given to Group 3, the Standard, Individual Group. It is very similar to the feedback for Group1 except for one difference. Feedback for Group 1 used averaged values of expert performances for a whole tree when reporting the reference for performance in terms of completion time, path length and error score. However, in Group 3 the blue bars represented averaged values for expert performance for single trials (the same trials subjects would have just performed). Although the method for Group 1 is similar to how standard performance metrics are presented, the method in Group 3 was used to make a closer comparison to the Group 2 metrics, which were expected to be most informative on a trial by trial basis.

5.7.4 Novel (Group 2) Feedback

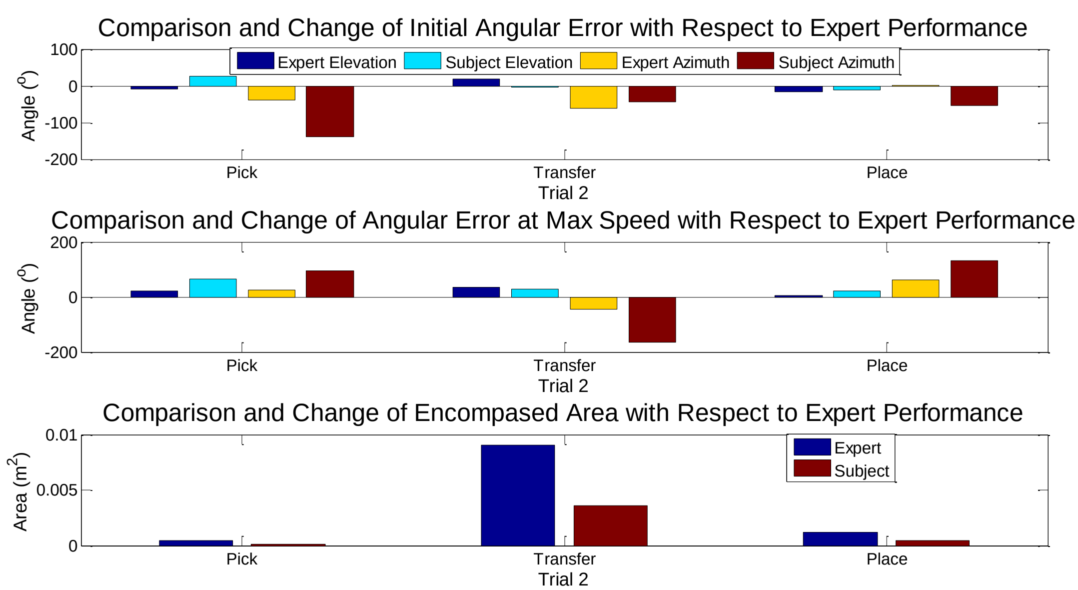

Figure 5.7: Typical Feedback Presented to Novice Subjects in Group 2 (Novel Metrics)

Feedback for Group 2 was much more involved than the feedback for Groups 1 and 3 as can be seen in Figure 5.7. The style of presentation is the same, with bar graphs representing the

values of the metrics but here we have a larger multitude of bars. The reason for this is that these metrics require a more detailed explanation. The top subplot represents the metric describing the direction of motion of the tool tip in the simulation space for the first 10% of the subject's motion used to transfer the object between branches during the specific phases of a trial. The middle subplot represents the same metric, except at the instant the subject attains maximum velocity during the specific phases of a trial.

In both the top and middle subplots, there are four bars associated with each metric for each phase. Two values are represented by these bars; elevation and azimuth, each with a reference bar and the subject bar. Elevation was defined as the angle, in degrees, the reference's or subject's velocity vector was raised or lowered from a theoretical, horizontal plane within the simulation space. Azimuth described the angle, again in degrees, the reference or subject velocity vector made from the positive x-axis within that theoretical, horizontal plane between -180^0 and 180^0. As a reminder, the positive x-axis of our experimental setup ran across and to the right of the subject performing the training task as depicted in Figure 3.12. Combining these two angles, conceptually, allows one to glean a general sense of direction after a trial has been performed.

The more important aspect of this presentation of performance metrics is the description one would receive if a bar was clicked on. For each bar, the text box would tell the subject how the tool tip had been moved within the task box while performing the trial and would also tell the subject the corresponding motion of the tool tip on the monitor being observed by the subjects while performing our training task. So the purpose of these first two metrics and the associated text boxes were to help the subjects link the relationship between the actual motions of the tool tip in the task box with the perceived motions on the monitor. Through this, we wanted to show

that individuals could learn and understand the transformation that occurs in a transformed space such as the ones that are encountered in MIS training and procedures.

The third subplot is easier to explain and understand than the other two because, like the other presentation styles, it simply relays an absolute value. The value in this case is arc area, measured in meters squared, encompassed by the tool tip as the subject moved it around the simulation space. This metric was meant to give the subject an idea of the influence that the weight of the tool had on its manipulation during the training task. Though the tool was fairly light, it still became a rigid extension of the hand and wrist of a subject during training and that could change the natural dynamics of a subject's arm and wrist. This metric was meant to enlighten a subject of that change.

5.7 Conducting Novice Experimentation

5.7.1 Recruiting Subjects

After expert/reference data was collected, the calculations of the standard and novel metrics made, the separation of subject groups performed and the feedback schemes for the subject groups created, novice subjects could be recruited to perform in the final experiment. Thirty-three (33) subjects in all were recruited from various affiliations within VCU and all were aged 18 years or older. The 33 subjects were divided randomly into three groups (1, 2, 3) and would receive specific feedback during their performance of the training task depending on the group to which they were assigned. This difference in feedback was the only difference among

the subjects concerning the experimental protocols. Everything else about procedure and order remained the same for all subjects across all groups across all task trees.

5.7.2 Preparing Subjects for Participation

The subjects were first familiarized with the experimental setup. The task box, laparoscopic tools and task trees were presented to the subjects and were shown as they exist in Figures 3.13 & 3.14. It was made clear to the subjects that the only action they were to perform was to use the pair of laparoscopic dissectors to move the objects from a starting branch to a target branch. They were then introduced to the tool to be used during the experiment. The features of the laparoscopic dissectors were presented and engaged for the subjects to witness. Specifically, the subjects were told how they needed to grip the objects.

The latter point was important as the manner in which the objects were gripped by the tool would determine, in small part, how easy or difficult a transfer would be. We wanted all subjects to have the same degree of difficulty in all trials so we specified to each subject how to grip the objects. We had all subjects grip the objects between the colored plastic disc and the colored cap on the objects, detailed in Figure 5.2. This area was designated as the top of the object. Also, the orientation of the tool relative to the objects once gripped was specific and was explained.

In addition, the end grips of the laparoscopic dissectors we used were curved slightly to facilitate better gripping. Subjects were instructed to grip objects in such a way that the convex edge of the grips would be facing the plastic disc on the object and the concave edge would face the colored cap of the object. The reason for this was so that the object could swivel slightly

within the grips. As subjects performed trials, the angle of the object in the grip when leaving a starting branch would usually be slightly different than the angle needed to smoothly insert the object into another target branch. The swivel would allow subjects to achieve the angle at which the object would easily be inserted into the target branch by physically pushing it around in the grips. Were the grips inverted, this swivel might be impeded, possibly making a transfer much more difficult. This also allowed for consistency of this factor across trials and across subjects.

Then subjects were informed of the potential hazards associated with performing in our experiment. When conducting our pilot tests, subjects tended to demonstrate symptoms associated with environmental disorientation. Some became dizzy, light-headed and in severe cases nauseous. These are all effects generally associated with the presentation of a new and rotated or inverted hand-eye relation. Subjects were briefed on the possible effects they may experience while performing in the experiment. Once briefed, the subjects were all asked to sign their name electronically into a ledger simply to confirm that they had been made aware of the possible health risks associated with our experiment. After this the subjects were given the procedural description of the experiment.

Novice Subjects would eventually perform on seven trees. However, only five unique trees were developed for this experiment and only five trees were used to test expert subjects for our reference data. The reason seven trees were used for the novice subjects was to allow them time to adjust to the new environment and task sufficiently to demonstrate adaptation. The extra trees were simply repeats of trees 1 and 2.

Once all seven trials had been performed on a single tree, subjects had a brief time to rest before performing trials for the next tree. This process continued until all seven trees were completed. Seven trees with seven trials each gave 49 separate trials for novice subjects. This

was part of the general outline of the procedure novice subjects received before performing the training task.

5.7.3 Organizing Data Collected

The analysis program was separate from the motion tracking software used and this meant that after the data for a trial was recorded and exported by the motion system, the analysis program would be accessed and run separately to call the stored data file and generate the metrics needed. This resulted in the processing time between trials taking a few seconds and allowing the subject a small rest before the next trial was started. This small respite turned out to be beneficial as well. In the pilot studies using a laparoscopic tool, some general feedback from subjects claimed that the tool handle would wear on the hand of the subject or their hand would cramp from using higher forces than necessary. The few seconds it took to process the data was a good time for the subjects to rest.

The most important aspect of our experiment also came during the processing of the data in between trials. The purpose of processing the data was to generate metrics for each subject and present them to the subject in a meaningful way. Which metrics the subject was presented with depended on the group the subject was in. The groups have been listed and explained above and the way in which the metrics were presented to a subject is the most important aspect to understand in the experiment. After each trial, data were processed into metrics. However, the performance metrics of a single subject were only presented to the subject after the second, fourth and seventh trials for every tree.

The reason for limiting the number of trials on which feedback was presented was so we could avoid subjects performing specifically with their feedback in mind rather than the task itself. Basically we did not want knowledge of results to decrease their focus on the task such that they focused on optimizing the metrics, resulting in subjects performing the task at hand with less dexterity or natural adaptation. For example, if a subject performs a task as quickly as possible, to better the completion time metric, that subject may sacrifice focus on the task and not keep control over the tool as well as a subject who is focusing on performing the task rather than bettering the metric. It has been shown that presenting subjects engaged in a motor task with feedback approximately 40% of the time is effective in supplementing learning without degrading it (Steinhauer, et al., 2000).

Once the subjects went through training with intermittent feedback using performance metrics and went through the testing phase, their participation in the experiment ended. Data analysis was performed using SPSS to compare the three groups. The results as well as any significance attributed to them are presented in the next section.

5.8 Results

5.8.1 Trial Based Summary Statistics

At the onset of analysis the most useful comparisons came from comparing groups concerning the standard metrics. The standard metrics have already been validated as good outcome measures to differentiate between experts and novices (Satava, et al., 2003). Figures 5.8-5.13 show this comparison between the first three novice groups and the expert group. In

each case, the data is presented as an average for the entire group and the data is shown over the course of all 49 trials subjects performed (35 for the expert group).

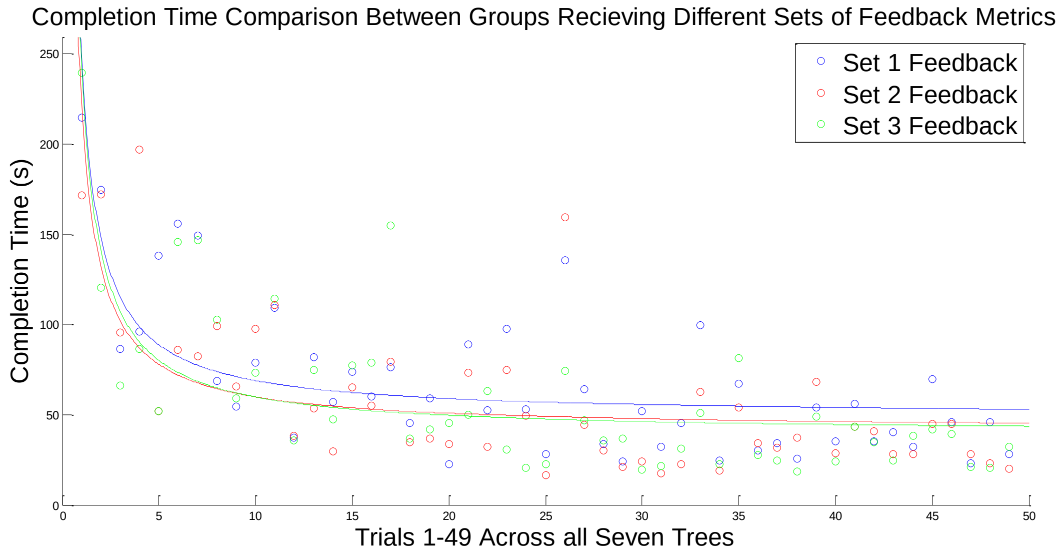

Figure 5.8: Comparison of Completion Time between Subject Groups

Figure 5.8 shows the performances of all novice subject groups in terms of completion time for the entire training task. Phases of a trial are not indicated in this analysis. The data is plotted as completion time in seconds (y-axis) as a function of increasing trial number (x-axis). Blue data points reference Group 1 subjects, red data points reference Group 2 Subjects and green points reference Group 3 subjects. Also added into the scatter plot of the data are inverse curves ($Y = B + A/X$) fitted to the data. The color of the line matches subject groups based on the same scheme mentioned for the scatter data. The trend lines represent inverse functions whose constants are displayed in Table 5.1. Not included in Figure 5.8 are the standard deviations each group demonstrated through the 49 trials: Group 1 – 44.2 s, Group 2 – 56.3 s, Group 3 – 63.6 s.

Expert data is also presented in Figure 5.9 to give an idea of the difference between the reference and the novice groups.

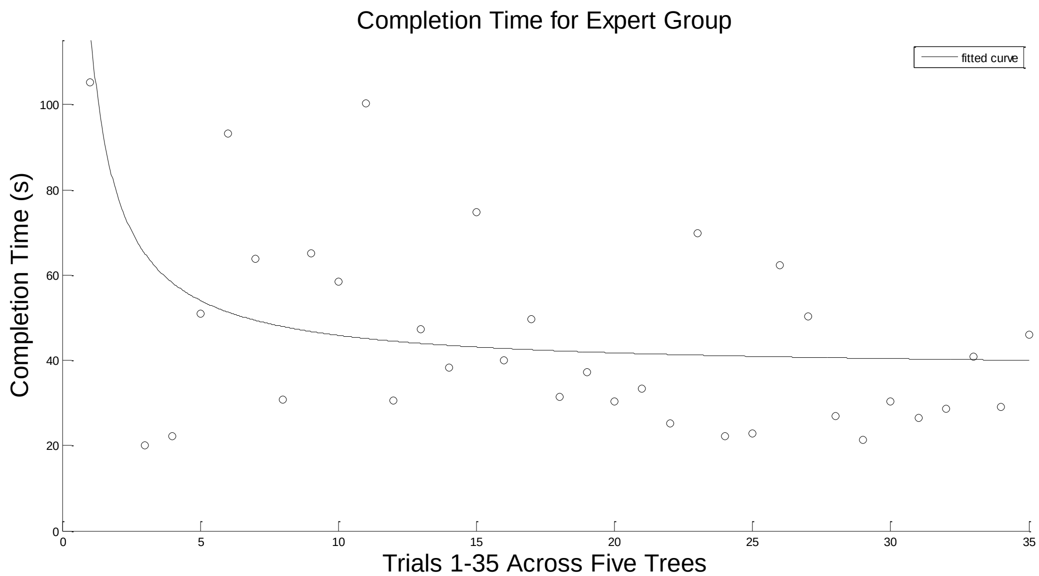

Figure 5.9: Expert Completion Times for Trials 1-35

Figure 5.9 shows completion times, in seconds, for the expert group for 35 trials. 35 trials are shown because the experts only performed on 5 trees, not seven. Also, this data is not presented on the same plot as the novice subjects because the experts did not receive feedback while performing the training task. A trend line is superimposed in the plot to give a general sense of adaptation to the task. The standard deviation for experts through 35 trials was 27.01 s.

Table 5.1 below shows the theoretical values of the constants for the data fitted to an inverse curve ($Y = B + A/X$). “B” represents the theoretical plateau of performance for the associated subject group and “A” represents the theoretical ‘learning rate’ of the subject group. This basic analysis is an interpretation of the analysis performed on learning curves by Feldman, et al., 2009. As can be seen, the plateau for performance is lowest for the expert group and highest for the Standard, Averaged Group (Group 1). Learning rate is also smallest for the experts. This makes sense because the experts would not have had to adapt very much to reach a comfortable level of performance. Therefore, smaller learning rate constants indicate quicker

adaptation between trials. It can also be seen that the lowest theoretical plateau for performance for a novice groups belongs to the Standard, Individual group.

Table 5.1: Constants Associated with Trend Lines in Figures 5.8 and 5.9

Subject Group	Theoretical Plateau	Learning Rate
Standard, Averaged (1)	49.03	198.7
Novel (2)	41.81	180.6
Standard, Individual (3)	39.51	203
Expert	37.66	82.07

The purpose of these values is twofold; to show the 'peak' level of performance the groups attained through our training task and to show how quickly the groups adapted to the training task. It should be noted that the values of the constants are relative to the metric being analyzed.

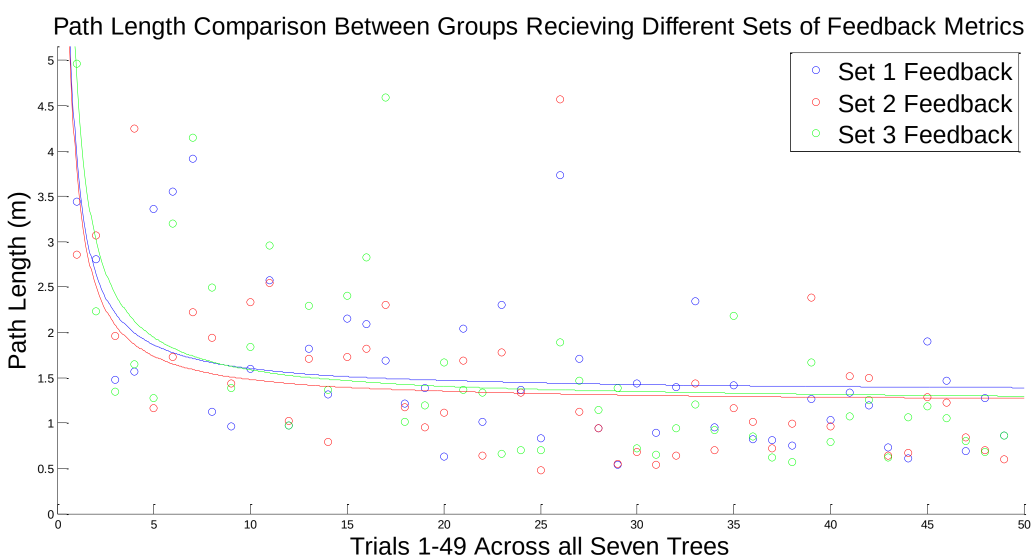

Figure 5.10: Comparison of Path Length between Subject Groups

Figure 5.10 shows data collected from subject groups in terms of path length. Path length, in meters, is depicted as a function of increasing trial number. The color code exists exactly as it

did for Figure 5.8. The standard deviations for the groups for path length were: Group 1 - .98 m, Group 2 – 1.02 m, Group 3 – 1.45 m.

Figure 5.11 below shows expert data in terms of path length with another imposed tend line.

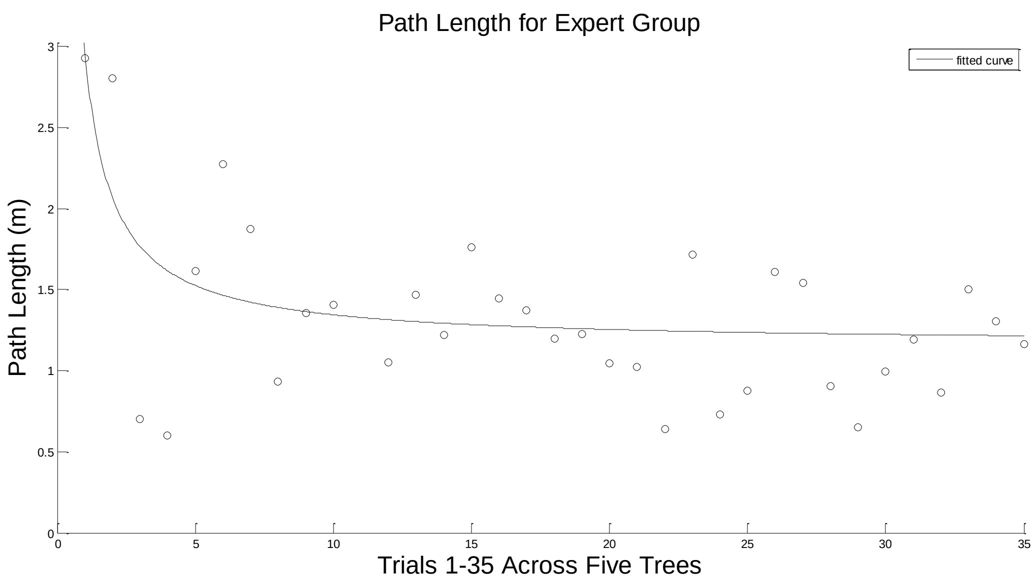

Figure 5.11: Expert Path Lengths for Trials 1-35

Table 5.2 below shows the constants associated with the trend lines in Figures 5.10 and 5.11. Standard deviation for experts was .63 m.

Table 5.2: Constants Associated with Trend Lines in Figures 5.10 & 5.11

Subject Group	Theoretical Plateau	Learning Rate
Standard, Averaged (1)	1.337	2.624
Novel (2)	1.221	2.581
Standard, Individual (3)	1.226	3.595
Expert	1.163	1.809

As with completion time, Table 5.2 indicates a notable difference between novice and expert groups concerning rate of change of this metric through multiple trials. Experts adapted

further and quicker than novice groups. Also, the only notable differences between novice groups are with the Standard, Averaged Group concerning theoretical plateau (highest) and with the Standard, Individual Group concerning learning rate (also highest).

Figure 5.12: Comparison of Error Score between Subject Groups

Again, the layout of Figure 5.12 follows that for Figures 5.8 & 5.10. Here, the number of errors accumulated is plotted against increasing trial number. Trend lines are also present and their constants are shown in Table 5.3. Standard deviations for the three groups for the 49 trials are: Group 1 - .4 errors, Group 2 - .38 errors, Group 3 - .54 errors. Below, in Figure 5.13, we present the graph relating expert performance with trial number. The standard deviation associated with the expert data in Figure 5.13 was .29 errors.

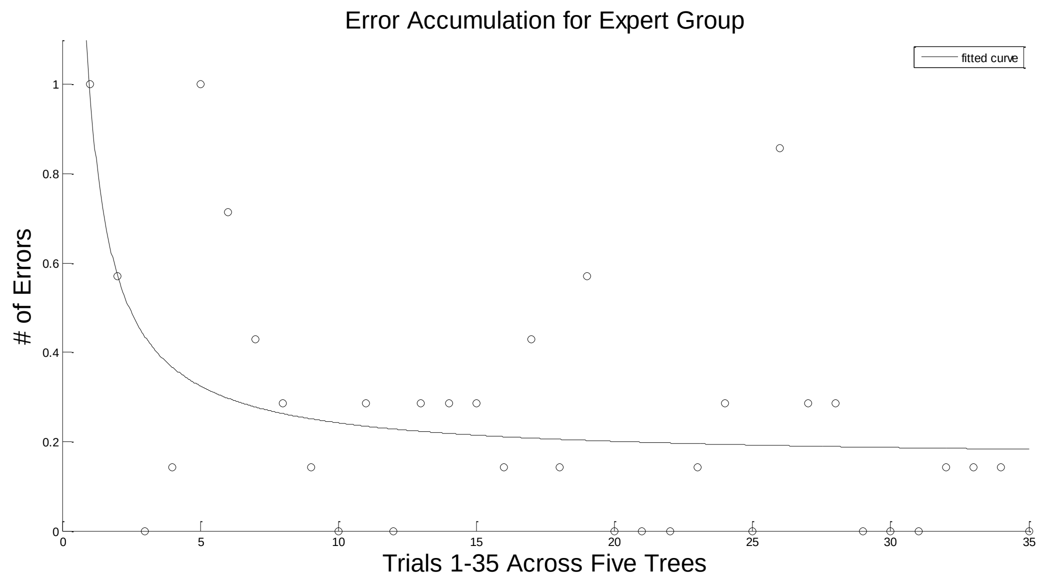

Figure 5.13: Expert Error Accumulation for Trials 1-35

Table 5.3: Constants Associated with Trend Lines in Figures 5.12 and 5.13

Subject Group	Theoretical Plateau	Learning Rate
Standard, Averaged (1)	.2453	.6047
Novel (2)	.1757	.5535
Standard, Individual (3)	.1562	1.013
Expert	.1591	.8276

Table 5.3 shows a different discrepancy between novice and expert subjects in terms of rate of adaptation. The experts only show quicker adaptation than the Standard, Individual Group. They actually adapt slower than the other two groups (Standard, Averaged and Novel), although the resulting proficiency reached is better than for the Standard, Averaged Group.

We will present a statistical analysis of the performance constants (plateau and learning rate) for all subjects and subject groups when we present a statistical analysis of the subject's metrics. In the next section we will continue with the general analysis.

5.8.2 Tree Based Summary Statistics

We also examined performance from a tree based perspective. Figures 5.14-5.16 show the performance means and standard deviations of the standard metrics for each group, averaged for each tree. By looking at the averages for each tree we can get a more concise look at the data and still glean some useful information.

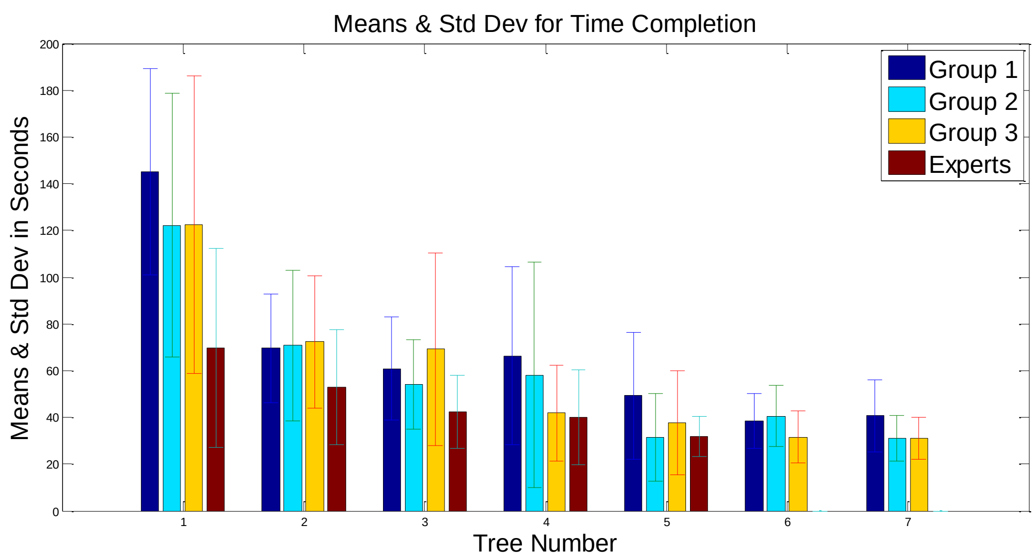

Figure 5.14: Means and Standard Deviations between All Groups for Completion Time

Figure 5.14 shows averages of completion times for entire trees between groups. Standard deviations from the means are also shown. The y-axis measures time in seconds and the x-axis describes progression through the training task in terms of tree number. The dark blue references the Standard, Averaged Group (Group 1), the light blue bar references the Novel Group (Group 2), the yellow bar references the Standard, Individual Group (Group 3) and the red bar references the Expert Group (reference data). This color scheme described also applies for Figures 5.15 and 5.16 shown below.

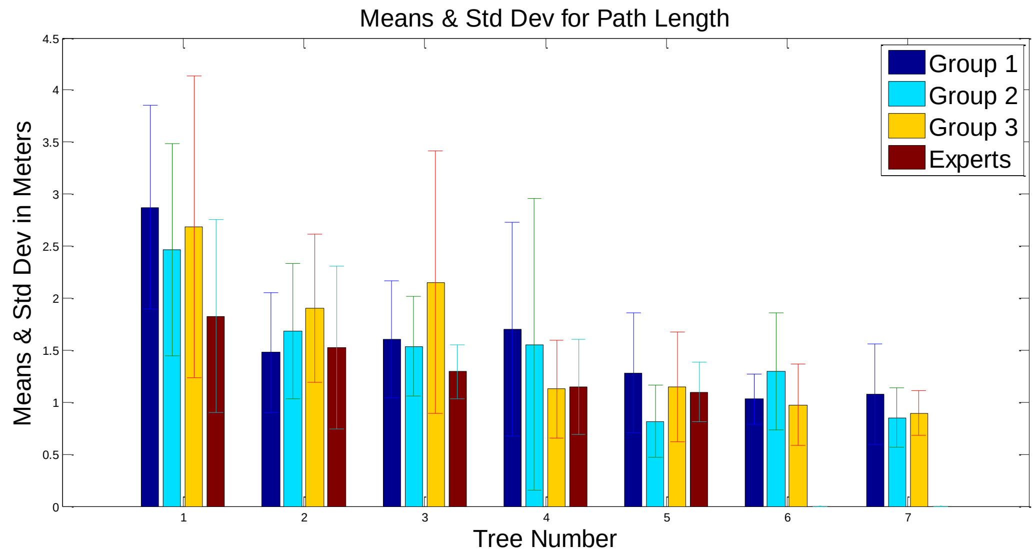

Figure 5.15: Means and Standard Deviations between All Groups for Path Length

Figure 5.15 shows the change of path length, in meters, over the course of the training task. Means and standard deviations are presented as they were in Figure 5.14.

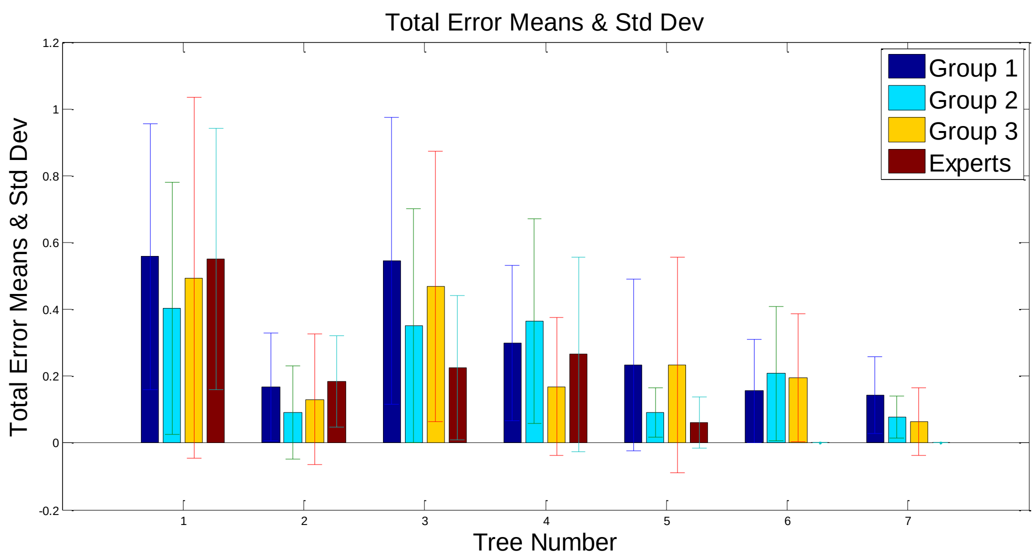

Figure 5.16: Means and Standard Deviations between All Groups for Error Score

Figure 5.16 shows the mean and standard deviations of accumulated errors for each tree committed by the subject groups. Here, the standard deviation is sometimes so large that an impossible, negative number of errors may be achieved. This, of course, never occurred and is a result of the way summary statistics are calculated and reported.

Figures 5.14-5.16 resemble the same trend shown in Figures 5.8-5.13. This is evidence that all subject groups that participated in the experiment improved with repeated trials during the performance of the training trials, in terms of the standard metrics.

Evidence that the groups are learning or performing differently is quantified more in the last section by looking at the coefficients associated with the trend lines fit to the trial-based data. However, to properly identify any significant difference between the subject groups, in terms of adaptation and performance, an in depth statistical comparison was performed.

5.8.3 Statistical Comparison of Training Phase Metrics

The comparison for all the trials completed between the subject groups for the standard metrics was not simple. For each metric within the standard set (completion time, path length and error score) the distribution of the data was not normal, negating the use of orthodox statistical analysis techniques such as ANOVA. The presentation of the statistical analysis will be one metric at a time starting with completion time and then running through path length and finally error score.

5.8.3.1 Completion Time

Figure 5.17 below presents the distribution of the completion time data for all subjects across all groups during the entire experiment. It is a histogram detailing how many trials fell within specific bounds of time. Also present are the mean and standard deviation of all the completion times achieved through the experiment by all subjects. The y-axis measures absolute

occurrences of completion times and the x-axis shows the scale of completion times subjects achieved through the experiment.

As can be seen, most trials were completed quickly compared to the longest times some trials took to complete. This skews the data in Figure 5.17 to the right. Standard transformation methods to attempt to produce a normal distribution (e.g., logarithmic or inverse) failed and therefore the data could not be analyzed by an ANOVA. To analyze this data a gamma distribution with a log link function was utilized.

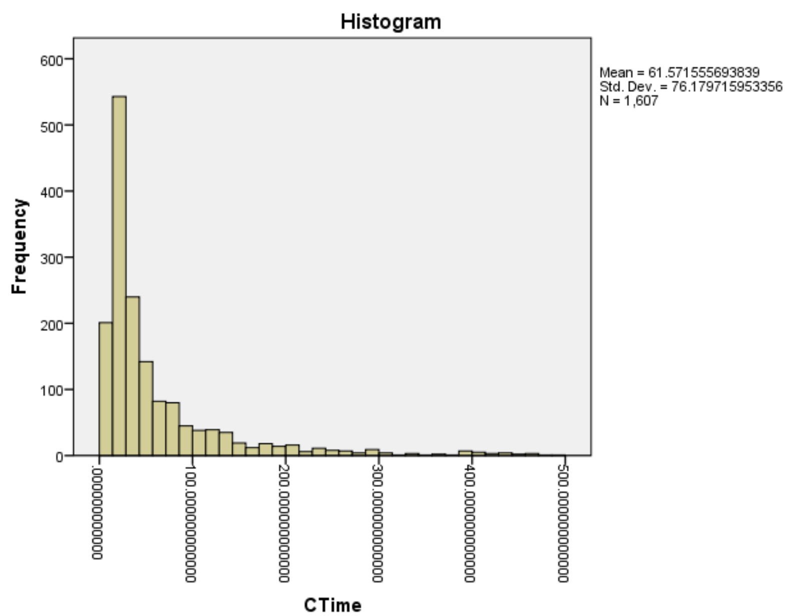

Figure 5.17: Histogram Representing all Completion Times Achieved by all Subjects

What follows are the results of the statistical analysis of completion time considering the 49 different trials performed by all subjects, the different metric groups (subject groups) and the interaction between these two categories as independent variables. As shown in Table 5.4, there was a significant effect considering trial number which means that completion times may be significantly different depending on which trial was performed. There was also a significant

interaction between trial number and metric group, which actually indicates a slight, complex effect from subject group. However, there was still no direct effect of subject group.

Table 5.4: Model Effects for Completion Time using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	Df	Sig.
(Intercept)	4833.148	1	.000
MetricGroup	1.973	2	.373
TrialNum	78007482054596.770	31	.000
MetricGroup * TrialNum	20997116049916.600	34	.000

As the metric group * trail number interaction suggest a complex effect of metric group, tables 5.5 and 5.6 report summary statistics and the pair-wise results for estimated marginal means, respectively, to more clearly discern trends.

Table 5.5: Estimates of Summary Statistics for Subjects Groups for Completion Time

Estimates

MetricGroup	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	56.892	6.279	45.824	70.633
2	47.602	4.241	39.974	56.685
3	47.505	4.383	39.645	56.922

Table 5.6: Pair-wise Comparison of Subject Groups' Completion Times

Pairwise Comparisons

(I) MetricGroup	(J) MetricGroup	Mean Difference (I-J)	Std. Error	Df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	9.289	7.578	1	.220	-5.563	24.142
	3	9.386	7.658	1	.220	-5.623	24.396
2	1	-9.289	7.578	1	.220	-24.142	5.563
	3	.097	6.099	1	.987	-11.857	12.052
3	1	-9.386	7.658	1	.220	-24.396	5.623
	2.	-.0971	6.099	1	.987	-12.052	11.857

Table 5.5 above shows that means for the three groups are relatively comparable. Table 5.6 relays the pair-wise differences between subject group's completion times as they performed the training task to magnify the differences any. It shows that differences are still not significant even when looking at only two subject groups at a time. Also reported are 95% confidence intervals.

As an important aspect of learning is to produce better performance results, the groups were also compared using the last 5 trials for all subjects. Table 5.7 summarizes the effects of a Wald Chi-Square test in the same fashion as Table 5.4. As shown, the test indicates no significance between subject groups when looking at the last five trials for the various sources, both in terms of direct and interaction effects, indicating similar performance between subject groups.

Table 5.7: Model Effects for Completion Time using a Wald Chi-Square Test for Last Five Trials

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	2863.335	1	.000
MetricGroup	2.999	2	.223
TrialNum	32.300	4	.000
MetricGroup * TrialNum	13.778	8	.088

Tables 5.8 and 5.9 give the summary statistics and pair-wise results for estimated marginal means. Again there is no significant difference in performance between subject groups concerning completion time, even when considering the magnification of the pair-wise results.

Table 5.8: Estimates of Summary Statistics for Subjects Groups for Completion Time for Last Five Trials

Estimates

MetricGroup	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	39.508	5.735	29.724	52.511
2	30.513	2.729	25.606	36.36
3	29.554	2.848	24.467	35.699

Table 5.9: Pair-wise Comparison of Subject Groups' Completion Times, Last 5 Trials

Pairwise Comparisons

(I) MetricGroup	(J) MetricGroup	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	8.995	6.351	1	.157	-3.453	21.444
	3	9.954	6.403	1	.120	-2.597	22.505
2	1	-8.995	6.351	1	.157	-21.444	3.453
	3	.958	3.944	1	.808	-6.773	8.690
3	1	-9.954	6.403	1	.120	-22.505	2.597
	2	-.958	3.944	1	.808	-8.690	6.773

5.9.3.2 Path Length

Figure 5.18 shows the histogram representing the distribution of path lengths achieved by all subjects across all trials for the experiment. Standard transformation methods to attempt to produce a normal distribution (e.g., logarithmic or inverse) failed and therefore the data could not be analyzed by an ANOVA. Due to this, another gamma distribution with a log link function was used for the analysis.

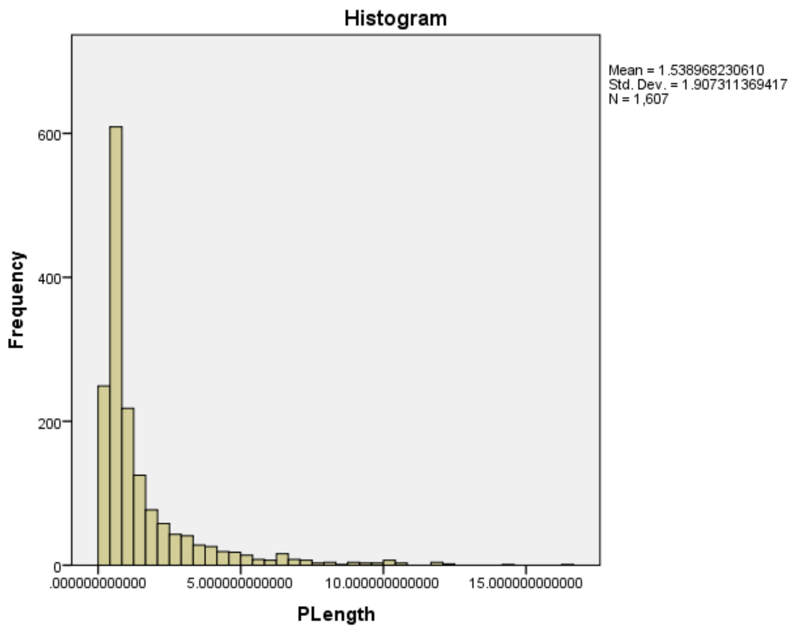

Figure 5.18: Histogram Representing all Path Lengths Achieved by all Subjects

Table 5.10 below shows the overall model effects considering the 49 trials completed by all subjects, the subject group (metric group) and the interaction between these two sources. Overall, there was a significant trial effect and interaction between trial number and metric group, but there was no significant effect concerning the subject groups.

Table 5.10: Model Effects Path Length using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	15.771	1	.000
MetricGroup	.340	2	.843
TrialNum	164336512372215.030	33	.000
MetricGroup * TrialNum	29375621858434.035	32	.000

As with completion time, there was no significance between subject groups in terms of path length, although there was an interaction effect between metric group and trail number. Tables 5.11 and 5.12 show the summary statistics and pair-wise results of the test when only

considering the effect of subject group for estimated marginal means. There was no significance when looking at the pair-wise results between any pairs subject groups.

Table 5.11: Estimates of Summary Statistics for Subjects Groups for Path Length

Estimates

MetricGroup	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	1.389	.192	1.058	1.824
2	1.255	.143	1.003	1.569
3	1.334	.152	1.067	1.668

Table 5.12: Pair-wise Comparison of Subject Groups' Path Lengths

Pairwise Comparisons

(I) MetricGroup	(J) MetricGroup	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	.134	.240	1	.576	-.336	.605
	3	.055	.245	1	.822	-.426	.536
2	1	-.134	.240	1	.576	-.605	.336
	3	-.079	.208	1	.705	-.488	.330
3	1	-.055	.245	1	.822	-.536	.426
	2	.079	.208	1	.705	-.330	.488

Table 5.13 shows the results of a Wald Chi-Square test when considering the main three sources as independent variables for our statistical analysis for the last five trials subjects completed.

Table 5.13: Model Effects for Path Length using a Wald Chi-Square Test for Last Five Trials

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	.090	1	.764
MetricGroup	1.699	2	.428
TrialNum	27.344	4	.000
MetricGroup * TrialNum	30.333	8	.000

Again, there was no significant difference between subject groups for the last five trials. There was, however, a significant trial effect and interaction between trial number and subject group. Tables 5.14 and 5.15 show the summary statistics and the pair-wise results of the test for the final five trials for all subjects when only considering the effect of subject group. Thought the estimates for the marginal means seem to have a larger difference between subject groups than in previous analysis, the pair-wise results show no significance between the groups.

Table 5.14: Estimates of Summary Statistics for Subjects Groups for Path Length for Last Five Trials

Estimates

MetricGroup	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	1.161	.214	.808	1.669
2	.889	.095	.72	1.097
3	.9	.104	.716	1.13

Table 5.15: Pair-wise Comparison of Subject Groups' Path Length, Last 5 Trials

Pairwise Comparisons

(I) MetricGroup	(J) MetricGroup	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	.272	.235	1	.247	-.188	.733
	3	.261	.238	1	.274	-.206	.729
2	1	-.272	.235	1	.247	-.733	.188
	3	-.01	.141	1	.938	-.288	.266
3	1	-.261	.238	1	.274	-.729	.206
	2	.01	.141	1	.938	-.266	.288

5.9.3.3 Error Score

The final standard metric considered in our statistical analysis was the error score that each subject achieved through all trials in our experiment. This analysis was complicated more than either completion time and path length by the fact that so many entries in the data array had

a value of zero. Because of this, the most appropriate interpretation seemed to be a Poisson distribution with a log link function. Figure 5.19 also shows the effect of the zeros as the histogram is heavily skewed to the right.

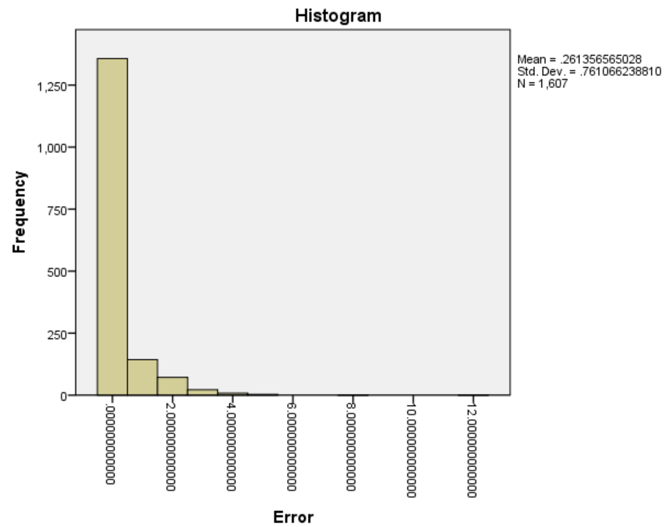

Figure 5.19: Histogram Representing all Error Scores Achieved by all Subjects

For this specific analysis only the subject group (metric group) was considered as an independent variable. Table 5.16 shows the effects when only considering subject group as an independent variable. There was no significant effect between subject groups for error score.

Table 5.16: Model Effects for Error Score using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	81.752	1	.000
MetricGroup	.465	2	.792

Tables 5.17 and 5.18 show the summary statistics and the test's pair-wise results, respectively. Again, no significance was reported for error score between subject groups when looking as paired differences.

Table 5.17: Estimates of Summary Statistics for Subjects Groups for Error Score

Estimates

MetricGroup	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	.301	.094	.162	.558
2	.227	.06	.134	.384
3	.254	.043	.181	.356

Table 5.18: Pair-wise Comparison of Subject Groups' Error Score

Pairwise Comparisons

(I) MetricGroup	(J) MetricGroup	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	.074	.112	1	.511	-.147	.295
	3	.046	.104	1	.653	-.157	.251
2	1	-.074	.112	1	.511	-.295	.147
	3	-.027	.075	1	.718	-.174	.12
3	1	-.046	.104	1	.653	-.251	.157
	2	.027	.075	1	.718	-.12	.174

As with the previous standard metrics, the last five trials for all subjects were isolated for analysis to see if a difference was present between subject groups toward the end of the experiment. Table 5.19 shows the results of the Wald Chi-Square test while considering subject group as the only independent variable.

Table 5.19: Model Effects for Error Score using a Wald Chi-Square Test for Last Five Trials

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	Df	Sig.
(Intercept)	61.537	1	.000
MetricGroup	3.208	2	.201

The analysis for estimated marginal means is presented in Tables 5.20 and 5.21 with estimates of the summary statistics and the pair-wise results of the overall test, respectively.

Table 5.20: Estimates of Summary Statistics for Subjects Groups for Error Score for Last Five Trials

Estimates

MetricGroup	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	.145	.063	.061	.342
2	.09	.053	.028	.289
3	.036	.023	.01	.127

Table 5.21: Pair-wise Comparison of Subject Groups' Error Score, Last 5 Trials

Pairwise Comparisons

(I) MetricGroup	(J) MetricGroup	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	.054	.083	1	.512	-.108	.217
	3	.109	.067	1	.107	-.023	.241
2	1	-.054	.083	1	.512	-.217	.108
	3	.054	.058	1	.351	-.06	.169
3	1	-.109	.067	1	.107	-.241	.023
	2	-.054	.058	1	.351	-.169	.06

The test results presented above for error score show that there was no significant difference in performance concerning any of the standard metrics between the three different subject groups. Although we had presented a general difference between subject groups at the start of this section with Figures 5.8-5.13 and Tables 5.1-5.3, this alone cannot be interpreted as proof that any one group performed significantly better than another during the training task. A statistical analysis of those constants must be performed.

5.8.4 Statistical Analysis of Performance Constants

The previous section revealed that there is no significant difference between subject groups in terms of the metrics calculated. However, this data were not the only variables that could be analyzed for statistics. In the general analysis for the training phase we developed trend

lines to fit to the data for subject groups and came away with values indicating theoretical plateaus of proficiency and rates for adaptation/learning. We also developed curves and derived constants for all individual subjects in the experiment and tested these constants between subject groups to see if there was any significance between them.

5.8.4.1 Completion Time

For all metrics, plateaus of proficiency and learning rate were considered between subject groups separately. For each constant, we performed an overall Wald Chi-Square test and we will present the results along with estimates and pair-wise results for estimated marginal means. For completion time, the distributions of plateau and learning rate values were both normal. Therefore we could use ANOVA to test for significance. Tables 5.22-5.24 show the results of the test for plateaus of proficiency between subject groups for completion times.

Table 5.22: Model Effects for Completion Time Plateaus using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	6699342099495840000000000000000000.000	1	.000
Group	.[a]	.	.

Table 5.23: Estimates for Subjects Groups for Completion Time Plateaus

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1.00	49.0282	.00000	49.0282	49.0282
2.00	41.8064	.00000	41.8064	41.8064
3.00	39.5082	.00000	39.5082	39.5082

Table 5.24: Pair-wise Comparison of Subject Groups' Completion Time Plateaus

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1.00	2.00	7.2218[a]	.00000	1	.000	7.2218	7.2218
	3.00	9.5200[a]	.00000	1	.000	9.5200	9.5200
2.00	1.00	-7.2218[a]	.00000	1	.000	-7.2218	-7.2218
	3.00	2.2982[a]	.00000	1	.000	2.2982	2.2982
3.00	1.00	-9.5200[a]	.00000	1	.000	-9.5200	-9.5200
	2.00	-2.2982[a]	.00000	1	.000	-2.2982	-2.2982

Tables 5.22-5.24 show that there is a significant difference between all subject groups concerning plateaus of proficiency for completion time. Specifically, the order of proficiency is 3 > 2 > 1. Tables 5.25-5.27 show results of a Wald Chi-Square test for completion time learning rates between subject groups.

Table 5.25: Model Effects for Completion Time Learning Rates using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	117984051439108220000000000000000.000	1	.000
Group	.[a]	.	.

Table 5.26: Estimates for Subjects Groups for Completion Time Learning Rates

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1.00	198.7391	.00000	198.7391	198.7391
2.00	180.5882	.00000	180.5882	180.5882
3.00	202.9891	.00000	202.9891	202.9891

Table 5.27: Pair-wise Comparison of Subject Groups' Completion Time Learning Rates

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1.00	2.00	18.1509[a]	.00000	1	.000	18.1509	18.1509
	3.00	-4.2500[a]	.00000	1	.000	-4.2500	-4.2500
2.00	1.00	-18.1509[a]	.00000	1	.000	-18.1509	-18.1509
	3.00	-22.4009[a]	.00000	1	.000	-22.4009	-22.4009
3.00	1.00	4.2500[a]	.00000	1	.000	4.2500	4.2500
	2.00	22.4009[a]	.00000	1	.000	22.4009	22.4009

Tables 5.25-5.27 show that learning rate differences are significant between all subject groups. Here, the order of proficiency proficiency is 2 > 1 > 3.

5.8.4.2 Path Length

Tables 5.28-5.30 show the results of a Wald Chi-Square test for the differences between subject groups concerning the plateaus of proficiency for path length. Path length plateau and learning rate data were a little different than that for completion time. This data did not demonstrate a normal distribution until a square root transformation was performed.

Table 5.28: Model Effects for Path Length Plateaus using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	Df	Sig.
(Intercept)	5657183551575284000000000000000000.000	1	.000
Group	.[a]	.	.

Table 5.29: Estimates for Subjects Groups for Path Length Plateaus

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1.00	1.1195	.00000	1.1195	1.1195
2.00	1.0724	.00000	1.0724	1.0724
3.00	1.0654	.00000	1.0654	1.0654

Table 5.30: Pair-wise Comparison of Subject Groups' Path Length Plateaus

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1.00	2.00	.0471[a]	.00000	1	.000	.0471	.0471
	3.00	.0541[a]	.00000	1	.000	.0541	.0541
2.00	1.00	-.0471[a]	.00000	1	.000	-.0471	-.0471
	3.00	.0070[a]	.00000	1	.000	.0070	.0070
3.00	1.00	-.0541[a]	.00000	1	.000	-.0541	-.0541
	2.00	-.0070[a]	.00000	1	.000	-.0070	-.0070

Tables 5.28-5.30 show that there is a significant difference between all subject groups concerning plateaus of proficiency for completion time. The order of proficiency here is 3 > 2 > 1. Table 5.31-5.33 show results of a Wald Chi-Square test for completion time learning rates between subject groups.

Table 5.31: Model Effects for Path Length Learning Rates using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	3980882335695601000000000000000000.000	1	.000
Group	.[a]	.	.

Table 5.32: Estimates for Subjects Groups for Path Length Learning Rates

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1.00	1.5250	.00000	1.5250	1.5250
2.00	1.6015	.00000	1.6015	1.6015
3.00	1.7760	.00000	1.7760	1.7760

Table 5.33: Pair-wise Comparison of Subject Groups' Path Length Learning Rates

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1.00	2.00	-.0765[a]	.00000	1	.000	-.0765	-.0765
	3.00	-.2510[a]	.00000	1	.000	-.2510	-.2510
2.00	1.00	.0765[a]	.00000	1	.000	.0765	.0765
	3.00	-.1745[a]	.00000	1	.000	-.1745	-.1745
3.00	1.00	.2510[a]	.00000	1	.000	.2510	.2510
	2.00	.1745[a]	.00000	1	.000	.1745	.1745

Tables 5.31-5.33 show that learning rate differences are significant between all subject groups in terms of path length. The order of proficiency is 1 > 2 > 3.

5.8.4.3 Error Score

Tables 5.34-5.36 show the results of a Wald Chi-Square test for the differences between subject groups concerning the plateaus of proficiency for error score. Error score plateau and learning rate data were similar to path length data in that this data did not demonstrate a normal distribution until a square root transformation was performed.

Table 5.34: Model Effects for Error Score Plateaus using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	52261646027044125000000000000000 0.000	1	.000
Group	.[a]	.	.

Table 5.35: Estimates for Subjects Groups for Error Score Plateaus

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1.00	.4654	.00000	.4654	.4654
2.00	.3786	.00000	.3786	.3786
3.00	.4470	.00000	.4470	.4470

Table 5.36: Pair-wise Comparison of Subject Groups' Error Score Plateaus

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1.00	2.00	.0868[a]	.00000	1	.000	.0868	.0868
	3.00	.0184[a]	.00000	1	.000	.0184	.0184
2.00	1.00	-.0868[a]	.00000	1	.000	-.0868	-.0868
	3.00	-.0684[a]	.00000	1	.000	-.0684	-.0684
3.00	1.00	-.0184[a]	.00000	1	.000	-.0184	-.0184
	2.00	.0684[a]	.00000	1	.000	.0684	.0684

Tables 5.34-5.36 show that there is a significant difference between all subject groups concerning plateaus of proficiency for error score. The order of proficiency is 2 > 3 > 1. Tables 5.37-5.39 show results of a Wald Chi-Square test for completion time learning rates between subject groups.

Table 5.37: Model Effects for Error Score Learning Rates using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	72339131590547 19000000000000 00000.000	1	.000
Group	.[a]	.	.

Table 5.38: Estimates for Subjects Groups for Error Score Learning Rates

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1.00	.8353	.00000	.8353	.8353
2.00	.7596	.00000	.7596	.7596
3.00	.9830	.00000	.9830	.9830

Table 5.39: Pair-wise Comparison of Subject Groups' Error Score Learning Rates

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1.00	2.00	.0757[a]	.00000	1	.000	.0757	.0757
	3.00	-.1477[a]	.00000	1	.000	-.1477	-.1477
2.00	1.00	-.0757[a]	.00000	1	.000	-.0757	-.0757
	3.00	-.2234[a]	.00000	1	.000	-.2234	-.2234
3.00	1.00	.1477[a]	.00000	1	.000	.1477	.1477
	2.00	.2234[a]	.00000	1	.000	.2234	.2234

Tables 35-37 show that learning rate differences are significant between all subject groups. The order of proficiency is 2 > 1 > 3.

5.8.5 Summary Statistics of the Testing Phase

As with the analysis of the training phase, the analysis of the testing phase was meant to expose any difference in performance between the subject groups.

Figure 5.20 below shows the overall performance of the three subject groups for the prompts in terms of elevation and azimuth. Values are averaged for each prompt for the three subject groups and reported as absolute errors, not indicating the specific direction a subject deviated from the ideal trajectories. Error bars are also plotted to indicate the standard deviations of the subjects' performances for each prompt.

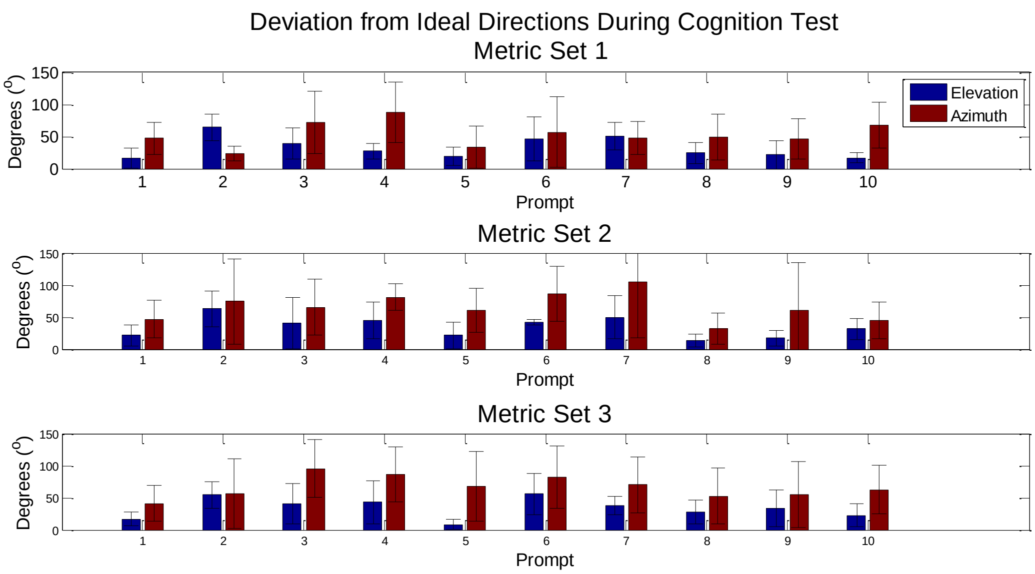

Figure 5.20: Absolute Errors Committed by Subjects during the Testing Phase

From Figure 5.20 it is seen that absolute error varies depending on the prompt, and thus the direction of motion the subjects are trying to achieve. However, there seems to be a general sense of agreement between subject groups across many of the same prompts. Table 5.40 below presents the average absolute errors for subject groups across all prompts accompanied by standard deviations.

Table 5.40: Average Error for Subject Groups Across all Trials

Subject Group	Average Elevation Error (deg)	Standard Deviation (deg)	Average Azimuth Error (deg)	Standard Deviation (deg)
Standard, Averaged	32.67	16.67	53.36	18.67
Novel	34.6	15.96	65.80	21.54

Standard, Individual	34.02	15.45	67.06	16.9

Table 5.40 shows that for the testing phase there was great similarity between how the three novice groups performed. For each angle type the difference between groups of average deviation from a given ideal trajectory was never more than ten degrees and usually fell within five degrees. Standard deviation from given means also demonstrated parity among the subject groups. An interesting note would be that in every case (mean and standard deviation) for each subject group, the values are almost always lower for elevation data compared to azimuth data.

As with the data representing the training phase, a more in depth statistical analysis was performed for the data representing the testing phase.

5.8.6 Statistical Analysis of the Testing Phase

For the testing phase, we wanted to determine if the performance metrics (deviation from an ideal trajectory measured through elevation (θ) and azimuth (φ) angles) indicated any significant difference between metric groups in the analysis. To do this, we considered the two angular deviation metrics separately as well as a resultant of their values where Equation 7 was used.

$$RES_A = \sqrt{\theta^2 + \varphi^2} \tag{7}$$

As with the data for the training phase, the raw data for the testing phase was not normal as indicated in Figure 5.21 below. The histogram shows the deviations achieved by subjects in terms of elevation (θ).

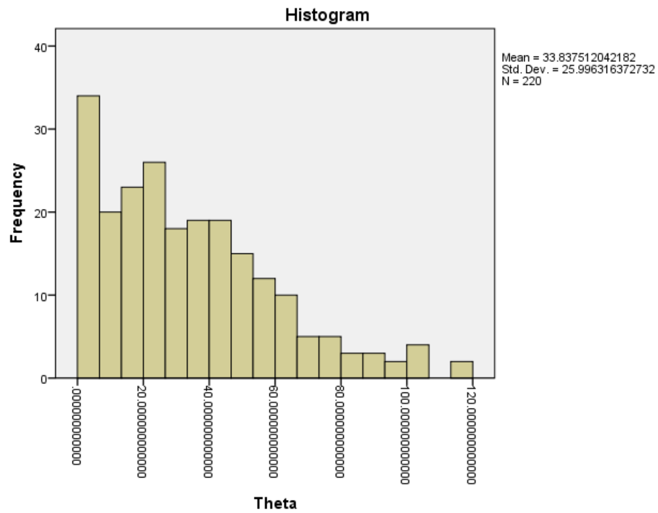

Figure 5.21: Histogram of Raw Testing Phase Elevation (θ) Data

However, unlike the training phase data, this data could be transformed using the square root of each data sample to produce a normal curve. Figure 5.22 shows this transformation.

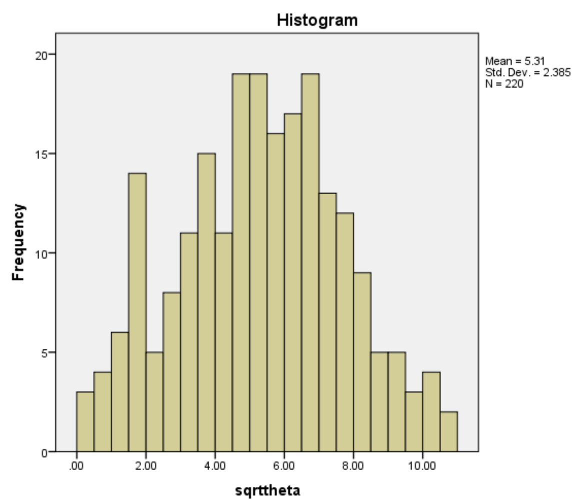

Figure 5.22: Histogram of Transformed, Normal Testing Phase Elevation (θ) Data

In a test to determine normality, Kolmogorov-Smirnov and Shapiro-Wilk values of .2 and .87, respectively, were found. This allowed us to use an identity link function with a normal distribution to determine significance between source groups. The data was modeled with primary effect of group and prompt and their interaction, with the results are summarized in Table 5.41. As seen, the effect of subject group is not significant. However, the effect of the

specific prompt number through the testing phase was significant and the interaction between prompt number and metric group was significant. We also present the estimates of the summary statistics for the transformed data in Table 5.42.

Table 5.41: Model Effects for Deviations in Elevation (θ) using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	1135.156	1	.000
Group	.216	2	.898
Prompt	176.194	9	.000
Group * Prompt	340.497	18	.000

Table 5.42: Estimates of Summary Statistics for Subjects Groups for Deviations in Elevation (θ)

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	5.241	.245	4.759	5.722
2	5.387	.206	4.983	5.791
3	5.291	.347	4.611	5.971

As we did with the training phase, we evaluated pair-wise data to observe the subject group interaction during performance on a paired basis.

Table 5.43: Pair-wise Comparison of Subject Groups' Elevations

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	-.146	.32	1	.649	-.774	.482
	3	-.05	.425	1	.905	-.883	.782
2	1	.146	.32	1	.649	-.482	.774
	3	.095	.403	1	.813	-.695	.886
3	1	.05	.425	1	.905	-.782	.883
	2	-.095	.403	1	.813	-.886	.695

After determining the significance of the elevation metric, the azimuth metric was investigated for significance. Azimuth (φ) is measured as the amount of deviation from an ideal trajectory within a theoretical horizontal plane within the task box. As with elevation, Figure 5.23 shows that the raw data for azimuth was not normal.

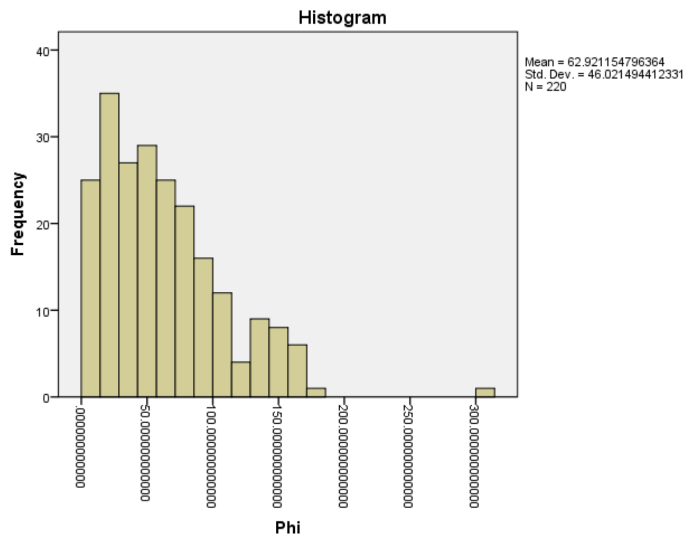

Figure 5.23: Histogram of Raw Testing Phase Azimuth (φ) Data

Also similar to the analysis of elevation, the square root of the data samples could be found to produce a normal distribution as indicated by Figure 5.24.

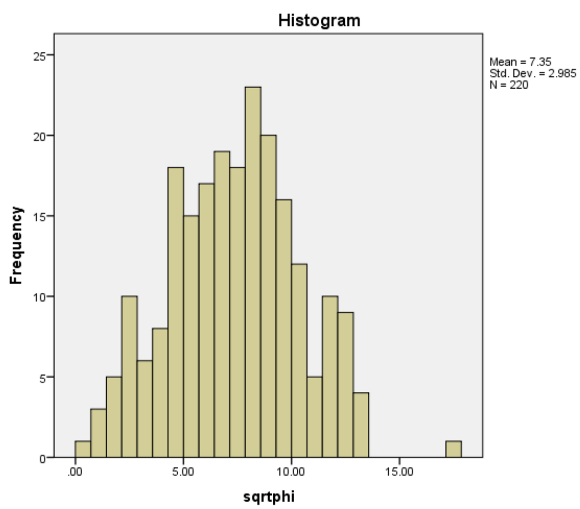

Figure 5.24: Histogram of Transformed, Normal Testing Phase Azimuth (φ) Data

This transformation to a normal distribution was supported by tests producing Kolmogorov-Smirnov and Shapiro-Wilk values of .2 and .26, respectively. Through this transformation, we could use another identity link function with the normal distribution to perform a Wald Chi-Square test to determine significance of our sources. Table 5.44 summarizes the effects of these sources. As with elevation, there was no significant effect of subject group on azimuth. There was, however, a significant effect of prompt number and interaction between prompt number and subject group. We also present the estimates of summary statistics in Table 5.45 and pair-wise data in Table 5.46.

Table 5.44: Model Effects for Deviations in Azimuth (φ) using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	630.222	1	.000
Group	1.775	2	.412
Prompt	43.461	9	.000
Group * Prompt	3148.523	18	.000

Table 5.45: Estimates of Summary Statistics for Subjects Groups for Deviations in Azimuth (φ)

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	6.782	.473	5.855	7.709
2	7.513	.36	6.805	8.22
3	7.606	.638	6.355	8.857

Table 5.46: Pair-wise Comparison of Subject Groups' Azimuths

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	-.73	.594	1	.220	-1.896	.435
	3	-.823	.794	1	.300	-2.38	.733
2	1	.73	.594	1	.220	-.435	1.896
	3	-.093	.733	1	.899	-1.53	1.343
3	1	.823	.794	1	.300	-.733	2.38
	2	.093	.733	1	.899	-1.343	1.53

The pair-wise results show no significance between pairs of groups.

For the final part of the statistical analysis of the results of our experiment, we needed to consider the combined effect of elevation (θ) and azimuth (φ), by the resultant in Equation 7. The fashion of the analysis after this transformation was similar to the ones conducted for elevation and azimuth separately. At first the distribution for the raw data after the resultant transformation was not normal.

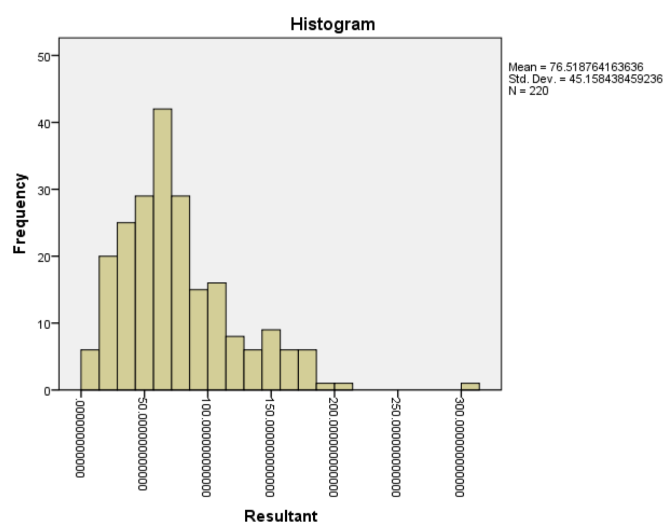

Figure 5.25: Histogram of Raw Testing Phase Resultant Data

However, this data too could be transformed to produce a normal distribution by calculating the square root of the data samples. This gave the distribution depicted in Figure 5.26.

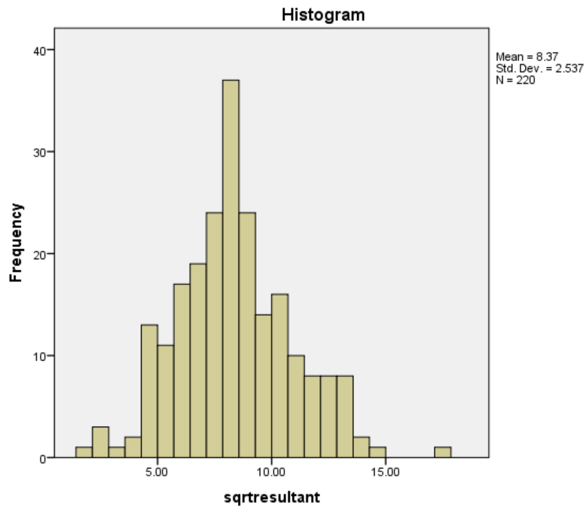

Figure 5.26: Histogram of Transformed, Normal Testing Phase Resultant Data

Tests of normality produced Kolmogorov-Smirnov and Shapiro-Wilk values of .051 and .114, respectively. Through our testing of model effects it was shown that even through the combination of the deviation metrics, the effect of subject groups was not significant. However, there was a significant effect of prompt number and a significant prompt number X subject group interaction.

Table 5.47: Model Effects for Resultant Data using a Wald Chi-Square Test

Tests of Model Effects

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	1114.097	1	.000
Group	1.055	2	.590
Prompt	101.819	9	.000
Group * Prompt	2460.312	18	.000

Table 5.48 below also shows the estimates of summary statistics for the resultant data and Table 5.49 shows pair-wise results which indicates no significance of the estimates between group pairs.

Table 5.48: Estimates of Summary Statistics for Subjects Groups for Resultant Data

Estimates

Group	Mean	Std. Error	95% Wald Confidence Interval	
			Lower	Upper
1	8.0003	.399	7.217	8.783
2	8.47	.292	7.896	9.043
3	8.546	.562	7.444	9.649

Table 5.49: Pair-wise Comparison of Resultants Produced from Elevation & Azimuth

Pairwise Comparisons

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	df	Sig.	95% Wald Confidence Interval for Difference	
						Lower	Upper
1	2	-.469	.495	1	.343	-1.44	.501
	3	-.546	.69	1	.428	-1.898	.806
2	1	.469	.495	1	.343	-.501	1.44
	3	-.076	.634	1	.904	-1.319	1.166
3	1	.546	.69	1	.428	-.806	1.898
	2	.076	.634	1	.904	-1.166	1.319

5.8.7 Summary of Results

The results presented above show the performances of our novice subject groups through their participation in our experiment during training and testing phases. For each phase, a general analysis is shown followed by a more in-depth statistical comparison between subject groups.

For the training phase, a general progression through the experiment was shown for the novice groups in terms of the standard metrics (completion time, path length and error score). The most informative part of this analysis was a nonlinear regression analysis which yielded a ‘plateau’ of learning for all groups and also gave a learning rate.

The next part of our analysis of the training phase was the statistical analysis. A Wald Chi-Square test was performed using the trial number, subject group and the interaction between

the two as independent variables for all the metrics (Error score only used subject group as an independent variable). In the case of each standard metric, it was shown that the only significant effect derived from the independent variable of trial number and interaction between trial number and subject group. There was no significant difference between subject groups.

A statistical analysis was also performed on the performance constants derived from our non-linear regression analysis. In terms of plateaus and learning rates for all metrics, all subject groups performed significantly different from one another. Table 5.50 below gives a sense of how these subject groups performed compared to one another in terms of the theoretical plateau and learning rate. This table was derived from the pair-wise comparisons made between subject groups.

Table 5.50: Order of Proficiency between Subject Groups for Theoretical Plateau and Learning Rates

Constant	Metric	Most Proficient Group	Intermediary Proficiency Group	Least Proficient Group
Theoretical Plateau	Completion Time	3	2	1
	Path Length	3	2	1
	Error Score	2	3	1
Learning Rate	Completion Time	2	1	3
	Path Length	1	2	3
	Error Score	2	1	3

After our analysis of the training phase, the testing phase data was examined. For a general analysis, performances were reported as deviations from an ideal trajectory where a value of zero indicated no deviation. It is seen that no one subject group performed consistently better than the other and that subject groups performed very similar to one another for many prompts.

For the statistical analysis, a Wald Chi-Square test was performed for the entire set of data collected from all subjects across all prompts during the testing phase. The statistical test was performed with the prompt number, subject group and the interaction between these two in mind. It was found that for all types of data (elevation, azimuth, resultant) there was a significant effect of prompt number and interaction between prompt number and subject group but no one subject group performed significantly better than another.

CHAPTER 6 DISCUSSION

6.1 Goals & Strategies

The purpose of this experiment was to investigate whether or not there existed means with which to train prospective minimally invasive surgery (MIS) surgeons more efficiently and effectively than what many common training curriculums offer. We tested to see if newly developed metrics, provided as supplemental feedback during training, caused subjects to adapt to and learn a novel MIS hand-eye environment more quickly and completely than subjects who received standard metrics as feedback.

This chapter will spend time justifying and developing reasoning for the results. This experiment's place in the literature will be highlighted and strengths and weaknesses of the experiment will also be touched upon. Finally, suggested future work will be presented and the projects conclusion will be mad

6.2 Training Phase Results

The results of our experiment have shown that the strategy employed to have novice subjects adapt quicker and to a better level than others receiving standard metrics as feedback did not generate any significant differences in performance between subject groups during the

training phase when looking solely at the metrics achieved by subject groups. This means that for the novice group receiving the newly proposed metrics as feedback, performance was neither significantly aided nor hindered relative to that of the other subject groups. Though our statistical analysis indicates that subjects tend to adapt to a laparoscopic environment independently of the feedback metrics used, there was a significant difference in performance between subject groups when considering the performance constants of theoretical plateau and learning rate in our general analysis.

In our general analysis of the training phase, we showed that each subject group adapted to the motor task presented over the course of 49 trials (35 for the expert group). This is evident by the fact that the standard metrics for each subject group decreased in value with repeated trials. This change in standard metrics was always a drastic increase in performance during early trials and a steady leveling off as the training continued. We also showed that the groups adapted differently by reporting the performance constants for a nonlinear regression analysis (inverse function).

Each group had associated with it a constant reflecting “plateau” of learning and a constant describing learning “rate”. For all standard metrics, lower values of these two constants (plateau and rate) indicate more proficiency and quicker adaptation, respectively. From a statistical analysis of these constants it was shown that all subject groups were statistically significant from one another.

The novel group significantly outperformed all other novice subject groups in terms of learning rate for the metrics of completion time and error score. This group also outperformed the other novice groups in terms of theoretical plateau for the metric of error score. However, the theoretical plateau this group achieved with respect to completion time and path length only

surpassed the performance of the group receiving novel metrics on an averaged, tree basis. For learning rate in terms of path length the group receiving novel metrics as feedback (Group 2) only surpassed the performance of the group receiving standard metrics as feedback on an individual ,trial basis (Group 3). These results show that the newly proposed metrics, and the way they were presented to subjects during the experiment, were meaningful but not entirely more effective in training than other metrics.

We were also able to perceive a difference between the two groups receiving the standard metrics as feedback. The group receiving these metrics as feedback on an averaged, tree basis (Group 1) always achieved a higher plateau (lower proficiency) and demonstrated a steeper learning rate than the group receiving the standard metrics as feedback on a trial basis (Group3) for all standard metrics. One possible explanation for this could be that subjects in Group 1 had less variation in the reference data their performances were compared to, so perhaps it took them less time to improve their performances. For subjects in Group 3, the reference data in their feedback was always different so that may lead to slower rates for learning. This, however, seems to lead to better proficiency for this group.

Our results representing the progression of subject performance over the course of all performed trials show that the novel metrics generally allow subjects to reach a plateau for performance quicker than if standard metrics are received as feedback. Though this doesn’t produce more or better adaptation to a laparoscopic environment, it is still useful to be able to train quickly. Turning out competent MIS surgeons at a quicker rate is practical from a training standpoint because it costs money to use and maintain training systems. Less time utilizing the systems lowers cost. Also, the effect of making more surgeons available is practically beneficial

for the pool of patients in need of their services. Patients can have procedures performed sooner and by surgeons who may not have been overworking.

We've shown that the novel metrics are useful and meaningful, but if one looks at the actual magnitude of differences in the pair-wise tables for the performance constants one can see that the greatest difference achieved by the novel metrics compared to either presentation of the standard metrics is only a few seconds in terms of completion time, a couple dozen centimeters concerning path length and tenths of an error when it comes to error score. What this means is that even with significant results, the effect the new metrics have in practice may be too marginal to consider useful depending on who would be utilizing them.

So what can account for the ineffectiveness of the novel metrics, where indicated, in Table 5.50? It was clear through the development of this experiment that the presentation for the novel metrics was much more complex than for the standard metrics. The process required subjects to not only perceive a difference between their own performance and a reference for multiple categories (elevation/azimuth, pick/transfer/place), but to also cognitively define the transformed laparoscopic hand-eye relation in their minds through the interactive text included with the feedback. It could be claimed that subjects may have not put the effort forward to utilize the feedback to its full potential, thus making these subject's training only so much more efficient based on the subject's continued willingness to look at the feedback. If this were the case, then the effect of more proficiency seen in Table 5.50 may be explained by inherit ability of subjects in Group 2 to perform MIS tasks in general.

Another explanation for the increased proficiency, where indicated, but less proficiency of performance, where indicated, in Table 5.50 could be that the novel metrics are effective, however the amount of trials we had subjects perform were too many and the task we employed

too simple to master that all subjects could only improve so much before some type of terminal level of performance was achieved. This would be a weakness of the experiment and could be remedied by developing a task requiring even more dexterity than the one we used for this investigation.

Another consideration is the effect of fatigue on a subject's ability to continue paying attention to the feedback in terms of the newly proposed metrics. It was observed during testing of Group 2 subjects that when presented with feedback for the first couple of trees, or first 14 trials, they usually spent the entire time limit (2 mins) focusing on the feedback. After this, the subjects focused less and less on the feedback. At the time, this was interpreted as the subjects becoming more comfortable with the feedback and understanding the implications made by it. This might account for the quicker learning observed. However, the fact that Group 2 subjects reached the same general level of performance as other groups may suggest that the decreased time spent on the feedback was really indifference toward it by Group 2 subjects. We developed the novel metrics to be as simple as possible for presentation but they still were much more complex than the standard metrics. So it is understandable if Group 2 subjects couldn't focus on all of the aspects of the feedback every time they were presented with it.

Overall, the novel metrics as feedback had a significant effect on subject performance and made more of a difference in performance in terms of learning rate and less of a difference in terms of learning plateau. The implications these results can make are varied but the fact that the novel metrics do make a difference at all means that the experiment could be modified to perhaps amplify the effects seen. Also, the level of precision made with feedback in terms of the standard metrics also makes a significant difference. Training with averaged, tree based feedback yields

steeper learning curves but training with individual, trial based feedback leads to better proficiency plateaus.

6.3 Testing Phase Results

The testing phase of the experiment was meant to be the telling sign concerning how well the subjects engaging in our training phase truly adapted to the transformed laparoscopic environment. For this phase, if subjects could achieve small deviations from the prompts displayed that would indicate adaptation had occurred during the training phase. Furthermore, since we tested subjects from three different groups (based on which metrics were delivered as feedback), we could compare the group's performances to one another and see if one group had a better cognitive understanding of the laparoscopic environment.

We analyzed the progression of performance in the testing phase in the same fashion as for the training phase, with a general analysis and a more in depth statistical analysis. The SPSS statistical analysis indicated no significant difference in performance between the subjects in the different groups. This links to the results demonstrated by the statistical analysis of the training phase when only considering the raw metrics as data. It was shown that by the end of that phase that the subject groups were performing very similar to one another, in terms of metrics achieved, so it makes sense they would perform similarly in the testing phase which took place immediately after the training. A consideration for this might be to administer the testing phase a day after the training phase took place. This would not only test an understanding of the laparoscopic environment but also retention of that understanding. This change may cause more disparity in performance levels of the subject groups but extended retention of a motor map was

not one of the goals of this experiment and so this change may have not been appropriate and we didn't want to risk degradation of subjects understanding of the laparoscopic space.

Also as part of this statistical analysis, we looked once more at pair-wise results for the estimated marginal means and a similar effect was seen for the testing phase as seen for the training phase considering metric values as data. When comparing the differences between just two subject groups, concerning elevation/azimuth/resultant, some differences between certain pairs of subject groups were again larger or smaller than others but none of the differences were significant.

For a general analysis, we simplified the strategies used as compared to those used for the general analysis of the training phase. We still averaged subject group scores for each individual prompt, but since this was the testing phase there shouldn't be any noticeable change in performance over the course of the phase so we didn't derive learning curves or performance constants as in the training phase. Subjects had already adapted to the laparoscopic environment and this phase was meant to test the understanding of that adaptation, not to test more adaptation to the training space. As such, Figure 5.20 shows that as subjects performed the training phase there wasn't a noticeable decreasing trend in absolute error from beginning to end in the testing phase. Some prompts were performed better than others but which prompts those were seems to be independent of the order in which those prompts were presented. This reinforces the notion that subjects have adapted about as much as they can to the new environment and this means that the testing phase could be administered to faithfully judge subjects' cognitive understanding of the training space without worrying about further adaptation.

One simple observation of the results for the testing phase is that absolute error in terms of elevation in the task box is almost always less than the errors committed with respect to

azimuth. This is easily explainable by the fact that elevation has only two distinct directions (up and down ranging from 0^0 to 90^0 in each direction), contrasting with azimuth which can operate on a 360^0 field.

Another effect seen in the results is the similarity between subject groups' performances concerning individual prompts. We have already claimed no significant difference between subject groups in terms of performance in the testing phase but specifically, individual prompts seem to produce remarkable similarity between subjects within the different groups. This shows that in our testing phase the interpretation of the prompts displayed was more standardized across subjects and they did not perceive different hypothetical directions of motion in the prompts. This supports the fashion in which the prompts were displayed.

6.4 Experimental Considerations

When researching the literature before conducting this experiment, there existed mostly two types of investigations; ones for motor adaptation and ones specifically for MIS. Investigations involving the broader subject of motor adaptation usually simply presented subjects with a novel hand-eye relation and measured motor errors committed as repeated trials of a motor task were performed. These types of errors can be deviations from a straight line trajectory, distance from a point one was meant to place a cursor or fingertip or even amount of time taken to start moving along a planned path in a new environment with a novel hand-eye relation. Investigations such as those performed by Brouwer, et al., 2006 and Krakauer, et al., 1999, show that these types of errors can be measured faithfully. Our experiment tried to take the extra step and actually convey the errors committed by subjects to those subjects during their

training. We also used the measured motor errors in the testing phase to interpret how well subjects had adapted to the laparoscopic training space. This type of utilization of motor errors, to simply witness adaptation, is a common use in investigations into motor adaptation.

The other main type of research made was concerning MIS and the different aspects of training used to develop a novice's skills in the area of laparoscopy. These types of investigations would usually review a training system or technique and determine if it is useful in training individuals. At the heart of all of these investigations was the usefulness of the metrics used for assessing subjects during the training. Our experiment once again questioned the use of the common metrics presented in most current training curriculums. However, this was done by matching them up against new metrics never used in any training system before. In effect, we tried to determine if current training methods could be expanded upon to create more adept individuals at demonstrating the skills needed for MIS. From out results, it seems our attempt may have utilized methods too complex for subjects to fully grasp so the new metrics did not outperform the common metrics in every way.

Just as any other experiment, this one had its strengths and weaknesses. Aspects about this experiment that could be improved upon have been touched on, such as the complexity of the new metrics or the ease with which the training task could be mastered. Other aspects that may be improved upon could be the presentation of the metrics and the presentation of the prompts during the testing phase. For our experiment, presentation was a key element since learning the skills necessary for MIS is all about perceived motion and linking that to real-world motion of the hands. So presenting the link (through metrics or prompts) needs to be descriptive and clear. Early on, a presentation of the novel metrics was considered that was more spatial than quantitative. Small pictures actually showing the directions of motion committed by subjects and

of motion committed by experts were developed. Of course we did not keep these because of their inconsistency with the presentation of the standard metrics for the other subject groups.

The presentation of the prompts could also be improved by creating actual video depictions of the hypothetical motions rather than using simple paper images. It turned out that the interpretation of the prompts was consistent across subjects but that interpretation may be slightly off since the presentation of the prompts was not as descriptive as it could have been.

This experiment also had its strengths. The consistency of the experimental methods across the subjects in each subject group ensures that the results will be valid. The program used to generate the metrics normalized the position data so that the positions of all the small parts of the experimental setup did not have to remain perfectly still between every trial. If something moved slightly between trials and needed to be reset quickly, the experimental setup was lenient in the positioning. The task, though too easy to master, did require substantial adaptation to do so and generated a large difference in performance between early and later trials. It was representative of the basic dexterity required for MIS and also marked a difference between experts and novices so the task is mostly useful for experimenting with MIS.

The results of the testing phase show us that for that phase, no significant adaptation was committed by subjects and this further validates the results of the testing phase. If adaptation had continued to occur, the testing would have not really tested a subject’s understanding of the laparoscopic space because that understanding would not have been fully developed yet.

6.5 Future Work

This experiment has shown that new metrics, in the way we developed and presented them, were not completely effective in training novice MIS performers better than standard metrics. However, we have shown that there is a significant difference in theoretical plateau and learning rate depending on which metrics were received as feedback. Future investigations may be able to make adjustments according to suggestions made in the previous section to exploit these differences.

If subjects receiving novel metrics as feedback are learning this task at a faster rate, then a natural question might be not only if they can learn another task quickly but perhaps a slightly altered hand-eye relation as well. Theoretically, the subjects receiving novel metrics as feedback should be able to explain internally how the space is transformed, so if they encounter a slightly rotated environment, perhaps they can learn that environment quicker than subjects who have trained with only standard metrics.

A final consideration for future work could be to train experts on the novel metrics. We've shown that the novel metrics do train novices significantly better than standard ones in terms of performance constants, so it may be worthwhile to train experts on these metrics. Their effect on experts were not considered at all for this experiment and it may be interesting to see if an expert MIS performer could be trained to think of a laparoscopic space in a new and unique way. Their performance in terms of standard metrics could then be viewed at beginning and end to see if improvement had indeed taken place.

6.6 Conclusion

Training and assessment in MIS is an area of great interest in the medical community as there is a constant need to produce capable surgeons for the OR. In an effort to enhance the effectiveness of training, we investigated new metrics never used before to push trainees to adapt quicker to a laparoscopic space and to cognitively define the transformation that takes place when interacting with a laparoscopic setup. We found that the new metrics made a significant difference as compared to the standard metrics when used as feedback in terms of performance constants (theoretical plateau and learning rate) calculated. However, this difference was not always in a positive direction. Though the new metrics make a difference depending on the performance constant considered and the specific metric calculated, the actual magnitude of that difference may not be large enough for administrators to utilize the novel metrics instead of the standard ones.

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APPENDIX 3.1

Accelerometer Specifications

SPECIFICATIONS

T_A = 25°C, V_S = 3 V, $C_X = C_Y = C_Z$ = 0.1 µF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

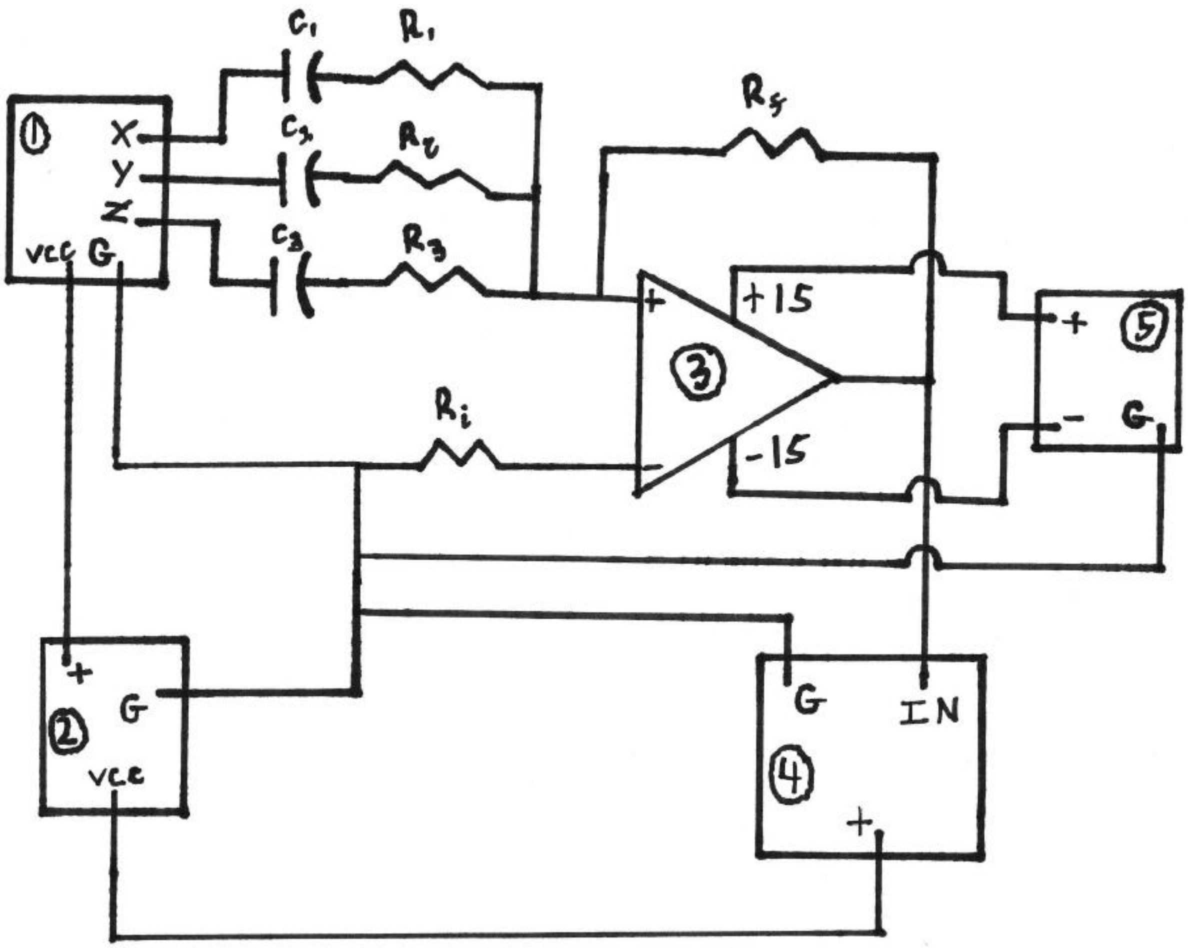
Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Interaxis Alignment Error			±0.1		Degrees
Cross-Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	V_S = 3 V		±0.01		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)					
0 *g* Voltage at X_{OUT}, Y_{OUT}	V_S = 3 V	1.35	1.5	1.65	V
0 *g* Voltage at Z_{OUT}	V_S = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			150		µ*g*/√Hz rms
Noise Density Z_{OUT}			300		µ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz
SELF-TEST[6]					
Logic Input Low			+0.6		V
Logic Input High			+2.4		V
ST Actuation Current			+60		µA
Output Change at X_{OUT}	Self-Test 0 to Self-Test 1	−150	−325	−600	mV
Output Change at Y_{OUT}	Self-Test 0 to Self-Test 1	+150	+325	+600	mV
Output Change at Z_{OUT}	Self-Test 0 to Self-Test 1	+150	+550	+1000	mV
OUTPUT AMPLIFIER					
Output Swing Low	No load		0.1		V
Output Swing High	No load		2.8		V
POWER SUPPLY					
Operating Voltage Range		1.8		3.6	V
Supply Current	V_S = 3 V		350		µA
Turn-On Time[7]	No external filter		1		ms
TEMPERATURE					
Operating Temperature Range		−40		+85	°C

[1] Defined as coupling between any two axes.
[2] Sensitivity is essentially ratiometric to V_S.
[3] Defined as the output change from ambient-to-maximum temperature or ambient-to-minimum temperature.
[4] Actual frequency response controlled by user-supplied external filter capacitors (C_X, C_Y, C_Z).
[5] Bandwidth with external capacitors = 1/(2 × π × 32 kΩ × C). For C_X, C_Y = 0.003 µF, bandwidth = 1.6 kHz. For C_Z = 0.01 µF, bandwidth = 500 Hz. For C_X, C_Y, C_Z = 10 µF, bandwidth = 0.5 Hz.
[6] Self-test response changes cubically with V_S.
[7] Turn-on time is dependent on C_X, C_Y, C_Z and is approximately 160 × C_X or C_Y or C_Z + 1 ms, where C_X, C_Y, C_Z are in microfarads (µF).

APPENDIX 3.2

Summing Circuit & Components List



Devices

1. Triple Axis Accelerometer/ADXL 335

    a. Signal Ports (x, y and z): Outputs acceleration signals in x, y and z directions to #3

    b. Ground Port (G): Connects to #2 to ground the Accelerometer

    c. Power Port (VCC): Connects to #2 to power the Accelerometer

2. National Instruments® USB-6008

    a. Output Port (+): +2.5v power relay to power #1

    b. Ground Port (G): Relays ground from #5 to both #1 and #3

    c. Power Port (VCC): Connects to #4 to power the DAQ

3. Texas Instruments LM741 Operational Amplifier

    a. Power Supply Ports ($\pm$15v): Connects to #5 to power the Op Amp

    b. Input Port (+): Receives acceleration signals from #1

    c. Ground Port (-): Connects to #2 to reach ground

4. Innovative Sports Training Inc. *The Motion Monitor®* v8.00

    a. Input Port (IN): Receives summed/amplified signal from #1 via #3

    b. Ground Port (G): Connects to #2 to reference ground

    c. Power Output Port (+): Connects to and powers #2

5. Agilent Technologies E3630A 35 W Triple Output, 6v, 2.5A & $\pm$20v, .5A

    a. Positive Power Output Port (+): Supplies positive power to #3

    b. Negative Power Output Port (-): Supplies negative power to #3

    c. Ground Port (G): Sources ground to be relayed by #2 to rest of circuit diagram

Components

$C_1 = C_2 = C_3 = 100$ nf

$R_1 = R_2 = R_3 = R_f = 150$ kΩ

$R_i = 100$ Ω Pot

APPENDIX 3.3

Device Specifications

Power Supply Specs

Specifications

	E3610A	E3611A	E3612A	E3614A	E3615A	E3616A	E3617A	E3620A	E3630A
Features	Dual range, 10 turn pots, Constant Voltage (CV), Constant Current (CC) modes.			Adjustable overvoltage protection, voltage & resistance programming, remote sense, rear outputs, ten turn pots, CV, CC modes. Multiple supplies can be connected for tracking or higher power.				Isolated dual outputs, 10 turn pots CV, CL	Tracking, CV, CL (±20 V) CV, CF (+6 V)
Number of outputs	1							2	3
Number of Output Ranges	2	2	2	1	1	1	1	1	1
DC Output Rating	8 V, 3 A 15 V, 2 A	20 V, 1.5 A 35 V, 0.85 A	60 V, 0.5 A 120 V, 0.25 A	8 V, 6 A	20 V, 3 A	35 V, 1.7 A	60 V, 1 A	25 V, 1 A 25 V, 1 A	+6 V, 2.5 A +20 V, 0.5 A −20 V, 0.5 A
Load and Line Regulation	< 0.01% + 2 mV								
Ripple and Noise (20 Hz to 20 MHz)									
Normal mode voltage	< 200 μVrms, < 2 mVpp			< 200 μVrms, < 1 mVpp				< 350 μVrms, < 1.5 mVpp	
Normal mode current	< 200 μArms, < 1 mVpp			< 0.02% + 3 mA	< 0.02% + 1.5 mA	< 0.02% + 1 mA	< 0.02% + 0.5 mA	–	
Common mode current	Not specified							< 1 μArms	
Transient Response Time	< 50 μsec following a change in output current from full load to half load for output to recover within:								
	10 mV			15 mV					
Meter Accuracy	±0.5% + 2 counts at 25 °C ±5 °C								
Meter Resolution									
Voltage	10 mV	100 mV	100 mV	10 mV	10 mV (0−20 V), 100 mV (>20 V)				10 mV
Current	10 mA	10 mA	1 mA	10 mA	10 mA	1 mA	1 mA	1 mA	10 mA
Isolation	240 Vdc								

DAQ Specs

Detailed Specifications

FThe following specifications are typical at 25 °C, unless otherwise noted.

Analog Input	
Converter type	Successive approximation
Analog inputs	8 single-ended, 4 differential, software selectable
Input resolution	
NI USB-6008	12 bits differential, 11 bits single-ended
NI USB-6009	14 bits differential, 13 bits single-ended
Max sampling rate (aggregate) [1]	
NI USB-6008	10 kS/s
NI USB-6009	48 kS/s
AI FIFO	512 bytes
Timing resolution	41.67 ns (24 MHz timebase)
Timing accuracy	100 ppm of actual sample rate
Input range	
Single-ended	±10 V
Differential	±20 V [2], ±10 V, ±5 V, ±4 V, ±2.5 V, ±2 V, ±1.25 V, ±1 V
Working voltage	±10 V
Input impedance	144 kΩ
Overvoltage protection	±35
Trigger source	Software or external digital trigger
System noise [3]	
Single-ended	
±10 V range	5 mVrms
Differential	
± 20 V range	5 mVrms
±1 V range	0.5 mVrms

Absolute accuracy at full scale, single-ended		
Range	Typical at 25 °C (mV)	Maximum over Temperature (mV)
±10	14.7	138

Absolute accuracy at full scale, differential [4]		
Range	Typical at 25 °C (mV)	Maximum over Temperature (mV)
±20	14.7	138
±10	7.73	84.8
±5	4.28	58.4
±4	3.59	53.1
±2.5	2.56	45.1
±2	2.21	42.5
±1.25	1.70	38.9
±1	1.53	37.5

Analog Output	
Analog outputs	2

Output resolution	12 bits
Maximum update rate	150 Hz, software-timed
Output range	0 to +5 V
Output impedance	50 Ω
Output current drive	5 mA
Power-on state	0 V
Slew rate	1 V/µs
Short circuit current	50 mA
Absolute accuracy (no load)	7 mV typical, 36.4 mV maximum at full scale

Digital I/O

Digital I/O	
P0.<0..7>	8 lines
P1.<0..3>	4 lines
Direction control	Each channel individually programmable as input or output
Output driver type	
NI USB-6008	Open collector (open-drain)
NI USB-6009	Each channel individually programmable as active drive (push-pull) or open collector (open-drain)
Compatibility	TTL, LVTTL, CMOS
Absolute maximum voltage range	–0.5 to 5.8 V with respect to GND
Pull-up resistor	4.7 kΩ to 5 V
Power-on state	Input

Digital logic levels

Level	Min	Max	Units
Input low voltage	–0.3	0.8	V
Input high voltage	2.0	5.8	V
Input leakage current	—	50	µA
Output low voltage (I = 8.5 mA)	—	0.8	V
Output high voltage			
Active drive (push-pull), I = –8.5 mA	2.0	3.5	V
Open collector (open-drain), I = –0.6 mA, nominal	2.0	5.0	V
Open collector (open-drain), I = –8.5 mA, with external pull-up resistor	2.0	—	V

External Voltage

+5 V output (200 mA maximum)	+5 V typical, +4.85 V minimum
+2.5 V output (1 mA maximum)	+2.5 V typical
+2.5 V accuracy	0.25% max
Reference temperature drift	50 ppm/°C max

Counter

Number of counters	1
Resolution	32 bits
Counter measurements	Edge counting (falling-edge)
Counter direction	Count up
Pull-up resistor	4.7 kΩ to 5 V
Maximum input frequency	5 MHz
Minimum high pulse width	100 ns

Minimum low pulse width	100 ns
Input high voltage	2.0 V
Input low voltage	0.8 V
Power Requirements	
USB	
4.10 to 5.25 VDC	80 mA typical, 500 mA max
USB suspend	300 µA typical, 500 µA max
Physical Characteristics	
Dimensions	
Without connectors	6.35 cm × 8.51 cm × 2.31 cm (2.50 in. × 3.35 in. × 0.91 in.)
With connectors	8.18 cm × 8.51 cm × 2.31 cm (3.22 in. × 3.35 in. × 0.91 in.)
I/O connectors	USB series B receptacle, (2) 16 position terminal block plug headers
Weight	
With connectors	84 g (3 oz)
Without connectors	54 g (1.9 oz)
Screw-terminal wiring	16 to 28 AWG
Torque for screw terminals	0.22–0.25 N · m (2.0–2.2 lb · in.)

Operational Amplifier Specs

Electrical Characteristics (1)

Parameter	Test Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25°C$										
	$R_S \leq 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \leq 50\Omega$		0.8	3.0							
	$T_{AMIN} \leq T_A \leq T_{AMAX}$										
	$R_S \leq 50\Omega$			4.0							mV
	$R_S \leq 10\ k\Omega$						6.0			7.5	
Average Input Offset Voltage Drift				15							µV/°C

(1) Unless otherwise specified, these specifications apply for $V_S = \pm15V$, $-55°C \leq T_A \leq +125°C$ (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to $0°C \leq T_A \leq +70°C$.

Electrical Characteristics[1] (continued)

Parameter	Test Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage Adjustment Range	$T_A = 25°C$, $V_S = ±20V$	±10				±15			±15		mV
Input Offset Current	$T_A = 25°C$		3.0	30		20	200		20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			70		85	500			300	
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	$T_A = 25°C$		30	80		80	500		80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	$T_A = 25°C$, $V_S = ±20V$	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, $V_S = ±20V$	0.5									
Input Voltage Range	$T_A = 25°C$							±12	±13		V
	$T_{AMIN} \le T_A \le T_{AMAX}$				±12	±13					
Large Signal Voltage Gain	$T_A = 25°C$, $R_L \ge 2$ kΩ										V/mV
	$V_S = ±20V$, $V_O = ±15V$	50									
	$V_S = ±15V$, $V_O = ±10V$				50	200		20	200		
	$T_{AMIN} \le T_A \le T_{AMAX}$, $R_L \ge 2$ kΩ,										V/mV
	$V_S = ±20V$, $V_O = ±15V$	32									
	$V_S = ±15V$, $V_O = ±10V$				25			15			
	$V_S = ±5V$, $V_O = ±2V$	10									
Output Voltage Swing	$V_S = ±20V$										V
	$R_L \ge 10$ kΩ	±16									
	$R_L \ge 2$ kΩ	±15									
	$V_S = ±15V$										V
	$R_L \ge 10$ kΩ				±12	±14		±12	±14		
	$R_L \ge 2$ kΩ				±10	±13		±10	±13		
Output Short Circuit Current	$T_A = 25°C$	10	25	35		25			25		mA
	$T_{AMIN} \le T_A \le T_{AMAX}$	10		40							
Common-Mode Rejection Ratio	$T_{AMIN} \le T_A \le T_{AMAX}$										dB
	$R_S \le 10$ kΩ, $V_{CM} = ±12V$				70	90		70	90		
	$R_S \le 50Ω$, $V_{CM} = ±12V$	80	95								
Supply Voltage Rejection Ratio	$T_{AMIN} \le T_A \le T_{AMAX}$, $V_S = ±20V$ to $V_S = ±5V$										dB
	$R_S \le 50Ω$	86	96								
	$R_S \le 10$ kΩ				77	96		77	96		
Transient Response	$T_A = 25°C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		μs
Overshoot			6.0	20		5			5		%
Bandwidth [2]	$T_A = 25°C$	0.437	1.5								MHz
Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5		V/μs
Supply Current	$T_A = 25°C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25°C$										mW
	$V_S = ±20V$		80	150							
	$V_S = ±15V$					50	85		50	85	

(2) Calculated value from: BW (MHz) = 0.35/Rise Time (μs).

Electrical Characteristics[1] (continued)

Parameter	Test Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
LM741A	$V_S = \pm 20V$ $T_A = T_{AMIN}$ $T_A = T_{AMAX}$			 165 135							mW
LM741	$V_S = \pm 15V$ $T_A = T_{AMIN}$ $T_A = T_{AMAX}$					 60 45	 100 75				mW

Thermal Resistance	CDIP (NAB0008A)	PDIP (P0008E)	TO-99 (LMC0008C)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100°C/W	100°C/W	170°C/W	195°C/W
θ_{jC} (Junction to Case)	N/A	N/A	25°C/W	N/A

Pot Resistor Specifications

Electrical Characteristics

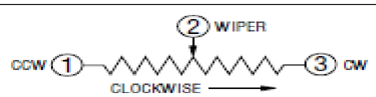
Standard Resistance Range
.... 100 ohms to 500K ohms
(see standard resistance table)
Resistance Tolerance .... ±10 % std.
Absolute Minimum Resistance
.... 1 % or 2 ohms max.
(whichever is greater)
Contact Resistance Variation
.... 3.0 % or 3 ohms max.
(whichever is greater)
Adjustability
Voltage Divider .... ±0.02 %
Rheostat.................................. ±0.05 %
Resolution .... Infinite
Insulation Resistance .... 500 vdc.
1,000 megohms min.
Dielectric Strength
Sea Level.................................. 600 vac
80,000 Feet .... 250 vac
Effective Travel ....12 turns nom.

Environmental Characteristics

Power Rating (300 volts max.)
70 °C .... 0.25 watt
150 °C .... 0 watt
Temperature Range .... -55 °C to +125 °C
Temperature Coefficient ... ±100 ppm/°C
Seal Test .... 85 °C Fluorinert†
Humidity .... MIL-STD-202 Method 103
96 hours (2 % ΔTR, 10 Megohms IR)
Vibration .... 30 G (1 % ΔTR; 1 % ΔVR)
Shock .... 100 G (1 % ΔTR; 1 % ΔVR)
Load Life... 1,000 hours 0.25 watt 70 °C
(3 % ΔTR; 3 % CRV)
Rotational Life .... 200 cycles
(4 % ΔTR; 3 % or 3 ohms,
whichever is greater, CRV)

Physical Characteristics

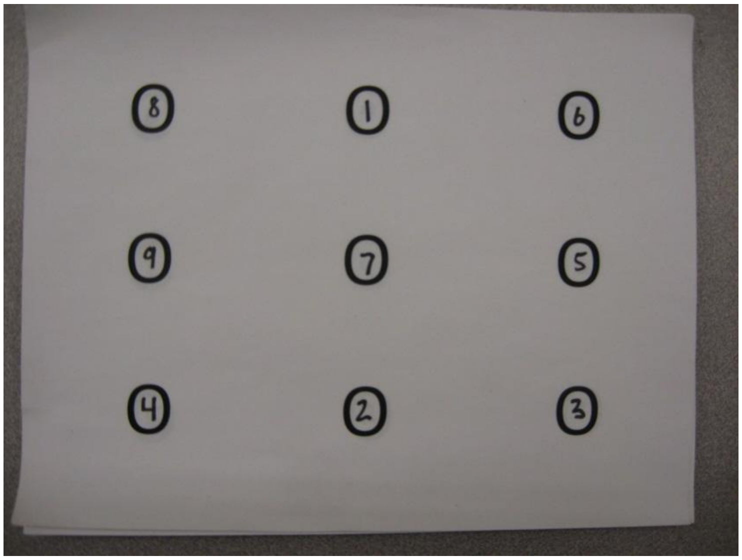
Torque .... 3.0 oz-in. max.
Mechanical Stops................. Wiper idles
Terminals .... Solderable pins
Weight .... 0.015 oz.
Marking........................... Manufacturer's
trademark, resistance code,
wiring diagram, date code,
manufacturer's model
number and style
Wiper .... 50 % (Actual TR) ±10 %
Flammability .... U.L. 94V-0
Standard Packaging ..... 50 pcs. per tube
Adjustment Tool.............................. H-90



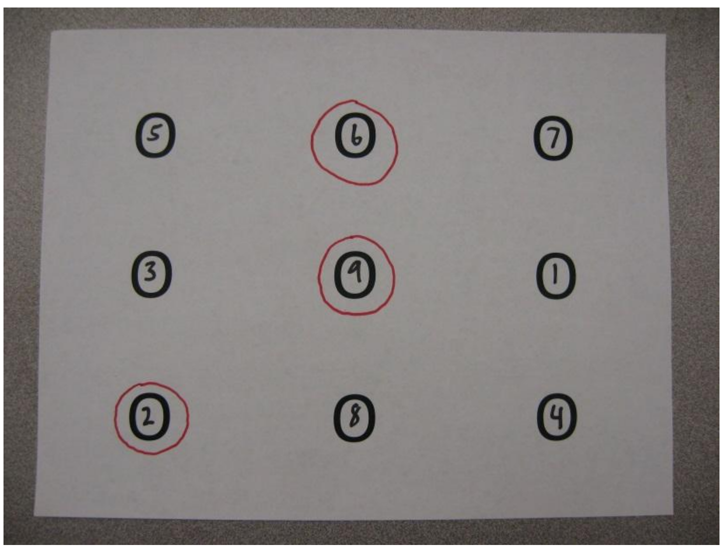
APPENDIX 4.1

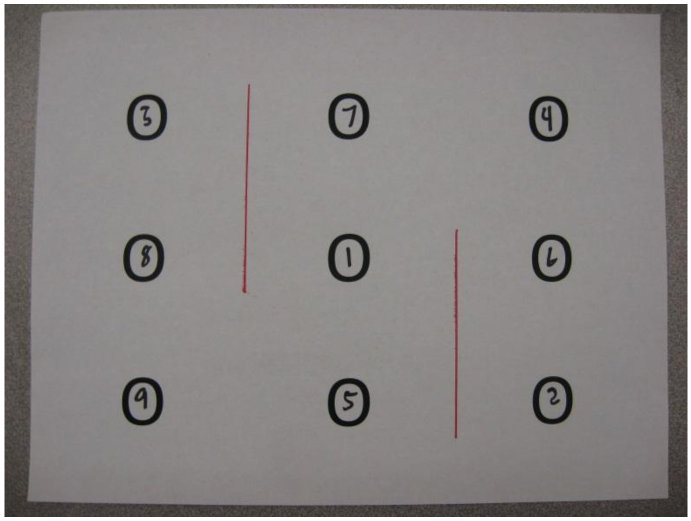
Correlation Study Diagrams

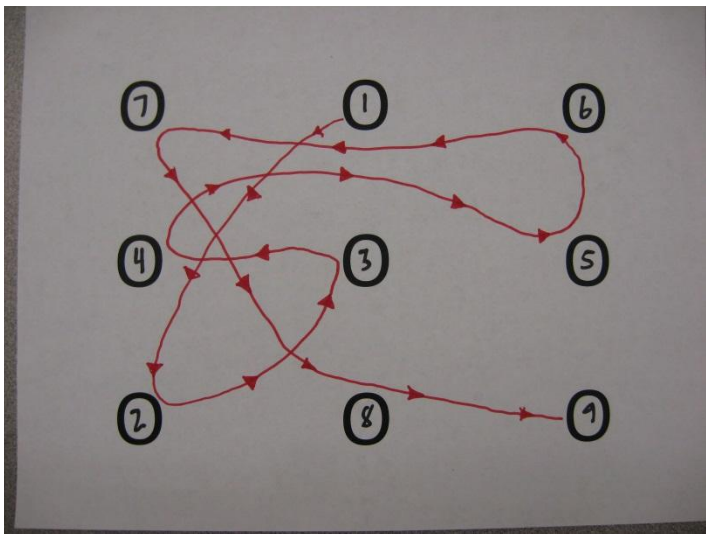
Image for First/Last 10 Diagrams

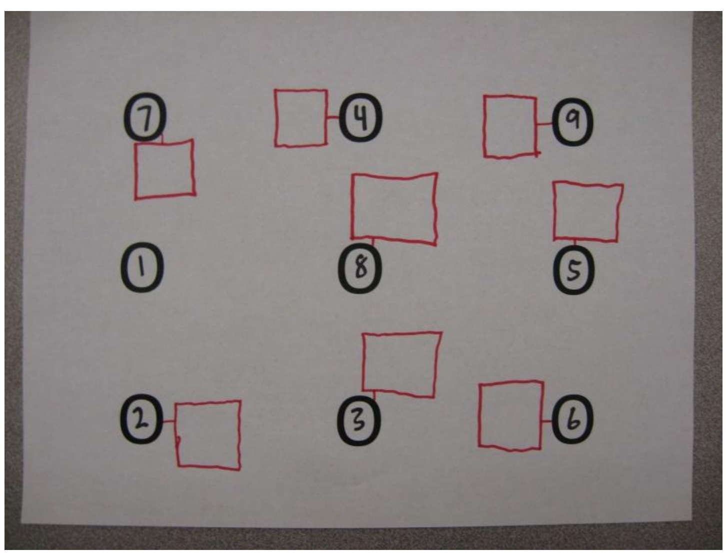


Images for Middle 20 Diagrams




3
7
4
8
1
6
9
5
2


7
1
6
4
3
5
2
8
9


7
4
9
1
8
5
2
3
6

APPENDIX 4.2

Correlation Algorithm

```
clear % Commnd to clear MatLab Worspace
clc   % Command to clear the MatLab Command Window

%% ======================== Section used to designate subject data

subject = input('\nName the subject you would like to analyze.\n(Enter in brackets with the
names in single quotes)\n\n');

if strcmp('Ravi',subject) == 1
   sn = 1;
end
if strcmp('Laura',subject) == 1
   sn = 2;
end
if strcmp('Ketan',subject) == 1
   sn = 3;
end
if strcmp('David',subject) == 1
   sn = 4;
end

metone = xlsread('Sub_Met_Corr.xls', sn, 'C5:F12');     % Commands to import
mettwo = xlsread('Sub_Met_Corr.xls', sn, 'I5:L12');     % data from Excel
metthree = xlsread('Sub_Met_Corr.xls', sn, 'O5:R12');   % Data is imported in
metfour = xlsread('Sub_Met_Corr.xls', sn, 'C15:F22');   % matrix form
metfive = xlsread('Sub_Met_Corr.xls', sn, 'I15:L22');
metsix = xlsread('Sub_Met_Corr.xls', sn, 'O15:R22');
metseven = xlsread('Sub_Met_Corr.xls', sn, 'C25:F32');
meteight = xlsread('Sub_Met_Corr.xls', sn, 'I25:L32');
metnine = xlsread('Sub_Met_Corr.xls', sn, 'O25:R32');
metten = xlsread('Sub_Met_Corr.xls', sn, 'C35:F42');
mettwelve = xlsread('Sub_Met_Corr.xls', sn, 'O35:R42');

ctmean = mean(metone);
plmean = mean(mettwo);
eommean = mean(metthree);
```

```
errmean = mean(metfour);
mvmean = mean(metfive);
mavmean = mean(metsix);
avmean = mean(metseven);
aavmean = mean(meteight);
sommean = mean(metnine);
```

```
cdmean = mean(metten);
aamean = mean(mettwelve);

md = [ctmean; plmean; eommean; errmean; mvmean; mavmean; avmean; aavmean; sommean;
cdmean; aamean]';

%% ========================= Section used to calculate correlation coefficients

[r,p] = corrcoef(md);       % Calling MatLab function to calculate
[a,b] = find(p>0 & p<=.2);  % correlation between metrics
[c,d] = find(p>.2 & p<=.4); % Also used to find specific values of
[e,f] = find(p>.4 & p<=.6); % coefficients according to bounds and assigning
[g,h] = find(p>.6 & p<=.8); % the associated metric titles to that category
[i,j] = find(p>.8 & p<1);

korig = [a,b];                          % Commands used to eliminate
colsort = find(korig(:,1)>korig(:,2));      % repeating correlations (i.e used
k1 = korig(:,1);                         % to eliminate "path length -
k2 = korig(:,2);                         % completion time" correlation
k1(colsort) = korig(colsort,2);             % when already outputting
k2(colsort) = korig(colsort,1);                    % “completion time - path length"
newk = [k1 k2];                                          % correlation
newerk = unique(newk,'rows');

lorig = [c,d];
colsort2 = find(lorig(:,1)>lorig(:,2));
l1 = lorig(:,1);
l2 = lorig(:,2);
l1(colsort2) = lorig(colsort2,2);
l2(colsort2) = lorig(colsort2,1);
newl = [l1 l2];
newerl = unique(newl,'rows');

morig = [e,f];
colsort3 = find(morig(:,1)>morig(:,2));
m1 = morig(:,1);
m2 = morig(:,2);
m1(colsort3) = morig(colsort3,2);
m2(colsort3) = morig(colsort3,1);
newm = [m1 m2];
newerm = unique(newm,'rows');

norig = [g,h];
colsort4 = find(norig(:,1)>norig(:,2));
n1 = norig(:,1);
n2 = norig(:,2);
```

```
n1(colsort4) = norig(colsort4,2);
n2(colsort4) = norig(colsort4,1);
newn = [n1 n2];
newern = unique(newn,'rows');

oorig = [i,j];
colsort5 = find(oorig(:,1)>oorig(:,2));
o1 = oorig(:,1);
o2 = oorig(:,2);
o1(colsort5) = oorig(colsort5,2);
o2(colsort5) = oorig(colsort5,1);
newo = [o1 o2];
newero = unique(newo,'rows');

sig = num2cell(newerk);
sig2 = num2cell(newerl);
sig3 = num2cell(newerm);
sig4 = num2cell(newern);
sig5 = num2cell(newero);

ctf = find([sig{:,:}] == 1);       % Commands used to find the specific
plf = find([sig{:,:}] == 2);       % positions of correlation coefficients
eomf = find([sig{:,:}] == 3);      % within the five sets of bounds defined
errf = find([sig{:,:}] == 4);      % above
mvf = find([sig{:,:}] == 5);
mavf = find([sig{:,:}] == 6);
avf = find([sig{:,:}] == 7);
aavf = find([sig{:,:}] == 8);
somf = find([sig{:,:}] == 9);
cdf = find([sig{:,:}] == 10);
aaf = find([sig{:,:}] == 11);
ctf2 = find([sig2{:,:}] == 1);
plf2 = find([sig2{:,:}] == 2);
eomf2 = find([sig2{:,:}] == 3);
errf2 = find([sig2{:,:}] == 4);
mvf2 = find([sig2{:,:}] == 5);
mavf2 = find([sig2{:,:}] == 6);
avf2 = find([sig2{:,:}] == 7);
aavf2 = find([sig2{:,:}] == 8);
somf2 = find([sig2{:,:}] == 9);
cdf2 = find([sig2{:,:}] == 10);
aaf2 = find([sig2{:,:}] == 11);
ctf3 = find([sig3{:,:}] == 1);
plf3 = find([sig3{:,:}] == 2);
eomf3 = find([sig3{:,:}] == 3);
errf3 = find([sig3{:,:}] == 4);
```

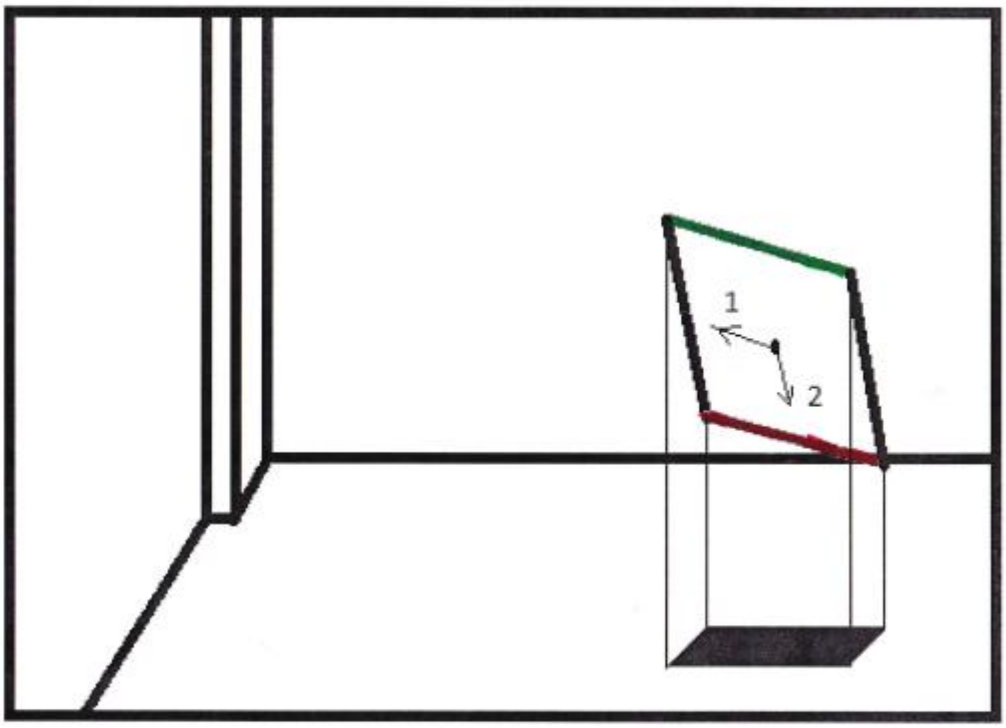
```
mvf3 = find([sig3{:,:}] == 5);
mavf3 = find([sig3{:,:}] == 6);
avf3 = find([sig3{:,:}] == 7);
aavf3 = find([sig3{:,:}] == 8);
somf3 = find([sig3{:,:}] == 9);
cdf3 = find([sig3{:,:}] == 10);
aaf3 = find([sig3{:,:}] == 11);
ctf4 = find([sig4{:,:}] == 1);
plf4 = find([sig4{:,:}] == 2);
eomf4 = find([sig4{:,:}] == 3);
errf4 = find([sig4{:,:}] == 4);
mvf4 = find([sig4{:,:}] == 5);
mavf4 = find([sig4{:,:}] == 6);
avf4 = find([sig4{:,:}] == 7);
aavf4 = find([sig4{:,:}] == 8);
somf4 = find([sig4{:,:}] == 9);
cdf4 = find([sig4{:,:}] == 10);
aaf4 = find([sig4{:,:}] == 11);
ctf5 = find([sig5{:,:}] == 1);
plf5 = find([sig5{:,:}] == 2);
eomf5 = find([sig5{:,:}] == 3);
errf5 = find([sig5{:,:}] == 4);
mvf5 = find([sig5{:,:}] == 5);
mavf5 = find([sig5{:,:}] == 6);
avf5 = find([sig5{:,:}] == 7);
aavf5 = find([sig5{:,:}] == 8);
somf5 = find([sig5{:,:}] == 9);
cdf5 = find([sig5{:,:}] == 10);
aaf5 = find([sig5{:,:}] == 11);

sig(ctf) = {'CT'};              % Commands assigning metric titles to the
sig(plf) = {'PL'};              % locations of correlation coefficients
sig(eomf) = {'EOM'};
sig(errf) = {'#ERR'};
sig(mvf) = {'MV'};
sig(mavf) = {'MAV'};
sig(avf) = {'AV'};
sig(aavf) = {'AAV'};
sig(somf) = {'SOM'};
sig(cdf) = {'CD'};
sig(aaf) = {'AA'};
sig2(ctf2) = {'CT'};
sig2(plf2) = {'PL'};
sig2(eomf2) = {'EOM'};
sig2(errf2) = {'#ERR'};
sig2(mvf2) = {'MV'};
```

```
sig2(mavf2) = {'MAV'};
sig2(avf2) = {'AV'};
sig2(aavf2) = {'AAV'};
sig2(somf2) = {'SOM'};
sig2(cdf2) = {'CD'};
sig2(aaf2) = {'AA'};
sig3(ctf3) = {'CT'};
sig3(plf3) = {'PL'};
sig3(eomf3) = {'EOM'};
sig3(errf3) = {'#ERR'};
sig3(mvf3) = {'MV'};
sig3(mavf3) = {'MAV'};
sig3(avf3) = {'AV'};
sig3(aavf3) = {'AAV'};
sig3(somf3) = {'SOM'};
sig3(cdf3) = {'CD'};
sig3(aaf3) = {'AA'};
sig4(ctf4) = {'CT'};
sig4(plf4) = {'PL'};
sig4(eomf4) = {'EOM'};
sig4(errf4) = {'#ERR'};
sig4(mvf4) = {'MV'};
sig4(mavf4) = {'MAV'};
sig4(avf4) = {'AV'};
sig4(aavf4) = {'AAV'};
sig4(somf4) = {'SOM'};
sig4(cdf4) = {'CD'};
sig4(aaf4) = {'AA'};
sig5(ctf5) = {'CT'};
sig5(plf5) = {'PL'};
sig5(eomf5) = {'EOM'};
sig5(errf5) = {'#ERR'};
sig5(mvf5) = {'MV'};
sig5(mavf5) = {'MAV'};
sig5(avf5) = {'AV'};
sig5(aavf5) = {'AAV'};
sig5(somf5) = {'SOM'};
sig5(cdf5) = {'CD'};
sig5(aaf5) = {'AA'};

%% ======================= Section recording the occurances of correlated metrics within the bounds defined above

questone = input('Would you like to record the correlation groups? (y/n) ', 's');

if strcmp(questone,'y') == 1
```

```
    if strcmp('Ravi', subject) == 1
        xlswrite('Corr_Freq.xls', sig, 1, 'B2')
        xlswrite('Corr_Freq.xls', sig2, 1, 'E2')
        xlswrite('Corr_Freq.xls', sig3, 1, 'H2')
        xlswrite('Corr_Freq.xls', sig4, 1, 'K2')
        xlswrite('Corr_Freq.xls', sig5, 1, 'N2')
    end
    if strcmp('Laura', subject) == 1
        xlswrite('Corr_Freq.xls', sig, 2, 'B2')
        xlswrite('Corr_Freq.xls', sig2, 2, 'E2')
        xlswrite('Corr_Freq.xls', sig3, 2, 'H2')
        xlswrite('Corr_Freq.xls', sig4, 2, 'K2')
        xlswrite('Corr_Freq.xls', sig5, 2, 'N2')
    end
    if strcmp('Ketan', subject) == 1
        xlswrite('Corr_Freq.xls', sig, 3, 'B2')
        xlswrite('Corr_Freq.xls', sig2, 3, 'E2')
        xlswrite('Corr_Freq.xls', sig3, 3, 'H2')
        xlswrite('Corr_Freq.xls', sig4, 3, 'K2')
        xlswrite('Corr_Freq.xls', sig5, 3, 'N2')
    end
    if strcmp('David', subject) == 1
        xlswrite('Corr_Freq.xls', sig, 4, 'B2')
        xlswrite('Corr_Freq.xls', sig2, 4, 'E2')
        xlswrite('Corr_Freq.xls', sig3, 4, 'H2')
        xlswrite('Corr_Freq.xls', sig4, 4, 'K2')
        xlswrite('Corr_Freq.xls', sig5, 4, 'N2')
    end
end
```

APPENDIX 5.1

Testing Phase Prompt



APPENDIX 5.2

Program for Generating Metrics

Parent Code for Generating and Displaying Metrics

```
%% % ===================== Code Header and Copyright

% Cumulative Code for Assesing Transfer Tasks in Parts
% Cristofer Madera, Dr. Dianne Pawluk, Dr. Peter Pidcoe
% Virginia Commonwealth University
% Last Updated: August 24, 2012

%% % ===================== Clearing Workspace & Command Window for Next Task

clear
clc

%% % ===================== User Assigned input for Analysis

Input_Sub_Name = input('Input the name of subject.\n\n', 's');

%% % ===================== Initializing Task Tree

Tree = input('\nWhich tree was used in this trial? (1, 2, 3, 4 or 5) ');

Input_Check_One = 0;
   if Tree == 1 || Tree == 2 || Tree == 3 || Tree == 4 || Tree == 5 || Tree                    == 11 || Tree
== 12 || Tree == 21 || Tree == 31 || Tree == 32 || Tree                        == 41 || Tree == 51
      Input_Check_One = 1;
   end

   while Input_Check_One ~= 1
        Tree = input('\nYou did not enter a valid tree! Please input 1, 2,                                   3, 4
or 5! ');

      if Tree_Order == 1 || Tree == 2 || Tree == 3 || Tree == 4 || Tree ==                      5 || Tree ==
11 || Tree == 12 || Tree == 21 || Tree == 31 || Tree                      == 32 || Tree == 41 || Tree == 51
         Input_Check_One = 1;
      end
```

```
    end

%% % ===================== Initializing Trial Number
```

```
Trial = input('\nWhat is the trial number for the current segment of                    training? ');

Input_Check_Two = 0;

   if isreal(Trial) == 1 && Trial >= 1 && Trial <= 7
     Input_Check_Two = 1;
   end

   while Input_Check_Two ~= 1
       Trial = input('\nYou did not enter a valid trial number! Enter a
        number 1 to 7! ');
      if isreal(Trial) == 1 && Trial >= 1 && Trial <= 7
        Input_Check_Two = 1;
      end
   end


%% % ==================== Creating the File to Load for Analysis

File_Name = strread(sprintf('%s_Tree%d_Trial%d.exp', Input_Sub_Name, Tree,
        Trial),'%s');
File_Name = char(File_Name);
File = importdata(File_Name);
Graphics = input('\nWould you like to see graphics representing your
performance (y/n)? ', 's');

Input_Check_Three = 0;

   if strcmp(Graphics, 'Y') == 1
     Graphics = 'y';
   end
   if strcmp(Graphics, 'N') == 1
     Graphics = 'n';
   end
   if strcmp(Graphics, 'y') == 1
     Input_Check_Three = 1;
   end
   if strcmp(Graphics, 'n') == 1
     Input_Check_Three = 1;
   end

   while Input_Check_Three ~= 1
       Graphics = input('\nYou did not enter yes(y) or no(n) for the
previous query. Please enter yes or no!\nWould you like                              to see
graphics representing your performance (y/n)? ',                              's');
        if strcmp(Graphics, 'Y') == 1
```

```
        Graphics = 'y';
      end
      if strcmp(Graphics, 'N') == 1
        Graphics = 'n';
      end
      if strcmp(Graphics, 'y') == 1
        Input_Check_Three = 1;
      end
      if strcmp(Graphics, 'n') == 1
        Input_Check_Three = 1;
      end
  end

%% % ==================== Separating Data based on Individual Movements

Point_Alpha = File(1,2:4);
Point_Omega = File(length(File(:,1)),2:4);

Dist_X_Alpha = File(:,2) - Point_Alpha(1);
Dist_Y_Alpha = File(:,3) - Point_Alpha(2);
Dist_Z_Alpha = File(:,4) - Point_Alpha(3);
Dist_X_Omega = File(:,2) - Point_Omega(1);
Dist_Y_Omega = File(:,3) - Point_Omega(2);
Dist_Z_Omega = File(:,4) - Point_Omega(3);

Dist_Alpha = sqrt(Dist_X_Alpha.^2 + Dist_Y_Alpha.^2 + Dist_Z_Alpha.^2);
Dist_Omega = sqrt(Dist_X_Omega.^2 + Dist_Y_Omega.^2 + Dist_Z_Omega.^2);

Alpha_Find = find(Dist_Alpha >= .032 & Dist_Alpha <= .04);
L_Alpha_Find = length(Alpha_Find);
Omega_Find = find(Dist_Omega <= .04 & Dist_Omega >= .032);
L_Omega_Find = length(Omega_Find);
Drop_Ind = find(File(1:(length(File) - 1),6) > 4 & File(2:length(File),6) <          4);
L_Drop_Ind = length(Drop_Ind);
Trig_Place = [Alpha_Find(L_Alpha_Find - 2*L_Drop_Ind) Omega_Find(1)];

Rows = size(File);
File_Trig = ones(Rows(1),1)*5;
File_Trig(Trig_Place(1):Trig_Place(1) + 5) = 0;
File_Trig(Trig_Place(2) - 5:Trig_Place(2)) = 0;

File(:,7) = File_Trig;

OK_Data = File(:,7);
l = length(OK_Data);
Start_Thresh = OK_Data(1:l-1)>=4 & OK_Data(2:l)<4;
```

```
Start_Int_One = find(Start_Thresh>0);
Start_Int = [Start_Int_One; Rows(1)];
End_Thresh = OK_Data(1:l-1)<4 & OK_Data(2:l)>=4;
End_Int_One = find(End_Thresh>0);
L_End = length(End_Int_One);
End_Int = [1; End_Int_One(1:L_End)];

New_Data_One(1:(Start_Int(1) - End_Int(1))+1,1:6) = File(End_Int(1):Start_Int(1),1:6);

New_Data_Two(1:(Start_Int(length(Start_Int) - 1) - End_Int(2)) + 1,1:6) =
File(End_Int(2):Start_Int(length(Start_Int) - 1),1:6);

New_Data_Three(1:(Start_Int(length(Start_Int)) - End_Int(length(End_Int)))+1,1:6) =
File(End_Int(length(End_Int)):Start_Int(length(Start_Int)),1:6);

%% % ==================== Allocating Data Based on Metrics Sets

Set_Metric = input('\nInput the metric set to be used for analysis/report.                    (1, 2,
3 or 31) ');

Input_Check_Four = 0;

   if Set_Metric == 1 || Set_Metric == 2 || Set_Metric == 3 || Set_Metric ==           31
      Input_Check_Four = 1;
   end

   while Input_Check_Four ~= 1
        Set_Metric = input('\nYou did not enter a valid metric set! Please
enter metric set 1, 2, 3 or 31! ');
      if Set_Metric == 1 || Set_Metric == 2 || Set_Metric == 3 ||                          Set_Metric
== 31
         Input_Check_Four = 1;
      end
   end

   if Set_Metric == 1 || Set_Metric == 31
     Metrics_One = Set_One_Call(New_Data_One);
     Metrics_Two = Set_One_Call(New_Data_Two);
     Metrics_Three = Set_One_Call(New_Data_Three);
   end
   if Set_Metric == 2
     Metrics_One = Set_Two_Call(New_Data_One);
     Metrics_Two = Set_Two_Call(New_Data_Two);
     Metrics_Three = Set_Two_Call(New_Data_Three);

     Metrics_Four = Set_One_Call(New_Data_One);
```

```
    Metrics_Five = Set_One_Call(New_Data_Two);
    Metrics_Six = Set_One_Call(New_Data_Three);
  end
  if Set_Metric == 3
    Metrics_One = Set_Three_Call(New_Data_One);
    Metrics_Two = Set_Three_Call(New_Data_Two);
    Metrics_Three = Set_Three_Call(New_Data_Three);
  end

%% % ==================== Descriptive Metrics Across the Trial

  if Set_Metric == 1 || Set_Metric == 31
    Whole_Time = [Metrics_One(1); Metrics_Two(1); Metrics_Three(1)];
    Whole_Path = [Metrics_One(2); Metrics_Two(2); Metrics_Three(2)];
    Whole_Err = [Metrics_One(3); Metrics_Two(3); Metrics_Three(3)];
  end
  if Set_Metric == 2
    Whole_Ini_Angle = [Metrics_One(1); Metrics_Two(1); Metrics_Three(1);
                Metrics_One(2); Metrics_Two(2); Metrics_Three(2)];
    Whole_Max_Angle = [Metrics_One(3); Metrics_Two(3); Metrics_Three(3);
                Metrics_One(4); Metrics_Two(4); Metrics_Three(4)];
    Whole_Area = [Metrics_One(5); Metrics_Two(5); Metrics_Three(5)];

    Whole_Time = [Metrics_Four(1); Metrics_Five(1); Metrics_Six(1)];
    Whole_Path = [Metrics_Four(2); Metrics_Five(2); Metrics_Six(2)];
    Whole_Err = [Metrics_Four(3); Metrics_Five(3); Metrics_Six(3)];
  end
  if Set_Metric == 3
    Whole_Path_Two = [Metrics_One(1); Metrics_Two(1); Metrics_Three(1)];
    Whole_Sped = [Metrics_One(2); Metrics_Two(2); Metrics_Three(2)];
    Whole_Jerk = [Metrics_One(3); Metrics_Two(3); Metrics_Three(3)];
  end

%% % ==================== Saving Trial Data

Save = input('\n\nWould you like to save the trial? (y/n)', 's');

Input_Check_Six = 0;

  if strcmp(Save, 'Y') == 1
    Save = 'y';
  end
  if strcmp(Save, 'N') == 1
    Save = 'n';
  end
  if strcmp(Save, 'y') == 1
```

```
    Input_Check_Six = 1;
  end
  if strcmp(Save, 'n') == 1
    Input_Check_Six = 1;
  end

  while Input_Check_Six ~= 1
       Save = input('\nYou did not enter yes(y) or no(n) for the previous
query. Please enter yes or no!\nWould you like to save the                    trial (y/n)? ', 's');
       if strcmp(Save, 'Y') == 1
         Save = 'y';
       end
       if strcmp(Save, 'N') == 1
         Save = 'n';
       end
       if strcmp(Save, 'y') == 1
         Input_Check_Six = 1;
       end
       if strcmp(Save, 'n') == 1
         Input_Check_Six = 1;
       end
  end

First_File_Name = strread(sprintf('%s_Tree%d', Input_Sub_Name, Tree),'%s');
First_File_Name = char(First_File_Name);

  if Set_Metric == 1 || Set_Metric == 31
    Time_File_Name = strread(sprintf('%s_Time.txt',
                First_File_Name),'%s');
    Time_File_Name = char(Time_File_Name);
    Path_File_Name = strread(sprintf('%s_Path.txt',
                First_File_Name),'%s');
    Path_File_Name = char(Path_File_Name);
    Err_File_Name = strread(sprintf('%s_Err.txt', First_File_Name),'%s');
    Err_File_Name = char(Err_File_Name);
  end
  if Set_Metric == 2
    Ini_Angle_File_Name = strread(sprintf('%s_Ini_Angle.txt',
                    First_File_Name),'%s');
    Ini_Angle_File_Name = char(Ini_Angle_File_Name);
    Max_Angle_File_Name = strread(sprintf('%s_Max_Angle.txt',
                            First_File_Name),'%s');
    Max_Angle_File_Name = char(Max_Angle_File_Name);
    Area_File_Name = strread(sprintf('%s_Area.txt',
                First_File_Name),'%s');
    Area_File_Name = char(Area_File_Name);
```

```
  Time_File_Name = strread(sprintf('%s_Time.txt',
                First_File_Name),'%s');
  Time_File_Name = char(Time_File_Name);
  Path_File_Name = strread(sprintf('%s_Path.txt',First_File_Name),'%s');
  Path_File_Name = char(Path_File_Name);
  Err_File_Name = strread(sprintf('%s_Err.txt', First_File_Name),'%s');
  Err_File_Name = char(Err_File_Name);
end
if Set_Metric == 3
  Path_File_Name = strread(sprintf('%s_Path_Two.txt',
                First_File_Name),'%s');
  Path_File_Name = char(Path_File_Name);
  Sped_File_Name = strread(sprintf('%s_Sped.txt',
                First_File_Name),'%s');
  Sped_File_Name = char(Sped_File_Name);
  Jerk_File_Name = strread(sprintf('%s_Jerk.txt',
      First_File_Name),'%s');
  Jerk_File_Name = char(Jerk_File_Name);
end

if strcmp(Save, 'y') == 1
   if Trial == 1
      if Set_Metric == 1 || Set_Metric == 31
        A = [];
        A(:,Trial) = Whole_Time;
        save(Time_File_Name, 'A', '-ASCII')
        B = [];
        B(:,Trial) = Whole_Path;
        save(Path_File_Name, 'B', '-ASCII')
        C = [];
        C(:,Trial) = Whole_Err;
        save(Err_File_Name, 'C', '-ASCII')
      end
      if Set_Metric == 2
        A = [];
        A(:,Trial) = Whole_Ini_Angle;
        save(Ini_Angle_File_Name, 'A', '-ASCII')
        B = [];
        B(:,Trial) = Whole_Max_Angle;
        save(Max_Angle_File_Name, 'B', '-ASCII')
        C = [];
        C(:,Trial) = Whole_Area;
        save(Area_File_Name, 'C', '-ASCII')

        D = [];
```

```
      D(:,Trial) = Whole_Time;
      save(Time_File_Name, 'D', '-ASCII')
      E = [];
      E(:,Trial) = Whole_Path;
      save(Path_File_Name, 'E', '-ASCII')
      F = [];
      F(:,Trial) = Whole_Err;
      save(Err_File_Name, 'F', '-ASCII')
    end
    if Set_Metric == 3
      A = [];
      A(:,Trial) = Whole_Path_Two;
      save(Path_File_Name, 'A', '-ASCII')
      B = [];
      B(:,Trial) = Whole_Sped;
      save(Sped_File_Name, 'B', '-ASCII')
      C = [];
      C(:,Trial) = Whole_Jerk;
      save(Jerk_File_Name, 'C', '-ASCII')
    end
end

if Trial > 1
    if Set_Metric == 1 || Set_Metric == 31
      A = load(Time_File_Name, '-ASCII');
      A(:,Trial) = Whole_Time;
      save(Time_File_Name, 'A', '-ASCII')
      B = load(Path_File_Name, '-ASCII');
      B(:,Trial) = Whole_Path;
      save(Path_File_Name, 'B', '-ASCII')
      C = load(Err_File_Name, '-ASCII');
      C(:,Trial) = Whole_Err;
      save(Err_File_Name, 'C', '-ASCII')
    end
    if Set_Metric == 2
      A = load(Ini_Angle_File_Name, '-ASCII');
      A(:,Trial) = Whole_Ini_Angle;
      save(Ini_Angle_File_Name, 'A', '-ASCII')
      B = load(Max_Angle_File_Name, '-ASCII');
      B(:,Trial) = Whole_Max_Angle;
      save(Max_Angle_File_Name, 'B', '-ASCII')
      C = load(Area_File_Name, '-ASCII');
      C(:,Trial) = Whole_Area;
      save(Area_File_Name, 'C', '-ASCII')

      D = load(Time_File_Name, '-ASCII');
```

```
          D(:,Trial) = Whole_Time;
          save(Time_File_Name, 'D', '-ASCII')
          E = load(Path_File_Name, '-ASCII');
          E(:,Trial) = Whole_Path;
          save(Path_File_Name, 'E', '-ASCII')
          F = load(Err_File_Name, '-ASCII');
          F(:,Trial) = Whole_Err;
          save(Err_File_Name, 'F', '-ASCII')
        end
        if Set_Metric == 3
          A = load(Path_File_Name, '-ASCII');
          A(:,Trial) = Whole_Path_Two;
          save(Path_File_Name, 'A', '-ASCII')
          B = load(Sped_File_Name, '-ASCII');
          B(:,Trial) = Whole_Sped;
          save(Sped_File_Name, 'B', '-ASCII')
          C = load(Jerk_File_Name, '-ASCII');
          C(:,Trial) = Whole_Jerk;
          save(Jerk_File_Name, 'C', '-ASCII')
        end
     end
   end

%% % ===================== Generating Graphics if Needed

   if strcmp(Graphics, 'y') == 1
     Exprt_File = strread(sprintf('Expert_Set%d_Tree%d.txt', Set_Metric,
Tree),'%s');
     Exprt_File = char(Exprt_File);
     Exprt_Data = load(Exprt_File, '-ASCII');
     if Set_Metric == 1
       Sub_Data_Time = load(Time_File_Name, '-ASCII');
        Sub_Data_Path = load(Path_File_Name, '-ASCII');
        Sub_Data_Err = load(Err_File_Name, '-ASCII');
        Sub_Data = [Sub_Data_Time; Sub_Data_Path; Sub_Data_Err];
        Graph = Metric_Set_One_Vis(Sub_Data, Exprt_Data, Trial);
     end
     if Set_Metric == 2
       Sub_Data_Ini_Angle = load(Ini_Angle_File_Name, '-ASCII');
       Sub_Data_Max_Angle = load(Max_Angle_File_Name, '-ASCII');
       Sub_Data_Area = load(Area_File_Name, '-ASCII');
       Sub_Data = [Sub_Data_Ini_Angle; Sub_Data_Max_Angle; Sub_Data_Area];
       Graph = Metric_Set_Two_Vis(Sub_Data, Exprt_Data, Trial);
     end
     if Set_Metric == 3
       Sub_Data_Path = load(Path_File_Name, '-ASCII');
```

```
        Sub_Data_Sped = load(Sped_File_Name, '-ASCII');
        Sub_Data_Jerk = load(Jerk_File_Name, '-ASCII');
        Sub_Data = [Sub_Data_Path; Sub_Data_Sped; Sub_Data_Jerk];
        Graph = Metric_Set_Three_Vis(Sub_Data, Exprt_Data, Trial);
      end
      if Set_Metric == 31
        Sub_Data_Time = load(Time_File_Name, '-ASCII');
        Sub_Data_Path = load(Path_File_Name, '-ASCII');
        Sub_Data_Err = load(Err_File_Name, '-ASCII');
        Sub_Data = [Sub_Data_Time; Sub_Data_Path; Sub_Data_Err];
        Graph = Metric_Set_Three_One_Vis(Sub_Data, Exprt_Data, Trial);
      end
   else
       Graph = 1;
   end

%% % ===================== Ending the Program

   if strcmp(Save, 'n') == 1 || Graph == 1
     fprintf('\n\nThank you for training with us today!\n')
   end
```

Functions for Calculating Metrics

Metric Set 1 & 3 (CT, PL, Error)

```
%% % ===================== Initializing the Function for Metric Set 1

function [Metrics] = Set_One_Call(New_Data)

%% % ===================== Initial Data Manipulation for Analysis

Capt_Rate = 100;
[m] = size(New_Data);
Time = New_Data(:,1)/Capt_Rate;
Metric_Data = New_Data(:,2:4);

Time = Time(:) - Time(1);
X = Metric_Data(:,1) - Metric_Data(1,1);
Y = Metric_Data(:,2) - Metric_Data(1,2);
Z = Metric_Data(:,3) - Metric_Data(1,3);

%% % ===================== Calculation of Completion Time

Comp_Time = Time(m(1));
```

```
%% % ===================== Calculation of Path Time

D_X = diff(X);
D_Y = diff(Y);
D_Z = diff(Z);
DX_DT = (D_X).^2;
DY_DT = (D_Y).^2;
DZ_DT = (D_Z).^2;
Square = sqrt(DX_DT + DY_DT + DZ_DT);

Path_Lengt = sum(Square);

%% % ===================== Calculation of Number of Errors

Start_Thresh = abs(-1*New_Data(1:m-1,5))<.2 & abs(-1*New_Data(2:m,5))>.2;
Start_Int = find(Start_Thresh>0);
Drop_Ind = find(New_Data(1:(m(1) - 1),6) > 4 & New_Data(2:m(1),6) < 4);
Num_Err = length(Start_Int) + length(Drop_Ind);

%% % ===================== Returning Metrics

Metrics = [Comp_Time Path_Lengt Num_Err];
```

Metric Set 2 (IDM, DMM, AA)

```
%% % ===================== Initializing the Function for Metric Set 2

function [Metrics] = Set_Two_Call(New_Data)

%% % ===================== Initial Data Manipulation for Analysis

Capt_Rate = 100;
[m] = size(New_Data);
Metric_Data = New_Data(:,2:4);
[a,b] = butter(2,((Capt_Rate/2)/50.1));
Period = 1/Capt_Rate;

X = Metric_Data(:,1) - Metric_Data(1,1);
Y = Metric_Data(:,2) - Metric_Data(1,2);
Z = Metric_Data(:,3) - Metric_Data(1,3);

%% % ===================== Calculation of Initial Angular Deviation

V_X = diff(X(1:ceil(m(1)*.1)))/Period;
V_Y = diff(Y(1:ceil(m(1)*.1)))/Period;
V_Z = diff(Z(1:ceil(m(1)*.1)))/Period;
```

```
V_10_Per = mean(sqrt(V_X.^2 + V_Y.^2 + V_Z.^2));

Theta_10 = asind(mean(V_Z)/V_10_Per);
Phi_10 = atan2(mean(V_Y),mean(V_X))*(180/pi);

%% % ===================== Calculation of Angular Deviation at Maximum
Velocity

D_X = diff(X);
D_Y = diff(Y);
D_Z = diff(Z);
DX_DT = D_X.^2;
DY_DT = D_Y.^2;
DZ_DT = D_Z.^2;
Square = sqrt(DX_DT + DY_DT + DZ_DT);

Vel = Square/Period;
Filt_Vel(:,1)=filtfilt(a,b,Vel(:,1));

V_Place = find(Filt_Vel == max(Filt_Vel));
V_X_Vec = D_X/Period;
V_Y_Vec = D_Y/Period;
V_Z_Vec = D_Z/Period;
V_X_Max = V_X_Vec(V_Place);
V_Y_Max = V_Y_Vec(V_Place);
V_Z_Max = V_Z_Vec(V_Place);

Theta_Max = asind(V_Z_Max/max(Filt_Vel));
Phi_Max = atan2(V_Y_Max,V_X_Max)*(180/pi);

%% % ===================== Calculation of Arc Area Circumscribed

P = New_Data(1:(m(1)),2:4);
A = New_Data(1,2:4);
B = New_Data(m(1),2:4);

AB = sqrt((B(1) - A(1))^2 + (B(2) - A(2))^2 + (B(3) - A(3))^2);
AB_Prime = AB/m(1);

Term_One = bsxfun(@minus, P, A);
Term_Two = bsxfun(@minus, P, B);
Term_Three = B - A;
Numer = (cross(Term_One', Term_Two'))';

Numer_Mag = sqrt(Numer(:,1).^2 + Numer(:,2).^2 + Numer(:,3).^2);
```

```
Denom_Mag = sqrt(Term_Three(1)^2 + Term_Three(2)^2 + Term_Three(3)^2);

Dist = Numer_Mag/Denom_Mag;

Mini_Area = Dist*AB_Prime;

Arc_Area = sum(Mini_Area);

%% % ===================== Returning Metrics

Metrics = [Theta_10 Phi_10 Theta_Max Phi_Max Arc_Area];
```

Functions for Graphing Metric Feedback

Metric Set 1 (CT, PL, Error)

```
%% % ===================== Initializing Function for Graphics Set One

function Graph = Metric_Set_One_Vis(Sub_Data, Exprt_Data, Trial)

%% % ===================== Calling Data for Completion Time

Comp_Time_Data = [Exprt_Data(:,1) Sub_Data(1:3,Trial)];

%% % ===================== Calling Data for Path Length

Path_Lengt_Data = [Exprt_Data(:,2) Sub_Data(4:6,Trial)];

%% % ===================== Calling Data for Number of Errors

Err_Data = [Exprt_Data(:,3) Sub_Data(7:9,Trial)];

%% % ===================== Creating Subplots for All Metrics

S_S = get(0,'ScreenSize');
set(figure,'Position',[S_S(1) S_S(2) S_S(3) S_S(4)])

Axis_One = subplot(3,1,1);
bar([Comp_Time_Data(:,1) Comp_Time_Data(:,2)])
Y_Lim_One = ylim;
title('Comparison and Change of Completion Time with Respect to Expert
        Performance','FontSize',20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Time (s)', 'Fontsize', 15)
set(Axis_One, 'XTick', [1 2 3], 'FontSize', 13)
```

```
set(Axis_One, 'XTicklabel', {'Pick', 'Transfer', 'Place'})
legend('Expert', 'Subject', 'Location', 'Best')

Axis_Two = subplot(3,1,2);
bar([Path_Lengt_Data(:,1) Path_Lengt_Data(:,2)])
Y_Lim_Two = ylim;
title('Comparison and Change of Path Length with Respect to Expert        Performance',
'FontSize', 20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Path Length (m)', 'FontSize', 15)
set(Axis_Two,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_Two,'XTicklabel',{'Pick', 'Transfer', 'Place'})

Axis_Three = subplot(3,1,3);
bar([Err_Data(:,1) Err_Data(:,2)])
title('Comparison and Change of Error Accumulation with Respect to Expert        Performance',
'FontSize', 20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('# of Errors', 'FontSize', 15)
set(Axis_Three,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_Three,'XTicklabel',{'Pick', 'Transfer', 'Place'})

Y_Lim = [Y_Lim_One(2) Y_Lim_Two(2)];
Max_Y_Lim = max(Y_Lim);

   if abs(diff([Y_Lim(1) Y_Lim(2)])) <= 1
     if Max_Y_Lim == Y_Lim_One(2)
       linkaxes([Axis_One Axis_Two],'y')
     end
     if Max_Y_Lim == Y_Lim_Two(2)
       linkaxes([Axis_Two Axis_One],'y')
     end
   end

%% % ===================== Initializing Point & Click Feature

Y_1 = [Comp_Time_Data(1,1) Comp_Time_Data(1,2) Comp_Time_Data(2,1)
Comp_Time_Data(2,2) Comp_Time_Data(3,1) Comp_Time_Data(3,2)];
Y_2 = [Path_Lengt_Data(1,1) Path_Lengt_Data(1,2) Path_Lengt_Data(2,1)
Path_Lengt_Data(2,2) Path_Lengt_Data(3,1) Path_Lengt_Data(3,2)];
Y_3 = [Err_Data(1,1) Err_Data(1,2) Err_Data(2,1) Err_Data(2,2) Err_Data(3,1) Err_Data(3,2)];
Ret = Point_Click_One(Y_1, Y_2, Y_3);

%% % ===================== Returning Values to Complete the Function
```

```
Graph = 1;
```

Metric Set 2 (IDM, DMM, AA)

```
%% % ==================== Initializing Function for Graphics Set Two

function Graph = Metric_Set_Two_Vis(Sub_Data, Exprt_Data, Trial)

%% % ==================== Calling Data for Initial Angular Deviation

First_Ini_Dev_Data = [Exprt_Data(1:6,Trial) Sub_Data(1:6,Trial)];
Ini_Dev_Data = [First_Ini_Dev_Data(1:3,:) First_Ini_Dev_Data(4:6,:)];

%% % ==================== Calling Data for Angular Deviation at Max Velocity

First_Max_Dev_Data = [Exprt_Data(7:12,Trial) Sub_Data(7:12,Trial)];
Max_Dev_Data = [First_Max_Dev_Data(1:3,:) First_Max_Dev_Data(4:6,:)];

%% % ==================== Calling Data for Encompassed Area

Area_Data = [Exprt_Data(13:15,Trial) Sub_Data(13:15,Trial)];

%% % ==================== Creating Plots for Initial Angular Deviation

S_S = get(0,'ScreenSize');
set(figure,'Position',[S_S(1) S_S(2) S_S(3) S_S(4)])

Axis_One = subplot(3,1,1);
bar(Ini_Dev_Data)
title('Comparison and Change of Initial Angular Error with Respect to Expert      Performance',
'FontSize', 20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Angle (^{o})', 'FontSize', 15)
set(Axis_One,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_One,'XTicklabel',{'Pick', 'Transfer', 'Place'})
legend('Expert Elevation', 'Subject Elevation', 'Expert Azimuth', 'Subject          Azimuth',
'Orientation', 'Horizontal', 'Location', 'Best')

%% % ==================== Creating Plots for Angular Deviation at Max
                             Velocity
Axis_Two = subplot(3,1,2);
bar(Max_Dev_Data)
title('Comparison and Change of Angular Error at Max Speed with Respect to      Expert
Performance', 'FontSize', 20)
```

```
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Angle (^{o})', 'FontSize', 15)
set(Axis_Two,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_Two,'XTicklabel',{'Pick', 'Transfer', 'Place'})

%% % ==================== Creating a Surface Graphic for Arc Area

Axis_Three = subplot(3,1,3);
bar([Area_Data(:,1) Area_Data(:,2)])
title('Comparison and Change of Encompased Area with Respect to Expert
        Performance', 'FontSize', 20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Area (m^{2})', 'FontSize', 15)
set(Axis_Three,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_Three,'XTicklabel',{'Pick', 'Transfer', 'Place'})
legend('Expert', 'Subject', 'Location', 'Best')

%% % ==================== Initializing Point & Click Feature

Y_1 = [Ini_Dev_Data(1,1) Ini_Dev_Data(1,2) Ini_Dev_Data(1,3)
Ini_Dev_Data(1,4) Ini_Dev_Data(2,1) Ini_Dev_Data(2,2)
Ini_Dev_Data(2,3) Ini_Dev_Data(2,4) Ini_Dev_Data(3,1)
Ini_Dev_Data(3,2) Ini_Dev_Data(3,3) Ini_Dev_Data(3,4)];
Y_2 = [Max_Dev_Data(1,1) Max_Dev_Data(1,2) Max_Dev_Data(1,3)
Max_Dev_Data(1,4) Max_Dev_Data(2,1) Max_Dev_Data(2,2)
Max_Dev_Data(2,3) Max_Dev_Data(2,4) Max_Dev_Data(3,1)
Max_Dev_Data(3,2) Max_Dev_Data(3,3) Max_Dev_Data(3,4)];
Y_3 = [Area_Data(1,1) Area_Data(1,2) Area_Data(2,1) Area_Data(2,2)
Area_Data(3,1) Area_Data(3,2)];
Ret = Point_Click_Two(Y_1, Y_2, Y_3);

%% % ==================== Returning Values to Complete the Function

Graph = 1;
```

Metric Set 3 (CT, PL, Error)

```
%% % ==================== Initializing Function for Graphics Set One

function Graph = Metric_Set_Three_One_Vis(Sub_Data, Exprt_Data, Trial)

%% % ==================== Calling Data for Completion Time

Comp_Time_Data = [Exprt_Data(1:3,Trial) Sub_Data(1:3,Trial)];
```

```
%% % ===================== Calling Data for Path Length

Path_Lengt_Data = [Exprt_Data(4:6,Trial) Sub_Data(4:6,Trial)];

%% % ===================== Calling Data for Number of Errors

Err_Data = [Exprt_Data(7:9,Trial) Sub_Data(7:9,Trial)];

%% % ===================== Creating Subplots for All Metrics

S_S = get(0,'ScreenSize');
set(figure,'Position',[S_S(1) S_S(2) S_S(3) S_S(4)])

Axis_One = subplot(3,1,1);
Y_One = bar([Comp_Time_Data(:,1) Comp_Time_Data(:,2)]);
Y_Lim_One = ylim;
title('Comparison and Change of Completion Time with Respect to Expert
        Performance','FontSize',20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Time (s)', 'Fontsize', 15)
set(Axis_One, 'XTick', [1 2 3], 'FontSize', 13)
set(Axis_One, 'XTicklabel', {'Pick', 'Transfer', 'Place'})
legend('Expert', 'Subject', 'Location', 'Best')

Axis_Two = subplot(3,1,2);
Y_Two = bar([Path_Lengt_Data(:,1) Path_Lengt_Data(:,2)]);
Y_Lim_Two = ylim;
title('Comparison and Change of Path Length with Respect to Expert        Performance',
'FontSize', 20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('Path Length (m)', 'FontSize', 15)
set(Axis_Two,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_Two,'XTicklabel',{'Pick', 'Transfer', 'Place'})

Axis_Three = subplot(3,1,3);
Y_Three = bar([Err_Data(:,1) Err_Data(:,2)]);
title('Comparison and Change of Error Accumulation with Respect to Expert        Performance',
'FontSize', 20)
Lab_X = sprintf('Trial %d', Trial);
xlabel(Lab_X, 'FontSize', 15)
ylabel('# of Errors', 'FontSize', 15)
set(Axis_Three,'XTick', [1 2 3], 'FontSize', 13)
set(Axis_Three,'XTicklabel',{'Pick', 'Transfer', 'Place'})
```

```
Y_Lim = [Y_Lim_One(2) Y_Lim_Two(2)];
Max_Y_Lim = max(Y_Lim);

   if abs(diff([Y_Lim(1) Y_Lim(2)])) <= 1
     if Max_Y_Lim == Y_Lim_One(2)
        linkaxes([Axis_One Axis_Two],'y')
     end
     if Max_Y_Lim == Y_Lim_Two(2)
        linkaxes([Axis_Two Axis_One],'y')
     end
   end

%% % ===================== Initializing Point & Click Feature

Y_1 = [Comp_Time_Data(1,1) Comp_Time_Data(1,2) Comp_Time_Data(2,1)
Comp_Time_Data(2,2) Comp_Time_Data(3,1) Comp_Time_Data(3,2)];
Y_2 = [Path_Lengt_Data(1,1) Path_Lengt_Data(1,2) Path_Lengt_Data(2,1)
Path_Lengt_Data(2,2) Path_Lengt_Data(3,1) Path_Lengt_Data(3,2)];
Y_3 = [Err_Data(1,1) Err_Data(1,2) Err_Data(2,1) Err_Data(2,2) Err_Data(3,1)
Err_Data(3,2)];
Ret = Point_Click_Three_One(Y_1, Y_2, Y_3);

%% % ===================== Returning Values to Complete the Function

Graph = 1;
```

APPENDIX 5.3

Code for Allowing Subject-Graphic Interaction (Feedback Text Boxes)

Metric Set 1 (CT, PL, Error)

```
function Ret = Point_Click_One(Y_1, Y_2, Y_3)

K = 1;
R = 0;
T = text(0,0,'.');

while K == 1
   if R == 2
      T = text(0,0,'.');
   end
   R = 0;
   P = ginput(1);
   S_P = get(0, 'PointerLocation');

   if S_P(2) < 913 && S_P(2) > 877 && S_P(1) > 155 && S_P(1) < 1169 %Title 1
      delete(T)
      T = text(P(1),P(2),'Time taken to complete the trial');
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 625 && S_P(2) > 589 && S_P(1) > 103 && S_P(1) < 1220 %Title 2
      delete(T)
      T = text(P(1),P(2),{'Length of the traversed path of the tool','tip                    during the
trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 338 && S_P(2) > 301 && S_P(1) > 159 && S_P(1) < 1164 %Title 3
      delete(T)
      T = text(P(1),P(2),{'Number of drops or excessive collisions','during                 the trial'});
      set(T,'BackgroundColor', 'w')
```

```
  R = 1;
end

if S_P(2) < 885 && S_P(2) > 676 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 1
  delete(T)
```

```
    T = text(P(1),P(2),'Time measured in seconds');
    set(T,'BackgroundColor', 'w')
    R = 1;
  end
  if S_P(2) < 598 && S_P(2) > 389 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 2
    delete(T)
    T = text(P(1),P(2),'Path length measured in meters');
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 309 && S_P(2) > 100 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 3
    delete(T)
    T = text(P(1),P(2),'Total number of errors detected');
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 315 && S_P(1) < 348 || S_P(2)          < 394
&& S_P(2) > 374 && S_P(1) > 315 && S_P(1) < 348 || S_P(2) < 106                  && S_P(2) >
86 && S_P(1) > 315 && S_P(1) < 348 % Pick
    delete(T)
    T = text(P(1),P(2),'Motion used to pull an object from a tube');
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 629 && S_P(1) < 696 || S_P(2)          < 394
&& S_P(2) > 374 && S_P(1) > 629 && S_P(1) < 696 || S_P(2) < 106                  && S_P(2) >
86 && S_P(1) > 629 && S_P(1) < 696 % Transfer
    delete(T)
    T = text(P(1),P(2),{'Motion used to move an object from one','tube to                another'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 971 && S_P(1) < 1014 ||
S_P(2) < 394 && S_P(2) > 374 && S_P(1) > 971 && S_P(1) < 1014 ||              S_P(2) < 106
&& S_P(2) > 86 && S_P(1) > 971 && S_P(1) < 1014 % Place
    delete(T)
    T = text(P(1),P(2),{'Motion used to insert an object into','a tube'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end
```

```
  if S_P(2) < 662 && S_P(2) > 638 && S_P(1) > 632 && S_P(1) < 688 || S_P(2)        < 374
&& S_P(2) > 351 && S_P(1) > 632 && S_P(1) < 688 || S_P(2) < 86              && S_P(2) >
63 && S_P(1) > 632 && S_P(1) < 688 % X-Label
     delete(T)
     T = text(P(1),P(2),{'Division of the trial into three','different,              physical
motions'});
     set(T,'BackgroundColor', 'w')
     R = 1;
  end

  if P(2) < Y_1(1) && S_P(2) > 682 && S_P(2) < 877 && S_P(1) > 247 &&
S_P(1) < 322 || P(2) < Y_1(3) && S_P(2) > 682 && S_P(2) < 877 &&             S_P(1) > 577
&& S_P(1) < 653 || P(2) < Y_1(5) && S_P(2) > 682 &&            S_P(2) < 877 && S_P(1) >
908 && S_P(1) < 984 % Expert Time
     delete(T)
     T = text(P(1),P(2),{'Time for experts to complete','this specific                    motion for
this tree'});
     set(T,'BackgroundColor', 'w')
     R = 1;
  end

  if P(2) < Y_1(2) && S_P(2) > 682 && S_P(2) < 877 && S_P(1) > 341 &&
S_P(1) < 417 || P(2) < Y_1(4) && S_P(2) > 682 && S_P(2) < 877 &&             S_P(1) > 672
&& S_P(1) < 748 || P(2) < Y_1(6) && S_P(2) > 682 &&            S_P(2) < 877 && S_P(1) >
1003 && S_P(1) < 1078 % Subject Time
     delete(T)
     T = text(P(1),P(2),{'Time for you to complete this','specific motion                 for this
trial'});
     set(T,'BackgroundColor', 'w')
     R = 1;
  end

  if P(2) < Y_2(1) && S_P(2) > 394 && S_P(2) < 589 && S_P(1) > 247 && S_P(1) < 322 ||
P(2) < Y_2(3) && S_P(2) > 394 && S_P(2) < 589 && S_P(1) > 577 && S_P(1) < 653 || P(2) <
Y_2(5) && S_P(2) > 394 && S_P(2) < 589 && S_P(1) > 908 && S_P(1) < 984 % Expert Path
     delete(T)
     T = text(P(1),P(2),{'How far experts moved the tool','tip for this                   specific
motion','for this tree'});
     set(T,'BackgroundColor', 'w')
     R = 1;
  end

  if P(2) < Y_2(2) && S_P(2) > 394 && S_P(2) < 589 && S_P(1) > 341 &&
S_P(1) < 417 || P(2) < Y_2(4) && S_P(2) > 394 && S_P(2) < 589 &&             S_P(1) > 672
&& S_P(1) < 748 || P(2) < Y_2(6) && S_P(2) > 394 &&            S_P(2) < 589 && S_P(1) >
1003 && S_P(1) < 1078 % Subject Path
```

```
      delete(T)
      T = text(P(1),P(2),{'How far you moved the tool tip for','this                              specific
motion for this','trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if P(2) < Y_3(1) && S_P(2) > 106 && S_P(2) < 301 && S_P(1) > 247 &&
S_P(1) < 322 || P(2) < Y_3(3) && S_P(2) > 106 && S_P(2) < 301 &&                  S_P(1) > 577
&& S_P(1) < 653 || P(2) < Y_3(5) && S_P(2) > 106 &&                S_P(2) < 301 && S_P(1) >
908 && S_P(1) < 984 % Expert Err
      delete(T)
      T = text(P(1),P(2),{'Number of drops or excessive collisions','experts       committed during
this','specific motion for this tree'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if P(2) < Y_3(2) && S_P(2) > 106 && S_P(2) < 301 && S_P(1) > 341 &&
S_P(1) < 417 || P(2) < Y_3(4) && S_P(2) > 106 && S_P(2) < 301 &&                  S_P(1) > 672
&& S_P(1) < 748 || P(2) < Y_3(6) && S_P(2) > 106 &&                S_P(2) < 301 && S_P(1) >
1003 && S_P(1) < 1078 % Subject Err
      delete(T)
      T = text(P(1),P(2),{'Number of drops or excessive collisions
you','committed during this specific','motion for this trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(1) < 50 || S_P(1) > 1200 % Close Out
      K = 0;
      close
      R = 1;
   end
   if R == 0;
      delete(T)
      R = 2;
   end
end

Ret = 1;
```

Metric Set 2 (IDM, DMM, AA)

```
function Ret = Point_Click_Two(Y_1, Y_2, Y_3)
```

```
K = 1;
R = 0;
T = text(0,0,'.');

while K == 1
   if R == 2
     T = text(0,0,'.');
   end
   R = 0;
   P = ginput(1);
   S_P = get(0, 'PointerLocation');

   if S_P(2) < 913 && S_P(2) > 877 && S_P(1) > 155 && S_P(1) < 1169 %Title 1
     delete(T)
     T = text(P(1),P(2),{'Direction of initial velocity during the
trial','Estimate of initial intention for motions'});
     set(T,'BackgroundColor', 'w')
     R = 1;
   end

   if S_P(2) < 625 && S_P(2) > 589 && S_P(1) > 103 && S_P(1) < 1220 %Title 2
     delete(T)
     T = text(P(1),P(2),{'Direction of maximum velocity achieved during the
trial','Estimate of direction of motion at full confidence'});
     set(T,'BackgroundColor', 'w')
     R = 1;
   end

   if S_P(2) < 338 && S_P(2) > 301 && S_P(1) > 159 && S_P(1) < 1164 %Title 3
     delete(T)
     T = text(P(1),P(2),{'Amount of area encompassed by the swing of the                tool tip
during the trial','Estimate of swivel deviating from a                              straight line'});
     set(T,'BackgroundColor', 'w')
     R = 1;
   end

   if S_P(2) < 885 && S_P(2) > 676 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 1
     delete(T)
     T = text(P(1),P(2),{'Angular directions of initial velocity','measured         in degrees'});
     set(T,'BackgroundColor', 'w')
     R = 1;
   end

   if S_P(2) < 598 && S_P(2) > 389 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 2
     delete(T)
```

```
      T = text(P(1),P(2),{'Angular directions of maximum velocity','measured             in
degrees'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 309 && S_P(2) > 100 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 3
      delete(T)
      T = text(P(1),P(2),{'Area encompassed by the tools swing','measured in             meters
squared'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 315 && S_P(1) < 348 || S_P(2)
         < 394 && S_P(2) > 374 && S_P(1) > 315 && S_P(1) < 348 || S_P(2) < 106
&& S_P(2) > 86 && S_P(1) > 315 && S_P(1) < 348 % Pick
      delete(T)
      T = text(P(1),P(2),'Motion used to pull an object from a tube');
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 629 && S_P(1) < 696 || S_P(2)          < 394
&& S_P(2) > 374 && S_P(1) > 629 && S_P(1) < 696 || S_P(2) < 106                 && S_P(2) >
86 && S_P(1) > 629 && S_P(1) < 696 % Transfer
      delete(T)
      T = text(P(1),P(2),{'Motion used to move an object from one','tube to                another'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 971 && S_P(1) < 1014 ||
S_P(2) < 394 && S_P(2) > 374 && S_P(1) > 971 && S_P(1) < 1014 ||             S_P(2) < 106
&& S_P(2) > 86 && S_P(1) > 971 && S_P(1) < 1014 % Place
      delete(T)
      T = text(P(1),P(2),'Motion used to insert an object into a tube');
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 662 && S_P(2) > 638 && S_P(1) > 632 && S_P(1) < 688 || S_P(2)          < 374
&& S_P(2) > 351 && S_P(1) > 632 && S_P(1) < 688 || S_P(2) < 86                  && S_P(2) >
63 && S_P(1) > 632 && S_P(1) < 688 % X-Label
      delete(T)
```

```
    T = text(P(1),P(2),{'Division of the trial into three','different,                    physical
motions'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if P(2) < Y_1(1) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 218 &&
S_P(1) < 266 && P(2) > 0 || P(2) < Y_1(5) && S_P(2) > 780 && S_P(2) <                    877
&& S_P(1) > 548 && S_P(1) < 596 && P(2) > 0 || P(2) < Y_1(9) &&                  S_P(2) > 780
&& S_P(2) < 877 && S_P(1) > 879 && S_P(1) < 927 && P(2) >   0 || P(2) < Y_2(1) &&
S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 218 &&         S_P(1) < 266 && P(2) > 0 || P(2) <
Y_2(5) && S_P(2) > 492 && S_P(2) <                  589 && S_P(1) > 548 && S_P(1) < 596
&& P(2) > 0 || P(2) < Y_2(9) &&                S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 879
&& S_P(1) < 927 && P(2) >  0 % Expert Positive Elevation
    delete(T)
    T = text(P(1),P(2),{'Expert elevation. Ideal amount of
tilting/pulling','the tool tip up in the box. A straight upward                motion (90^{o})','will
move the tool tip to the upper-left corner                    of the screen.','A flat motion (0^{o}) will
move the tool tip                        to','the upper-right corner or lower-left corner.'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 780 && P(2) > Y_1(1) && S_P(2) > 682 && S_P(1) > 218 &&
S_P(1) < 266 && P(2) < 0 || S_P(2) < 780 && P(2) > Y_1(5) && S_P(2) >                    682
&& S_P(1) > 548 && S_P(1) < 596 && P(2) < 0 || S_P(2) < 780 &&                  P(2) > Y_1(9)
&& S_P(2) > 682 && S_P(1) > 879 && S_P(1) < 927 && P(2)              < 0 || S_P(2) < 492
&& P(2) > Y_2(1) && S_P(2) > 394 && S_P(1) > 218                && S_P(1) < 266 && P(2) <
0 || S_P(2) < 492 && P(2) > Y_2(5) && S_P(2)       > 394 && S_P(1) > 548 && S_P(1) < 596
&& P(2) < 0 || S_P(2) < 492 &&                  P(2) > Y_2(9) && S_P(2) > 394 && S_P(1) > 879
&& S_P(1) < 927 && P(2)              < 0 % Expert Negative Elevation
    delete(T)
    T = text(P(1),P(2),{'Expert declination. Ideal amount of
tilting/pushing','the tool tip down in the box. A straight                        downward motion
(-90^{o})','will move the tool tip to the lower-                    right corner of the screen.','A flat
motion (0^{o}) will move the                      tool tip to','the upper-right corner or lower-left
corner.'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if P(2) < Y_1(2) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 278 &&
S_P(1) < 326 && P(2) > 0 || P(2) < Y_1(6) && S_P(2) > 780 && S_P(2) <                    877
&& S_P(1) > 608 && S_P(1) < 656 && P(2) > 0 || P(2) < Y_1(10) &&                S_P(2) > 780
&& S_P(2) < 877 && S_P(1) > 939 && S_P(1) < 987 && P(2) >   0 || P(2) < Y_2(2) &&
S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 278 &&                S_P(1) < 326 && P(2) > 0 ||
```

```
P(2) < Y_2(6) && S_P(2) > 492 && S_P(2) <                   589 && S_P(1) > 608 && S_P(1) <
656 && P(2) > 0 || P(2) < Y_2(10) &&                  S_P(2) > 492 && S_P(2) < 589 && S_P(1)
> 939 && S_P(1) < 987 && P(2) >    0 % Subject Positive Elevation
      delete(T)
      T = text(P(1),P(2),{'Your elevation. Amount of tilting/pulling the                    tool tip','up
in the box you produced. A straight upward motion                 (90^{o})','will move the tool tip
to the upper-left corner of the                             screen.','A flat motion (0^{o}) will move the tool
tip to','the                     upper-right corner or lower-left corner.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if S_P(2) < 780 && P(2) > Y_1(2) && S_P(2) > 682 && S_P(1) > 278 &&
S_P(1) < 326 && P(2) < 0 || S_P(2) < 780 && P(2) > Y_1(6) && S_P(2) >                    682
&& S_P(1) > 608 && S_P(1) < 656 && P(2) < 0 || S_P(2) < 780 &&                  P(2) >
Y_1(10) && S_P(2) > 682 && S_P(1) > 939 && S_P(1) < 987 && P(2)    < 0 || S_P(2) < 492
&& P(2) > Y_2(2) && S_P(2) > 394 && S_P(1) > 278                 && S_P(1) < 326 && P(2) <
0 || S_P(2) < 492 && P(2) > Y_2(6) && S_P(2)       > 394 && S_P(1) > 608 && S_P(1) < 656
&& P(2) < 0 || S_P(2) < 492 &&                   P(2) > Y_2(10) && S_P(2) > 394 && S_P(1) >
939 && S_P(1) < 987 && P(2)         < 0 % Subject Negative Elevation
      delete(T)
      T = text(P(1),P(2),{'Your declination. Amount of tilting/pushing the                  tool
tip','down in the box you produced. A straight downward                   motion (-90^{o})','will
move the tool tip to the lower-right                     corner of the screen.','A flat motion (0^{o}) will
move the tool                tip to','the upper-right corner or lower-left corner.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if P(2) < Y_1(3) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 338 &&
S_P(1) < 386 && P(2) > 0 && P(2) < 90 && Y_1(3) < 90 || P(2) < Y_1(7)                   &&
S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 669 && S_P(1) < 717 &&             P(2) > 0 &&
P(2) < 90 && Y_1(7) < 90 || P(2) < Y_1(11) && S_P(2) > 780       && S_P(2) < 877 &&
S_P(1) > 999 && S_P(1) < 1047 && P(2) > 0 && P(2) <    90 && Y_1(11) < 90 || P(2) <
Y_2(3) && S_P(2) > 492 && S_P(2) < 589 &&      S_P(1) > 338 && S_P(1) < 386 && P(2) >
0 && P(2) < 90 && Y_2(3) < 90                || P(2) < Y_2(7) && S_P(2) > 492 && S_P(2) <
589 && S_P(1) > 669 &&              S_P(1) < 717 && P(2) > 0 && P(2) < 90 && Y_2(7) < 90
|| P(2) < Y_2(11)        && S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 999 && S_P(1) <
1047 &&                  P(2) > 0 && P(2) < 90 && Y_2(11) < 90 % Expert Left-Into Screen
                   Azimuth
      delete(T)
      T = text(P(1),P(2),{'Expert azimuth. Movement within a horizontal                  plane in the
box.','Moving the tool tip AWAY FROM and TO THE RIGHT          OF you (between 0^{o}
and 90^{o})','will show the tool tip on the                    LEFT side of','the screen moving INTO
it.'});
      set(T,'BackgroundColor', 'w')
```

```
        R = 1;
    end

    if P(2) < Y_1(3) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 338 &&
S_P(1) < 386 && P(2) < 180 && Y_1(3) > 90 || P(2) < Y_1(7) && S_P(2) >        780 &&
S_P(2) < 877 && S_P(1) > 669 && S_P(1) < 717 && P(2) < 180 &&                 Y_1(7) > 90 ||
P(2) < Y_1(11) && S_P(2) > 780 && S_P(2) < 877 &&                S_P(1) > 999 && S_P(1) <
1047 && P(2) < 180 && Y_1(11) > 90 || P(2) <                Y_2(3) && S_P(2) > 492 &&
S_P(2) < 589 && S_P(1) > 338 && S_P(1) < 386     && P(2) < 180 && Y_2(3) > 90 || P(2) <
Y_2(7) && S_P(2) > 492 &&                  S_P(2) < 589 && S_P(1) > 669 && S_P(1) < 717
&& P(2) < 180 && Y_2(7) >            90 || P(2) < Y_2(11) && S_P(2) > 492 && S_P(2) < 589
&& S_P(1) > 999                 && S_P(1) < 1047 && P(2) < 180 && Y_2(11) > 90 % Expert
Left-Out                    Screen Azimuth
        delete(T)
        T = text(P(1),P(2),{'Expert azimuth. Movement within a horizontal                    plane in the
box.','Moving the tool tip AWAY FROM and TO THE LEFT                      OF you (between
90^{o} and 180^{o})','will show the tool tip on                     the LEFT side of','the screen
moving OUT OF it.'});
        set(T,'BackgroundColor', 'w')
        R = 1;
    end

    if S_P(2) < 780 && P(2) > Y_1(3) && S_P(2) > 682 && S_P(1) > 338 &&
S_P(1) < 386 && P(2) < 0 && P(2) > -90 && Y_1(3) > -90 || S_P(2) < 780         && P(2) >
Y_1(7) && S_P(2) > 682 && S_P(1) > 669 && S_P(1) < 717 &&                     P(2) < 0 &&
P(2) > -90 && Y_1(7) > -90 || S_P(2) < 780 && P(2) >                 Y_1(11) && S_P(2) > 682
&& S_P(1) > 999 && S_P(1) < 1047 && P(2) < 0             && P(2) > -90 && Y_1(11) > -90 ||
S_P(2) < 492 && P(2) > Y_2(3) &&                    S_P(2) > 394 && S_P(1) > 338 && S_P(1)
< 386 && P(2) < 0 && P(2) > -90      && Y_2(3) > -90 || S_P(2) < 492 && P(2) > Y_2(7) &&
S_P(2) > 394 &&                 S_P(1) > 669 && S_P(1) < 717 && P(2) < 0 && P(2) > -90 &&
Y_2(7) > -90    || S_P(2) < 492 && P(2) > Y_2(11) && S_P(2) > 394 && S_P(1) > 999 &&
            S_P(1) < 1047 && P(2) < 0 && P(2) > -90 && Y_2(11) > -90 % Expert             Right-
Into Screen Azimuth
        delete(T)
        T = text(P(1),P(2),{'Expert azimuth. Movement within a horizontal                    plane in the
box.','Moving the tool tip INTO and TO THE RIGHT OF                  you (between 0^{o} and -
90^{o})','will show the tool tip on the                          RIGHT side of','the screen moving INTO
it.'});
        set(T,'BackgroundColor', 'w')
        R = 1;
    end

    if S_P(2) < 780 && P(2) > Y_1(3) && S_P(2) > 682 && S_P(1) > 338 &&
S_P(1) < 386 && P(2) > -180 && Y_1(3) < -90 || S_P(2) < 780 && P(2) >
Y_1(7) && S_P(2) > 682 && S_P(1) > 669 && S_P(1) < 717 && P(2) > -180              &&
Y_1(7) < -90 || S_P(2) < 780 && P(2) > Y_1(11) && S_P(2) > 682 &&              S_P(1) > 999
```

```
&& S_P(1) < 1047 && P(2) > -180 && Y_1(11) < -90 ||                S_P(2) < 492 && P(2) >
Y_2(3) && S_P(2) > 394 && S_P(1) > 338 &&                S_P(1) < 386 && P(2) > -180 &&
Y_2(3) < -90 || S_P(2) < 492 && P(2) >                Y_2(7) && S_P(2) > 394 && S_P(1) > 669
&& S_P(1) < 717 && P(2) > -180                && Y_2(7) < -90 || S_P(2) < 492 && P(2) >
Y_2(11) && S_P(2) > 394 &&                S_P(1) > 999 && S_P(1) < 1047 && P(2) > -180
&& Y_2(11) < -90 % Expert   Right-Out Screen Azimuth
      delete(T)
      T = text(P(1),P(2),{'Expert azimuth. Movement within a horizontal                plane in the
box.','Moving the tool tip INTO and TO THE LEFT OF                you (between -90^{o} and
-180^{o})','will show the tool tip on the                RIGHT side of','the screen moving OUT OF
it.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if P(2) < Y_1(4) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 398 &&
           S_P(1) < 446 && P(2) > 0 && P(2) < 90 && Y_1(4) < 90 || P(2) < Y_1(8)
&& S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 729 && S_P(1) < 777 &&                P(2) >
0 && P(2) < 90 && Y_1(8) < 90 || P(2) < Y_1(12) && S_P(2) > 780        && S_P(2) < 877
&& S_P(1) > 1059 && S_P(1) < 1107 && P(2) > 0 && P(2)                < 90 && Y_1(12) <
90 || P(2) < Y_2(4) && S_P(2) > 492 && S_P(2) < 589                && S_P(1) > 398 &&
S_P(1) < 446 && P(2) > 0 && P(2) < 90 && Y_2(4) <                90 || P(2) < Y_2(8) &&
S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 729 &&        S_P(1) < 777 && P(2) > 0 && P(2)
< 90 && Y_2(8) < 90 || P(2) < Y_2(12)        && S_P(2) > 492 && S_P(2) < 589 && S_P(1) >
1059 && S_P(1) < 1107 &&            P(2) > 0 && P(2) < 90 && Y_2(12) < 90 % Subject Left-
Into Screen                Azimuth
      delete(T)
      T = text(P(1),P(2),{'Your azimuth. Movement within a horizontal plane
            in the box.','Moving the tool tip AWAY FROM and TO THE RIGHT OF
you (between 0^{o} and 90^{o})','will show the tool tip on the                LEFT side of','the
screen moving INTO it.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
   end

   if P(2) < Y_1(4) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 398 &&
           S_P(1) < 446 && P(2) < 180 && Y_1(4) > 90 || P(2) < Y_1(8) && S_P(2) >
           780 && S_P(2) < 877 && S_P(1) > 729 && S_P(1) < 777 && P(2) < 180 &&
           Y_1(8) > 90 || P(2) < Y_1(12) && S_P(2) > 780 && S_P(2) < 877 &&
           S_P(1) > 1059 && S_P(1) < 1107 && P(2) < 180 && Y_1(12) > 90 || P(2) <
           Y_2(4) && S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 398 && S_P(1) < 446
           && P(2) < 180 && Y_2(4) > 90 || P(2) < Y_2(8) && S_P(2) > 492 &&
           S_P(2) < 589 && S_P(1) > 729 && S_P(1) < 777 && P(2) < 180 && Y_2(8) >
           90 || P(2) < Y_2(12) && S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 1059
           && S_P(1) < 1107 && P(2) < 180 && Y_2(12) > 90 % Subject Left-Out
           Screen Azimuth
```

```
    delete(T)
    T = text(P(1),P(2),{'Your azimuth. Movement within a horizontal plane
          in the box.','Moving the tool tip AWAY FROM and TO THE LEFT OF you
          (between 90^{o} and 180^{o})','will show the tool tip on the LEFT
          side of','the screen moving OUT OF it.'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 780 && P(2) > Y_1(4) && S_P(2) > 682 && S_P(1) > 398 &&
        S_P(1) < 446 && P(2) < 0 && P(2) > -90 && Y_1(4) > -90 || S_P(2) < 780
        && P(2) > Y_1(8) && S_P(2) > 682 && S_P(1) > 729 && S_P(1) < 777 &&
        P(2) < 0 && P(2) > -90 && Y_1(8) > -90 || S_P(2) < 780 && P(2) >
        Y_1(12) && S_P(2) > 682 && S_P(1) > 1059 && S_P(1) < 1107 && P(2) < 0
        && P(2) > -90 && Y_1(12) > -90 || S_P(2) < 492 && P(2) > Y_2(4) &&
        S_P(2) > 394 && S_P(1) > 398 && S_P(1) < 446 && P(2) < 0 && P(2) > -90
        && Y_2(4) > -90 || S_P(2) < 492 && P(2) > Y_2(8) && S_P(2) > 394 &&
        S_P(1) > 729 && S_P(1) < 777 && P(2) < 0 && P(2) > -90 && Y_2(8) > -90
        || S_P(2) < 492 && P(2) > Y_2(12) && S_P(2) > 394 && S_P(1) > 1059 &&
        S_P(1) < 1107 && P(2) < 0 && P(2) > -90 && Y_2(12) > -90 % Subject
        Right-Into Screen Azimuth
    delete(T)
    T = text(P(1),P(2),{'Your azimuth. Movement within a horizontal plane
          in the box.','Moving the tool tip INTO and TO THE RIGHT OF you
          (between 0^{o} and -90^{o})','will show the tool tip on the RIGHT                side
of','the screen moving INTO it.'});
    set(T,'BackgroundColor', 'w')
    R = 1;
  end

  if S_P(2) < 780 && P(2) > Y_1(4) && S_P(2) > 682 && S_P(1) > 398 &&
        S_P(1) < 446 && P(2) > -180 && Y_1(4) < -90 || S_P(2) < 780 && P(2) >
        Y_1(8) && S_P(2) > 682 && S_P(1) > 729 && S_P(1) < 777 && P(2) > -180
        && Y_1(8) < -90 || S_P(2) < 780 && P(2) > Y_1(12) && S_P(2) > 682 &&
        S_P(1) > 1059 && S_P(1) < 1107 && P(2) > -180 && Y_1(12) < -90 ||
        S_P(2) < 492 && P(2) > Y_2(4) && S_P(2) > 394 && S_P(1) > 398 &&
        S_P(1) < 446 && P(2) > -180 && Y_2(4) < -90 || S_P(2) < 492 && P(2) >
        Y_2(8) && S_P(2) > 394 && S_P(1) > 729 && S_P(1) < 777 && P(2) > -180
        && Y_2(8) < -90 || S_P(2) < 492 && P(2) > Y_2(12) && S_P(2) > 394 &&
        S_P(1) > 1059 && S_P(1) < 1107 && P(2) > -180 && Y_2(12) < -90 %
        Subject Right-Out Screen Azimuth
    delete(T)
    T = text(P(1),P(2),{'Your azimuth. Movement within a horizontal plane
          in the box.','Moving the tool tip INTO and TO THE LEFT OF you
          (between -90^{o} and -180^{o})','will show the tool tip on the
          RIGHT side of','the screen moving OUT OF it.'});
```

```
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < .001 && P(2) > -.001 && S_P(1) > 218 && S_P(1) < 266 && Y_1(1)
      < .001 && Y_1(1) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) >
      548 && S_P(1) < 596 && Y_1(5) < .001 && Y_1(5) > -.001 || P(2) < .001
      && P(2) > -.001 && S_P(1) > 879 && S_P(1) < 927 && Y_1(9) < .001 &&
      Y_1(9) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 218 &&
      S_P(1) < 266 && Y_2(1) < .001 && Y_2(1) > -.001 || P(2) < .001 && P(2)
      > -.001 && S_P(1) > 548 && S_P(1) < 596 && Y_2(5) < .001 && Y_2(5) > -
      .001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 879 && S_P(1) < 927 &&
      Y_2(9) < .001 && Y_2(9) > -.001 % Expert Elevation of 0
  delete(T)
  T = text(P(1),P(2),{'Expert elevation of 0^{o}.','A completely flat
        motion.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < .001 && P(2) > -.001 && S_P(1) > 278 && S_P(1) < 326 && Y_1(2)
      < .001 && Y_1(2) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) >
      608 && S_P(1) < 656 && Y_1(6) < .001 && Y_1(6) > -.001 || P(2) < .001
      && P(2) > -.001 && S_P(1) > 939 && S_P(1) < 987 && Y_1(10) < .001 &&
      Y_1(10) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 278 &&
      S_P(1) < 326 && Y_2(2) < .001 && Y_2(2) > -.001 || P(2) < .001 && P(2)
      > -.001 && S_P(1) > 608 && S_P(1) < 656 && Y_2(6) < .001 && Y_2(6) > -
      .001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 939 && S_P(1) < 987 &&
      Y_2(10) < .001 && Y_2(10) > -.001 % Subject Elevation of 0
  delete(T)
  T = text(P(1),P(2),{'Your elevation of 0^{o}.','Acompletely flat
        motion.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < .001 && P(2) > -.001 && S_P(1) > 338 && S_P(1) < 386 && Y_1(3)
      < .001 && Y_1(3) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) >
      669 && S_P(1) < 717 && Y_1(7) < .001 && Y_1(7) > -.001 || P(2) < .001
      && P(2) > -.001 && S_P(1) > 999 && S_P(1) < 1047 && Y_1(11) < .001 &&
      Y_1(11) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 338 &&
      S_P(1) < 386 && Y_2(3) < .001 && Y_2(3) > -.001 || P(2) < .001 && P(2)
      > -.001 && S_P(1) > 669 && S_P(1) < 717 && Y_2(7) < .001 && Y_2(7) > -
      .001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 999 && S_P(1) < 1047
      && Y_2(11) < .001 && Y_2(11) > -.001 % Expert Azimuth of 0 Angle
  delete(T)
```

```
  T = text(P(1),P(2),{'Expert azimuth of 0^{o}. Tool tip moves
        along','the VERTICAL CENTER of the screen,','moving INTO it.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < .001 && P(2) > -.001 && S_P(1) > 398 && S_P(1) < 446 && Y_1(4)
      < .001 && Y_1(4) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) >
      729 && S_P(1) < 777 && Y_1(8) < .001 && Y_1(8) > -.001 || P(2) < .001
      && P(2) > -.001 && S_P(1) > 1059 && S_P(1) < 1107 && Y_1(12) < .001 &&
      Y_1(12) > -.001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 398 &&
      S_P(1) < 446 && Y_2(4) < .001 && Y_2(4) > -.001 || P(2) < .001 && P(2)
      > -.001 && S_P(1) > 729 && S_P(1) < 777 && Y_2(8) < .001 && Y_2(8) > -
      .001 || P(2) < .001 && P(2) > -.001 && S_P(1) > 1059 && S_P(1) < 1107
      && Y_2(12) < .001 && Y_2(12) > -.001 % Subject Azimuth of 0 Angle
  delete(T)
  T = text(P(1),P(2),{'Your azimuth of 0^{o}. Tool tip moves along','the
        VERTICAL CENTER of the screen,','moving INTO it.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < Y_1(3) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 338 &&
      S_P(1) < 386 && Y_1(3) == 90 || P(2) < Y_1(7) && S_P(2) > 780 &&
      S_P(2) < 877 && S_P(1) > 669 && S_P(1) < 717 && Y_1(7) == 90 || P(2) <
      Y_1(11) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 999 && S_P(1) <
      1047 && Y_1(11) == 90 || P(2) < Y_2(3) && S_P(2) > 492 && S_P(2) < 589
      && S_P(1) > 338 && S_P(1) < 386 && Y_2(3) == 90 || P(2) < Y_2(7) &&
      S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 669 && S_P(1) < 717 && Y_2(7)
      == 90 || P(2) < Y_2(11) && S_P(2) > 492 && S_P(2) < 589 && S_P(1) >
      999 && S_P(1) < 1047 && Y_2(11) == 90 % Expert Azimuth of 90 Angle
  delete(T)
  T = text(P(1),P(2),{'Expert azimuth of 90^{o}. Tool tip moves
        along','the HORIZONTAL CENTER of the screen','and to the LEFT.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < Y_1(4) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 338 &&
      S_P(1) < 386 && Y_1(4) == 90 || P(2) < Y_1(8) && S_P(2) > 780 &&
      S_P(2) < 877 && S_P(1) > 669 && S_P(1) < 717 && Y_1(8) == 90 || P(2) <
      Y_1(12) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 999 && S_P(1) <
      1047 && Y_1(12) == 90 || P(2) < Y_2(4) && S_P(2) > 492 && S_P(2) < 589
      && S_P(1) > 338 && S_P(1) < 386 && Y_2(4) == 90 || P(2) < Y_2(8) &&
      S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 669 && S_P(1) < 717 && Y_2(8)
      == 90 || P(2) < Y_2(12) && S_P(2) > 492 && S_P(2) < 589 && S_P(1) >
```

```
      999 && S_P(1) < 1047 && Y_2(12) == 90 % Subject Azimuth of 90 Angle
  delete(T)
  T = text(P(1),P(2),{'Your azimuth of 90^{o}. Tool tip moves
        along','the HORIZONTAL CENTER of the screen','and to the LEFT.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) > Y_1(3) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 338 &&
      S_P(1) < 386 && Y_1(3) == -90 || P(2) > Y_1(7) && S_P(2) < 780 &&
      S_P(2) > 682 && S_P(1) > 669 && S_P(1) < 717 && Y_1(7) == -90 || P(2)
      > Y_1(11) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 999 && S_P(1) <
      1047 && Y_1(11) == -90 || P(2) > Y_2(3) && S_P(2) < 492 && S_P(2) >
      394 && S_P(1) > 338 && S_P(1) < 386 && Y_2(3) == -90 || P(2) > Y_2(7)
      && S_P(2) < 492 && S_P(2) > 394 && S_P(1) > 669 && S_P(1) < 717 &&
      Y_2(7) == -90 || P(2) > Y_2(11) && S_P(2) < 492 && S_P(2) > 394 &&
      S_P(1) > 999 && S_P(1) < 1047 && Y_2(11) == -90 % Expert Azimuth of –
      90 Angle
  delete(T)
  T = text(P(1),P(2),{'Expert azimuth of -90^{o}. Tool tip moves
        along','the HORIZONTAL CENTER of the screen','and to the
        RIGHT.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) > Y_1(4) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 338 &&
      S_P(1) < 386 && Y_1(4) == -90 || P(2) > Y_1(8) && S_P(2) < 780 &&
      S_P(2) > 682 && S_P(1) > 669 && S_P(1) < 717 && Y_1(8) == -90 || P(2)
      > Y_1(12) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 999 && S_P(1) <
      1047 && Y_1(12) == -90 || P(2) > Y_2(4) && S_P(2) < 492 && S_P(2) >
      394 && S_P(1) > 338 && S_P(1) < 386 && Y_2(4) == -90 || P(2) > Y_2(8)
      && S_P(2) < 492 && S_P(2) > 394 && S_P(1) > 669 && S_P(1) < 717 &&
      Y_2(8) == -90 || P(2) > Y_2(12) && S_P(2) < 492 && S_P(2) > 394 &&
      S_P(1) > 999 && S_P(1) < 1047 && Y_2(12) == -90 % Subject Azimuth of –
      90 Angle
  delete(T)
  T = text(P(1),P(2),{'Your azimuth of -90^{o}. Tool tip moves
      along','the HORIZONTAL CENTER of the screen','and to the RIGHT.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < Y_1(3) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 338 &&
     S_P(1) < 386 && Y_1(3) == 180 || P(2) < Y_1(7) && S_P(2) > 780 &&
      S_P(2) < 877 && S_P(1) > 669 && S_P(1) < 717 && Y_1(7) == 180 || P(2)
```

```
    < Y_1(11) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 999 && S_P(1) <
    1047 && Y_1(11) == 180 || P(2) < Y_2(3) && S_P(2) > 492 && S_P(2) <
    589 && S_P(1) > 338 && S_P(1) < 386 && Y_2(3) == 180 || P(2) < Y_2(7)
    && S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 669 && S_P(1) < 717 &&
    Y_2(7) == 180 || P(2) < Y_2(11) && S_P(2) > 492 && S_P(2) < 589 &&
    S_P(1) > 999 && S_P(1) < 1047 && Y_2(11) == 180 % Expert Azimuth of
    180 Angle
  delete(T)
  T = text(P(1),P(2),{'Expert azimuth of 180^{o}. Tool tip moves
      along','the VERTICAL CENTER of the screen,','moving OUT OF it.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) < Y_1(4) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 338 &&
    S_P(1) < 386 && Y_1(4) == 180 || P(2) < Y_1(8) && S_P(2) > 780 &&
    S_P(2) < 877 && S_P(1) > 669 && S_P(1) < 717 && Y_1(8) == 180 || P(2)
    < Y_1(12) && S_P(2) > 780 && S_P(2) < 877 && S_P(1) > 999 && S_P(1) <
    1047 && Y_1(12) == 180 || P(2) < Y_2(4) && S_P(2) > 492 && S_P(2) <
    589 && S_P(1) > 338 && S_P(1) < 386 && Y_2(4) == 180 || P(2) < Y_2(8)
    && S_P(2) > 492 && S_P(2) < 589 && S_P(1) > 669 && S_P(1) < 717 &&
    Y_2(8) == 180 || P(2) < Y_2(12) && S_P(2) > 492 && S_P(2) < 589 &&
    S_P(1) > 999 && S_P(1) < 1047 && Y_2(12) == 180 % Subject Azimuth of
    180 Angle
  delete(T)
  T = text(P(1),P(2),{'Your azimuth of 180^{o}. Tool tip moves
      along','the VERTICAL CENTER of the screen,','moving OUT OF it.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if P(2) > Y_1(3) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 338 &&
    S_P(1) < 386 && Y_1(3) == -180 || P(2) > Y_1(7) && S_P(2) < 780 &&
    S_P(2) > 682 && S_P(1) > 669 && S_P(1) < 717 && Y_1(7) == -180 || P(2)
    > Y_1(11) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 999 && S_P(1) <
    1047 && Y_1(11) == -180 || P(2) > Y_2(3) && S_P(2) < 492 && S_P(2) >
    394 && S_P(1) > 338 && S_P(1) < 386 && Y_2(3) == -180 || P(2) > Y_2(7)
    && S_P(2) < 492 && S_P(2) > 394 && S_P(1) > 669 && S_P(1) < 717 &&
    Y_2(7) == -180 || P(2) > Y_2(11) && S_P(2) < 492 && S_P(2) > 394 &&
    S_P(1) > 999 && S_P(1) < 1047 && Y_2(11) == -180 % Expert Azimuth of –
    180 Angle
  delete(T)
  T = text(P(1),P(2),{'Expert azimuth of -180^{o}. Tool tip moves
      along','the VERTICAL CENTER of the screen,','moving OUT OF it.'});
  set(T,'BackgroundColor', 'w')
  R = 1;
```

```
    end

    if P(2) > Y_1(4) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 338 &&
            S_P(1) < 386 && Y_1(4) == -180 || P(2) > Y_1(8) && S_P(2) < 780 &&
            S_P(2) > 682 && S_P(1) > 669 && S_P(1) < 717 && Y_1(8) == -180 || P(2)       >
Y_1(12) && S_P(2) < 780 && S_P(2) > 682 && S_P(1) > 999 && S_P(1) <
            1047 && Y_1(12) == -180 || P(2) > Y_2(4) && S_P(2) < 492 && S_P(2) >
            394 && S_P(1) > 338 && S_P(1) < 386 && Y_2(4) == -180 || P(2) > Y_2(8)
            && S_P(2) < 492 && S_P(2) > 394 && S_P(1) > 669 && S_P(1) < 717 &&
            Y_2(8) == -180 || P(2) > Y_2(12) && S_P(2) < 492 && S_P(2) > 394 &&
            S_P(1) > 999 && S_P(1) < 1047 && Y_2(12) == -180 % Subject Azimuth of
            -180 Angle
      delete(T)
      T = text(P(1),P(2),{'Your azimuth of -180^{o}. Tool tip moves
              along','the VERTICAL CENTER of the screen,','moving OUT OF it.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if P(2) < Y_3(1) && S_P(2) > 106 && S_P(2) < 301 && S_P(1) > 247 &&
            S_P(1) < 322 || P(2) < Y_3(3) && S_P(2) > 106 && S_P(2) < 301 &&
            S_P(1) > 577 && S_P(1) < 653 || P(2) < Y_3(5) && S_P(2) > 106 &&
            S_P(2) < 301 && S_P(1) > 908 && S_P(1) < 984 % Expert Area
      delete(T)
      T = text(P(1),P(2),{'Expert arc area encompassed. More swing in','tool
            tip motion increases arc area.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if P(2) < Y_3(2) && S_P(2) > 106 && S_P(2) < 301 && S_P(1) > 341 &&
            S_P(1) < 417 || P(2) < Y_3(4) && S_P(2) > 106 && S_P(2) < 301 &&
            S_P(1) > 672 && S_P(1) < 748 || P(2) < Y_3(6) && S_P(2) > 106 &&
            S_P(2) < 301 && S_P(1) > 1003 && S_P(1) < 1078 % Subject Area
      delete(T)
      T = text(P(1),P(2),{'Your arc area encompassed. More swing in','tool
              tip motion increases arc area.'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if S_P(1) < 50 || S_P(1) > 1200 % Close Out
      K = 0;
      close
      R = 1;
    end
```

```
    if R == 0;
      delete(T)
      R = 2;
    end
end

Ret = 1;
```

Metric Set 3 (CT, PL, Error)

```
function Ret = Point_Click_Three_One(Y_1, Y_2, Y_3)

K = 1;
R = 0;
T = text(0,0,'.');

while K == 1
    if R == 2
      T = text(0,0,'.');
    end
    R = 0;
    P = ginput(1);
    S_P = get(0, 'PointerLocation');

    if S_P(2) < 913 && S_P(2) > 877 && S_P(1) > 155 && S_P(1) < 1169 %Title 1
      delete(T)
      T = text(P(1),P(2),'Time taken to complete the trial');
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if S_P(2) < 625 && S_P(2) > 589 && S_P(1) > 103 && S_P(1) < 1220 %Title 2
      delete(T)
      T = text(P(1),P(2),{'Length of the traversed path of the tool','tip
            during the trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if S_P(2) < 338 && S_P(2) > 301 && S_P(1) > 159 && S_P(1) < 1164 %Title 3
      delete(T)
      T = text(P(1),P(2),{'Number of drops or excessive collisions','during
            the trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
```

```
end

if S_P(2) < 885 && S_P(2) > 676 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 1
  delete(T)
  T = text(P(1),P(2),'Time measured in seconds');
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if S_P(2) < 598 && S_P(2) > 389 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 2
  delete(T)
  T = text(P(1),P(2),'Path length measured in meters');
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if S_P(2) < 309 && S_P(2) > 100 && S_P(1) > 97 && S_P(1) < 167 %Y-Label 3
  delete(T)
  T = text(P(1),P(2),'Total number of errors detected');
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 315 && S_P(1) < 348 || S_P(2)
      < 394 && S_P(2) > 374 && S_P(1) > 315 && S_P(1) < 348 || S_P(2) < 106
      && S_P(2) > 86 && S_P(1) > 315 && S_P(1) < 348 % Pick
  delete(T)
  T = text(P(1),P(2),'Motion used to pull an object from a tube');
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 629 && S_P(1) < 696 || S_P(2)
      < 394 && S_P(2) > 374 && S_P(1) > 629 && S_P(1) < 696 || S_P(2) < 106
      && S_P(2) > 86 && S_P(1) > 629 && S_P(1) < 696 % Transfer
  delete(T)
  T = text(P(1),P(2),{'Motion used to move an object from one tube','to
         another'});
  set(T,'BackgroundColor', 'w')
  R = 1;
end

if S_P(2) < 682 && S_P(2) > 662 && S_P(1) > 971 && S_P(1) < 1014 ||
      S_P(2) < 394 && S_P(2) > 374 && S_P(1) > 971 && S_P(1) < 1014 ||
      S_P(2) < 106 && S_P(2) > 86 && S_P(1) > 971 && S_P(1) < 1014 % Place
  delete(T)
```

```
    T = text(P(1),P(2),'Motion used to insert an object into a tube');
    set(T,'BackgroundColor', 'w')
    R = 1;
end

if S_P(2) < 662 && S_P(2) > 638 && S_P(1) > 632 && S_P(1) < 688 || S_P(2)
        < 374 && S_P(2) > 351 && S_P(1) > 632 && S_P(1) < 688 || S_P(2) < 86
        && S_P(2) > 63 && S_P(1) > 632 && S_P(1) < 688 % X-Label
    delete(T)
    T = text(P(1),P(2),{'Division of the trial into three','different,
            physical motions'});
    set(T,'BackgroundColor', 'w')
    R = 1;
end

if P(2) < Y_1(1) && S_P(2) > 682 && S_P(2) < 877 && S_P(1) > 247 &&
        S_P(1) < 322 || P(2) < Y_1(3) && S_P(2) > 682 && S_P(2) < 877 &&
        S_P(1) > 577 && S_P(1) < 653 || P(2) < Y_1(5) && S_P(2) > 682 &&
        S_P(2) < 877 && S_P(1) > 908 && S_P(1) < 984 % Expert Time
    delete(T)
    T = text(P(1),P(2),{'Time for experts to complete','this specific
            motion for this trial'});
    set(T,'BackgroundColor', 'w')
    R = 1;
end

if P(2) < Y_1(2) && S_P(2) > 682 && S_P(2) < 877 && S_P(1) > 341 &&
        S_P(1) < 417 || P(2) < Y_1(4) && S_P(2) > 682 && S_P(2) < 877 &&
        S_P(1) > 672 && S_P(1) < 748 || P(2) < Y_1(6) && S_P(2) > 682 &&
        S_P(2) < 877 && S_P(1) > 1003 && S_P(1) < 1078 % Subject Time
    delete(T)
    T = text(P(1),P(2),{'Time for you to complete this','specific motion
            for this trial'});
    set(T,'BackgroundColor', 'w')
    R = 1;
end

if P(2) < Y_2(1) && S_P(2) > 394 && S_P(2) < 589 && S_P(1) > 247 &&
        S_P(1) < 322 || P(2) < Y_2(3) && S_P(2) > 394 && S_P(2) < 589 &&
        S_P(1) > 577 && S_P(1) < 653 || P(2) < Y_2(5) && S_P(2) > 394 &&
        S_P(2) < 589 && S_P(1) > 908 && S_P(1) < 984 % Expert Path
    delete(T)
    T = text(P(1),P(2),{'How far experts moved the tool tip','for this
            specific motion for','this trial'});
    set(T,'BackgroundColor', 'w')
    R = 1;
```

```
    end

    if P(2) < Y_2(2) && S_P(2) > 394 && S_P(2) < 589 && S_P(1) > 341 &&
            S_P(1) < 417 || P(2) < Y_2(4) && S_P(2) > 394 && S_P(2) < 589 &&
            S_P(1) > 672 && S_P(1) < 748 || P(2) < Y_2(6) && S_P(2) > 394 &&
            S_P(2) < 589 && S_P(1) > 1003 && S_P(1) < 1078 % Subject Path
      delete(T)
      T = text(P(1),P(2),{'How far you moved the tool tip for
              this','specific motion for this','trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if P(2) < Y_3(1) && S_P(2) > 106 && S_P(2) < 301 && S_P(1) > 247 &&
            S_P(1) < 322 || P(2) < Y_3(3) && S_P(2) > 106 && S_P(2) < 301 &&
            S_P(1) > 577 && S_P(1) < 653 || P(2) < Y_3(5) && S_P(2) > 106 &&
            S_P(2) < 301 && S_P(1) > 908 && S_P(1) < 984 % Expert Err
      delete(T)
      T = text(P(1),P(2),{'Number of drops or excessive collisions','experts
              committed during this','specific motion for this trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if P(2) < Y_3(2) && S_P(2) > 106 && S_P(2) < 301 && S_P(1) > 341 &&
            S_P(1) < 417 || P(2) < Y_3(4) && S_P(2) > 106 && S_P(2) < 301 &&
            S_P(1) > 672 && S_P(1) < 748 || P(2) < Y_3(6) && S_P(2) > 106 &&
            S_P(2) < 301 && S_P(1) > 1003 && S_P(1) < 1078 % Subject Err
      delete(T)
      T = text(P(1),P(2),{'Number of drops or excessive collisions
              you','committed during this specific','motion for this trial'});
      set(T,'BackgroundColor', 'w')
      R = 1;
    end

    if S_P(1) < 50 || S_P(1) > 1200 % Close Out
      K = 0;
      close
      R = 1;
    end
    if R == 0;
      delete(T)
      R = 2;
    end
end
```

```
Ret = 1;
```