AN ABSTRACT OF THE THESIS OF

Patricia B. Zárate for the degree of Master of Science in Industrial Engineering presented on January 13, 1997. Title: A Study of the Ergonomics of Emergency Stop Pushbuttons.

Abstract approved: Redacted for Privacy

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Emergency stop controls are essential parts of industrial machinery because they are designed to stop the operation in case of emergencies without risks to operators, equipment, products, or facilities. Current guidelines for emergency stop controls have been formulated based on experience but not on empirical studies.

The main objectives of this research were to determine the effects of the type and orientation of emergency stop pushbuttons on the reaction time, mode of activation, and preferences of subjects in order to formulate guidelines for their selection.

An experiment consisting of a simple, cooperative assembly operation with a Microbot was designed for this study.

The main conclusions of this research are that reaction time to activate emergency stop pushbutton is not affected by the orientation of the control but it is influenced by the type of control. The mode of activation of emergency stop pushbuttons is influenced by both the type and the orientation of the control. Subjects preferred emergency stop pushbuttons without guards or with half guards over controls with full guards, and subjects also preferred an inclined orientation of the control over horizontal or vertical orientations.

The following guidelines are recommended for the selection of emergency stop pushbuttons. Select emergency stop pushbuttons without guards. If a guard is absolutely required, select a guard with slots or a half guard to ensure adequate visibility of and access to the button. If possible, give emergency stop pushbuttons an inclined orientation (about 45°) on the control panel. Avoid using vertical orientations for these controls.

A Study of the Ergonomics of Emergency Stop Pushbuttons

by

Patricia B. Zárate

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed January 13, 1997
Commencement June 1997

Master of Science thesis of Patricia B. Zárate presented on January 13, 1997

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Patricia B. Zárate, Author

ACKNOWLEDGMENTS

I received the help of many dear persons while doing my research, without them it would not have been possible to do it. This is my opportunity to thank them.

I would like to expressed my profound gratitude to my major professor, Dr. Kenneth Funk for all his support throughout my graduate studies at Oregon State University, for his time, for sharing part of his vast knowledge with me, and for his patience. He was more than an academic advisor to me, giving me the words and encouragement that I needed. He helped me to keep my hope and to continue working, even in adverse times. He was the spark that made me continue working toward my goal.

I also would like to thank Rob Hooper, safety consultant at Hewlett Packard, for giving me the opportunity to do this study, for giving me some of his valuable time, for his patience, for all the knowledge that he shared with me, and for showing me how good it feels to work on something you like.

Thanks to the members of my committee, Dr. Edward McDowell, Dr. Brian Paul, and Dr. Roger Nielsen, for their valuable input and suggestions while doing my research.

I also would like to thank all Industrial and Manufacturing Engineering Department faculty and staff members for their help and support during my graduate studies at OSU. Thanks for the smiles and the words that showed me you cared for me.

I want to give special thanks to Norbert Araujo, my husband, for being there in good and bad moments, for helping me to deal with my worries and hurries, for the love and care he showed me, for his sparkling humor, and for being just as he is.

Special thanks to Yiannakis Mylonas for all his technical support, for his sincere and profound friendship, and for his words of encouragement while doing my research.

I would like to express my gratitude to all my friends here in Corvallis, especially to Soraya Matos, for being with me during this wonderful experience. These will be memorable times, and I will keep them forever in my mind and heart.

Finally, I would like to thank my family and friends in Venezuela, for keeping me in touch with my roots even when I was not there and for letting me know I belong there. Special thanks to my mom, dad, and aunts for their love and care.

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This thesis is dedicated to my mother and father for their immense love and unfailing belief in me.

A Study of the Ergonomics of
Emergency Stop Pushbuttons

1. INTRODUCTION

Emergency stop controls are essential parts of industrial machinery because they are designed to stop the operation in case of emergencies. In these cases it is highly desirable that the operator stops the machine as quickly as possible without risks to themselves, to the equipment, or to the product.

Emergency stop controls are critical devices because failure to stop machinery accounts for 5% of the accidents in industrial environments (Raouf and Dhillon, 1985). The main types of emergency stop controls are pushbuttons, pull-cords, enabling devices (dead man's switches), and foot pushbuttons.

Some standards and norms recommend guidelines for emergency stop pushbuttons. However, they have been formulated based on experience but not on empirical studies of these controls. There is a lack of information about how people really activate them, about whether or not their orientation influences the mode of activation or the time required to activate them, and about the preferences of the users for the different types of emergency stop controls. There is a need for studies designed and developed with the specific purpose of analyzing the ergonomics of emergency stop controls.

The main objectives of this research were to determine the effects of the type and orientation of emergency stop pushbuttons on reaction time, mode of activation, and preferences of subjects in order to formulate guidelines for their selection.

An experiment was designed for this study to gather information related to the way people activate emergency stop pushbuttons and how their type and orientation influence the time to activate them. The results of the experiment were analyzed following some statistical methods such as ANOVA, Least Significant Difference for all pairwise comparisons, and Chi-Square test of homogeneity.

The main conclusions of this research are that reaction time to activate emergency stop pushbutton is not affected by the orientation of the control but it is influenced by the type of control. The mode of activation of emergency stop pushbuttons is influenced by both the type and the orientation of the control. Subjects preferred emergency stop pushbuttons without guards or with half guards over controls with full guards, and subjects also preferred an inclined orientation of the control over horizontal or vertical orientations.

The following are guidelines to select emergency stop pushbuttons based on the results of this study:

- Select emergency stop pushbuttons without guards. If a guard is absolutely required, select a guard with slots or a half guard to ensure adequate visibility of and access to the button.
- If possible, give emergency stop pushbuttons an inclined orientation (about 45°) on the control panel. Avoid using vertical orientations for emergency stop pushbuttons.

The following is an overview of the thesis and organization of material.

Chapter 2 provides some background on controls in general and on emergency stop controls in particular. It describes main types, some considerations about controls, and current guidelines to select or design controls.

Chapter 3 deals with the specific objectives of this research.

Chapter 4 contains the methodology followed in the experiments. It describes the subjects, apparatus, experimental task, procedure, and the experimental design for this study.

Chapter 5 has the results that were obtained from the experiment. The results included reaction time to active the control, mode of activation of emergency stop pushbuttons, and preferences of subjects for the different types, orientations, and reset methods of emergency stop pushbuttons.

Chapter 6 deals with the analysis of the results. It describes the statistical methods used to analyze the results and the conclusions that were obtained from them.

Chapter 7 contains a discussion of various aspects of the research such as the experiment, the results, and the guidelines to select emergency stop pushbuttons.

Finally, Chapter 8 presents a summary of the study, the conclusions, the recommended design guidelines, and the recommendations for further research.

2. BACKGROUND

2.1 Human-Machine Systems

A human-machine system is a group of one or more human beings and one or more physical components that interact to produce a desired output from certain inputs (Sanders and McCormick, 1993). Human-machine systems can go from very simple systems like a person with a hammer to very complex systems like aircraft or oil refineries and their personnel (Sanders and McCormick, 1993).

Human-machine systems can be either "closed-loop" or "open-loop" systems (National Safety Council, 1974, p.220). In closed loop systems, operators can correct systems' performance while open loop systems do not permit corrective actions. Pulat (1992) explains that human-machine systems in the work environment are usually closed loop systems.

According to the National Safety Council (1974) humans serve three functions in human-machine systems: as sensors, information processors and controllers. Machines have displays with information about the operations that act as stimuli for operators who process this information and produce actions to control the operation of the machines (Sanders and McCormick, 1993). Humans interact with machines at two points: displays and controls. Humans read the displays, which generally are visual, auditory or tactual, and then decide how to use controls to adjust the operation of machines (National Safety Council, 1974).

Human Factors Engineering, or Ergonomics, is the study of the interaction between humans and machines and the environment in which they function (Pulat, 1992 and The National Safety Council, 1974). Sanders and McCormick (1993) explain that the central focus of Human Factors is the consideration of human beings in the design of objects, machines, and environments. According to the National Safety Council (1974) the purpose of Human Factors Engineering is to minimize errors when using displays and controls by designing systems that are compatible with both humans and machines.

The main objectives of Human Factors Engineering are to "design for human use" and to "fit the task to the person" (Pulat, 1992, p.3). It is important to consider Human Factors in design because to do so means to take into account the capabilities, limitations, and needs of people (Sanders and McCormick, 1993).

Some of the consequences of not considering Human Factors Engineering in design are "less production output, increased lost time, higher medical costs, higher material costs, increased absenteeism, low-quality work, injuries and strains, increased probability of accidents and errors, increased labor turnover, and less spare capacity to deal with emergencies" (Pulat, 1992, pp.2-3).

In my opinion, Human Factors is the art of considering human characteristics in the design of all places, equipment and tools that have to be used and/or operated by human beings. Human Factors does not only apply to industrial settings, it can and should be applied to improving the design of the environment for humans, not only at work but in all aspects of everyday life.

2.2 Controls

Controls are the means by which people transmit their ideas or decisions to machines (Dul and Weerdmeester, 1993). Controls are devices that convert human outputs to machine inputs and serve as interfaces between humans and machines (Pulat, 1992).

2.2.1 Functions

Robert Bailey (1982) explains that most controls are used for the following kind of functions:

a. Activation: a binary action, for example, on and off.

b. Discrete setting: the setting of three or more positions of the control representing discrete systems responses. An example of this setting is the gear positions in an automobile such as park, reverse, neutral, and drive.

c. Quantitative settings: the setting of individual positions of the control that vary along a continuous quantitative dimension. The adjustment of the volume on a radio is an example of quantitative setting.

2.2.2 Types

Controls can be classified according to different criteria. The following are the most common control classifications (Asfour, et al, 1991 and Konz, 1990):

a. Discrete or continuous

Discrete controls: They can take only a limited number of finite states or exact positions (Asfour et al, 1991). Chapanis and Kinkade (1972) indicate that these controls are generally used to turn equipment on and off, select modes of operation, and choose meter scales. Some types of discrete controls are pushbuttons, toggle switches, detent thumbwheels, rotary selector switches, legend switches, rocker switches, and knife switches (Pulat, 1992 and Chapanis and Kinkade, 1972).

Continuous controls: These controls can take any position between the limits of movement of the control (Asfour et al, 1991 and Chapanis and Kinkade, 1972). These controls are used when fine adjustments are necessary (Asfour et al, 1991). Some types of continuous controls are control knobs, continuous thumbwheels, cranks, handwheels, levers, pedals, and joysticks (Pulat, 1992 and Chapanis and Kinkade, 1972).

b. Linear or rotary

Linear controls: They move in a straight line and the control motion or displacement is linear (Eastman Kodak Company, 1983, Asfour et al, 1991 and Konz, 1990). Some types of linear controls are pushbuttons, toggle switches, legend switches, knife switches, and pedals (Asfour et al, 1991 and Chapanis and Kinkade, 1972).

Rotary controls: These controls move in an arc and the control motion or displacement is rotary (Eastman Kodak Company, 1983 and Asfour et al, 1991). Some types of rotary controls are rotary selector switches, controls knobs, handwheels, and cranks (Asfour et al, 1991 and Chapanis and Kinkade, 1972).

<u>Other types of controls</u>: Controls are usually activated by means of hands and feet, but there are new trends in the design of control devices (Sanders and McCormick, 1993). Advances in technology have introduced the use of voice, eye movements, head movements, and body temperature to activate controls (Konz, 1990, Sanders and McCormick, 1993, and Pulat, 1992). Eye-activated controls are mostly found in the military field (Sanders and McCormick, 1993). Some examples of these innovative technologies are the use of speech recognition to record data and to operate devices for handicapped people (Pulat, 1992 and Sanders and McCormick, 1993).

2.2.3 Selection

The following are the questions the designer should take into account when selecting the appropriate control for a particular task (Chapanis and Kinkade, 1972, Bailey, 1982, and *Human Factors Engineering Design for Army Materiel*, 1992).

a. Function of the control: What are the general purpose and functions of the control? What is to be controlled? How important is the control? What changes will the use of the control originate? Does the control provide just a minor adjustment? Is the control critical to the successful operation of the system?

b. Requirements of the control task: What degree of precision is required? What are the ranges in which the control should work? What should be the speed, precision, and force to be applied to the control? What problems may emerge if these requirements are not met?

c. Information needs of the operator: What and how should the operator know about the control location, setting, and changes in position? What must be done to help the operator locate the control?

d. Requirements imposed by the workplace: Where should the control be located? How much space is available? Should the control be grouped with other sets of controls and/or displays? How does the position affect operator efficiency?

e. Consequences of inadvertent activation: What are the risks in case of inadvertent activation of the control?

2.2.4 Coding

The correct identification of controls may be critical in systems in which rapid and correct activation of controls is necessary (Sanders and McCormick, 1993). Making controls easy to identify decreases the likelihood of using a wrong control, reduces the time to find the correct control, and also reduces training time (Bailey, 1982 and Pulat, 1992).

According to Sanders and McCormick (1993) the identification of controls is a coding problem. The National Safety Council (1974) recommends that all controls should be coded in some way.

The type of coding method to be used depends on the following factors (Bailey, 1982, Pulat, 1992, and *Human Factors Engineering Design for Army Materiel*, 1992):

a. Coding methods already in use in the system.

b. Kinds of information to be used.

c. Nature of the task to be performed.

d. Illumination of the workplace.

e. Speed and accuracy required to identify the controls.

f. Space available for the location of controls.

g. Number of controls to be coded.

h. Need for redundant or combination coding.

The main coding methods are shape, texture, size, location, operational method, color, and labels (Sanders and McCormick, 1993, Helander, 1995, Pulat, 1992, and Kvalseth, 1985).

a. Shape: The identification of controls by shape involves tactual sensitivity (Sanders and McCormick, 1993); this is especially useful when controls must be identified without the use of vision (Bailey, 1982). Using different shapes also helps in the visual identification of controls. The selection of functional shapes that suggest the purpose of the control is highly recommended (Chapanis and Kinkade, 1972). According to Helander (1995) operators can distinguish up to 12 different shape-coded control knobs under stress conditions. A disadvantage of this coding method is that the use of gloves reduces the ability to discriminate among different shapes (National Safety Council, 1974, and Bailey, 1982).

b. Texture: The identification of controls by their surface texture involves tactual sensitivity (Sanders and McCormick, 1993). This method of identification is not recommended when operators need to use gloves (National Safety Council, 1974, and Sanders and McCormick, 1993).

c. Size: When coding controls by size it is necessary that the different sizes are distinguishable from each other (Sanders and McCormick, 1993). According to Helander (1995) an operator can distinguish, at most, three different sizes of control knobs under conditions of stress. The use of gloves reduces the ability to discriminate among different sizes (National Safety Council, 1974, Chapanis and Kinkade, 1972, and Bailey, 1982).

d. Location: This coding method consists of locating specific controls in the same area (Sanders and McCormick, 1993). In automobiles most of the control locations are standardized, so drivers know where to find the controls for certain functions such as ignition (Helander, 1995).

e. Operational method: With this coding method each control has a unique method of operation (Sanders and McCormick, 1993, and Helander, 1995). An example of this coding method is when the system has two controls and one is a push-pull type and the other one is a rotary type, so each control has its own method of operation (Sanders and McCormick, 1993). According to Sanders and McCormick (1993) this method is not appropriate when operation time or operating errors are critical for the system and it should be avoided except when it seems to be really appropriate for the system.

f. Color: This identification method consists of coloring controls depending upon their functions and the task (Helander, 1995). Color coding can be very effective when the color has a specific meaning related to it, for instance, red for emergency stop controls (Sanders and McCormick, 1993, Chapanis and Kinkade, 1972, and Bailey, 1982). One disadvantage of color coding, according to Helander (1995) is that reaction time can be longer since it is necessary to analyze the meaning of the color before activating the control. This coding method should not be used as the primary or only code to identify controls (Chapanis and Kinkade, 1972 and Bailey, 1982). Color coding should be combined with other coding methods to make sure color blind subjects can distinguish the controls. Sanders and McCormick (1993) indicate that color coding should not be used with poor illumination or when the control is likely to become dirty. Chapanis and Kinkade (1972) recommend using only five colors for single-color coding: red, orange, yellow, green, and blue. Table 1 shows the color coding recommended by the International Electrotechnical Commission (1996) for pushbuttons actuators for electrical equipment of machines.

Table 1: Color coding for pushbutton actuators and their meaning.

Color	**Meaning**	**Explanation**
Red	Emergency	Actuate in the event of a hazardous condition or emergency.
Yellow	Abnormal	Actuate in the event of an abnormal condition.
Green	Safe	Actuate to indicate a safe situation of normal conditions.
Blue	Mandatory	Actuate for a condition requiring mandatory action.
White Grey Black	No specific meaning assigned	For general initiation of functions such as start/on or stop/off except emergency stop.

(Source: Adapted from International Electrotechnical Commission, 1996, IEC204-1)

g. Labels: Identifying controls with labels consists of using a written label to describe the function of the control (Helander, 1995). According to Sanders and McCormick (1993) labels are the most common method for identifying controls, but they should not be used as the only method for control coding when the speed of the operation is important because they take time to read. Helander (1995) explains that the use of labels increases the reaction time because it is necessary to read and understand the label before activating the control. Pulat (1992) explains that labels should indicate the function being controlled and the positions to which the controls can be set. Labels should be placed very close to the control, preferably above the controls (Sanders and

McCormick, 1993 and Konz, 1990), in a horizontal orientation to make them easy to read (Pulat, 1992). According to Helander (1995) vertical labels should be avoided because they take longer to read. Labels should be brief and precise and understandable by the operator. Try to use consistent words and avoid using abbreviations (Konz, 1990).

2.2.5 Control Resistance

It is always necessary to apply some force to activate controls (Sanders and McCormick, 1993, Pulat, 1992, Chapanis and Kinkade, 1972). Designers usually try to minimize control resistance, to reduce the force that is required to activate controls, in order to widen the target population. However, they do not eliminate resistance because it helps to prevent inadvertent activation of controls (Pulat, 1992). According to Pulat (1992) hand controls should require less activation force than foot controls.

There are four major types of resistance: elastic, frictional, viscous-damping, and inertial (Chapanis and Kinkade, 1972, Kvalseth, 1985, Sanders and McCormick, 1993, and Pulat, 1992). Chapanis and Kinkade (1972) explain that the type and amount of resistance can affect the precision and speed of the operation of controls, the smoothness of the control movement, and the possibility of accidental activation.

a. Elastic resistance: It is also called spring loading (Chapanis and Kinkade, 1972 and Pulat, 1992). This resistance varies with control displacement, it increases as the displacement of the control device increases, and it applies force toward the null position when the control is released (Sanders and McCormick, 1993 and Pulat 1992). According to Chapanis and Kinkade (1972) and Sanders and McCormick (1993) this resistance is ideal for momentary-contact or "dead-man" switches, and it reduces the likelihood of inadvertent activation of controls.

b. Frictional resistance: This resistance is the result of the static and sliding friction. Static friction is maximum at the initiation of movement but it decreases sharply when the control starts to move, then sliding friction continues as a resistance to the control movement (Chapanis and Kinkade, 1972, Sanders and McCormick, 1993, and Pulat, 1992). Sliding friction is not related to either velocity or displacement of controls (Chapanis and Kinkade, 1972, Sanders and McCormick, 1993, and Pulat, 1992). According to Sanders and McCormick (1993) and Chapanis and Kinkade (1972) static friction reduces the possibility of accidental activation of controls.

c. Viscous-damping resistance: It resists quick movements and helps the operator in making smooth control movements (Pulat, 1992, Sanders and McCormick, 1993, and Chapanis and Kinkade, 1972). Chapanis and Kinkade (1972) explain that viscous damping resistance helps operators in making precise settings and small changes in control position. This resistance is related to control velocity but it is independent from displacement or acceleration (Pulat, 1992 and Sanders and McCormick, 1993).
d. Inertial resistance: It is the resistance to movement caused by the mass of the control mechanism (Sanders and McCormick, 1993). Inertial resistance varies directly with control acceleration and helps operators make smooth control movements; however, it makes it difficult to perform small and precise control adjustments (Chapanis and Kinkade, 1972, Sanders and McCormick, 1993, and Pulat, 1992). According to Sanders and McCormick (1993) and Chapanis and Kinkade (1972) inertial friction reduces the possibility of accidental activation of controls.

2.2.6 Control-Response Ratio

This concept is related to continuous controls or when a quantitative setting should be made with a control; it does not apply to controls that can be set at discrete settings (Sanders and McCormick, 1993 and Pulat, 1992). According to Sanders and McCormick (1993) control-response ratio (C/R ratio) is the ratio of the movement of the control device to the movement of the system response. This concept was called control-display ratio (C/D ratio) in the past (Chapanis and Kinkade, 1972) but in systems in which displays are not present there is still a system response, so control-response ratio is a more appropriate term. The reciprocal of the C/R ratio is called gain and it is the sensitivity of the control device (Sanders and McCormick, 1993).

There are two types of movements when adjusting controls, "gross-adjustment" and "fine-adjustment" movements (Sanders and McCormick, 1993, p.345). With the gross-adjustment movement the operator brings the system to the approximate desired position, the time it takes to do this is called "travel time" or "slewing time" (Chapanis and Kinkade, 1972, p.349 and Sanders and McCormick, 1993, p.345). With the fine-adjustment movement the operator brings the system to the exact desired position, the time it takes to do this is called "fine adjust time" (Chapanis and Kinkade, 1972, p.349 and Sanders and McCormick, 1993). The optimum C/R ratio for a specific system has to be determined taking into account these two movements and the total time it takes to adjust the control, that is the sum of the travel time and the adjust time (Chapanis and Kinkade, 1972). Sanders and McCormick (1993) explain that travel time is decreased with low C/R ratio (high sensitivity) and adjust time is decreased with high C/R ratio (low sensitivity). The optimum C/R ratio has to be determined experimentally for the system under consideration and it depends on the type of control, the size of the display, the tolerances and the time delay or lag in the system (Chapanis and Kinkade, 1972 and Sanders and McCormick, 1993).

Detailed information, pictures, and diagrams of controls may be found in the following references: *Workspace, Equipment and Tool Design* by Asfour, Omachonu, Diaz, and Abdel-Moty, 1991; *Human engineering Guide to Equipment Design* by Chapanis and Kinkade, 1972; *Ergonomic Design for People at Work.* Vol. 1. by The Eastman Kodak Company, 1983; *Work Design: Industrial Ergonomics* by Konz, 1990; *Human Factors Engineering Design for Army Materiel*, 1992; and *Fundamentals of Industrial Ergonomics* by Pulat, 1992.

2.2.7 General Principles for Control Design or Selection

The following are general principles to take into account when designing or selecting controls (Chapanis and Kinkade, 1972, Bailey, 1982, Eastman Kodak Company, 1983, and Asfour et al, 1991). The designer has to use some judgement when using these guidelines, according to the system under consideration, because some of them can be contradictory.

a. Critical and frequently used controls should be located within easy reach of the operator.

b. Keep the total number of controls to a minimum.

c. Select controls that can be easily identified and use control coding to aid their identification.

d. Control movements should be simple, easy, and natural, and they should be compatible with the operator's expectations.

e. Control movements should be as short as possible.

f. The force, speed, accuracy, and range of body movement required to operate controls should not exceed the limits of the least capable operator.

g. Use discrete controls when:

- There is a limited number of control states, usually less than 25.
- On-Off or Yes-No information is required.
- Only small mechanical forces are required or available. (Kantowitz and Sorkin, 1983 as cited in Asfour et al, 1991).

h. Use continuous controls when:

- There is a large number of control states, usually more than 25.
- Speed of operation is more important than accuracy of control setting.
- The operator must apply a large force to activate the control. (Kantowitz and Sorkin, 1983 as cited in Asfour et al, 1991).

i. Control surfaces should be designed to prevent slippage of fingers, hands, or feet when activating controls.

j. Controls should be designed and located to prevent or reduce the probability of accidental operation (inadvertent activation). Use guards or covers to protect critical controls.

k. Controls should provide a positive indication of activation to the operator so a malfunction will be obvious to the operator.

l. Assign to the hands controls that require rapid and precise settings. Assign to the feet controls that require large or continuous applications of force. Do not assign more than two controls to each foot.

m. Group controls that are functionally related to reduce reaching movements, to aid in sequential operations, or to reduce panel space.

n. Arrange controls in such a way the operator can adjust posture frequently, especially if extended hours of monitoring are required.

o. If a control requires a precision movement place it on the right side of the operator since about 90 percent of the population are right handed (Eastman Kodak Company, 1983).

2.3 Emergency Stop Controls

Emergency stop controls are devices that require an intentional action to bring a machine to rest when danger is recognized (British Standards Institution, 1988). According to the International Electrotechnical Commission (1995) emergency stop devices are "manually actuated controls" used to avoid or reduce hazards to people, machinery, or work in progress and they have to be actuated by a single human action (pp.4-5).

Emergency stop controls are critical devices because failure to stop machinery accounts for 5% of the accidents in industrial environments (Raouf and Dhillon, 1985). Inadvertent start, intended movements and abnormal movements are the other major causes of industrial accidents (Raouf and Dhillon, 1985).

Asfour et al (1991) recommend using emergency stop devices whenever possible and Konz (1990) indicates that all equipment should have emergency stop controls. The National Fire Protection Association (1994) and the International Electrotechnical Commission (1996) recommend locating emergency stop devices at all operating stations where emergency shutdown may be required. According to Hooper (1995) there should be an accessible emergency stop control for any situation that may be harmful to an employee.

Helander (1995) indicates it is necessary to give special attention to the design and location of emergency controls because it is vital to find them quickly in case of emergencies. Operators are under stress during emergencies and likely to make mistakes. Therefore, the design of emergency stop controls should allow rapid actions without errors (Helander, 1995). The Eastman Kodak Company (1983) recommends designing emergency stop controls for easy access by using color coding, adequate lighting and a standard location. However, emergency stop controls should not be located where accidental activation could occur (Hooper, 1986).

Most authors agree that emergency stop controls should not be used for any other purpose than stopping machines in case of emergencies (Hooper, 1995, Pulat, 1992 and British Standards Institution, 1988). If used in other ways, operators will not see these devices as critical as they really are.

2.3.1 Types

The main types of emergency stop controls are pushbuttons, pull-cords, enabling devices (dead man's switches), and foot pushbuttons (Helander, 1995, British Standards Institution, 1988, National Fire Protection Association, 1994, and International Electrotechnical Commission, 1996). The main types of emergency stop controls used in Europe are pushbuttons and pull-cords (British Standard Institution, 1988 and European Committee for Standardization, 1992a and 1992b). In the U.S. the most commonly used types of emergency stop controls are pushbuttons (National Fire Protection Association, 1994).

Pushbuttons: in general, pushbuttons are devices to set two discrete states, generally on and off (Pulat, 1992). Pushbuttons can be operated with a finger or with the palm depending on the size, the position, and the force required to activate the buttons (Pulat, 1992 and Niebel, 1993).

Some standards and norms recommend the following guidelines for emergency stop pushbuttons. However, they have been formulated based on experience but not on empirical studies on these controls. Emergency stop pushbuttons should be palm or mushroom head type, colored red, and the background should be colored yellow (National Fire Protection Association, 1994, European Committee for Standardization, 1992a and 1992b, British Standards Institution, 1988 and 1991). Emergency stop pushbuttons should be labeled, whenever possible, indicating that they are emergency devices (Chapanis and Kinkade, 1972 and Eastman Kodak Company, 1983). Helander (1995) recommends to use a large rather than a small pushbutton.

Emergency stop pushbuttons should be located between 45 inches and 30 inches high at the workstation and if more than one controls is required they should be at minimum intervals of 6 feet (Hewlett-Packard, 1994).

The European Norms require that emergency stop controls should be the lock-in type, so the operator cannot restart the machinery until the emergency stop control has been manually reset (British Standards Institution, 1988, International Electrotechnical Commission, 1996). In the U.S. it is not required that emergency stop controls be the lock-in type and they can be either momentary or self-latching type (National Fire Protection Association, 1994).

Pull-cords: Pull cords are wires that disconnect a discrete switch when pulled (British Standards Institution, 1988 and Hewlett-Packard, 1994).

As with emergency stop pushbuttons, there are guidelines for pull-cords based on experience but not on structured experiments or empirical studies. The British Standards Institution (1988) recommends using pull cords when it is necessary to have emergency stops between and around workstations. Konz (1990) also recommends having pull cords when it is necessary to have emergency stop controls at multiple locations. According to the European Committee for Standardization (1992) it is necessary to consider the amount of deflection required to activate the pull cord, the maximum deflection possible, and the minimum distance between the rope and the nearest object for the design of these emergency controls. In case the pull cord breaks the emergency signal should be activated and the machinery should stop (European Committee for Standardization, 1992). Pull cords should be clearly visible and located within easy reach (British Standards Institution, 1988). If necessary use flag markers to make the pull cord visible for the operators (European Committee for Standardization, 1992). Pull cords should be mounted at a maximum height of 6 feet to make sure all operators can reach them (Hewlett-Packard, 1994). Drops can be included with the pull cord if it has to be installed higher than 6 feet (Hewlett-Packard, 1994).

Enabling devices (also known as dead man's switches): when this control is being pressed the machine keeps operating, if the switch is released the machine stops immediately (Helander, 1995 and Konz, 1990). The main disadvantage of this type of control is that it has to be actively pressed during the whole operation limiting the amount and nature of tasks operators can perform.

Foot pushbuttons: foot pushbuttons are switches to set two discrete states, generally on and off. They are useful when hands may become overburdened with many operations (Pulat, 1992). These switches have to be protected to prevent inadvertent activation by falling objects or by accidentally stepping on the switch (National Fire Protection Association, 1994).

2.3.2 General Principles for Emergency Stop Controls Design or Selection

The following are general principles to take into account when designing or selecting emergency stop controls. These principles have been developed based on experience during normal operations but not on studies specifically designed to analyze the ergonomics of emergency stop controls.

a. Emergency stop controls should be located within immediate or easy reach of the operator (British Standards Institution, 1988 and 1991).
b. Emergency controls should be located in a position that is natural for the operator to reach (Helander, 1995).
c. Emergency stop controls should be located in a position that all personnel including those physically impaired can actuate the switch (Hooper, 1995).
d. If there is more than one workstation, an emergency stop control should be positioned at each station (British Standards Institution, 1988 and Hooper, 1995).

e. All emergency controls should be colored red to give them the visual emphasis they demand, and only a few other controls should be color coded (*Human Factors Engineering Design for Army Materiel*, 1992).

f. The color red should be used only for Stop, Emergency Stop, or Off controls (National Fire Protection Association, 1994 and International Electrotechnical Commission, 1996).

g. Emergency controls should be located away from other frequently used controls and they should be easy to distinguish to avoid inadvertent activation (Helander, 1995).

h. Use emergency controls that are large and easy to activate (Helander, 1995).

2.4 Problem Statement

As it was explained before, emergency stop controls are essential parts of industrial machinery because they are designed to stop the operation in case of emergencies. In these cases it is highly desirable that the operator stops the machine as quickly as possible without risks to themselves, to the equipment, or to the product.

There is information in the literature about the different types of emergency stop controls that are commonly used and general guidelines for their use based on experience. However, there is a lack of information about how people really activate them, about whether or not their orientation influences the mode of activation or the time required to activate them, or about the preferences of the users for the different types of emergency stop controls. There is a need for studies designed and developed with the specific purpose of analyzing the ergonomics of emergency stop controls.

It is important to know if operators can activate an emergency stop control quicker if it is of a specific type or if it is located in a specific orientation on the control panel. Emergencies call for quick responses. Not only are products, equipment, and/or facilities in danger during emergency situations but also the safety and lives of operators are at risk and seconds might be the difference between death and life.

The purpose of this study was to formulate guidelines to select emergency stop pushbuttons and their orientation. The experiment designed for this study gathered information related to the way people activate these controls and how their type and orientation influence the time to activate them. The guidelines resulting from this study will help to improve the selection and orientation of emergency stop pushbuttons for industrial machinery.

3. OBJECTIVES

The following were the main objectives of this research:

1. To determine whether or not reaction time to activate emergency stop pushbuttons is influenced by the type or the orientation of the control.
2. To study the mode of activation of emergency stop pushbuttons in order to determine:
   a. what part of the hand people use to activate these controls.
   b. whether or not the mode of activation is influenced by the type or the orientation of the control.
3. To analyze the preferences of people for different types, orientations, and reset methods of emergency stop pushbuttons.
4. To use the results to establish general guidelines to select the type of emergency stop pushbuttons according to the reaction time to activate them, mode of activation, and preferences of people.
5. To establish general guidelines for the orientation of emergency stop pushbuttons in machines to enhance quick activation, while at the same time avoiding inadvertent activation during normal operation.

4. METHODOLOGY

An experiment was designed to study the effect of the type and orientation of emergency stop pushbuttons on reaction time and mode of activation when using these devices. The experiment consisted of performing a simple, cooperative assembly operation with a Microbot placing rings on pegs. Each subject had to test six different types of emergency stop pushbuttons and three different orientations of the control panel: horizontal, vertical, and inclined at a 45° angle. The apparatus was designed to allow a quick change of panels and controls. During the operation the Microbot performed a wrong movement not following the pre-established sequence for the operation and the subject had to stop it by pressing the emergency stop pushbutton. The computer program kept record of the reaction time of subjects to activate the emergency stop pushbutton. The operation was video-taped to study the mode of activation of the emergency stop pushbuttons.

4.1 Subjects

Eighteen subjects participated in the study. The subjects were recruited from among Oregon State University (OSU) students. The average age of the subjects was 25 years. There were 11 males and 7 females. Fifteen subjects were right-handed and three were left-handed.

4.2 Apparatus

The apparatus consisted of a personal computer (PC), a Microbot TeachMover robot, a parallel digital interface board for the PC, and a custom-made control panel. All of this equipment was integrated in a mockup designed to simulate a simple assembly operation. The operation was recorded with a Panasonic Industrial video camera, and then the tapes were analyzed using a VHS video cassette recorder and a television set. The following is the description of the components of the apparatus. Figure 1 shows the apparatus.

4.2.1 Computer:

The computer was an HCE 386 IBM PC compatible model.

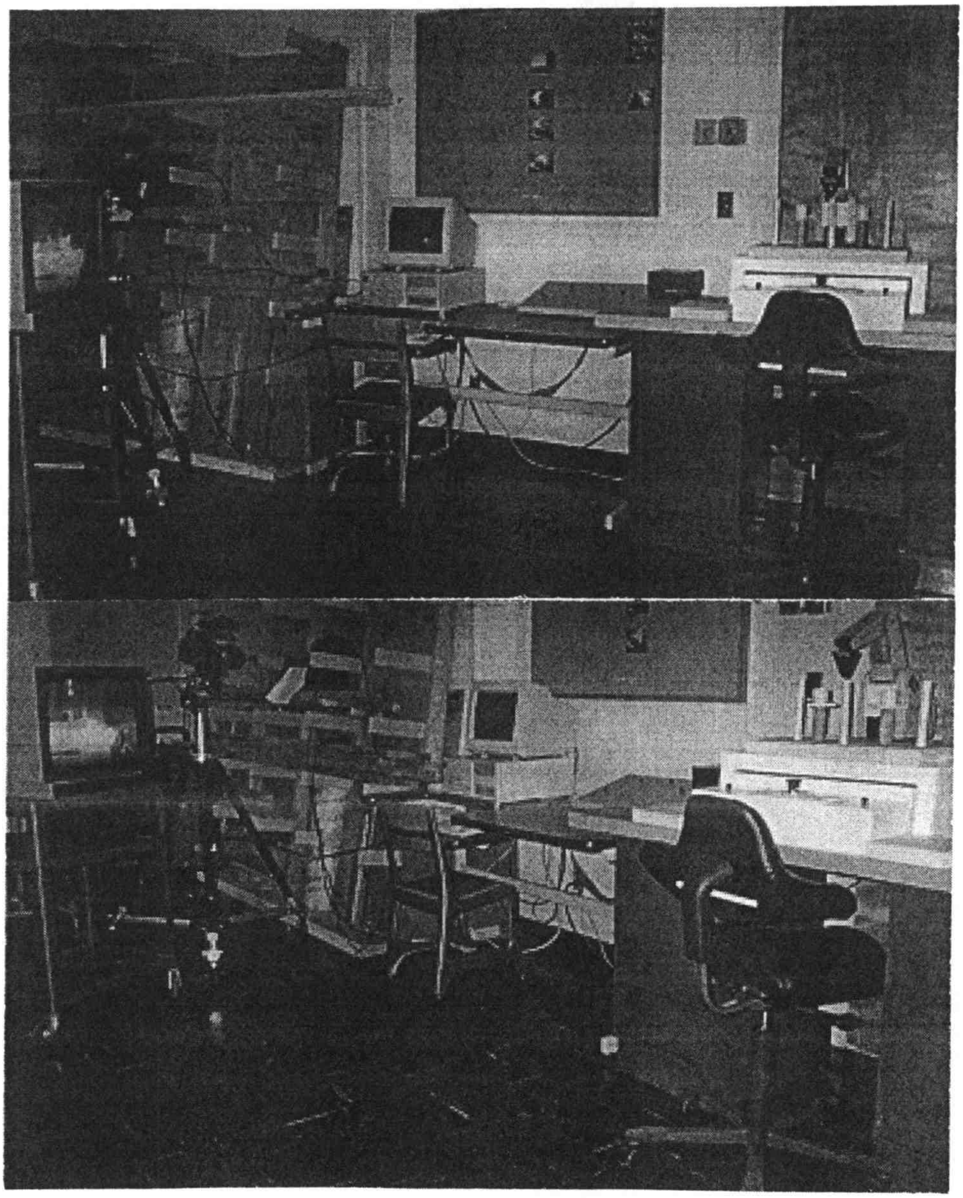

Figure 1: Two views of the apparatus designed for the experiment.

4.2.2 Microbot:

The Microbot TeachMover robot is a small instructional, microprocessor-controlled, six-jointed mechanical arm (Microbot, 1984). Figure 2 shows a diagram of the major structural components of the Microbot. The Microbot can be used for applications in "education, industrial automation, experimentation, and enjoyment" (Microbot, 1984, p. 1.1).

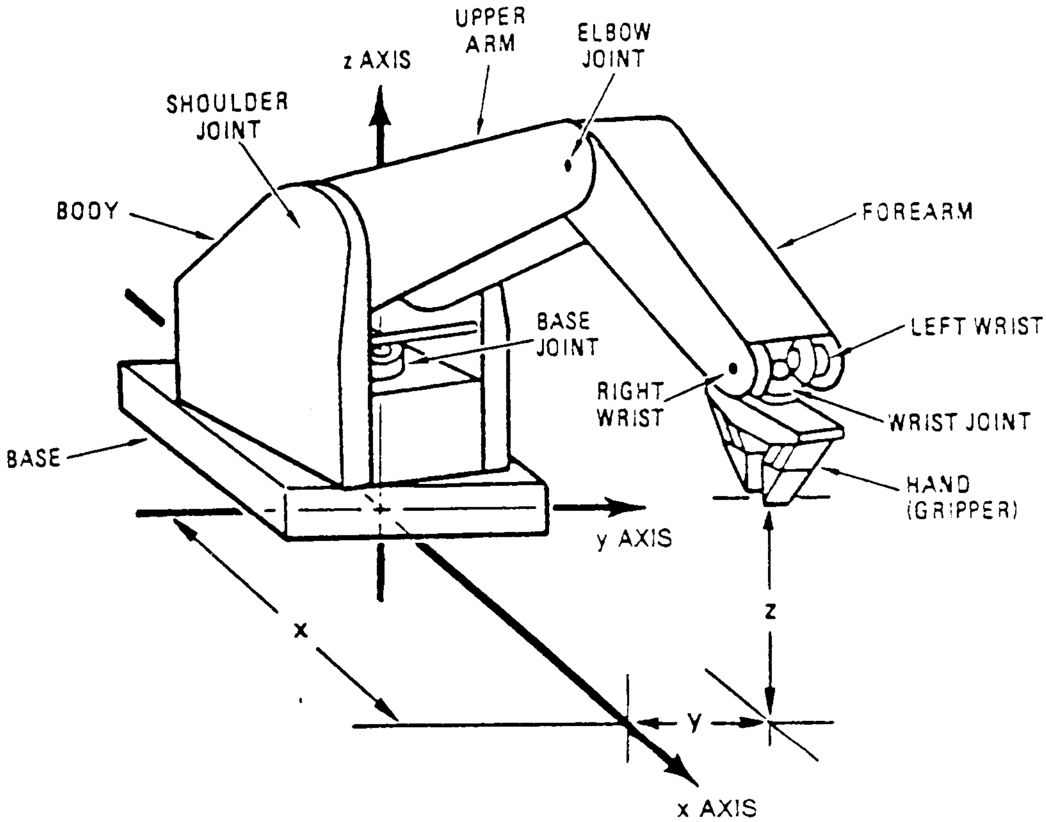

Figure 2: Major structural components of the Microbot
(Adapted from TeachMover User Manual)

The Microbot was used in a serial interface mode, in which the arm was controlled by the computer via a built-in RS-232 asynchronous serial communication line (Microbot, 1984). The computer was connected to the right serial port of the Microbot. Figure 3 shows diagrams of the connection between the computer and the Microbot.

The Microbot has a transmission rate of 9,600 baud for both sending and receiving. The following is the data format used by the Microbot: word length 8 bits, 1 start bit, 1 stop bit, no parity bit, and full duplex.

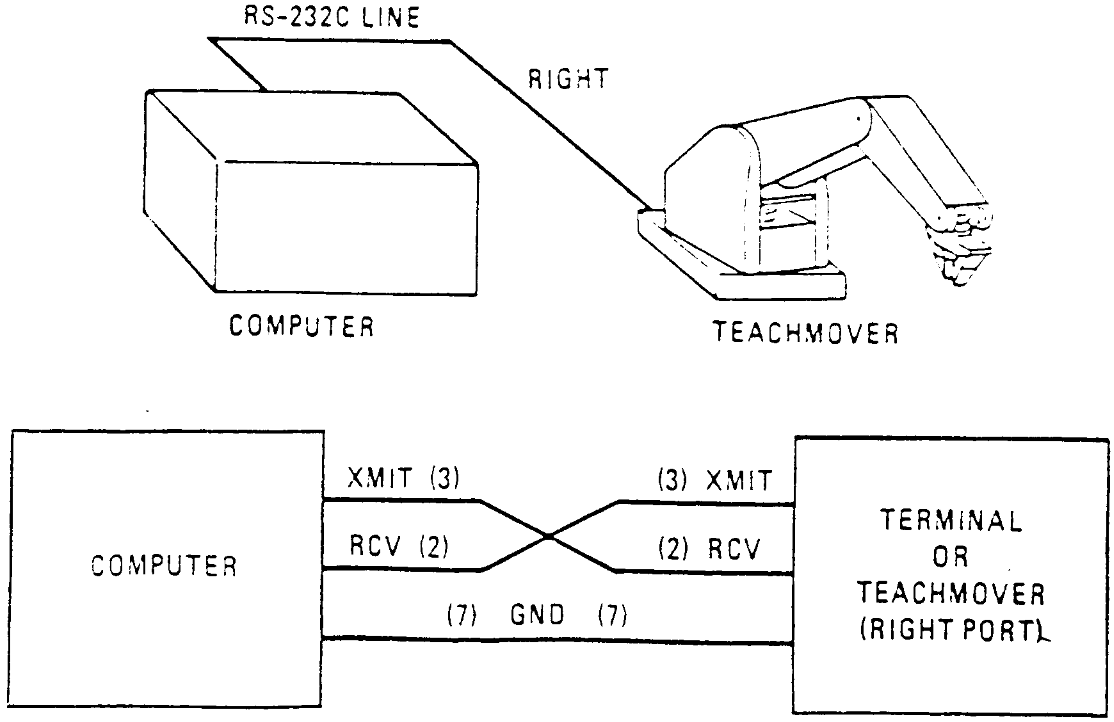

Figure 3: Computer-to-terminal serial connection.
(Adapted from TeachMover User Manual)

4.2.3 Parallel Digital Interface Board:

Keithley MetraByte Corporation is the manufacturer of the PIO-12 parallel digital interface board used for the apparatus. The PIO-12 is a 24-line, parallel, digital I/O interface board that uses an 8255 Peripheral Interface Programmable Circuit. This board is designed for IBM PC/XT/AT or compatibles. It is a flexible interface for "parallel input/output devices such as instruments and displays and user-constructed systems and equipment" (Keithley MetraByte Corporation, 1991, p. 1-2). Applications of the PIO-12 include activities such as "communicating with peripherals, operating relays, reading switch inputs, etc" (Keithley MetraByte Corporation, 1991).

4.2.4 Control Panel:

There were three interchangeable control panels, one for each one of three different orientations of the emergency stop control: horizontal (Figure 4), vertical (Figure 5), and inclined at a 45° angle (Figure 6).

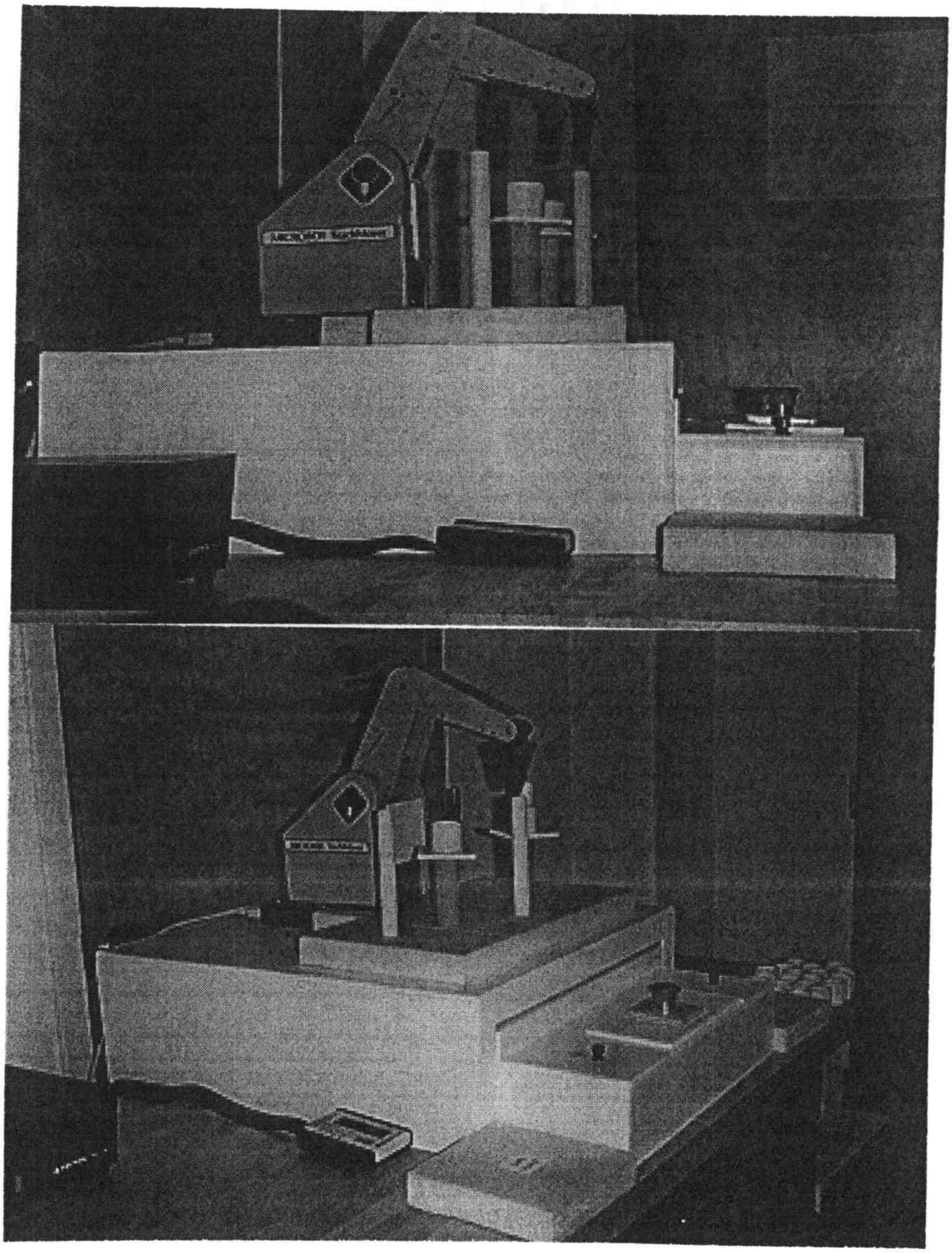

Figure 4: Two views of the horizontal control panel.

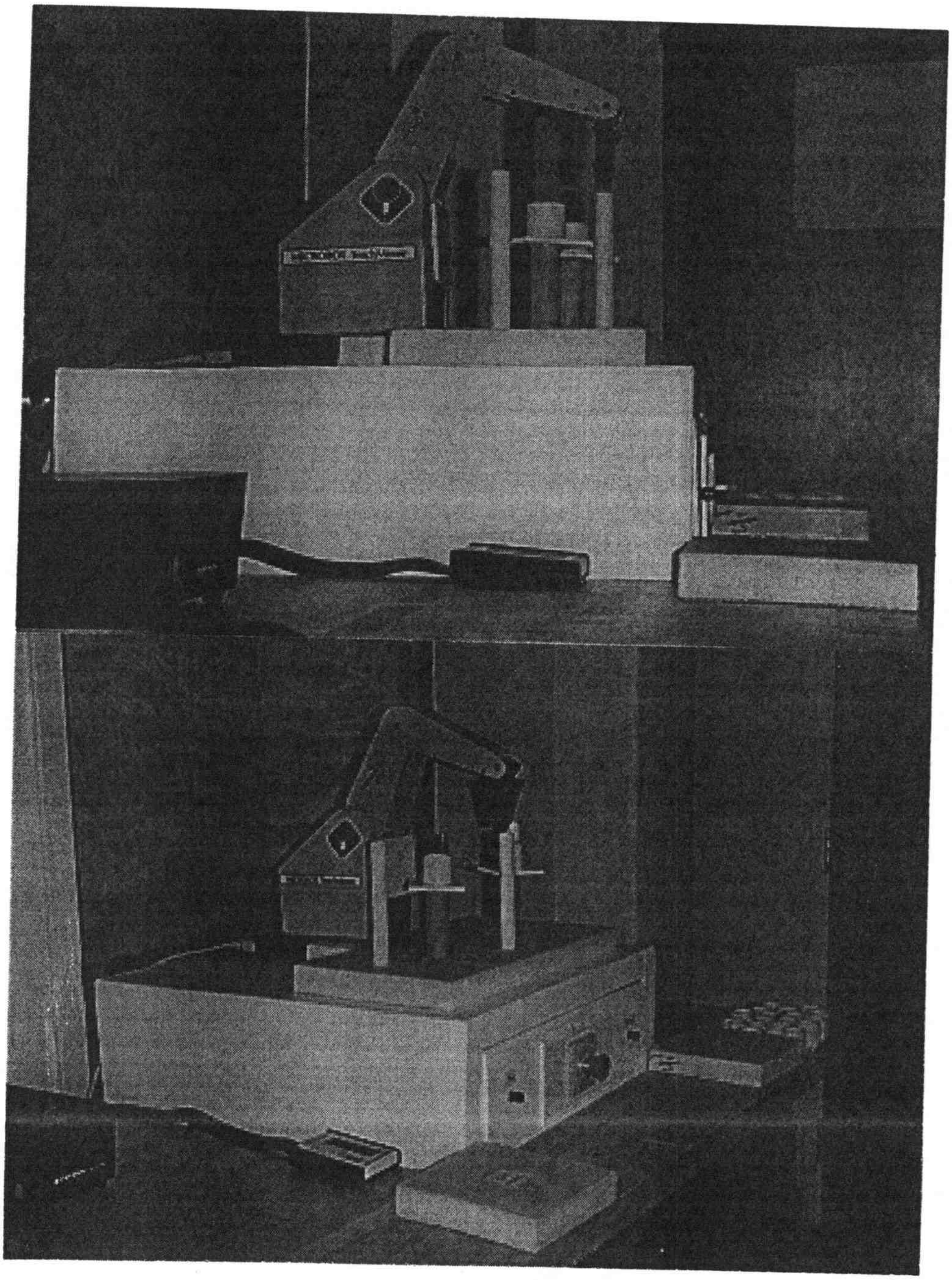

Figure 5: Two views of the vertical control panel.

Each control panel had three buttons: two buttons for the normal operation and one emergency stop pushbutton. The normal operation buttons were two simple black momentary contact pushbuttons and they were fixed at the same position for each panel.

The emergency stop pushbutton could be changed so each control panel could have either one of six different emergency stop controls.

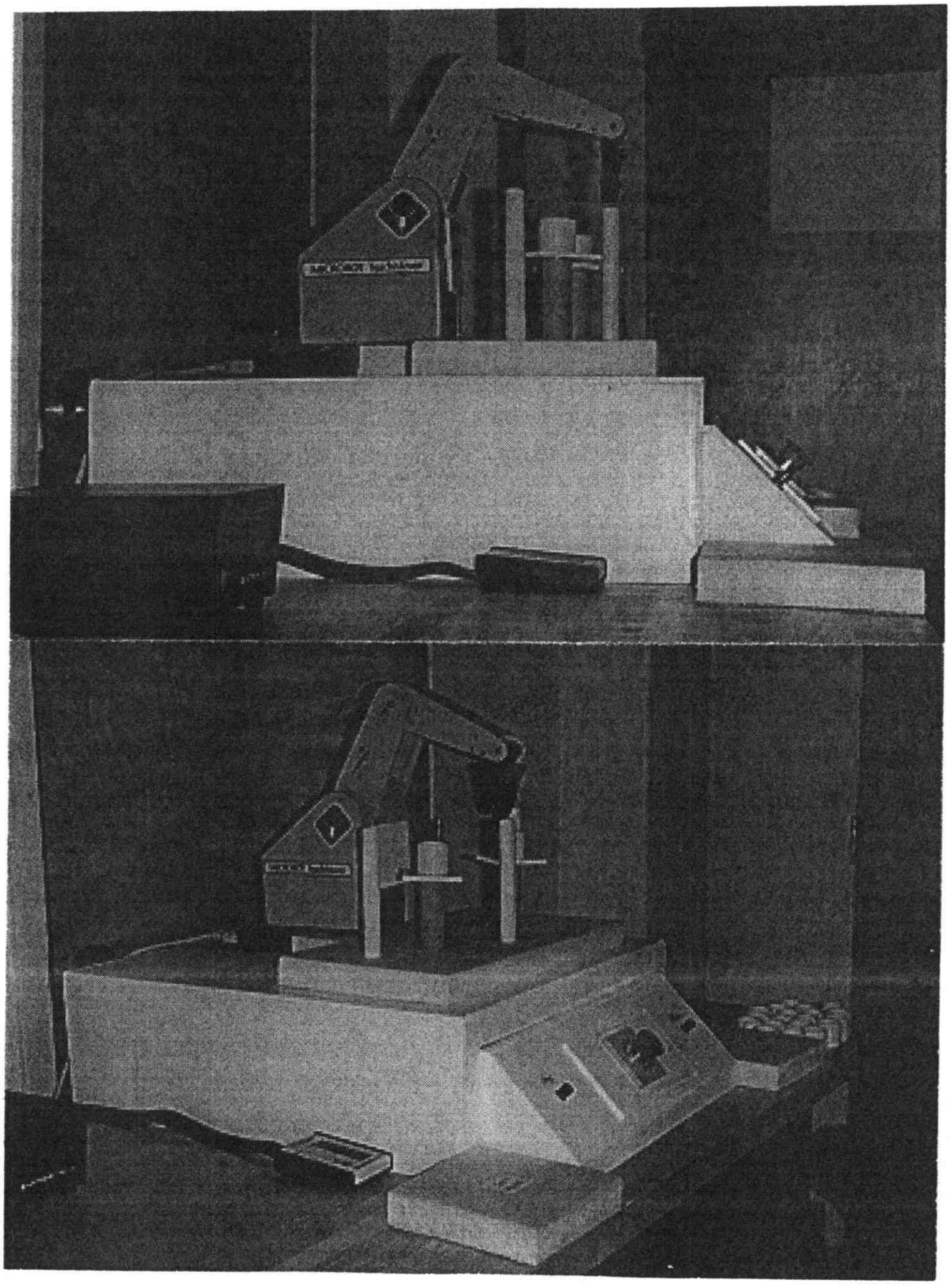

Figure 6: Two views of the inclined control panel.

The control panels and emergency stop controls were easily changed; it took less than two minutes to change one panel for another. Figures 4 to 6 show the control panels with the three different orientations. In these figures you can also see the two normal operation buttons for each panel and the emergency stop pushbutton. Figure 7 shows the workstation for the subjects with the Microbot, the control panel, and an ergonomic chair.

The buttons of the control panel were connected to the digital interface board. This board read the signals when the buttons were pushed by the operator and transmitted them to the computer.

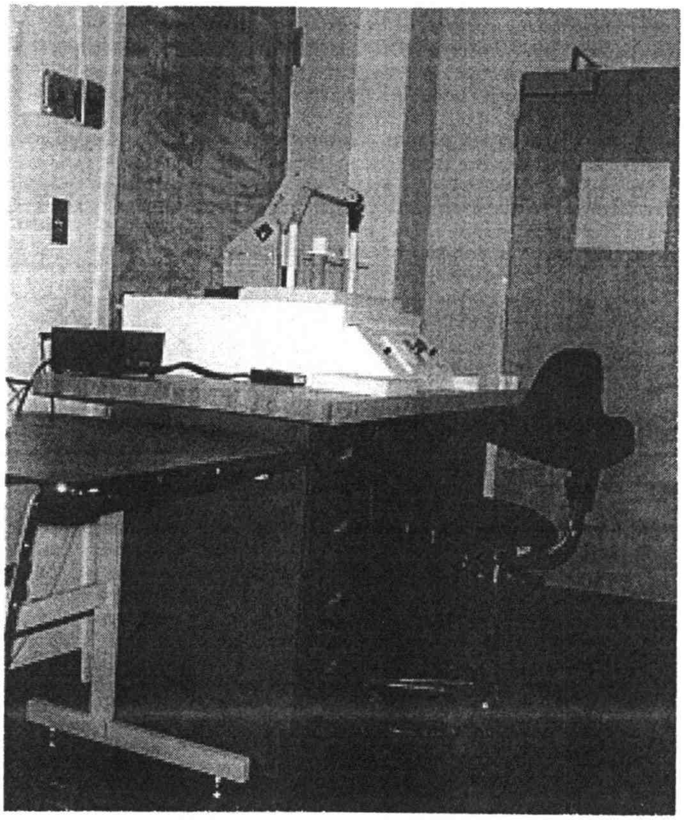

Figure 7: Workstation for subjects during the experiment.

4.2.5 Emergency Stop Pushbuttons:

There were six different types of emergency stop pushbuttons, numbered from 1 to 6. All buttons were enclosed in cases to make them interchangeable for all controls panels. The cases were designed to ensure that the centers of all buttons had the same position in the panel.

Emergency Stop Pushbutton 1 was a Square D/Telemecanique ZB2-BT4 red mushroom operator with a ZB2-BZ19 switch guard. It is a fully guarded button. The button is red and the guard and background are yellow. The diameter of the button is 40 mm (1.57 inch). The button has to be twisted to be reset. Figure 8 shows this button.

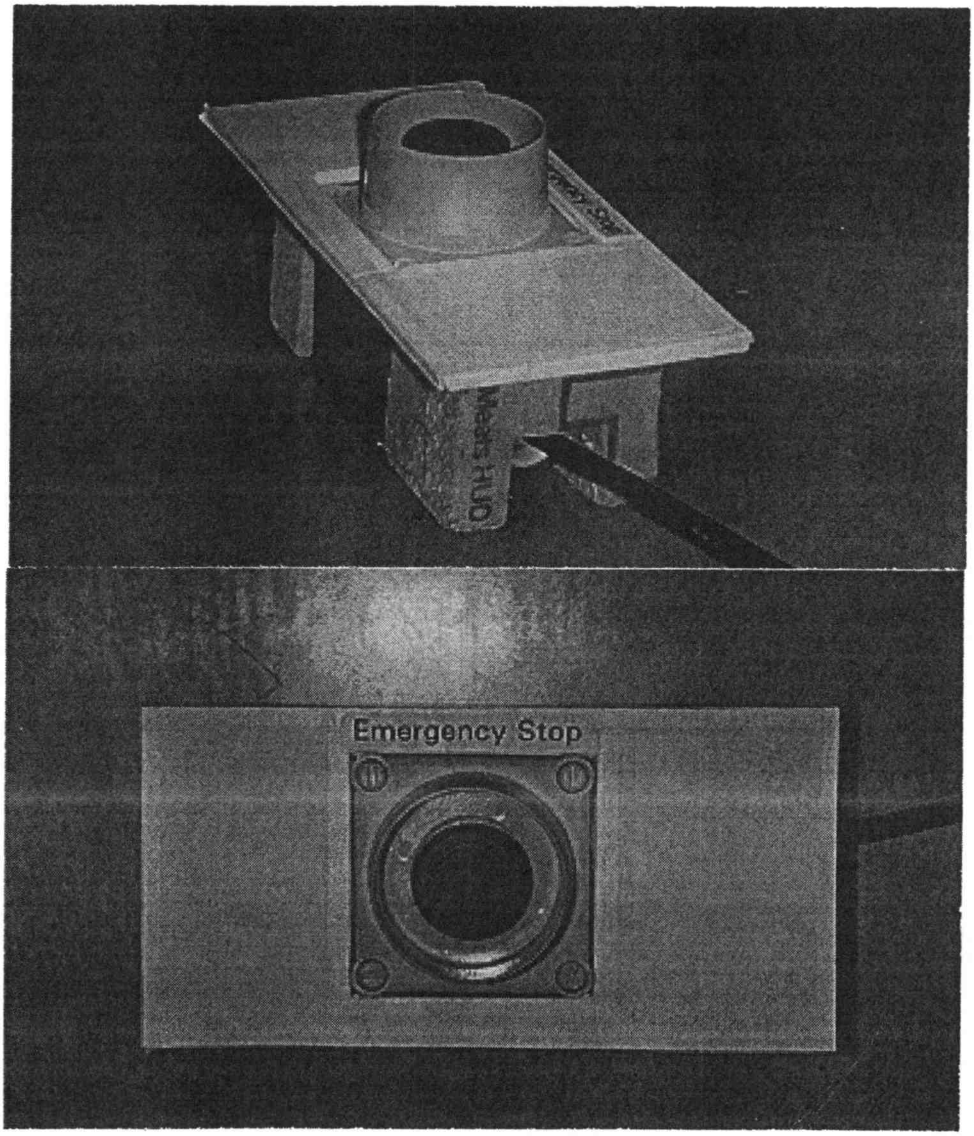

Figure 8: Two views of the emergency stop pushbutton 1, a Square D/Telemecanique ZB2-BT4 red mushroom operator with a ZB2-BZ19 switch guard.

Emergency Stop Pushbutton 2 was a Square D/Telemecanique SKR9RH13 red mushroom switch with a K564YM mushroom plastic guard. This is also a guarded button. The button is red and the guard is yellow. The guard of this button has two slots to facilitate access to the button. The diameter of the button is 35 mm (1 3/8 inch). The button has to be pulled to be reset. Figure 9 shows this button.

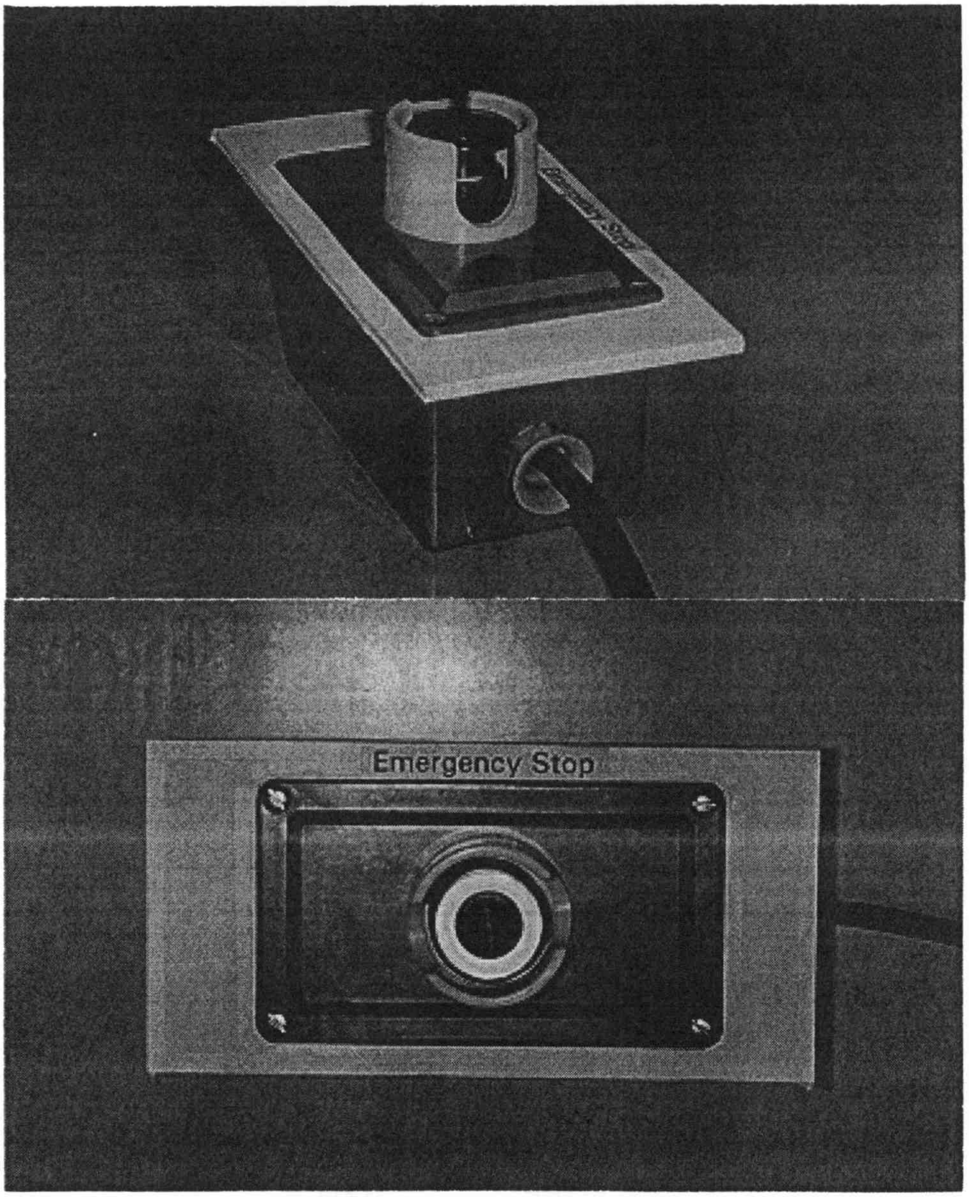

Figure 9: Two views of the emergency stop pushbutton 2, a Square D/Telemecanique SKR9RH13 red mushroom switch with a K564YM mushroom plastic guard.

Emergency Stop Pushbutton 3 was a Square D/Telemecanique ZB2-BS844 red mushroom operator with a ZB2-BZ1804 switch guard. This is a guarded button. The button and the guard are red and the background is yellow. The guard has two slots to facilitate the access to the button. The diameter of the button is 30 mm (1.18 inch). The button has to be twisted to be reset. Figure 10 shows this button.

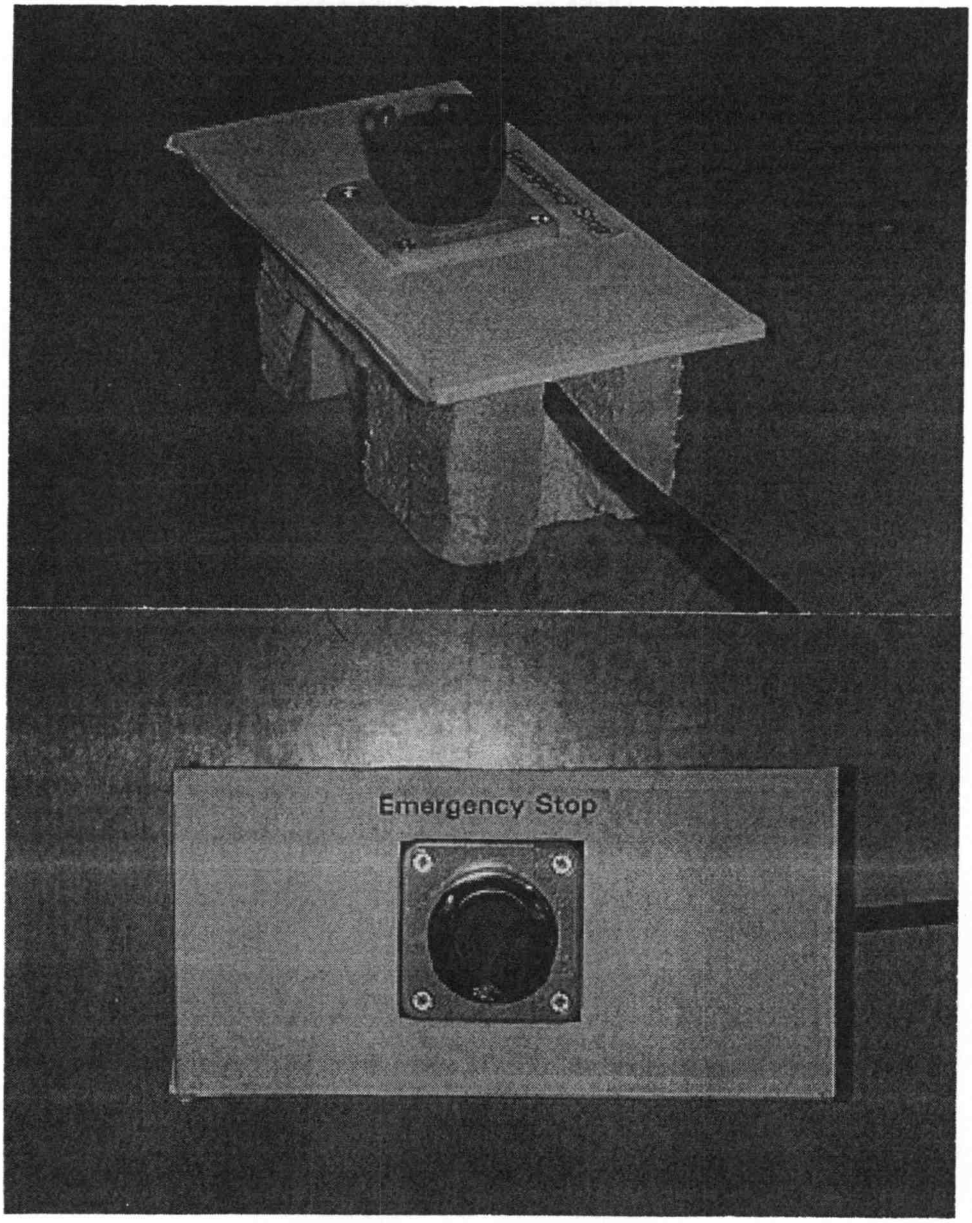

Figure 10: Two views of the emergency stop pushbutton 3, a Square D/Telemecanique ZB2-BS844 red mushroom operator with a ZB2-BZ1804 switch guard.

Emergency Stop Pushbutton 4 was a Schmersal D-SC1-90-11 E-Stop station. This is an unguarded button. The button is red and the background is yellow. The diameter of the button is 80 mm (3.15 inch). The button has a 14 mm diameter blue button in its center that has to be pressed to reset the emergency control. Figure 11 shows this button.

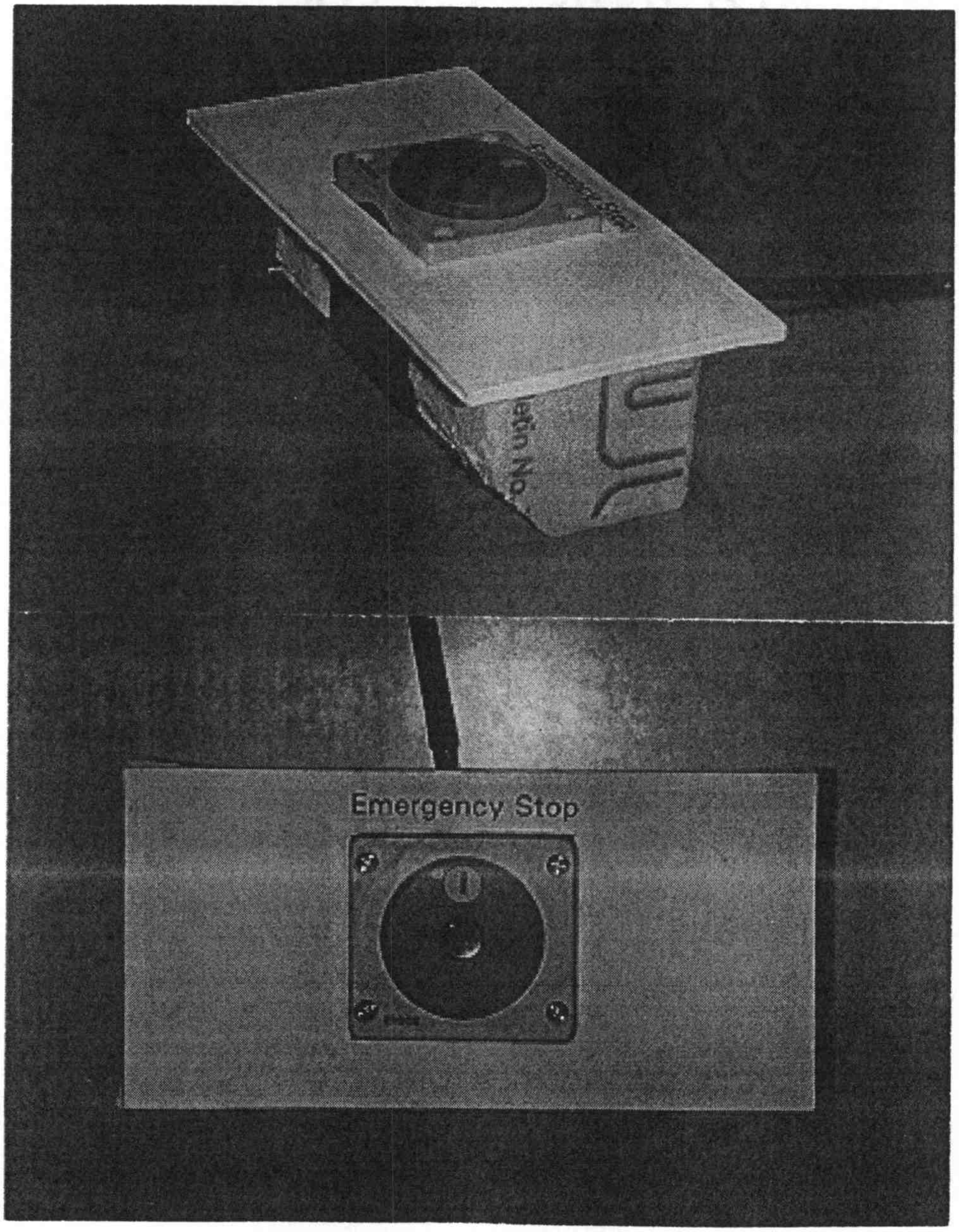

Figure 11: Two views of the emergency stop pushbutton 4, a Schmersal D-SC1-90-11 E-Stop station.

Emergency Stop Pushbutton 5 was a Square D/Telemecanique ZB2-BT4 mushroom pushbutton. This is also an unguarded button. The button is red and the background is yellow. The diameter of the button is 40 mm (1.57 inch). The button has to be pulled to be reset. Figure 12 shows this button.

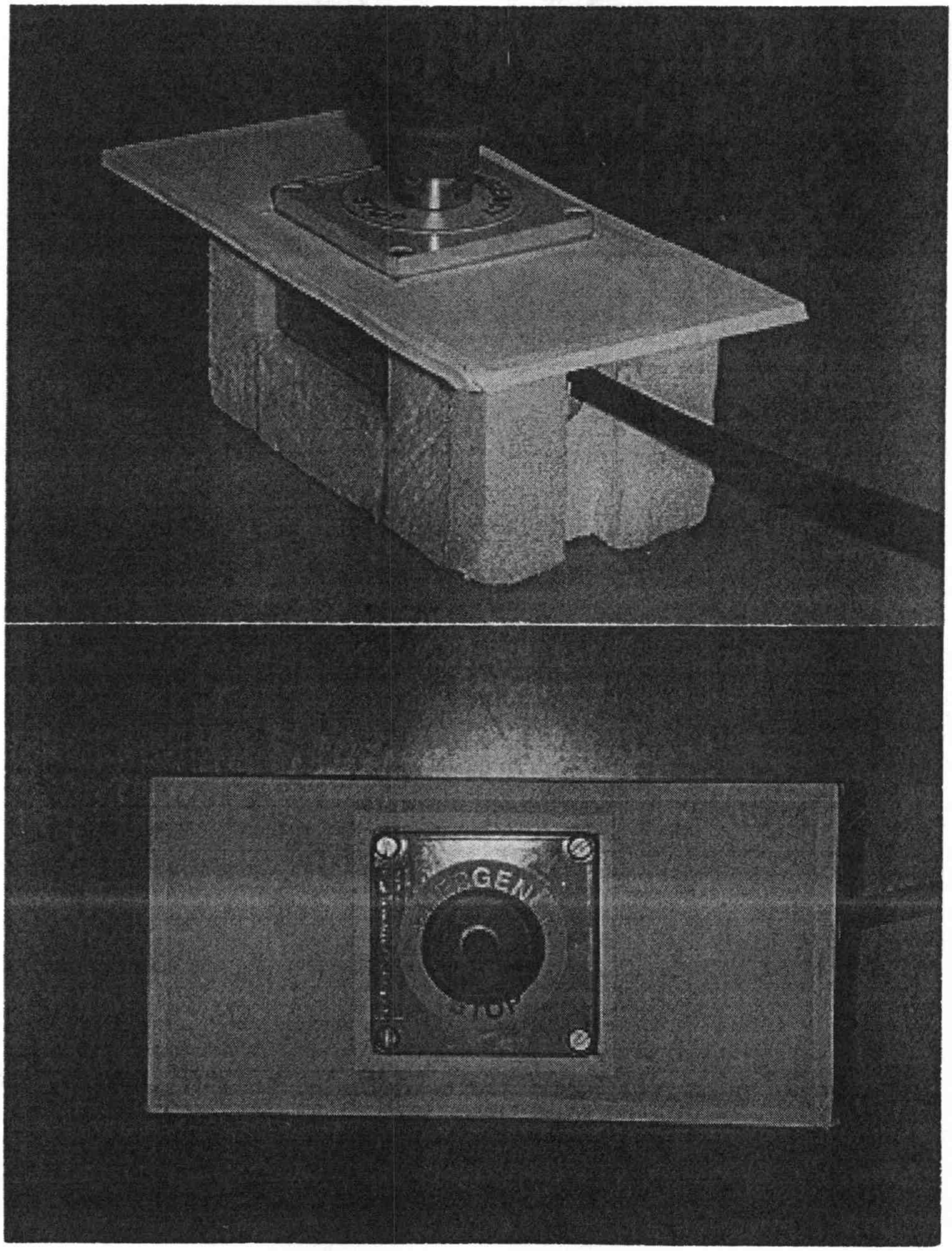

Figure 12: Two views of the emergency stop pushbutton 5, a Square D/Telemecanique ZB2-BT4 mushroom pushbutton.

Emergency Stop Pushbutton 6 was a General Electric CR104-P heavy-duty mushroom pushbutton with a PXG15 (HP-modified) mushroom guard. This is a half-guarded button. The button is red and the half-guard is metallic. The guard covers just half of the button to facilitate access. The diameter of the button is 40 mm (1.57 inch). The button has to be twisted to be reset. Figure 13 shows this button.

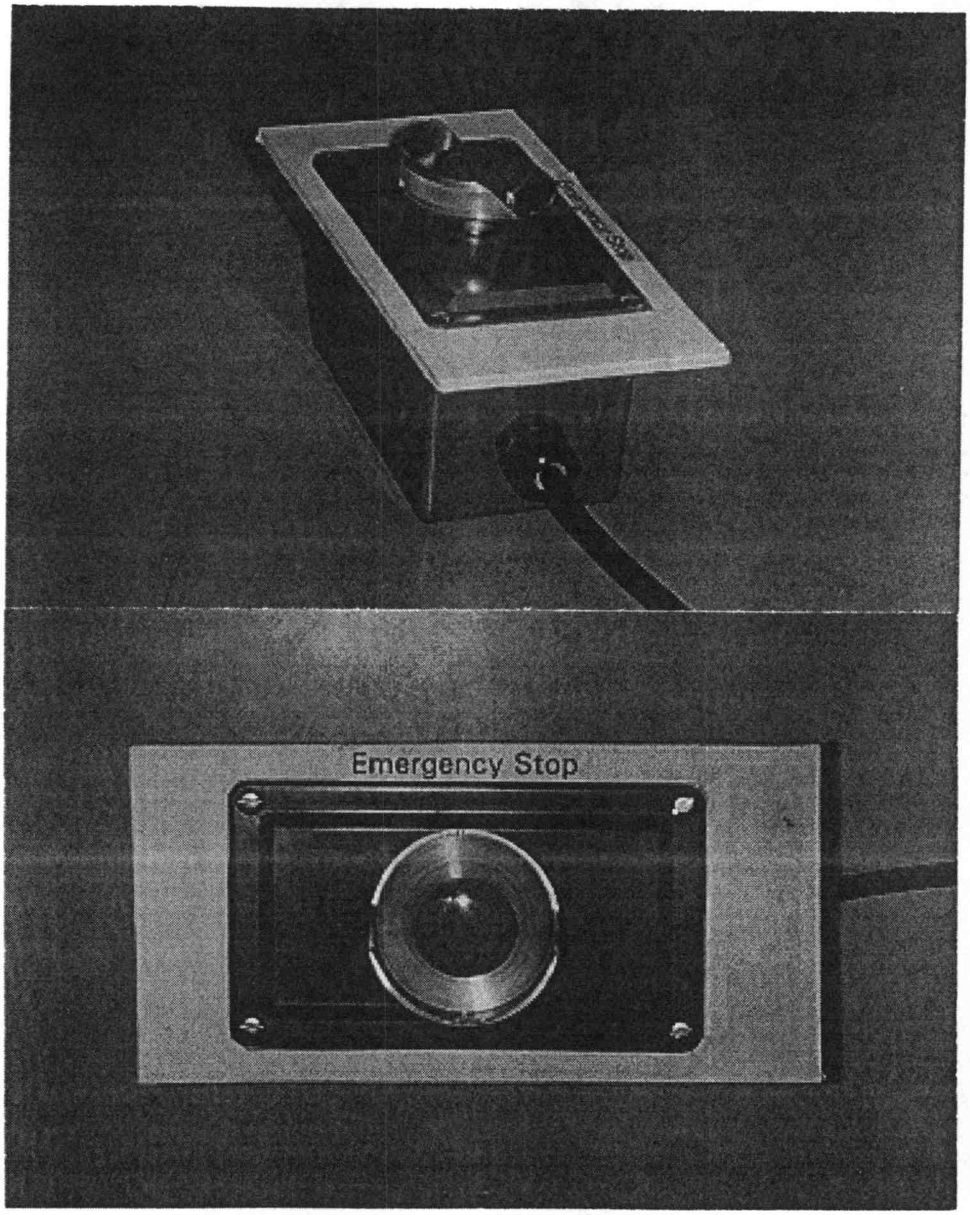

Figure 13: Two views of the emergency stop pushbutton 6, a General Electric CR104-P heavy-duty mushroom pushbutton with a PXG15 (HP-modified) mushroom guard.

The forces required to activate each emergency stop pushbutton were measured using a Shimpo Force Gauge with a maximum reading of 100 lb and 0.5 lb increments was used. For each control four measurements were taken and the average of them was calculated and recorded as the required activation force. Table 2 shows these forces.

A short code was created for each type of emergency stop pushbutton. Each code has three elements: make (T, S, or G), type of guard (F, H, or U), and diameter in mm (80, 40, 35, or 30). The following list explains the meaning of each one of these letters.

Make	Type of guard	Diameter
T: Square D/Telemecanique	F: full guard	80: 80 mm
S: Schmersal	H: half guard	40: 40 mm
G: General Electric	U: unguarded	35: 35 mm
		30: 30 mm

These codes are included in each table that refers to the type of control, so the reader can easily determine the main characteristics of each control.

Table 2: Activation forces for each type of emergency stop pushbutton.

	Type of Emergency Stop Pushbutton					
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
Force (lb)	8.5	7	8	5	13	5
	8	7.5	7	5	14	5.5
	8	7.5	7	4.5	12	4.5
	8	8	7.5	4.5	12	5.5
Average	8.1	7.5	7.4	4.8	12.8	5.1

4.2.6 Video Equipment:

The video equipment used to record the operation was a Panasonic Industrial Camera model WV-3250, a Panasonic VHS AG-2400 Video Cassette Recorder, and a Sony TV. Once the experiments were finished, the video tapes of the operation for each one of the 18 subjects were analyzed to study the mode of activation of each type and orientation of emergency stop pushbutton.

4.2.7 Operation:

Throughout the operation, the computer controlled the Microbot through a QBASIC program. The operation consisted of placing rings on pegs, see Figure 14. There were two sources to take rings from (A or B, the pegs with square collars in Figure 14) and three pegs to place rings on (1, 2, or 3). There were six different pre-established sequences for the operation. The program controlled the movements of the Microbot for each one of the pre-established sequences, indicating what the source for the ring was and on which peg to place the ring. The 6 sequences used during the experiments are shown in Appendix A. Table 3 shows an example of one of these pre-established sequences. This table shows the operations that both the robot and the operator had to follow. It indicates from which source the robot had to take the ring and on which peg it had to place it, and also on which source and peg the operator had to place rings.

Table 3: Sequence 1 for the experiment.

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	2	A	1
B	2	B	3
A	1	A	3
B	3	B	1
A	1	A	3
B	2	B	1

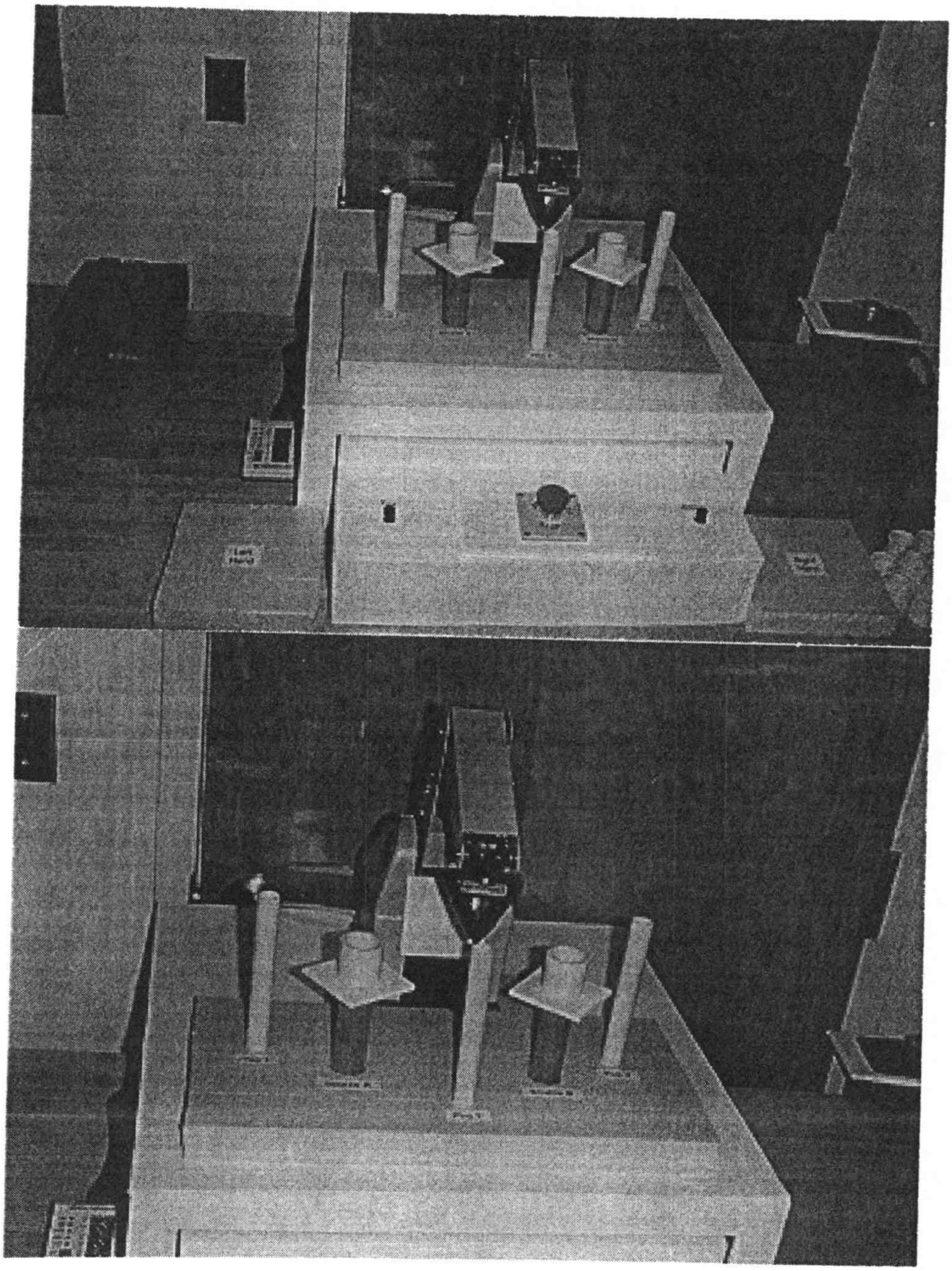

Figure 14: Two detailed views of the workstation for the experiment.

During the operation the Microbot performed a wrong movement, according to the pre-established sequence, inserting a ring on a wrong peg. The operator had to stop the operation by pressing the emergency stop pushbutton. The program kept record of when the subject activated the emergency stop pushbutton. The emergency stop pushbutton was checked by the parallel digital interface board to verify whether it had been pressed or not. When it was pressed the parallel digital interface board sent a signal to the computer, so that time was recorded as the time of activation. Then the program calculated the difference between the times recorded and kept it as the reaction time. Figure 15 shows a simplified flowchart of the operation.

4.3 Experimental Task

Subjects controlled an interactive operation with the Microbot during the experiment. The operation consisted of placing rings on three pegs to simulate a simple interactive assembly operation. The robot took one ring from either source A or B and placed it on peg 1, 2, or 3, then it went back to its original position. Then, the operator put a ring on the source that was empty and placed another ring on a peg following a pre-established sequence. There were six different sequences of movements for the robot. For each trial subjects were given a table with one of the pre-established sequences, see Table 3. Subjects had to follow the operation described on the table to verify that the robot was doing the correct movements and to know what tasks they had to perform. The operator had to press two buttons: a button labeled "Source"after he/she put a ring on the source for the robot and a button labeled "Peg" after he/she placed a ring on a peg. This last task started the next movement of the robot. This operation continued during the experiment.

During the sequence of placing rings, the robot made a mistake placing a ring on a wrong peg, according to the pre-established sequence, so the operator had to stop the operation by pressing the emergency stop pushbutton. Operators knew that a wrong movement occurred when the robot began moving in the wrong direction according to the sequence of the table given for that trial. The normal operation buttons were close enough to the emergency stop control to create opportunities for inadvertent activation with different body parts. For the subjects, the main task was to perform the assembly

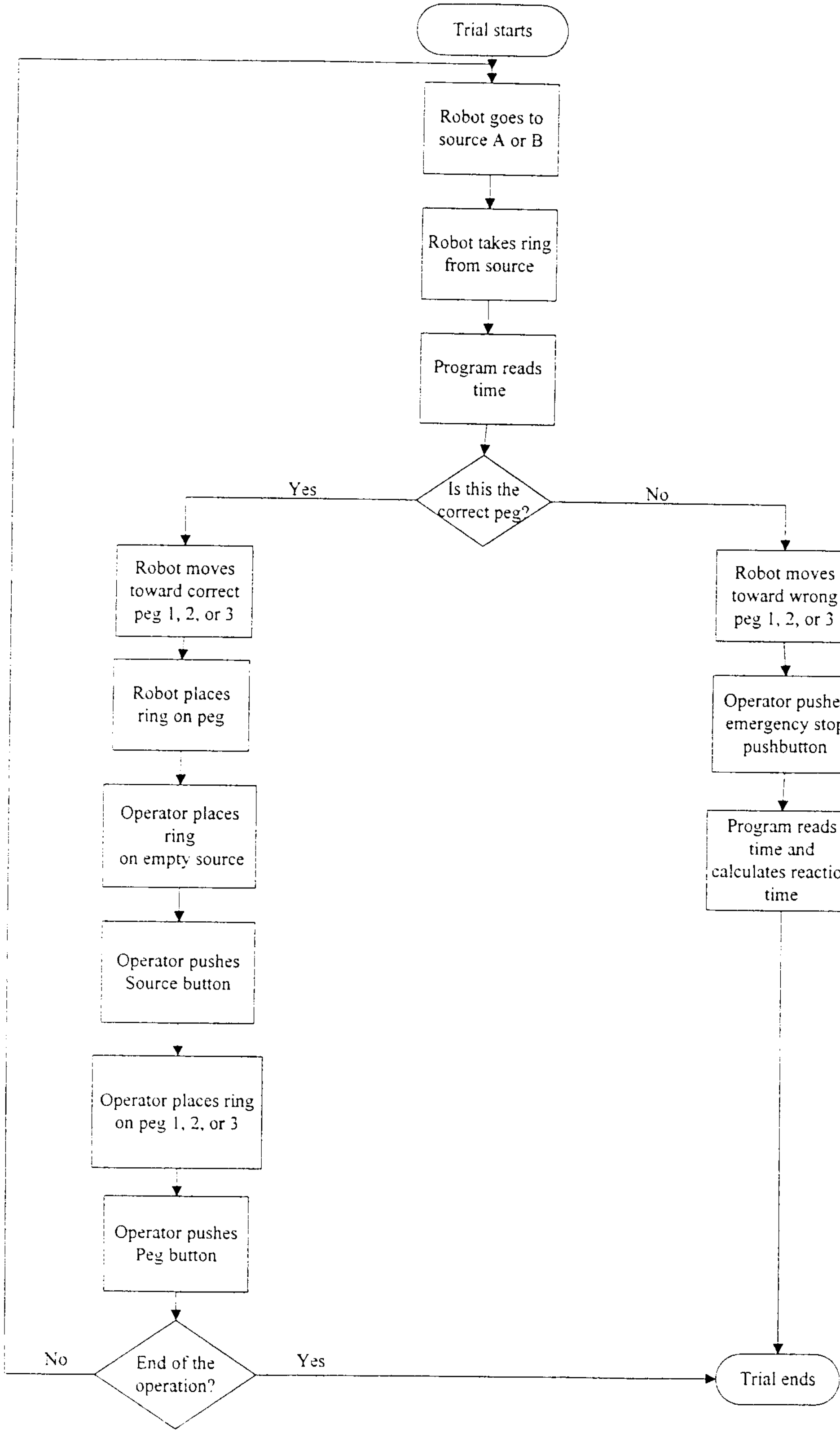

Figure 15: Flowchart of the operation during the experiments.

operation. The activation of the emergency stop control due to an error in the assembly operation was presented as a secondary task.

4.4 Procedure

An informed consent document was given to the subjects to explain the general aspects of the experiment and to indicate the benefits and potential risks. After they read it, they had to sign the document as an indication that they agreed to participate in the experiment. A copy of the informed consent document is in Appendix B. Then a pre-test questionnaire was given to the subjects as a screening device to ensure a homogeneous population. My intention was to screen out subjects, for instance, who did not have enough sleep the night before the experiment or who were taking medication that might affect their performance. A copy of the pre-test questionnaire is in Appendix C.

After the paperwork was done, subjects were trained to do the operation before they performed the experimental task. They learned how the Microbot would take the rings and place them on the pegs and also how they would place the rings. Then subjects chose randomly, from a bowl, a piece of paper with the order of the 18 trials they were to perform. This training took approximately five minutes.

Subjects were seated on an ergonomic chair in front of a table with the apparatus. The height of the seat was adjusted according to the height of the subjects, so they were appropriately seated in front of the table. In order to have a consistent position of subjects, they were required to have their feet either on the ground or on the foot rest and their elbows had to be at the same height of the table. During the trials, subjects also were required to have their hands on two pads labeled "right hand" and "left hand" whenever they were not performing a task. They performed the experimental task 18 times, with six different types of emergency stop controls and three different orientations (horizontal, vertical, and inclined at a 45° angle) for each one of the emergency stop controls. The control panel was changed for each one of the 18 trials to change the type of emergency stop control and its orientation. The experiment was video taped to enable further analysis of the mode of activation of the different emergency stop controls. Two performance measures were collected for each trial: the reaction time to activate the emergency stop control and the mode of activation.

After the experiment was over the subjects filled out a post-test questionnaire. The purpose of this questionnaire was to collect data about the subjects' preferences among the different types of emergency stop controls, their orientations, their reset methods, and the quality of the training for this experiment. A copy of the post-test questionnaire is in Appendix D.

4.5 Experimental Design

4.5.1 Design Structure

In this experiment 18 subjects performed 18 trials each for a total of 324 trials in the study. Subjects tested six types of emergency stop controls with three different orientations (horizontal, vertical, and inclined at a 45° angle) for each one. The order of each combination of emergency stop control type and orientation was designed following a Latin Square model to make sure that each combination was done at each trial. These sequences are shown in Table 4. In this table T1 to T18 are the trials from 1 to 18, H,V, and I are the three orientations: horizontal, vertical, and inclined at a 45° angle, and 1 to 6 are the different types of emergency stop pushbuttons.

A subject number from 1 to 18 was assigned to each one of these combinations. The 18 subjects randomly chose a subject number and they performed the trials according to the selected order.

This design is a balanced complete block design with the orientation and type of emergency stop control being the 3x6 factorial treatment and the subjects being the blocks. The experimental units were each one of the trials given to each subject.

Table 4: Combination of type and orientation of emergency stop pushbutton for trials 1 to 18 for each subject.

Subject	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18
1	H1	V2	I3	V4	I5	H6	I2	H3	V5	H4	V6	I1	V3	I4	H5	I6	H2	V1
2	V3	I2	H4	I5	H6	V1	H3	V4	I6	V5	I1	H2	I4	H5	V6	H1	V2	I3
3	I3	H1	V5	H3	V1	I2	V4	I5	H6	I4	H2	V3	H5	V6	I1	V2	I6	H4
4	H4	V2	I6	V4	I2	H3	I5	H6	V1	H2	V3	I4	V6	I1	H5	I3	H1	V5
5	V5	I3	H1	I6	H3	V4	H6	V1	I2	V6	I4	H5	I1	H2	V3	H4	V2	I5
6	I6	H1	V5	H4	V2	I5	V1	I2	H3	I4	H5	V6	H2	V3	I1	V4	I3	H6
7	V2	I1	H3	I4	H5	V6	H2	V3	I5	V4	I6	H1	I3	H4	V5	H6	V1	I2
8	I1	H2	V4	H5	V6	I5	V3	I4	H6	I3	H1	V2	H4	V5	I6	V1	I2	H3
9	H3	V4	I5	V6	I1	H2	I4	H5	V3	H1	V2	I3	V5	I6	H4	I2	H6	V1
10	V4	I5	H6	I1	H2	V3	H5	V6	I2	V1	I3	H4	I6	H1	V2	H3	V5	I4
11	I5	H6	V1	H2	V3	I4	V6	I1	H5	I3	H4	V5	H1	V2	I6	V4	I2	H3
12	H3	V1	I2	V3	I4	H5	I1	H2	V6	H1	V5	I6	V2	I3	H4	I5	H6	V4
13	I1	H2	V6	H5	V1	I4	V2	I3	H4	I5	H6	V5	H3	V4	I6	V3	I2	H1
14	H2	V3	I4	V5	I2	H1	I3	H4	V6	H5	V1	I6	V4	I5	H6	I1	H3	V2
15	V3	I4	H5	I3	H1	V2	H4	V5	I6	V4	I2	H3	I5	H6	V1	H2	V6	I1
16	I4	H5	V6	H1	V2	I3	V5	I6	H2	I1	H3	V4	H6	V1	I2	V3	I5	H4
17	H5	V6	I1	V2	I3	H4	I6	H1	V5	H3	V4	I5	V1	I2	H6	I4	H2	V3
18	V6	I1	H2	I6	H4	V5	H1	V2	I3	V4	I5	H6	I2	H3	V1	H5	V3	I4

T1 to T18: Trial 1 to trial 18 H: horizontal V: vertical I: inclined at a 45° angle 1 to 6: emergency stop pushbutton 1 to 6

4.5.2 Independent Variables:

There were two independent variables in this experiment: the type of emergency stop control and its orientation.

1) Type of emergency stop control:

There were six emergency stop pushbuttons with different button sizes and with or without guarding. They were numbered from 1 to 6.

2) Orientation of the emergency stop control in the control panel:

- Horizontal (H)
- Vertical (V)
- Inclined at a 45° angle (I).

At the beginning of the study the location of the emergency stop control in the control panel was to be considered, but this location depends on the type, size and design of industrial machinery. Therefore the location was fixed for all trials in the experiment at a standard position in front of the operator at a height of 40" above the floor.

4.5.3 Dependent Variables:

There were 3 types of performance measures in this experiment: speed, accuracy, and user satisfaction.

1) Speed:

- Reaction time: how long it took the operator to activate the emergency stop control after the emergency condition appeared (during the operation the Microbot performed a wrong movement, according to the pre-established sequence, inserting a ring on a different peg; this was the emergency signal for the subject). The initial event to start measuring reaction time was the first movement of the robot that did not follow the sequence for the trial. The end event of the reaction time measurement was the activation of the emergency stop pushbutton.

2) Accuracy:

- Number of inadvertent activations (as a percentage of all activations).

3) User satisfaction:

- Emergency stop control type preferred by users (1-6).
- Orientation of emergency stop control preferred by users (H, V, I).
- Reset method of emergency stop control preferred by users (twist, pull, or press a button to reset).

5. RESULTS

5.1 Pre-test Questionnaire Results

The results of the pre-test questionnaire are shown in Table 5. The purpose of this questionnaire was to screen out subjects and to collect data about the subjects in case some results could be considered out of the range. The results showed that there were 11 males and 7 females among the 18 subjects. The average age of the subjects was 25 years. Three of the subjects were left-handed and 15 were right-handed. Most of the subjects (16) had 6 hours of sleep or more the night before the experiment. Just one of the subjects was taking any medication but it was of a type not likely to affect her performance. On the average each subject had less than one cup of coffee or tea prior to the experiment. Most of the subjects (16) expressed that they did not have any pain or aches at the moment of the experiment. None of the subjects was color blind and 11 used corrective lenses. Just 4 of the subjects had any prior experience using emergency stop controls.

5.2 Experiment Results

Two main results were obtained from the experiments: the reaction time (in seconds) and the mode of activation of emergency stop pushbuttons. The results of the experiments for each subject are shown in Appendix E.

The tables in Appendix E not only show the results but also the independent variables (type and orientation of emergency stop pushbuttons) and other factors that might have some effect on the results such as the trial number and the sequence for the emergency signal used for each trial, i.e., the steps the robot followed before performing a wrong movement (see Table 3 in Chapter 4). There was no inadvertent activation of the emergency stop pushbuttons during the experiments. An example of these tables is shown in Table 6.

The mode of activation referred to the part of the hand subjects used to activate the emergency stop pushbuttons. These modes of activation were taken from the video

Table 5: Results of the pre-test questionnaire.

Subject	Male	Female	Age	Left-handed	Right-handed	Hours of sleep the night before: More than 8	Between 8 and 6	Less than 6	Taking Medications: Yes	No	Cups of Coffee or Tea	Has pains or aches: Yes	No	Uses lenses: Yes	No	Color blind: Yes	No	Experience using ESC: Yes	No
1	1		24		1			1		1	0		1		1		1		1
2	1		27		1		1			1	3		1	1			1		1
3	1		27		1			1		1	0		1		1		1	1	
4		1	21	1			1			1	0		1	1			1	1	
5	1		30		1		1			1	1		1	1			1	1	
6		1	23		1	1				1	0		1		1		1		1
7	1		29		1		1			1	0		1		1		1	1	
8	1		22		1	1				1	0	1		1			1		1
9	1		22		1		1			1	0		1	1			1		1
10	1		23		1		1			1	0		1	1			1		1
11	1		25		1	1				1	1		1		1		1		1
12	1		23	1		1				1	0		1		1		1		1
13		1	21		1	1				1	2		1	1			1		1
14		1	29		1		1			1	0		1	1			1		1
15		1	31		1		1			1	0		1	1			1		1
16		1	26		1	1			1		1.5		1	1			1		1
17		1	23	1			1			1	2		1	1			1		1
18	1		25		1	1				1	2	1			1		1		1
Total	**11**	**7**		**3**	**15**	**7**	**9**	**2**	**1**	**17**		**2**	**16**	**11**	**7**	**0**	**18**	**4**	**14**
Average			**25**								**0.69**								

tape of the experiments. The hand that was used by the subjects was also recorded. There were four main ways to activate these controls: with one finger, with two fingers, with three fingers, or with other parts of the hand. Figure 16 shows the name of the different parts of the hands that were used by the subjects to activate the emergency stop pushbuttons. The different modes of activation are explained in Table 7.

The frequency of each mode of activation according to the type and orientation of emergency stop pushbuttons is shown in Table 8.

Table 6: Results of the experiment for subject 1.

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Orientation	**Type of Emergency Stop Pushbutton**											
	1		**2**		**3**		**4**		**5**		**6**	
Horizontal	1	1	17	1	8	3	10	5	15	5	6	6
	1.261719		1.050781		0.988281		1.160156		1.042969		1.378906	
	R	4	R	4	R	4	R	4	R	4	R	4
Vertical	18	2	2	2	13	3	4	4	9	4	11	6
	0.992188		1.273438		1.433594		1.648438		1.039063		1.273438	
	R	1	R	1	R	1	L	1	R	1	R	1
Inclined 45°	12	1	7	2	3	3	14	4	5	5	16	6
	1.039063		0.988281		1.421875		1.097656		1.050781		1.152344	
	R	1	R	4	R	4	R	4	R	11	R	4

It is important to say at this point that during the experiments some subjects who did not have previous experience with emergency stop pushbuttons were confused with some features of the controls. For instance, the figure of the arrows in controls 1, 3, and 6 indicate that it is necessary to twist the button to reset it; however, it was confusing for 5 subjects as they tried to twist the buttons to activate them. Emergency stop pushbutton 4 also has a confusing feature. It has a small blue button in its center that has to be pressed to reset the control. From 18 subjects, 12 either asked whether they had to push the blue button to activate the control or actually pushed that blue button to activate the control instead of pushing the red area of the button.

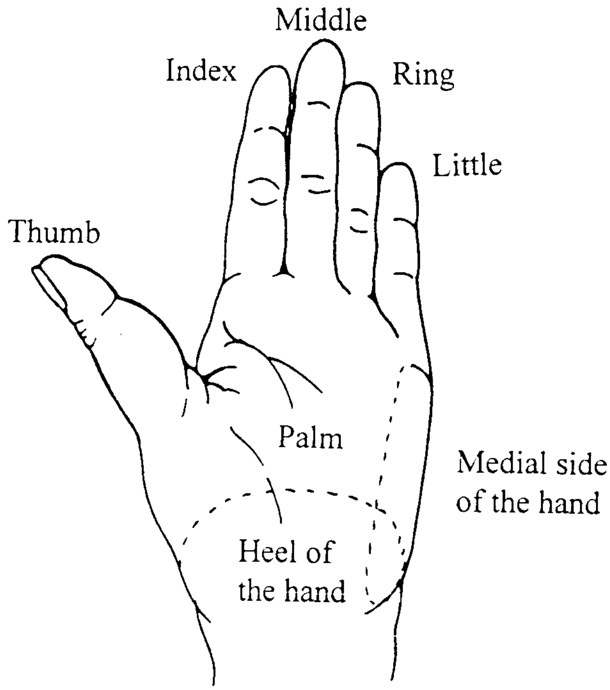

Figure 16: Names of the different parts of the hand used by the subjects to activate emergency stop pushbuttons.

5.3 Post-test Questionnaire Results

The post-test questionnaire was filled out by each subject after the experiments were finished. The subjects had to rank the type, orientation, and reset method of each emergency stop pushbutton according to their preferences. The results of these rankings are shown in Table 9.

Subjects were also asked about the training for the experiment and their comments. All subjects agreed that the training was adequate for the experimental task; two subjects even expressed that it could have been shorter than it was. Three subjects commented that the speed of the robot was too slow, making the task somewhat boring.

Table 7: Mode of activation of emergency stop pushbuttons.

Mode of Activation of Emergency Stop Pushbuttons		Number assigned
With one finger	Tip of the thumb	1
	Tip of the index	2
	Tip of the middle	3
With two fingers	Tips of the index and middle	4
	Tips of the middle and ring	5
	Tips of the index and thumb	6
With three fingers	Tips of the thumb, index, and middle	7
	Tips of the index, middle, and ring	8
	Extended index, middle, and ring	9
With other parts of the hand	Palm	10
	Heel of the hand	11
	Medial side of the fist	12

Table 8: Frequency of each mode of activation for emergency stop pushbuttons.

Orientation	Mode of Activation	Type of Emergency Stop Pushbutton					
		1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
	1		1				
	2	1	1	4	2		
	3		2	2			
	4	15	12	11	11	7	14
	5	1			1		1
Horizontal	6						
	7		1	1			1
	8	1	1			3	2
	9				4	2	
	10					4	
	11					1	
	12					1	
	1	18	18	18	15	15	16
	2				1		
	3						
	4					1	
	5				1	1	1
Vertical	6				1		1
	7						
	8						
	9						
	10						
	11						
	12					1	
	1	6	9	8	5	2	9
	2	2	2	3	2		1
	3			1			
	4	6	5	4	6	3	2
	5	2	1	2	1	1	1
Inclined 45	6				1		
	7	1				2	1
	8	1	1		1	2	4
	9					1	
	10					3	
	11				1	4	
	12				1		

Table 9: Results of the post-test questionnaire.

	Type of Emergency Stop Pushbutton						Orientation			Reset method		
Subject	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40	Horizontal	Vertical	Inclined 45	Twist	Pull	Press a button
1	3	5	2	1	6	4	2	1	3	1	2	3
2	2	6	5	1	3	4	2	1	3	3	1	2
3	5	3	4	6	1	2	2	3	1	2	1	3
4	1	3	2	6	5	4	2	1	3	3	1	2
5	3	1	2	6	5	4	2	1	3	1	2	3
6	1	3	2	5	6	4	2	1	3	2	1	3
7	5	2	3	6	1	4	2	1	3	3	1	2
8	3	2	1	6	5	4	3	1	2	2	3	1
9	4	2	3	6	5	1	2	1	3	1	2	3
10	1	3	2	5	4	6	2	1	3	2	1	3
11	4	3	1	2	6	5	2	1	3	3	2	1
12	4	2	1	3	5	6	2	3	1	2	3	1
13	1	4	3	6	2	5	3	1	2	1	2	3
14	2	6	5	1	4	3	2	1	3	3	2	1
15	2	1	3	5	4	6	2	1	3	1	2	3
16	2	1	4	3	5	6	2	1	3	3	1	2
17	1	5	3	4	6	2	1	2	3	1	3	2
18	3	2	1	5	6	4	2	1	3	3	2	1
Total	47	54	47	77	79	74	37	23	48	37	32	39
Average	2.61	3	2.61	4.28	4.39	4.11	2.06	1.28	2.67	2.06	1.78	2.17

6. ANALYSIS OF RESULTS

6.1 Reaction Time to Activate Emergency Stop Pushbuttons

The hypothesis for the experiment was that the reaction time to activate the emergency stop pushbuttons varied depending on the type and orientation of the controls. The independent variables for the experiment were the type and the orientation of the emergency stop pushbuttons. In the experiments there were other factors that might have effects on the reaction time, such as the number of the trial (1 to 18) and the sequence for the emergency signal (1 to 6). Therefore, before analyzing the effect of the type and the orientation of emergency stop pushbuttons on reaction time, it was necessary to determine if these other factors had any effect on the reaction times. The tables in Appendix E show the reaction times (in seconds), the type of emergency stop pushbutton, the orientation, the number of the trial, and the sequence (steps the robot followed before performing a wrong movement) used for the emergency signal for each one of the subjects.

I used the SAS system, a statistical software package, to do the ANOVA for the different variables that might affect the reaction time to activate emergency stop pushbuttons.

The first step was to determine if the reaction time was independent from the number of the trial. That is, if there was not a learning effect that made the reaction times of subjects decrease during the last trials. A regression analysis was done to test the independence of reaction time vs. number of trial. The output from the SAS system is in Appendix F. The results showed that the p value for the ANOVA table was 0.0001, less than 0.05. Therefore, there is a statistically significant relationship between the reaction time and the number of the trial at the 95% confidence level. Figure 17 shows the plot of reaction time vs. number of trial. The equation of the linear model to describe the relationship between reaction time and number of trial is:

Reaction Time= 1.77025 - 0.0258819*Number of Trial.

This model indicates that reaction time tends to decrease with the number of trials performed by the operator.

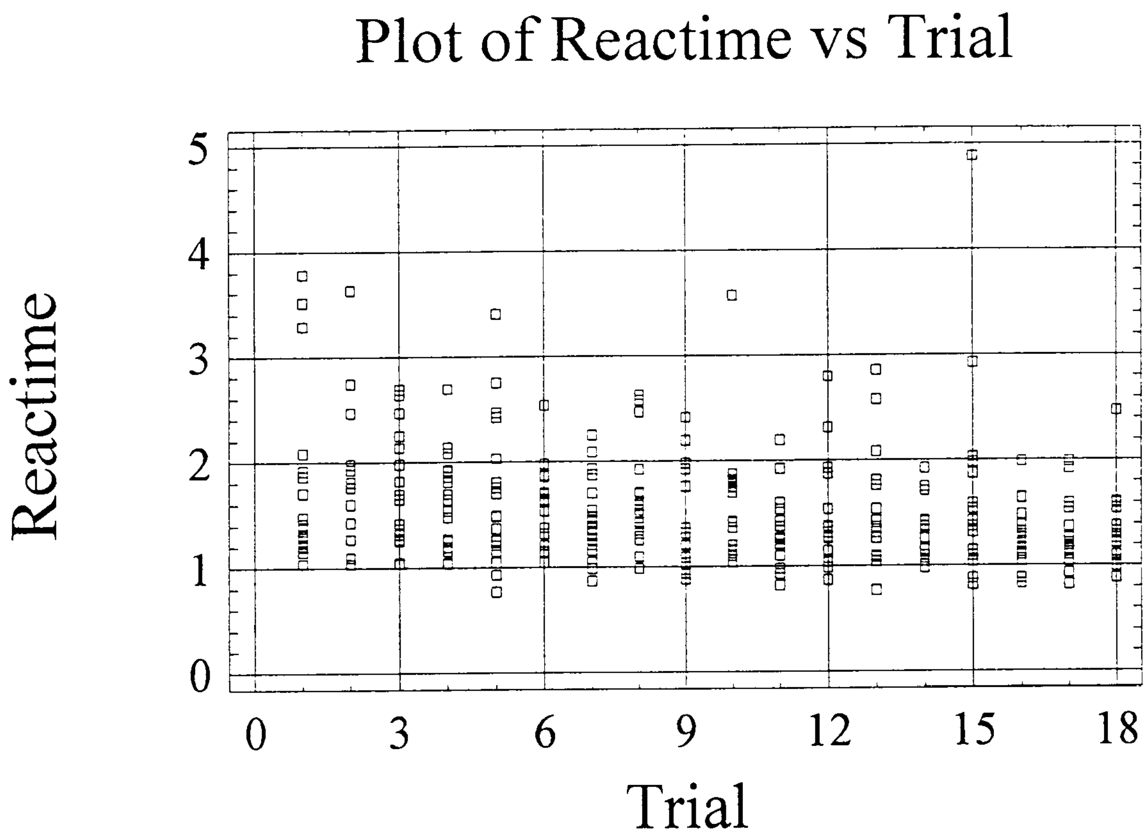

Figure 17: Plot of reaction time vs. number of trial for original data.

The second step to analyze the data was to determine if the reaction time was independent from the sequence for the emergency signal. An Analysis of Variance (ANOVA) was done to test the effect of the sequence for the emergency signal on the reaction time. The output from the SAS system is in Appendix G. The results showed that the p value for the ANOVA table was 0.0702, greater than 0.05. Therefore, there is no evidence of a statistically significant effect of the sequence of the emergency signal on the reaction time at the 95% confidence level. The sequence of the emergency signal could be eliminated from the model.

After determining that the effect of the number of trials on reaction time was statistically significant and that the effect of the sequence for the emergency signal was not statistically significant, the following step was to determine the effect of type and orientation of emergency stop pushbutton on reaction time. The model to establish which variables had effects on reaction time included the subjects (the blocks of the experiment), the trial, the type and the orientation of the emergency stop pushbuttons, and their interaction in case these variables were not independent. The design of the experiment was a completely randomized block, so I could assume that there was no interaction between the blocks and other variables (subjects and type or orientation of the emergency stop pushbuttons).

Before doing the analysis of variance, the outlier point during trial 15 with a reaction time of 4.88 seconds (see Figure 17) was analyzed. During the experiment, this subject expressed that he was not really paying attention to the task when the emergency signal occurred and that is why this reaction time was considerably greater than all other reaction times. Therefore, this point was taken out from the data. The new plot of reaction time vs. number of trial for the adjusted data is shown in Figure 18.

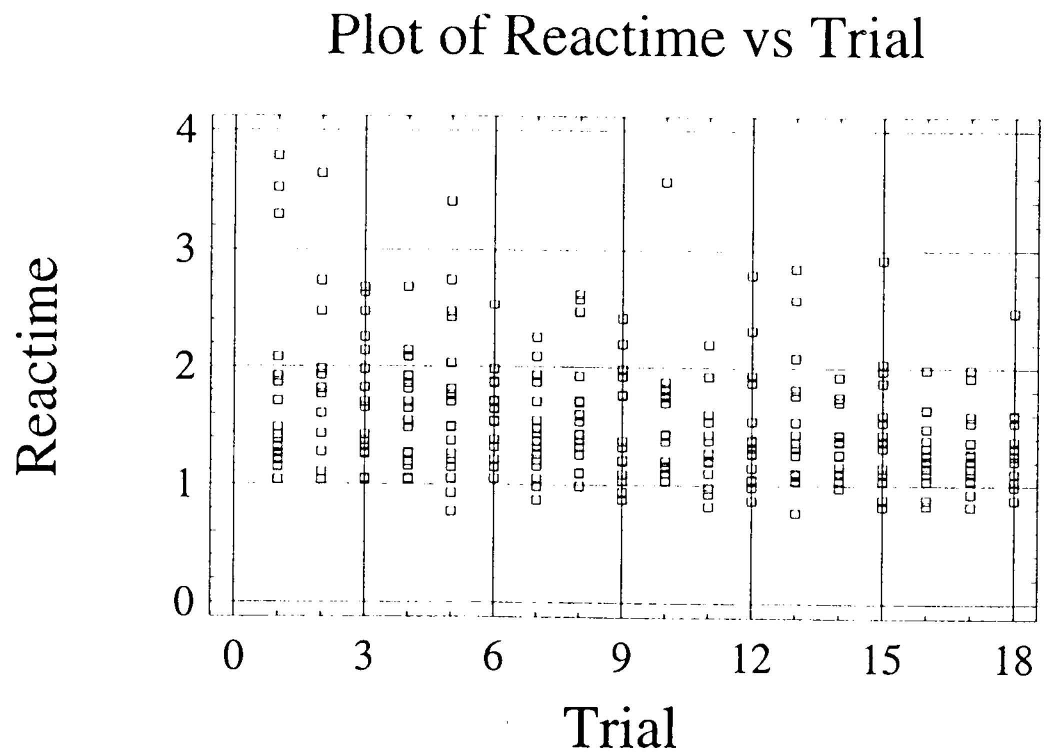

Figure 18: Plot of reaction time vs. number of trial for adjusted data.

The output of the SAS system for the ANOVA for the adjusted data is shown in Appendix H. Table 10 shows the ANOVA table.

Table 10: ANOVA table for the effect of subjects, trial, type, and orientation of emergency stop pushbuttons on reaction time for the adjusted data.

Source of Variation	Degrees of freedom	Sum of Squares	Mean Square	f value	p value
Subject	17	37.0272	2.1781	13.73	0.0001
Trial	17	9.2688	0.5452	3.44	0.0001
Type	5	1.9033	0.3807	2.40	0.0375
Orientation	2	0.1329	0.0665	0.42	0.6582
Type*Orientation	10	1.3129	0.1317	0.83	0.5995
Error	271	49.6496	0.1586		
Total	322	92.636			

The p value of 0.5995, larger than 0.05, from the ANOVA table showed that there was no statistical evidence of interaction between the type and the orientation of emergency stop pushbuttons. There was no statistical evidence of the effect of orientation on the reaction time, according to the p value of 0.6582, larger than 0.05, at the 95% confidence level. The p values of 0.0375 and 0.001, less than 0.05, indicated statistically significant evidence of the effect of the type of emergency stop pushbuttons, number of trial, and subjects on the reaction times at the 95% confidence level. However, the subjects variable accounted for 37.03% of the variability in reaction times while the trial accounted for 9.27% and the type of emergency stop pushbutton accounted for just 1.90% of this variability.

The output of the SAS system for the ANOVA for the original data is shown in Appendix I. The results are basically the same as those obtained with the adjusted data, only the significance of the effect of the type of emergency stop pushbutton is higher.

After establishing that the type of emergency stop pushbuttons had an effect on the reaction times, a multiple comparison test was done to determine if there was a specific type of control with the shortest reaction time. Figure 19 shows the average reaction time in seconds for each type of emergency stop pushbutton.

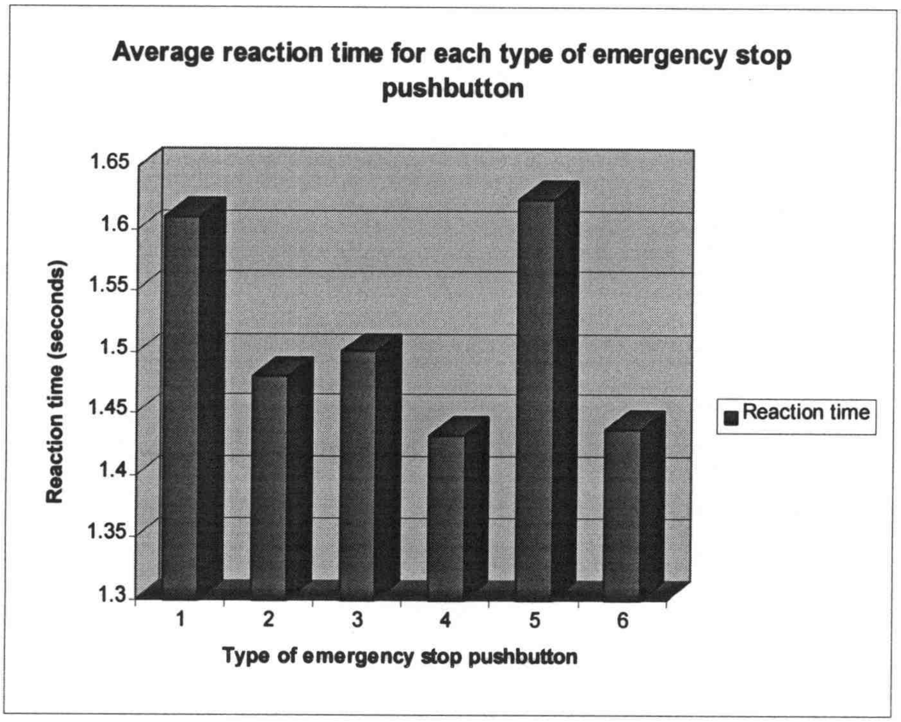

Figure 19: Average reaction time for each type of emergency stop pushbutton.
(1: T-F-40 2: T-F-35 3: T-F-30 4: S-U-80 5: T-U-40 6: G-H-40)

I used the SAS system to apply the Least Significant Difference test to compare the means (least square means) of the reaction times for the different types of emergency stop pushbuttons. Appendix J shows the output of the SAS system for this test. This test show that there are statistically significant differences among different types of controls at the 95% confidence level, but there is not a specific control that is different from all others. When a more conservative test, such as the Student-Newman-Keuls (SNK) multiple range test, is used no statistically significant differences are detected, even though the ANOVA reflects that the effect of the type of emergency stop pushbutton is indeed significant at the 95% confidence level.

6.2 Mode of Activation of Emergency Stop Pushbuttons

The objective of the analysis of the mode of activation of emergency stop pushbuttons was to determine if the type or orientation of the control influenced its mode of activation. The frequency of each mode of activation is categorical data, therefore I applied a Chi-Square test to test the homogeneity of the frequency of each one of the 12 the different modes of activation found in the experiment for each type and each orientation of emergency stop pushbuttons. The frequencies of each mode of activation for the different types and orientations of emergency stop pushbuttons are shown in Tables 11 and 12. Figures 20 and 21 show graphics of the frequency of each mode of activation for the types and orientations of emergency stop pushbuttons.

The Chi-Square test statistic value is :

$$X^2 = \sum_{\text{all cells}} \frac{(\text{observed - estimated expected})^2}{\text{estimated expected}}$$

The null hypothesis Ho: $p_i = p_j$ is rejected if $X^2 > X^2_{\alpha, I-1}$ where I= number of different categories and $(1-\alpha)$ is the confidence level (Devore, 1.991).

Table 11: Frequencies of each mode of activation for the types of emergency stop pushbuttons (See Table 7 for modes of activation description).

Mode of Activation	Type of Emergency Stop Pushbutton					
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
1	24	28	26	20	17	25
2	3	3	7	5	0	1
3	0	2	3	0	0	0
4	21	17	15	17	11	16
5	3	1	2	3	2	3
6	0	0	0	2	0	1
7	1	1	1	0	2	2
8	2	2	0	1	5	6
9	0	0	0	4	3	0
10	0	0	0	0	7	0
11	0	0	0	1	5	0
12	0	0	0	1	2	0

Table 12: Frequencies of each mode of activation for the orientations of emergency stop pushbuttons (See Table 7 for modes of activation description).

Mode of Activation	Orientation		
	Horizontal	Vertical	Inclined 45
1	1	100	39
2	8	1	10
3	4	0	1
4	70	1	26
5	3	3	8
6	0	2	1
7	3	0	4
8	7	0	9
9	6	0	1
10	4	0	3
11	1	0	5
12	1	1	1

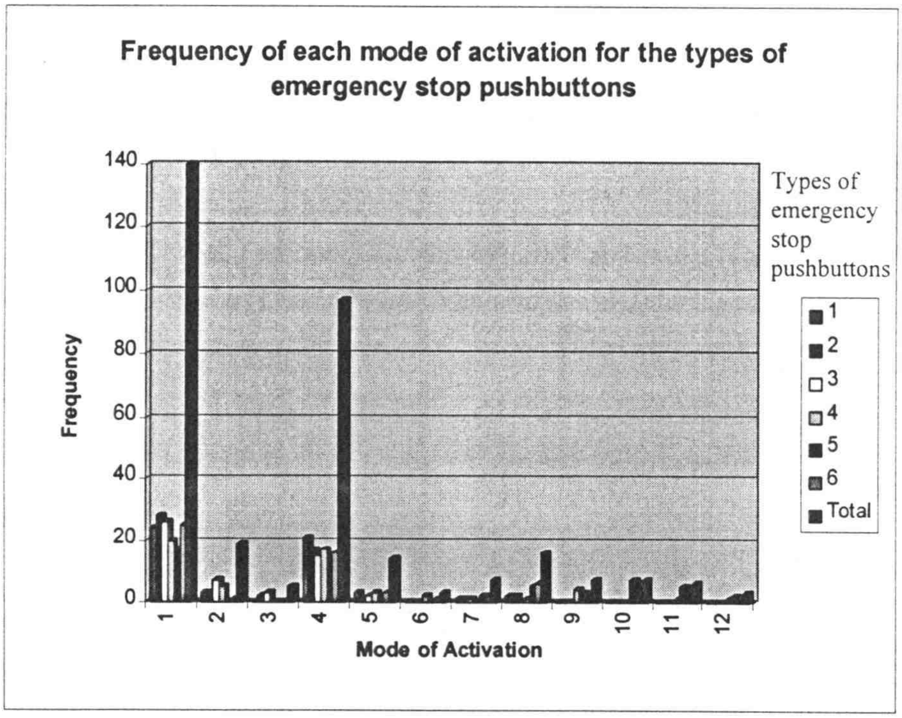

Figure 20: Frequencies of each mode of activation for the types of emergency stop pushbuttons.

The expected frequency for each cell in Table 11 is 324/(12*6) = 4.5 observations and the expected frequency for each cell in Table 12 is 324/(12*3) = 9 observations.

The test statistic values for the type and orientation of emergency stop pushbuttons are shown in Tables 13 and 14. Appendix K shows the table with the critical values $X^2_{\alpha, v}$ for the Chi-Square distribution.

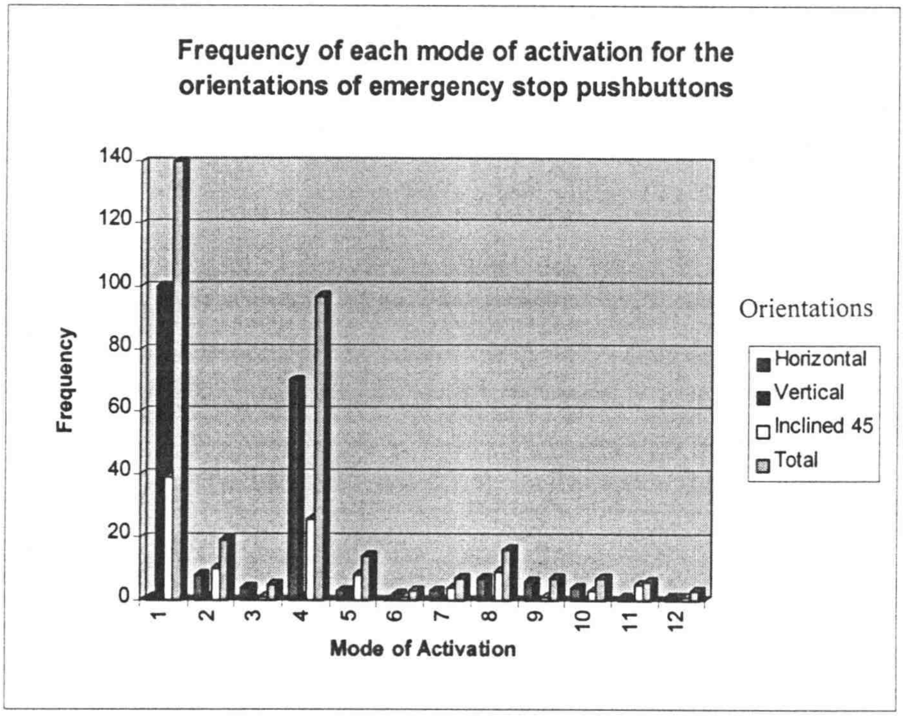

Figure 21: Frequencies of each mode of activation for the orientations of emergency stop pushbuttons.

The Chi-Square test for the homogeneity of the modes of activation for the type of emergency stop pushbutton was as follows:

$X^2 = 177.11+188.67+160.22+111.78+63.78+153.11= 854.67$

I= 6 different types of emergency stop pushbuttons

$\alpha = 0.05$

$X^2_{0.05, 5} = 11.070$

$854.67 > 11.070$

The null hypothesis is rejected, indicating that there is statistical evidence, at the 95% confidence level, that the type of emergency stop pushbutton influenced its mode of activation. Analyzing the frequencies of the modes of activation in Table 11 and in Figure 20, we can see that the most common modes of activation for different types of emergency stop pushbuttons are with the tip of the thumb and with the tips of the index and middle fingers.

Table 13: Values of the Chi-Square test of the mode of activation for the types of emergency stop pushbuttons.

Mode of Activation	Type of Emergency Stop Pushbutton					
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
1	84.5	122.72	102.72	53.39	34.72	93.39
2	0.5	0.5	1.39	0.06	4.5	2.72
3	4.5	1.39	0.5	4.5	4.5	4.5
4	60.5	34.72	24.5	34.72	9.39	29.39
5	0.5	2.72	1.39	0.5	1.39	0.5
6	4.5	4.5	4.5	1.39	4.5	2.72
7	2.72	2.72	2.72	4.5	1.39	1.39
8	1.39	1.39	4.5	2.72	0.06	0.5
9	4.5	4.5	4.5	0.06	0.5	4.5
10	4.5	4.5	4.5	4.5	1.39	4.5
11	4.5	4.5	4.5	2.72	0.06	4.5
12	4.5	4.5	4.5	2.72	1.39	4.5
Total	177.11	188.67	160.22	111.78	63.78	153.11

The Chi-Square test for the homogeneity of the modes of activation for the orientation of emergency stop pushbutton was as follows:

$X^2 = 458.89+1004.89+169.33= 1633.11$

I= 3 different orientations of emergency stop pushbuttons

$\alpha = 0.05$

$X^2_{0.05,\,2} = 5.992$

$1633.11 > 5.992$

The null hypothesis is rejected, indicating that there is statistical evidence, at the 95% confidence level, that the orientation of the emergency stop pushbutton influenced its mode of activation. Analyzing the frequencies of the modes of activation in Table 12 and in Figure 21, we can see that the most common mode of activation for horizontally oriented emergency stop pushbuttons is with the tips of the index and middle fingers, for vertically oriented emergency stop pushbuttons is with the tip of the thumb, and for emergency stop pushbuttons inclined at a 45° angle is with the tip of the thumb or with the tips of the index and middle fingers.

Table 14: Values of the Chi-Square test of the mode of activation for the orientations of emergency stop pushbuttons.

Mode of Activation	Orientation		
	Horizontal	Vertical	Inclined 45
1	7.11	920.11	100
2	0.11	7.11	0.11
3	2.78	9	7.11
4	413.44	7.11	32.11
5	4	4	0.11
6	9	5.44	7.11
7	4	9	2.78
8	0.44	9	0
9	1	9	7.11
10	2.78	9	4
11	7.11	9	1.78
12	7.11	7.11	7.11
Total	458.89	1004.89	169.33

6.3 Preferences for Types, Orientation, and Reset Method of Emergency Stop Pushbuttons

The post-test questionnaire asked the subject about their preferences for type, orientation, and reset method of emergency stop pushbuttons.

I applied a Chi-Square test to determine if there was a significant difference in the preference of subjects for a specific type, orientation, or reset method. If the difference for preferences was statistically significant I applied an analysis of categorical data to determine which category was the best preferred.

6.3.1 Preferences for Types of Emergency Stop Pushbuttons

The frequencies of the preferences of subjects for each type of control are shown in Table 15. The expected frequency for each cell in Table 15 is 18/6 = 3 observations. The test statistic values for the type and orientation of emergency stop pushbuttons are shown in Table 16.

Table 15: Frequencies of preferences for each type of emergency stop pushbuttons.

Type	Preferences for Emergency Stop Pushbuttons					
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
1	5	4	4	3	2	0
2	3	5	5	1	2	2
3	4	5	5	2	2	0
4	3	1	2	1	4	7
5	2	1	1	3	6	5
6	1	2	1	8	2	4

Table 16: Values of the Chi-Square test of the preferences for the types of emergency stop pushbuttons.

Type	Preferences for Emergency Stop Pushbuttons					
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
1	1.33	0.33	0.33	0	0.33	3
2	0	1.33	1.33	1.33	0.33	0.33
3	0.33	1.33	1.33	0.33	0.33	3
4	0	1.33	0.33	1.33	0.33	5.33
5	0.33	1.33	1.33	0	3	1.33
6	1.33	0.33	1.33	8.33	0.33	0.33
Total	3.33	6	6	11.33	4.67	13.33

The Chi-Square test for the homogeneity of the modes of activation for the type of emergency stop pushbutton was as follows:

$X^2 = 3.33+6.00+6.00+11.33+4.67+13.33= 44.67$

I= 6 different categories for the preferences for the type of emergency stop pushbuttons.

$\alpha = 0.05$

$X^2_{0.05,5} = 11.070$

$44.67 > 11.070$

The null hypothesis is rejected indicating that there is statistical evidence, at the 95% confidence level, that the preferences for the type of emergency stop pushbutton are different.

An analysis of categorical data was done to establish the type of emergency stop pushbutton that subjects preferred most. This analysis was developed by Grizzle et al. (1969). The first step was to determine the mean score for each type of control by constructing a linear combination based on the proportions of the preference scores (p_i).

$\lambda_i = 1*p_1 + 2*p_2 + 3*p_3 + ... + n*p_n$

The results of this linear combination are shown in Table 17.

The variance of the score for each type of control can be determined with the following formulas:

$$\text{var}(\lambda_i) = [\text{ scores }] \begin{bmatrix} v_1 & c_{12} & c_{13} & \cdots & c_{1n} \\ c_{21} & v_2 & c_{23} & \cdots & c_{2n} \\ & & & & \\ c_{n1} & c_{n2} & c_{n3} & \cdots & v_{nm} \end{bmatrix} \begin{bmatrix} s \\ c \\ o \\ r \\ e \\ s \end{bmatrix}$$

where: $v_i = \text{var}(p_i) = \dfrac{p_i(1-p_i)}{\text{number of subjects}}$ $\qquad c_{ij} = \text{cov}(p_i,p_j) = -\dfrac{p_i p_j}{\text{number of subjects}}$

The calculations of these values are shown in Appendix L and the results for the mean and the variance of the preference scores for each type of emergency stop pushbutton are shown in Table 18.

I did a pairwise comparison to determine which type was more preferred. The statistic to test the null hypothesis Ho: $\lambda_i = \lambda_j$ was:

$$\frac{\lambda_i - \lambda_j}{\text{var}(\lambda_i) + \text{var}(\lambda_j)} \sim N(0,1)$$

The value of N(0,1) for a 95% confidence level is 1.96. Appendix M shows the table with the critical values for the Standard Normal distribution.

Table 17: Proportion and linear combination of scores for each type of emergency stop pushbutton.

Type	Proportion of Preferences for Emergency Stop Pushbuttons						
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40	Linear Combination
1	0.28	0.22	0.22	0.17	0.11	0.00	2.61
2	0.17	0.28	0.28	0.06	0.11	0.11	3.00
3	0.22	0.28	0.28	0.11	0.11	0.00	2.61
4	0.17	0.06	0.11	0.06	0.22	0.39	4.28
5	0.11	0.06	0.06	0.17	0.33	0.28	4.39
6	0.06	0.11	0.06	0.44	0.11	0.22	4.11

Table 18: Values of mean and variance of the preference scores for each type of emergency stop pushbuttons.

	Type of Emergency Stop Pushbutton					
	1 T-F-40	2 T-F-35	3 T-F-30	4 S-U-80	5 T-U-40	6 G-H-40
λ	2.61	3	2.61	4.28	4.39	4.11
var(λ)	0.098	0.1389	0.088	0.1954	0.1399	0.1101

Table 19 shows the results of the pairwise comparison for the preferences of types of emergency stop pushbuttons. Comparing the test statistics obtained with the critical value of 1.96, the conclusion is that there are two differentiated groups for the preference of subject for the types of emergency stop pushbuttons. Controls 6, 4, and 5 are more preferred than controls 1, 3, and 2. This result is interesting because emergency stop pushbuttons 1, 2 and, 3 had guards while controls 4 and 5 were unguarded and control 6 had a half guard. It seemed that subjects preferred the controls without guards or with a half guards over controls that had a guard all around the button.

6.3.2 Preferences for Orientation of Emergency Stop Pushbuttons

The frequencies of the preferences of subjects for the orientation of emergency stop pushbuttons are shown in Table 20. The expected frequency for each cell in Table 20 is 18/3 = 6 observations. The test statistic values for the type and orientation of emergency stop pushbuttons are shown in Table 21.

Table 19: Results of the pairwise comparison for the preferences of types of emergency stop pushbuttons.

			Type of Emergency Stop Pushbutton					
			1 T-F-40	3 T-F-35	2 T-F-30	6 S-U-80	4 T-U-40	5 G-H-40
			2.61	2.61	3.00	4.11	4.28	4.39
	1	2.61		0.0000	0.8006	3.2850	3.0810	3.6463
	3	2.61			0.8195	3.3736	3.1392	3.7319
Type	2	3.00				2.2245	2.2138	2.6325
	6	4.11					0.0000	0.3400
	4	4.28						0.0000
	5	4.39						

Table 20: Frequencies of preferences for each orientation of emergency stop pushbuttons.

Orientation	**Preference**		
	1	2	3
Horizontal	1	15	2
Vertical	15	1	2
Inclined 45	2	2	14

Table 21: Values of the Chi-Square test of the preferences for the orientations of emergency stop pushbuttons.

Orientation	**Preference**		
	1	2	3
Horizontal	4.17	13.5	2.67
Vertical	13.5	4.17	2.67
Inclined 45	2.67	2.67	10.67
Total	20.33	20.33	16

The Chi-Square test for the homogeneity of the preferences for the orientation of emergency stop pushbuttons was as follows:

$X^2 = 20.33+20.33+16.00= 56.67$

I= 3 different categories for the preferences for the orientation of emergency stop pushbuttons.

$\alpha = 0.05$

$X^2_{0.05, 2} = 5.992$

$56.67 > 5.992$

The null hypothesis is rejected, indicating that there is statistical evidence, at the 95% confidence level, that the preferences for the orientation of emergency stop pushbutton are different.

An analysis of categorical data was done to establish the orientation of emergency stop pushbutton that subjects preferred most. The procedure followed was the same as the one used to do pairwise comparison for the preferences for the type of emergency stop pushbuttons.

Table 22 shows the results of the linear combination of preference scores for each orientation of emergency stop pushbuttons and Table 23 shows the mean and variance for the preference scores for each orientation. The calculations of these values are shown in Appendix N.

Table 22: Proportion and linear combination of scores for each orientation of emergency stop pushbutton.

Orientation	**Proportion of Preference**			
	1	2	3	Linear Combination
Horizontal	0.06	0.83	0.11	2.05
Vertical	0.83	0.06	0.11	1.28
Inclined 45	0.11	0.11	0.78	2.67

Table 24 shows the results of the pairwise comparison for the preferences of orientation of emergency stop pushbuttons. Comparing the test statistics obtained with the critical value of 1.96, the conclusion is that for emergency stop pushbuttons subjects preferred the inclined orientation the best, then the horizontal orientation, and the vertical orientation was preferred the least.

Table 23: Values of mean and variance of the preference scores for each orientation of emergency stop pushbuttons.

	Orientation		
	H	V	I
λ	2.06	1.28	2.67
var(λ)	0.01	0.024	0.025

Table 24: Results of the pairwise comparison for the preferences of orientation of emergency stop pushbuttons.

			Orientation		
			V	H	I
			1.28	2.06	2.67
	V	1.28		4.2301	6.2858
Orientation	H	2.06			3.2841
	I	2.67			

6.3.3 Preferences for Reset Method of Emergency Stop Pushbuttons

The frequencies of the preferences of subjects for the reset method of emergency stop pushbuttons are shown in Table 25. The expected frequency for each cell in Table 25 is 18/3 = 6 observations. The test statistic values for the type and orientation of emergency stop pushbuttons are shown in Table 26.

Table 25: Frequencies of preferences for each reset method of emergency stop pushbuttons.

Reset Method	**Preference**		
	1	2	3
Twist	6	5	7
Pull	7	8	3
Press a button	5	5	8

Table 26: Values of the Chi-Square test of the preferences for the reset method of emergency stop pushbuttons.

Reset Method	**Preference**		
	1	2	3
Twist	0	0.17	0.17
Pull	0.17	0.67	1.5
Press a button	0.17	0.17	0.67
Total	0.33	1	2.33

The Chi-Square test for the homogeneity of the preferences for the reset method of emergency stop pushbuttons was as follows:

$X^2 = 0.33+1.00+2.33= 3.67$

I= 3 different categories for the preferences for the reset method of emergency stop pushbuttons.

$\alpha = 0.05$

$X^2_{0.05,2} = 5.992$

$3.67 < 5.992$

The null hypothesis cannot be rejected, indicating that there is no statistical evidence, at the 95% confidence level, that the preferences for the reset method of emergency stop pushbutton are different.

7. DISCUSSION

The main objectives of this research were to determine the effects of the type and orientation of emergency stop pushbuttons on the reaction time, mode of activation, and preferences of subjects in order to formulate guidelines for their selection. An experiment was design to meet these objectives. The methodology followed in the experiment was described in Chapter 4. The results and analysis were presented in Chapters 5 and 6.

The discussion in this chapter is about the experiment, the results, and the guidelines for the selection of emergency stop pushbuttons that can be derived from the results.

7.1 Experiment

The experiment consisted of performing a simple, cooperative assembly operation with a Microbot placing rings on pegs. Eighteen subjects participated in the study. Each subject had to test six different types of emergency stop pushbuttons and three different orientations of the control panel: horizontal, vertical, and inclined at a 45° angle. Prior to running the experiments, a pilot test was performed to verify the design of the test and to correct the problems that might emerge. The main changes that had to be done during the pilot test were related to the connections of the control panel in the apparatus. The connectors were changed to allow a faster change of panels.

The subjects had to fill out an Informed Consent Document and a pre-test questionnaire before the experiment, and a post-test questionnaire after the experiment. In the post-test questionnaire the subjects had to rank the type, orientation, and reset method of emergency stop pushbuttons according to their preferences. They were also asked for comments. Most subjects did not make comments about their preferences, but some expressed interesting comments about the design of some controls. For instance, 5 subjects expressed that the reset method of pushbutton 4, press a button to reset, was not convenient because the reset button is located in the center of the control and it is very likely that one will push it when trying to activate the control. Six subjects expressed that pushbutton 3 was too small and it did not have enough space between the button and the guard to be able to reset it comfortably. And finally, 4 subjects expressed that the arrows that indicate twist to reset on pushbuttons 1, 3 and 6 were confusing because the first impression was that one needed to twist the button to activate it.

In general, all subjects were willing to cooperate and finish the experiments and the questionnaires.

7.2 Results

A summary of the results found in this study is presented in Table 27.

The hypothesis for the experiments was that the different types and orientations of the emergency stop pushbuttons had an effect on the reaction time and mode of activation. The results showed that there was no statistical evidence of the effect of orientation on reaction time but that the type of control has an effect on the reaction time. The results also showed that both the type and orientation of emergency stop pushbuttons affected the mode of activation. The specific modes of activation for each case are summarized in Table 27.

The number of inadvertent activations was the variable to be used to measure accuracy. Unfortunately, there were no inadvertent activations during the experiments, so this performance measure could not be used.

The results of the post-test questionnaire were used to study the preferences of subjects for the different types, orientations, and reset methods of emergency stop pushbuttons. Subjects preferred emergency stop pushbuttons without guards or with half guard over pushbuttons with guards. The inclined panel was the most preferred, followed by the horizontal, and the vertical was the least preferred. There was no statistical evidence of preferences among the different types of reset methods.

Table 27: Summary of results.

Variable analyzed	**Significant at 95% confidence level**	**Comments**
Effect of type of emergency stop pushbutton on reaction time	Yes	Reaction time is affected by the type of emergency stop pushbutton
Effect of orientation of emergency stop pushbutton on reaction time	No	No statistical evidence of the effect of orientation on the reaction time
Effect of type of emergency stop pushbutton on the mode of activation	Yes	Mode of activation is influenced by the type of emergency stop pushbutton
Most common modes of activation for the types of emergency stop controls		For all types of emergency stop pushbuttons: tip of the thumb and tips of the index and middle fingers
Effect of orientation of emergency stop pushbutton on the mode of activation	Yes	Mode of activation is influenced by the orientation of emergency stop pushbutton
Most common modes of activation for the orientations of emergency stop controls		Horizontal: tips of the index and middle fingers Vertical: tip of the thumb Inclined: tip of the thumb or tips of the index and middle fingers
Preferences for different types of emergency stop pushbuttons	Yes	Controls 6, 4, and 5 (without guards or with a half guard) are preferred over controls 1, 3, and 2 (with full guards)
Preferences for different orientations of emergency stop pushbuttons	Yes	Inclined is the most preferred, followed by horizontal, and vertical is the least preferred
Preferences for different reset methods of emergency stop pushbuttons	No	No statistical evidence of preference among the reset methods

7.3 Guidelines to Select Emergency Stop Pushbuttons

The results showed that the type of emergency stop pushbutton had an effect on reaction time. In the post-test questionnaire, subjects expressed their preference for controls without guards or with half guards over controls with full guards. The following guideline is based on this preference:

- Select emergency stop pushbuttons without guards. If a guard is absolutely required, select a guard with slots or a half guard to ensure adequate visibility and access of the button.

Subjects preferred the inclined panel the most, and they expressed that it was the most comfortable to use and the one that made easiest to reach the emergency stop pushbuttons. The horizontal orientation was the second in subjects' preferences and the vertical orientation was the least preferred. The following guideline is based on this preferences:

- If possible try to give emergency stop pushbuttons an inclined orientation (about 45°) in the control panel. Avoid using vertical orientations for emergency stop pushbuttons.

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Summary

Emergency stop controls are essential parts of industrial machinery because they are designed to stop the operation in case of emergencies. In these cases it is highly desirable that the operator stops the machine as quickly as possible without risks to themselves, to the equipment, or to the product. These controls are critical devices because failure to stop machinery accounts for 5% of the accidents in industrial environments (Raouf and Dhillon, 1985).

The main types of emergency stop controls are pushbuttons, pull-cords, dead man's switches, and foot pushbuttons. Some standards and norms recommend guidelines for emergency stop pushbuttons; however, they have been formulated based on experience but not on empirical studies on these controls. Therefore, there is a need for studies designed and developed with the specific purpose of analyzing the ergonomics of emergency stop controls.

The purpose of this study was to formulate guidelines to select emergency stop pushbuttons and their orientation. The experiment designed for this study gathered information related to the way people activate these controls and how their type and orientation influence the time to activate them. Chapter 4 contains the methodology followed in the experiments. It describes the subjects, apparatus, experimental task, procedure, and the experimental design for this study.

The results that were obtained from the experiment are presented in Chapter 5. The results included reaction time to active the control, mode of activation of emergency stop pushbuttons, and preferences of subjects for the different types, orientations, and reset methods of emergency stop pushbuttons.

The analysis of the results is presented in Chapter 6. It describes the statistical methods used to analyze the results and the conclusions that were obtained from them.

Chapter 7 contains the discussion of various aspects of the research such as the experiment, the results, and the guidelines to select emergency stop pushbuttons.

8.2 Conclusions

The reaction time to activate emergency stop pushbutton is not affected by the orientation of the control but it is influenced by the type of control.

The mode of activation of emergency stop pushbuttons is influenced by both the type and the orientation of the control. The most common modes of activation are with the tip of the thumb and with the tip of the index and middle fingers.

Subjects preferred emergency stop pushbuttons without guards or with half guards over controls with full guards. Subjects preferred the inclined orientation of emergency stop pushbuttons over the horizontal or vertical orientations.

The following are guidelines to select emergency stop pushbuttons based on the results of this study:

- Select emergency stop pushbuttons without guards. If a guard is absolutely required, select a guard with slots or a half guard to ensure an adequate visibility of the button.
- If possible try to give emergency stop pushbuttons an inclined orientation (about 45°) in the control panel. Avoid using vertical orientations for emergency stop pushbuttons.

8.3 Recommendations

The main variables considered for this study were the type and orientation of emergency stop pushbuttons. The location of the emergency stop pushbuttons in the control panel was to be considered, but this location depends on the type, size and design of industrial machinery, and it was fixed for all trials in the experiment at a standard position in front of the operator at a height of 40" above the floor. A study with different locations of emergency stop pushbuttons in the control panel is recommended to analyze if the location variable has an effect on reaction time, mode of activation, and preferences of subjects.

In this study no inadvertent activations occurred, it might be interesting to do a study to determine what variables are most likely to cause inadvertent activation of controls in industrial machinery.

This study focused on emergency stop pushbuttons because they are the emergency controls most commonly used in the U.S.A.; however, a broader study that includes other types of emergency stop controls would be very interesting to verify the effect of different types of controls on reaction time and preferences of subjects.

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APPENDICES

Appendix A: Sequences for the operation during the experiments.

Sequence 1

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	2	A	1
B	2	B	3
A	1	A	3
B	3	B	1
A	1	A	3
B	2	B	1

Sequence 2

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	2	A	3
B	2	B	1
A	3	A	1
B	3	B	1
A	2	A	3
B	2	B	1

Sequence 3

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	1	A	3
B	2	B	1
A	2	A	3
B	2	B	1
A	1	A	3
B	2	B	3

Sequence 4

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	3	A	1
B	2	B	3
A	2	A	1
B	3	B	1
A	1	A	3
B	2	B	3

Sequence 5

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	2	A	1
B	1	B	3
A	1	A	3
B	2	B	1
A	2	A	3
B	1	B	3

Sequence 6

Robot		Operator	
Take from source	Place in Peg	Place in source	Place in Peg
A	1	A	3
B	3	B	1
A	2	A	1
B	1	B	3
A	2	A	3
B	2	B	1

Appendix B: Informed Consent Document

Industrial & Manufacturing Engineering
Oregon State University

INFORMED CONSENT DOCUMENT

I understand that this study is being conducted by Patricia Zarate, graduate student at Oregon State University under the supervision of Dr. Kenneth Funk of the Industrial & Manufacturing Engineering Department and with the collaboration of Rob Hooper, Safety Consultant at Hewlett Packard. I understand that this experiment will require that I monitor an interactive operation with a Microbot located in the Human Factors Laboratory at Covell Hall on the Oregon State University Campus. After a half hour training session I will perform and monitor the operation, and I will fill out a brief questionnaire when the experiment is over. The entire experiment should not last longer than 3 hours, including training.

I am aware that this is an unpaid experiment. Physiological risks and psychological stress during the experiment are minimal. While the experiment is being run, the evaluator will video tape the operation. The video tape will never be used for anything other than the current study.

My identification (name, sex, age, etc.) will not be recorded or released to any other persons, organizations, or publications. All references to subjects in this study will be encoded and kept confidential, and all identity related information destroyed within three years of the experiment.

Any questions concerning aspects or rights related to this experiment should be directed to Patricia Zarate or Dr. Kenneth Funk at 541-737-2357. I understand that Oregon State University does not provide compensation or medical treatment in the event the subject is injured as a result of this experiment.

I understand that participation is voluntary, and my refusal to participate will not result in penalties or loss of benefits to which I am otherwise entitled. My signature below indicates that I have read and that I understand the procedures described above and give my informed and voluntary consent to participate in this study. I understand that I will receive a signed copy of this consent form.

____
Subject's Name

______________________________ ____________________
Subject's Signature Date Signed

____
____
______________________________ ____________________
Subject's Address Subject's Phone Number

Appendix C: Pre-test questionnaire

Industrial & Manufacturing Engineering
Oregon State University

PRE-TEST QUESTIONNAIRE

1. Sex:
____ Male ____ Female

2. What is your age?
____ years.

3. Are you left or right-handed?
____ Left ____ Right

4. How many hours of sleep did you have last night?
____ More than 8 hours ____ Between 6 and 8 hours ____ Less than 6 hours

5. Are you taking any medication that can make you feel drowsy?
____Yes ____No

6. How many cups of coffee or tea have you had today?
____

7. Do you have any pain or aches at this moment?
____Yes ____No

8. Do you use corrective lenses?
____Yes ____No

9. If no, have you seen a optometrist within the last year?
____Yes ____No

10. Are you color blind?
____Yes ____No

11. Do you have any experience using automated equipment with Emergency Stop Controls?
____Yes ____No

12. If yes, what is your experience?
____
____
____

Appendix D: Post-test questionnaire

Industrial & Manufacturing Engineering
Oregon State University

POST-TEST QUESTIONNAIRE

1. Rank the emergency stop pushbuttons from 1 to 6 according to your preferences (1 the least preferred and 6 the most preferred control) and make comments about your preferences.

Emergency Stop Pushbutton	Rank (1 to 6)	Comments
1		
2		
3		
4		
5		
6		

2. Rank the orientations of the emergency stop pushbuttons from 1 to 3 according to your preferences (1 the least preferred and 3 the most preferred orientation) and make comments about your preferences.

Orientation of Emergency Stop Pushbutton	Rank (1 to 3)	Comments
1. Horizontal		
2. Vertical		
3. Inclined 45°		

3. Rank the reset methods for the emergency stop pushbuttons from 1 to 3 according to your preferences (1 the least preferred and 3 the most preferred reset method) and make comments about your preferences.

Reset Method of Emergency Stop Pushbutton	Rank (1 to 3)	Comments
1. Twist to reset		
2. Pull to reset		
3. Press a button to reset		

4. Was the training time adequate to explain to you the experimental operation?
____Yes ____No

5. Why?

____
____
____

6. Was the training adequate to help you perform the experimental operation?
____Yes ____No

7. Why?

____
____
____

8. Where you able to anticipate ahead of time when to activate the Emergency Stop Pushbutton?

____
____
____

9. Do you have any other comments about this experiment?

____
____
____

Appendix E: Results of the experiments for each subject

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 1

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	1	1	17	1	8	3	10	5	15	5	6	6
	1.261719		1.050781		0.988281		1.160156		1.042969		1.378906	
	R	4	R	4	R	4	R	4	R	4	R	4
Vertical	18	2	2	2	13	3	4	4	9	4	11	6
	0.992188		1.273438		1.433594		1.648438		1.039063		1.273438	
	R	1	R	1	R	1	L	1	R	1	R	1
Inclined 45°	12	1	7	2	3	3	14	4	5	5	16	6
	1.039063		0.988281		1.421875		1.097656		1.050781		1.152344	
	R	1	R	4	R	4	R	4	R	11	R	4

Subject No. 2

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	16	6	12	1	7	2	3	3	14	4	5	5
	1.984375		2.3125		2.25		2.6875		1.75		2.75	
	R	4	R	4	R	4	R	4	R	10	R	7
Vertical	6	6	17	1	1	1	8	3	10	5	15	5
	2.53125		1.539063		3.515625		2.578125		3.570313		1.976563	
	R	1	R	1	L	1	R	1	R	1	R	1
Inclined 45°	11	6	2	2	18	2	13	3	4	4	9	4
	2.195313		2.742188		2.46875		2.578125		2.085938		2.414106	
	R	1	R	1	R	1	R	4	R	4	R	1

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 3

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	2	2	11	6	4	4	18	2	13	3	9	4
	1.8125		0.820313		1.050781		1.539063		2.851563		0.941406	
	L	4	R	4	L	3	L	4	L	12	L	4
Vertical	5	5	16	6	12	1	7	2	3	3	14	4
	3.402349		1.320313		0.871094		1.429688		1.039063		1.039063	
	L	1	L	1	R	1	R	1	R	1	R	1
Inclined 45°	15	5	6	6	1	1	10	5	8	3	17	1
	4.878906		1.539063		1.707031		1.820313		1.378906		0.820313	
	R	2	L	2	R	2	R	12	L	11	R	1

Subject No. 4

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	17	1	10	5	6	6	1	1	15	5	8	3
	1.917969		1.371094		1.871094		3.289063		2.03125		1.539063	
	R	4	R	4	R	4	R	2	R	8	R	4
Vertical	9	4	2	2	11	6	4	4	18	2	13	3
	1.320313		1.929688		1.921875		1.859375		1.210938		1.046875	
	R	1	R	1	R	1	L	1	R	1	R	1
Inclined 45°	14	4	5	5	16	6	12	1	7	2	3	3
	1.367188		1.488281		1.210938		1.320313		2.089844		1.257813	
	R	4	R	4	R	5	R	4	R	8	R	8

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 5

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	3	3	14	4	5	5	16	6	12	1	7	2
	1.371094		0.980469		1.257813		0.878906		1.148438		1.050781	
	R	4	R	4	R	2	R	4	R	4	R	4
Vertical	8	3	17	1	15	5	6	6	1	1	10	5
	1.097656		1.046875		1.097656		1.050781		1.480469		1.039063	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	13	3	9	4	2	2	11	6	18	2	4	4
	1.101563		1.089844		1.601563		0.929688		1.039063		2.691406	
	R	1	R	1	R	1	R	4	R	10	R	2

Subject No. 6

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	2	2	13	3	9	4	4	4	11	6	18	2
	1.429688		1.261719		1.980469		1.480469		1.378906		1.320313	
	R	4	R	4	R	4	R	4	R	4	R	4
Vertical	7	2	5	5	14	4	16	6	3	3	12	1
	1.480469		1.703125		1.371094		1.382813		2.136719		1.371094	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	15	5	8	3	17	1	10	5	6	6	1	1
	1.429688		1.710938		1.371094		1.871094		1.210938		1.417969	
	R	1	R	1	R	1	R	1	R	11	R	1

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 7

Orientation	Type of Emergency Stop Pushbutton											
	1		**2**		**3**		**4**		**5**		**6**	
Horizontal	12	1	7	2	3	3	14	4	5	5	16	6
	1.542969		1.261719		1.652344		1.257813		1.808594		1.207031	
	R	4	R	4	R	2	R	9	R	9	R	4
Vertical	17	1	1	1	8	3	10	5	15	5	6	6
	1.273438		2.082031		1.429688		1.699219		1.539063		1.980469	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	2	2	18	2	13	3	4	4	9	4	11	6
	1.980469		1.257813		1.320313		1.699219		1.371094		1.210938	
	R	4	R	1	R	1	R	4	R	10	R	1

Subject No. 8

Orientation	Type of Emergency Stop Pushbutton											
	1		**2**		**3**		**4**		**5**		**6**	
Horizontal	11	6	2	2	18	2	13	3	4	4	9	4
	1.210938		1.101563		1.257813		0.769531		1.039063		0.878906	
	R	4	R	2	R	2	R	4	R	4	R	4
Vertical	16	6	12	1	7	2	3	3	14	4	5	5
	0.828125		0.988281		1.371094		1.050781		1.050781		0.773438	
	R	1	R	1	R	1	R	1	R	12	R	1
Inclined 45°	1	1	17	1	10	5	8	3	6	6	15	5
	1.917969		0.929688		1.039063		1.421875		1.699219		0.820313	
	R	2	R	2	R	2	R	2	L	4	R	1

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 9

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	10	5	6	6	1	1	15	5	8	3	17	1
	1.148438		1.210938		1.210938		1.320313		1.257813		1.039063	
	R	8	R	4	R	7	R	9	R	8	R	4
Vertical	18	2	11	6	9	4	2	2	13	3	4	4
	1.257813		1.601563		2.195313		1.429688		1.539063		1.8125	
	R	1	R	1	R	1	R	1	R	1	R	6
Inclined 45°	5	5	16	6	12	1	7	2	3	3	14	4
	2.421875		1.320313		1.320313		1.929688		2.46875		1.15625	
	R	4	R	4	R	3	R	11	R	7	R	8

Subject No. 10

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	14	4	5	5	16	6	12	1	7	2	3	3
	1.921875		2.03125		1.257813		1.382813		1.703125		1.822031	
	R	4	R	4	R	2	R	9	R	4	R	4
Vertical	10	5	15	5	6	6	1	1	17	1	8	3
	1.804688		1.039063		1.210938		1.039063		1.257813		1.601563	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	4	4	9	4	11	6	18	2	2	2	13	3
	1.195313		1.320313		1.539063		1.601563		2.46875		1.085938	
	R	1	R	1	R	1	R	6	R	1	R	1

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 11

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	13	3	4	4	18	2	11	6	9	4	2	2
	1.100037		1.914063		1.209961		1.209991		1.319826		2.46875	
	R	4	R	4	R	3	R	4	L	10	R	4
Vertical	3	3	14	4	5	5	16	6	12	1	7	2
	2.640625		1.26001		1.484375		1.039795		1.36995		1.476563	
	R	1	R	1	R	1	R	1	R	4	R	1
Inclined 45°	8	3	17	1	10	5	6	6	1	1	15	5
	1.585938		1.26001		1.700001		1.148438		1.867188		1.150024	
	L	5	R	4	R	4	R	1	R	5	R	1

Subject No. 12

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	10	5	8	3	1	1	15	5	6	6	17	1
	1.101563		0.988281		1.148438		0.879063		1.152344		0.929688	
	L	5	L	4	R	4	L	5	R	4	L	5
Vertical	2	2	13	3	4	4	18	2	11	6	9	4
	1.039063		1.042969		1.269531		1.039063		1.199219		0.93375	
	L	1	L	1	L	1	L	5	L	5	L	5
Inclined 45°	7	2	3	3	14	4	5	5	16	6	12	1
	0.871094		1.039063		1.101563		0.929688		1.648438		1.046875	
	L	5	R	5	L	5	L	5	L	10	L	5

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 13

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	18	2	2	2	13	3	9	4	4	4	11	6
	1.539063		3.632813		1.765625		1.320313		2.140625		1.429688	
	R	4	R	3	R	4	R	4	R	10	R	4
Vertical	5	5	7	2	16	6	14	4	12	1	3	3
	2.46875		1.871094		1.640625		1.710938		2.796875		2.25	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	1	1	17	1	8	3	6	6	10	5	15	5
	3.78281		1.984375		2.46875		1.648438		3.570313		1.59375	
	R	4	R	1	R	1	R	4	R	4	R	1

Subject No. 14

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	6	6	1	1	17	1	8	3	10	5	15	5
	1.859375		1.378906		1.589844		1.699219		1.421875		1.871094	
	R	4	L	7	R	4	R	4	R	4	R	8
Vertical	11	6	18	2	2	2	13	3	4	4	9	4
	1.257813		1.589844		1.101563		1.101563		1.699219		1.761719	
	R	1	R	1	R	1	R	1	L	1	R	1
Inclined 45°	16	6	5	5	7	2	3	3	14	4	12	1
	1.210938		1.14843		1.367188		1.699219		1.378906		1.871094	
	R	7	R	1	R	4	R	4	R	11	R	7

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 15

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	5	5	16	6	12	1	7	2	3	3	14	4
	1.492188		1.484375		1.273438		1.320313		2.6875		1.265625	
	R	2	R	4	R	4	R	2	R	11	R	4
Vertical	15	5	6	6	1	1	10	5	8	3	17	1
	1.375		1.710938		1.304688		1.203125		1.320313		1.148438	
	R	1	R	1	R	1	R	6	R	1	R	1
Inclined 45°	18	2	11	6	4	4	2	2	13	3	9	4
	1.375		1.101563		1.257813		1.273438		1.8125		1.210938	
	R	4	R	1	R	1	R	2	R	7	R	8

Subject No. 16

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	4	4	9	4	12	1	18	2	2	2	14	4
	1.160156		1.199219		1.050781		0.878906		1.101563		0.980469	
	R	4	R	1	R	4	R	4	R	10	R	4
Vertical	13	3	5	5	16	6	11	6	7	2	3	3
	1.367188		1.210938		1.039063		0.980469		1.160156		1.320313	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	10	5	15	5	6	6	1	1	17	1	8	3
	1.429688		1.097656		1.53125		1.152344		1.210938		1.101563	
	R	1	R	1	R	1	R	8	R	1	R	4

Orientation	Type of Emergency Stop Pushbutton	
	Trial (1-18)	Sequence (1-6)
	Reaction Time (sec)	
	Hand (R/L)	Mode of Activation (1-12)

Subject No. 17

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	8	3	17	1	10	5	6	6	1	1	15	5
	1.921875		1.367188		1.757813		1.640625		1.320313		2.03125	
	L	4	L	8	L	4	L	9	L	8	L	8
Vertical	13	3	4	4	18	2	11	6	9	4	2	2
	2.082031		1.921875		1.589844		1.257813		1.921875		1.765625	
	L	1	R	1	L	1	L	2	L	1	L	1
Inclined 45°	3	3	14	4	5	5	16	6	12	1	7	2
	1.976563		1.421875		1.757813		1.261719		1.929688		1.210938	
	L	8	L	8	L	4	L	4	L	8	L	8

Subject No. 18

Orientation	Type of Emergency Stop Pushbutton											
	1		2		3		4		5		6	
Horizontal	7	2	3	3	14	4	5	5	16	6	12	1
	1.542969		1.269531		1.429688		1.371094		1.101563		1.265625	
	R	4	R	3	R	4	R	4	R	9	R	4
Vertical	15	5	8	3	17	1	10	5	6	6	1	1
	2.921875		2.628906		1.101563		1.75		1.320313		1.203125	
	R	1	R	1	R	1	R	1	R	1	R	1
Inclined 45°	2	2	13	3	9	4	18	2	11	6	4	4
	1.039063		1.101563		1.757813		1.101563		1.101563		1.539063	
	R	4	R	4	R	2	R	4	R	9	R	1

Appendix F: ANOVA results for the effect of number of trials on reaction time.

The SAS System
23:47 Saturday, November 30, 199

General Linear Models Procedure

Dependent Variable: REACTIME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	5.84195263	5.84195263	19.18	0.0001
Error	322	98.08180573	0.30460188		
Corrected Total	323	103.92375836			

R-Square	C.V.	Root MSE	REACTIME Mean
0.056214	36.20555	0.5519075	1.5243727

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TRIAL	1	5.84195263	5.84195263	19.18	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TRIAL	1	5.84195263	5.84195263	19.18	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.770250588	27.67	0.0001	0.06397130
TRIAL	-0.025881883	-4.38	0.0001	0.00590994

Appendix G: ANOVA results for the effect of the sequence of the emergency signal on reaction time.

The SAS System

23:47 Saturday, November 30, 199

General Linear Models Procedure

Dependent Variable: REACTIME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	3.26044926	0.65208985	2.06	0.0702
Error	318	100.66330910	0.31655129		
Corrected Total	323	103.92375836			

R-Square	C.V.	Root MSE	REACTIME Mean
0.031373	36.90888	0.5626289	1.5243727

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SEQUENCE	5	3.26044926	0.65208985	2.06	0.0702

Source	DF	Type III SS	Mean Square	F Value	Pr > F
SEQUENCE	5	3.26044926	0.65208985	2.06	0.0702

Appendix H: ANOVA results for the effect of subjects, trial, type, and orientation of emergency stop pushbuttons on reaction time for adjusted data.

The SAS System 12:24 Friday, January 17, 1997

General Linear Models Procedure

Dependent Variable: REACTIME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	51	49.64956630	0.97352091	6.14	0.0001
Error	271	42.98645971	0.15862162		
Corrected Total	322	92.63602600			

R-Square	C.V.	Root MSE	REACTIME Mean
0.535964	26.30625	0.39827330	1.51398715

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SUBJECT	17	37.02718474	2.17806969	13.73	0.0001
TRIAL	17	9.26882408	0.54522495	3.44	0.0001
TYPE	5	1.90332374	0.38066475	2.40	0.0375
ORIENT	2	0.13291105	0.06645552	0.42	0.6582
TYPE*ORIENT	10	1.31732269	0.13173227	0.83	0.5995

The SAS System

General Linear Models Procedure
Least Squares Means

TRIAL	REACTIME LSMEAN	Std Err LSMEAN	Pr > |T| H0:LSMEAN=0
1	1.78862327	0.09479562	0.0001
2	1.72069692	0.09510182	0.0001
3	1.77089624	0.09447493	0.0001
4	1.65625310	0.09479465	0.0001
5	1.67846499	0.09479241	0.0001
6	1.52771452	0.09448244	0.0001
7	1.46527800	0.09387392	0.0001
8	1.59548628	0.09387392	0.0001
9	1.45205459	0.09545541	0.0001
10	1.70054742	0.09576218	0.0001
11	1.31540416	0.09417261	0.0001
12	1.44505261	0.09478155	0.0001
13	1.45168031	0.09416973	0.0001
14	1.32070986	0.09416973	0.0001
15	1.47913478	0.09929718	0.0001
16	1.28087150	0.09447343	0.0001
17	1.27232928	0.09574526	0.0001
18	1.33216766	0.09507822	0.0001

TYPE	REACTIME LSMEAN	Std Err LSMEAN	Pr > |T| H0:LSMEAN=0
1	1.61045316	0.05527168	0.0001
2	1.48006620	0.05520980	0.0001
3	1.50044962	0.05461002	0.0001
4	1.43182397	0.05522637	0.0001
5	1.62451688	0.05449085	0.0001
6	1.43714534	0.05531153	0.0001

ORIENT	REACTIME LSMEAN	Std Err LSMEAN	Pr > |T| H0:LSMEAN=0
1	1.48585129	0.03836403	0.0001
2	1.53263046	0.03836403	0.0001
3	1.52374583	0.03853404	0.0001

Appendix I: ANOVA results for the effect of subjects, trial, type, and orientation of emergency stop pushbuttons on reaction time for original data.

General Linear Models Procedure

Dependent Variable: REACTIME

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	51	51.56723170	1.01112219	5.25	0.0001
Error	272	52.35655350	0.19248733		
Corrected Total	323	103.92378520			

	R-Square	C.V.	Root MSE	REACTIME Mean
	0.496202	28.78127	0.43873378	1.52437271

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SUBJECT	17	37.48815322	2.20518548	11.46	0.0001
TRIAL	17	9.66580899	0.56857700	2.95	0.0001
TYPE	5	2.70640928	0.54128186	2.81	0.0170
ORIENT	2	0.26666282	0.13333141	0.69	0.5011
TYPE*ORIENT	10	1.44019739	0.14401974	0.75	0.6786

Appendix J: Least Significant Difference test for the mean reaction time for the different types of emergency stop pushbuttons.

The SAS System

General Linear Models Procedure

T tests (LSD) for variable: REACTIME

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

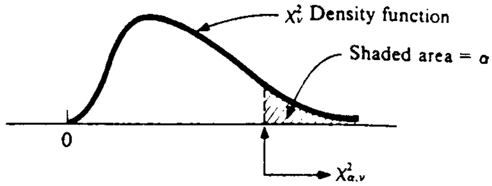
Alpha= 0.05 Confidence= 0.95 df= 271 MSE= 0.158622
Critical Value of T= 1.96876

Comparisons significant at the 0.05 level are indicated by '***'.

TYPE Comparison	Lower Confidence Limit	Difference Between Means	Upper Confidence Limit	
5 - 1	-0.14638	0.00523	0.15684	
5 - 3	-0.01392	0.13698	0.28788	
5 - 2	0.02231	0.17321	0.32411	***
5 - 4	0.04301	0.19391	0.34481	***
5 - 6	0.06385	0.21475	0.36565	***
1 - 5	-0.15684	-0.00523	0.14638	
1 - 3	-0.01986	0.13175	0.28336	
1 - 2	0.01637	0.16798	0.31959	***
1 - 4	0.03706	0.18868	0.34029	***
1 - 6	0.05790	0.20952	0.36113	***
3 - 5	-0.28788	-0.13698	0.01392	
3 - 1	-0.28336	-0.13175	0.01986	
3 - 2	-0.11467	0.03623	0.18713	
3 - 4	-0.09397	0.05693	0.20783	
3 - 6	-0.07313	0.07777	0.22867	
2 - 5	-0.32411	-0.17321	-0.02231	***
2 - 1	-0.31959	-0.16798	-0.01637	***
2 - 3	-0.18713	-0.03623	0.11467	
2 - 4	-0.13020	0.02070	0.17160	
2 - 6	-0.10936	0.04154	0.19244	
4 - 5	-0.34481	-0.19391	-0.04301	***
4 - 1	-0.34029	-0.18868	-0.03706	***
4 - 3	-0.20783	-0.05693	0.09397	
4 - 2	-0.17160	-0.02070	0.13020	
4 - 6	-0.13006	0.02084	0.17174	
6 - 5	-0.36565	-0.21475	-0.06385	***
6 - 1	-0.36113	-0.20952	-0.05790	***
6 - 3	-0.22867	-0.07777	0.07313	
6 - 2	-0.19244	-0.04154	0.10936	
6 - 4	-0.17174	-0.02084	0.13006	

Appendix K: Critical values $X^2_{\alpha,v}$ for the Chi-Square distribution.

Table A.6 Critical Values $\chi^2_{\alpha,\nu}$ for the Chi-Squared Distribution



ν \ α	.995	.99	.975	.95	.90	.10	.05	.025	.01	.005
1	0.000	0.000	0.001	0.004	0.016	2.706	3.843	5.025	6.637	7.882
2	0.010	0.020	0.051	0.103	0.211	4.605	5.992	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.344	12.837
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	1.610	9.236	11.070	12.832	15.085	16.748
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.440	16.812	18.548
7	0.989	1.239	1.690	2.167	2.833	12.017	14.067	16.012	18.474	20.276
8	1.344	1.646	2.180	2.733	3.490	13.362	15.507	17.534	20.090	21.954
9	1.735	2.088	2.700	3.325	4.168	14.684	16.919	19.022	21.665	23.587
10	2.156	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.724	26.755
12	3.074	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217	28.300
13	3.565	4.107	5.009	5.892	7.041	19.812	22.362	24.735	27.687	29.817
14	4.075	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141	31.319
15	4.600	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.577	32.799
16	5.142	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000	34.267
17	5.697	6.407	7.564	8.682	10.085	24.769	27.587	30.190	33.408	35.716
18	6.265	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805	37.156
19	6.843	7.632	8.906	10.117	11.651	27.203	30.143	32.852	36.190	38.580
20	7.434	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566	39.997
21	8.033	8.897	10.283	11.591	13.240	29.615	32.670	35.478	38.930	41.399
22	8.643	9.542	10.982	12.338	14.042	30.813	33.924	36.781	40.289	42.796
23	9.260	10.195	11.688	13.090	14.848	32.007	35.172	38.075	41.637	44.179
24	9.886	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.980	45.558
25	10.519	11.523	13.120	14.611	16.473	34.381	37.652	40.646	44.313	46.925
26	11.160	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642	48.290
27	11.807	12.878	14.573	16.151	18.114	36.741	40.113	43.194	46.962	49.642
28	12.461	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278	50.993
29	13.120	14.256	16.147	17.708	19.768	39.087	42.557	45.772	49.586	52.333
30	13.787	14.954	16.791	18.493	20.599	40.256	43.773	46.979	50.892	53.672
31	14.457	15.655	17.538	19.280	21.433	41.422	44.985	48.231	52.190	55.000
32	15.134	16.362	18.291	20.072	22.271	42.585	46.194	49.480	53.486	56.328
33	15.814	17.073	19.046	20.866	23.110	43.745	47.400	50.724	54.774	57.646
34	16.501	17.789	19.806	21.664	23.952	44.903	48.602	51.966	56.061	58.964
35	17.191	18.508	20.569	22.465	24.796	46.059	49.802	53.203	57.340	60.272
36	17.887	19.233	21.336	23.269	25.643	47.212	50.998	54.437	58.619	61.581
37	18.584	19.960	22.105	24.075	26.492	48.363	52.192	55.667	59.891	62.880
38	19.289	20.691	22.878	24.884	27.343	49.513	53.384	56.896	61.162	64.181
39	19.994	21.425	23.654	25.695	28.196	50.660	54.572	58.119	62.426	65.473
40	20.706	22.164	24.433	26.509	29.050	51.805	55.758	59.342	63.691	66.766

For $\nu > 40$, $\chi^2_{\alpha,\nu} \doteq \nu\left(1 - \frac{2}{9\nu} + z_\alpha\sqrt{\frac{2}{9\nu}}\right)^3$

Source: This table is reproduced with the kind permission of the Trustees of Biometrika from E. S. Pearson and H. O. Hartley (eds.), *The Biometrika Tables for Statisticians*, vol. 1, 3rd ed., *Biometrika*, 1966.

Appendix L: Calculations of mean and variance of preference scores for each type of emergency stop pushbuttons.

Preferences in Emergency Stop Pushbuttons

	Preferences for Emergency Stop Pushbuttons					
Type	1	2	3	4	5	6
1	5	4	4	3	2	0
2	3	5	5	1	2	2
3	4	5	5	2	2	0
4	3	1	2	1	4	7
5	2	1	1	3	6	5
6	1	2	1	8	2	4

	Proportion of Preferences for Emergency Stop Pushbuttons						
Type	1	2	3	4	5	6	Linear Combination
1	0.28	0.22	0.22	0.17	0.11	0.00	2.61
2	0.17	0.28	0.28	0.06	0.11	0.11	3.00
3	0.22	0.28	0.28	0.11	0.11	0.00	2.61
4	0.17	0.06	0.11	0.06	0.22	0.39	4.28
5	0.11	0.06	0.06	0.17	0.33	0.28	4.39
6	0.06	0.11	0.06	0.44	0.11	0.22	4.11

v1= 0.0111	v2= 0.0096	v3= 0.0096	v4= 0.0077	v5= 0.0055	v6= 0.0000
c12=c21= -0.0034					
c13=c31= -0.0034	c23=c32 -0.0027				
c14=c41= -0.0026	c24=c42 -0.0021	c34=c43 -0.0021			
c15=c51= -0.0017	c25=c52 -0.0014	c35=c53 -0.0014	c45=c54= -0.0010		
c16=c61= 0.0000	c26=c62 0.0000	c36=c63 0.0000	c46=c64= 0.0000	c56=c65 0.0000	

v1= 0.0077	v2= 0.0111	v3= 0.0111	v4= 0.0029	v5= 0.0055	v6= 0.0055
c12=c21= -0.0026					
c13=c31= -0.0026	c23=c32 -0.0043				
c14=c41= -0.0005	c24=c42 -0.0009	c34=c43 -0.0009			
c15=c51= -0.0010	c25=c52 -0.0017	c35=c53 -0.0017	c45=c54= -0.0003		
c16=c61= -0.0010	c26=c62 -0.0017	c36=c63 -0.0017	c46=c64= -0.0003	c56=c65 -0.0007	

v1= 0.0096	v2= 0.0111	v3= 0.0111	v4= 0.0055	v5= 0.0055	v6= 0.0000
c12=c21= -0.0034					
c13=c31= -0.0034	c23=c32 -0.0043				
c14=c41= -0.0014	c24=c42 -0.0017	c34=c43 -0.0017			
c15=c51= -0.0014	c25=c52 -0.0017	c35=c53 -0.0017	c45=c54= -0.0007		
c16=c61= 0.0000	c26=c62 0.0000	c36=c63 0.0000	c46=c64= 0.0000	c56=c65 0.0000	

v1= 0.0077	v2= 0.0029	v3= 0.0055	v4= 0.0029	v5= 0.0096	v6= 0.0132
c12=c21= -0.0005					
c13=c31= -0.0010	c23=c32 -0.0003				
c14=c41= -0.0005	c24=c42 -0.0002	c34=c43 -0.0003			
c15=c51= -0.0021	c25=c52 -0.0007	c35=c53 -0.0014	c45=c54= -0.0007		
c16=c61= -0.0036	c26=c62 -0.0012	c36=c63 -0.0024	c46=c64= -0.0012	c56=c65 -0.0048	

v1= 0.0055	v2= 0.0029	v3= 0.0029	v4= 0.0077	v5= 0.0123	v6= 0.0111
c12=c21= -0.0003					
c13=c31= -0.0003	c23=c32 -0.0002				
c14=c41= -0.0010	c24=c42 -0.0005	c34=c43 -0.0005			
c15=c51= -0.0021	c25=c52 -0.0010	c35=c53 -0.0010	c45=c54= -0.0031		
c16=c61= -0.0017	c26=c62 -0.0009	c36=c63 -0.0009	c46=c64= -0.0026	c56=c65 -0.0051	

v1= 0.0029	v2= 0.0055	v3= 0.0029	v4= 0.0137	v5= 0.0055	v6= 0.0096
c12=c21= -0.0003					
c13=c31= -0.0002	c23=c32 -0.0003				
c14=c41= -0.0014	c24=c42 -0.0027	c34=c43 -0.0014			
c15=c51= -0.0003	c25=c52 -0.0007	c35=c53 -0.0003	c45=c54= -0.0027		
c16=c61= -0.0007	c26=c62 -0.0014	c36=c63 -0.0007	c46=c64= -0.0055	c56=c65 -0.0014	

```
 -----------------------------------------------------
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 -----------------------------------------------------

Commands to get started: intro, demo, help help
Commands for more information: help, whatsnew, info, subscribe

» A=[1 2 3 4 5 6]

A =

     1     2     3     4     5     6

» C=[1
2
3
4
5
6]

C =

     1
     2
     3
     4
     5
     6

» B1=[.0111 -.0034 -.0034 -.0026 -.0017 0
-.0034 .0096 -.0027 -.0021 -.0014 0
-.0034 -.0027 .0096 -.0021 -.0014 0
-.0026 -.0021 -.0021 .0077 -.0010 0
-.0017 -.0014 -.0014 -.0010 .0055 0
0 0 0 0 0 0]

B1 =

    0.0111   -0.0034   -0.0034   -0.0026   -0.0017         0
   -0.0034    0.0096   -0.0027   -0.0021   -0.0014         0
   -0.0034   -0.0027    0.0096   -0.0021   -0.0014         0
   -0.0026   -0.0021   -0.0021    0.0077   -0.0010         0
   -0.0017   -0.0014   -0.0014   -0.0010    0.0055         0
         0         0         0         0         0         0

» B2=[.0077 -.0026 -.0026 -.0005 -.0010 -.0010
-.0026 .0111 -.0043 -.0009 -.0017 -.0017
-.0026 -.0043 .0111 -.0009 -.0017 -.0017
-.0005 -.0009 -.0009 .0029 -.0003 -.0003
-.0010 -.0017 -.0017 -.0003 .0055 -.0007
-.0010 -.0017 -.0017 -.0003 -.0007 .0055]

B2 =

    0.0077   -0.0026   -0.0026   -0.0005   -0.0010   -0.0010
   -0.0026    0.0111   -0.0043   -0.0009   -0.0017   -0.0017
   -0.0026   -0.0043    0.0111   -0.0009   -0.0017   -0.0017
   -0.0005   -0.0009   -0.0009    0.0029   -0.0003   -0.0003
   -0.0010   -0.0017   -0.0017   -0.0003    0.0055   -0.0007
   -0.0010   -0.0017   -0.0017   -0.0003   -0.0007    0.0055

» B3=[.0096 -.0034 -.0034 -.0014 -.0014 0
-.0034 .0111 -.0043 -.0017 -.0017 0
-.0034 -.0043 .0111 -.0017 -.0017 0
-.0014 -.0017 -.0017 .0055 -.0007 0
-.0014 -.0017 -.0017 -.0007 .0055 0
0 0 0 0 0 0]

B3 =

    0.0096   -0.0034   -0.0034   -0.0014   -0.0014         0
   -0.0034    0.0111   -0.0043   -0.0017   -0.0017         0
   -0.0034   -0.0043    0.0111   -0.0017   -0.0017         0
   -0.0014   -0.0017   -0.0017    0.0055   -0.0007         0
   -0.0014   -0.0017   -0.0017   -0.0007    0.0055         0
         0         0         0         0         0         0

» B4=[.0077 -.0005 -.0010 -.0005 -.0021 -.0036
-.0005 .0029 -.0003 -.0002 -.0007 -.0012
-.0010 -.0003 .0055 -.0003 -.0014 -.0024
-.0005 -.0002 -.0003 .0029 -.0007 -.0012
-.0021 -.0007 -.0014 -.0007 .0096 -.0048
-.0036 -.0012 -.0024 -.0012 -.0048 .0132]

B4 =

    0.0077   -0.0005   -0.0010   -0.0005   -0.0021   -0.0036
   -0.0005    0.0029   -0.0003   -0.0002   -0.0007   -0.0012
   -0.0010   -0.0003    0.0055   -0.0003   -0.0014   -0.0024
   -0.0005   -0.0002   -0.0003    0.0029   -0.0007   -0.0012
   -0.0021   -0.0007   -0.0014   -0.0007    0.0096   -0.0048
   -0.0036   -0.0012   -0.0024   -0.0012   -0.0048    0.0132

» B5=[.0055 -.0003 -.0003 -.0010 -.0021 -.0017
-.0003 .0029 -.0002 -.0005 -.0010 -.0009
-.0003 -.0002 .0029 -.0005 -.0010 -.0009
-.0010 -.0005 -.0005 .0077 -.0031 -.0026
-.0021 -.0010 -.0010 -.0031 .0123 -.0051
-.0017 -.0009 -.0009 -.0026 -.0051 .0111]

B5 =

    0.0055   -0.0003   -0.0003   -0.0010   -0.0021   -0.0017
   -0.0003    0.0029   -0.0002   -0.0005   -0.0010   -0.0009
   -0.0003   -0.0002    0.0029   -0.0005   -0.0010   -0.0009
   -0.0010   -0.0005   -0.0005    0.0077   -0.0031   -0.0026
   -0.0021   -0.0010   -0.0010   -0.0031    0.0123   -0.0051
   -0.0017   -0.0009   -0.0009   -0.0026   -0.0051    0.0111

» B6=[.0029 -.0003 -.0002 -.0014 -.0003 -.0007
-.0003 .0055 -.0003 -.0027 -.0007 -.0014
-.0002 -.0003 .0029 -.0014 -.0003 -.0007
-.0014 -.0027 -.0014 .0137 -.0027 -.0055
-.0003 -.0007 -.0003 -.0027 .0055 -.0014
-.0007 -.0014 -.0007 -.0055 -.0014 .0096]

B6 =

    0.0029   -0.0003   -0.0002   -0.0014   -0.0003   -0.0007
   -0.0003    0.0055   -0.0003   -0.0027   -0.0007   -0.0014
   -0.0002   -0.0003    0.0029   -0.0014   -0.0003   -0.0007
   -0.0014   -0.0027   -0.0014    0.0137   -0.0027   -0.0055
   -0.0003   -0.0007   -0.0003   -0.0027    0.0055   -0.0014
   -0.0007   -0.0014   -0.0007   -0.0055   -0.0014    0.0096

» A*B1*C

ans =

    0.0984

» A*B2*C

ans =

    0.1389

» A*B3*C

ans =

    0.0876

» A*B4*C

ans =

    0.1954

» A*B5*C

ans =

    0.1399

» A*B6*C

ans =

    0.1101
```
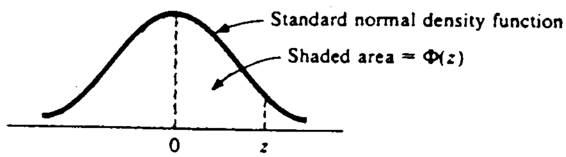

Appendix M: Critical values for the Standard Normal distribution.

Standard Normal Curve Areas

$\Phi(z) = P(Z \leq z)$



z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
−3.4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002
−3.3	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003
−3.2	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005
−3.1	0.0010	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007
−3.0	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0011	0.0010	0.0010
−2.9	0.0019	0.0018	0.0017	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014
−2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
−2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
−2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
−2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
−2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
−2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
−2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
−2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
−2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
−1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
−1.8	0.0359	0.0352	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
−1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
−1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
−1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
−1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0722	0.0708	0.0694	0.0681
−1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
−1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
−1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
−1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
−0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
−0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
−0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
−0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
−0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
−0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
−0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
−0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
−0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
−0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641

Appendix N: Calculations of mean and variance of preference scores for each orientation of emergency stop pushbuttons.

Preferences in Orientation of Emergency Stop Pushbuttons

Orientation	Preference			Proportion of Preference			
	1	2	3	1	2	3	Linear Combination
Horizontal	1	15	2	0.06	0.83	0.11	2.06
Vertical	15	1	2	0.83	0.06	0.11	1.28
Inclined 45	2	2	14	0.11	0.11	0.78	2.67

Horizontal:

v1= 0.0029   v2= 0.0077   v3= 0.0055
c12=c21= -0.0026
c13=c31= -0.0003   c23=c32 -0.0051

Vertical:

v1= 0.0077   v2= 0.0029   v3= 0.0055
c12=c21= -0.0026
c13=c31= -0.0051   c23=c32 -0.0003

Inclined 45 :

v1= 0.0055   v2= 0.0055   v3= 0.0096
c12=c21= -0.0007
c13=c31= -0.0048   c23=c32 -0.0048

```
 --------------------------------------------------
|                                                  |
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|               Oregon State Univ.                 |
|                                                  |
 --------------------------------------------------

Commands to get started: intro, demo, help help
Commands for more information: help, whatsnew, info, subscribe

» A=[1 2 3]

A =

     1     2     3

» C=[1
2
3
]

C =

     1
     2
     3

» B1=[.0029 -.0026 -.0003
-.0026 .0077 -.0051
-.0003 -.0051 .0055]

B1 =

    0.0029   -0.0026   -0.0003
   -0.0026    0.0077   -0.0051
   -0.0003   -0.0051    0.0055

» B2=[.0077 -.0026 -.0051
-.0026 .0029 -.0003
-.0051 -.0003 .0055]

B2 =

    0.0077   -0.0026   -0.0051
   -0.0026    0.0029   -0.0003
   -0.0051   -0.0003    0.0055

» B3=[.0055 -.0007 -.0048
-.0007 .0055 -.0048
-.0048 -.0048 .0096]

B3 =

    0.0055   -0.0007   -0.0048
   -0.0007    0.0055   -0.0048
   -0.0048   -0.0048    0.0096

» A*B1*C

ans =

    0.0098

» A*B2*C

ans =

    0.0242

» A*B3*C

ans =

    0.0247

»
```