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GLOVED OPERATOR PERFORMANCE STUDY

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This study is to determine whether greater minimum spacing is required between push buttons for gloved operation than for bare-handed operation. Seventy-two undergraduate students served as subjects in groups of 12, one group for each of the six hand-wear conditions. The six hand-wear conditions consisted of one bare-handed group and five glove groups. Each of these five groups wore one of the following glove types: a butyl and cotton glove assembly, a butyl and nomex glove assembly, a leather and wool glove assembly, a fire-fighting glove, or a thin vinyl glove. Subjects performed two button-pushing tasks. One task was self paced, allowing subjects to determine response times. The other task was machine paced, allowing subjects decreasing amounts of time to respond. Subjects performed these tasks on three different panels containing nine buttons each. The three panels varied by spacing between the buttons. One panel contained buttons 13 mm apart, another 19 mm apart, and another 25 mm apart. Results from the self-paced task indicate that subjects responded faster on the 13-mm and 19-mm panels than on the 25-mm panel. This suggests that the 13-mm spacing is adequate for speed of operation for gloved operators. Error data and machine-paced time data neither support nor contradict this result. Results also indicate that subjects with larger hands tend to score faster times with more errors in the machine-paced task. This effect does not seem to be because of gender differences.

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Approved for public release;
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GLOVED OPERATOR PERFORMANCE STUDY

INTRODUCTION

The proper spacing of controls for gloved operators is not specified in published literature. A few sources offer some very general guidelines. Bullinger, Kern, and Muntzinger (1987) suggest allowing approximately 10% for inner and outer dimensions of a control layout if gloves are worn; however, they offer no support for the 10% figure or for any adjustments for gloves of various bulk. Boff and Lincoln (1988) caution that operation time may increase when gloves are worn while users operate controls that are small or crowded during a task that requires accurate finger aiming. Taylor and Berman (1982a) state only that bulky glove assemblies can increase optimum center-to-center distances between keys, but do not state to what extent bulky gloves affect these distances. The military standard (MIL-STD) 1472D (1989) requires that minimum spacing between controls be increased for operation with hand wear, but the amount of increased spacing that is necessary for hand wear is unknown. Garrett (1968) suggests distances needed between some controls while wearing a pressurized glove, but these distances are based on static measures, not performance. This study is to determine how much additional distance in minimum spacing, if any, is needed for operation of push-button switches by users wearing gloves of various types.

Though previous research in the area of gloves and controls does not offer information specifically about spacing between push buttons, some effects of gloves on control operation have been determined. Boff and Lincoln (1988) made several general observations about glove effects based on existing literature. They state that control operating time generally increases with gloves during three conditions: when controls are smooth so that the glove slips easily; when gloves are thick and cumbersome; and when gloves are loose fitting, making them sloppy to use. An exception to the expected performance decrement with gloves occurs when gloves protect the hand from hard contact with a control that can cause pain, such as a toggle switch that is actuated with high force. A knob with sharp edges is also operated more efficiently with a glove. Boff and Lincoln conclude that the maximum torque that is applied to rotary controls is slightly reduced with gloves; however, some instances of greater torque exerted with gloves are discussed in this report. The authors also conclude that keyboard data entry is not affected by gloves unless the keys are smooth or rapid data entry is required. Boff and Lincoln state that data entry with thumb wheels is not affected by gloves because a high degree of manual flexibility is not required. The gloved operator cannot discriminate control shapes as well as the bare-handed operator, depending on the thickness of the glove and the tactile sensitivity required. Boff and Lincoln assert that the effect of gloves on control operation is complex because the effect varies as a function of the control type, glove characteristics, and operating characteristics. Other authors have agreed with this assertion (Bradley, 1969a; McGinnis, Bensel, & Lockhart, 1973).

The following citations illustrate how the glove effect varies by control, glove, and task type. Griffin (1944) (cited in Bradley, 1969a) found that performance with six different types of gloves is inferior to bare-handed performance in a test requiring pegs to be moved from hole to hole around a cribbage board. Stump (1953) reported data that suggest knob adjustment took longer for gloved subjects than bare-handed subjects. Jenkins (1956) (cited in Bradley, 1969a) showed a similar effect for knob adjustment but only with small knobs. Bradley (1969b) tested 18 different gloves and 5 different controls. Results show that a push button is more sensitive to the general glove effect than two levers, a toggle switch, or a rotary knob. The author states, however, that the effects may be related to the manufacturer's brand of controls used in the study. Taylor and Berman (1982a) found significant effects for some gloves in a tracking task but not for others.

Glove Characteristics

Bradley (1961, 1969b) rates gloves on four characteristics to determine how much these characteristics affected performance. The first characteristic is tenacity. Bradley defines tenacity as the resistance of a glove to slipping across a grasped or pushed surface and measures it by dragging the palm of a weighted glove across polished aluminum to ascertain the coefficient of kinetic friction.

In these two studies, Bradley found that tenacity correlates negatively with operation time of toggle switches and push buttons. Gloves with a higher coefficient of kinetic friction work better in operating these controls than the more "slippery" gloves, such as a wool glove, apparently because high friction prevents the gloves from slipping off the controls. The buttons used in these studies had convex surfaces, so they were particularly prone to cause slipping. The author states that knobs and levers in these studies are not affected by tenacity, probably because a sufficient grip could be applied to avoid slipping. Taylor and Berman (1982a) found that tenacity seems to be a more important factor than bulk and loss of dexterity in operating a joystick.

The second characteristic is snugness, defined as the closeness of fit. The inside width of the glove where the palm joins the fingers serves as the index of snugness. Bradley's measure of snugness is of limited use because the index is only applicable for studies in which one size glove is used and when all subjects have approximately the same hand size. If more than one size glove is used, the glove type will have more than one index of snugness. If subjects' hands vary in size, one glove will be less snug on one subject and more snug on another. The 1961 article is very short and does not explain in detail how glove sizing is performed. Another study (Bradley, 1969a) used two sizes of each glove and did not discuss the snugness characteristic. Bradley's (1969b) study used one size each of 18 different gloves and only used subjects whose hands fit snugly in the tightest glove. The size used for each glove was the size that fit the author best.

Bradley (1969b) states that snugness affects both on and off controls (push buttons and toggles) and adjustable controls (levers and knobs). When a control requires striking or pushing for activation, the finger must occupy the part of the glove contacting the control surface for optimum performance. Snugness helps this type of control operation and is important in adjustable controls because it allows slight finger movements to be transferred to the controls.

The third characteristic is suppleness or pliability. This is measured by using a finger of the glove for a hinge to connect the arm of a pendulum to its point of support. The more supple gloves allow the pendulum to swing longer.

Suppleness seems to have an effect on operation of knobs and levers but not on operation of on and off controls (Bradley, 1961, 1969b). Suppleness helps in applying delicate adjustments but does not seem to matter when the controls require no fine finger manipulations. Bradley's (1969b) study found that suppleness and protectiveness negatively correlate with each other and oppositely correlate, when significant, with operation time. This is probably because protective gloves tend to lack suppleness. Bradley concludes that protectiveness has less to do with the experiment's results than the suppleness factor had to do with the experiment's results. Taylor and Berman (1982a) conclude that restrictions on movement caused by bulky glove assemblies is an important factor in keying performance.

The last characteristic is protectiveness, the ability of a glove to protect the flesh from injury, such as that which could occur when a finger strikes a solid protrusion. Bradley divides the weight of the glove by the product of the length and width to provide a measure of protectiveness.

A toggle switch can cause the type of injury previously mentioned because a lot of force is applied to the toggle arm to actuate the switch. Evidence for the existence of this effect is shown in Bradley's (1969a) study. Subjects may have been able to operate the toggle switch quickly with more forceful contact when wearing the bulky, more protective gloves; however, the lack of suppleness inherent in protectiveness seemed to play a more important role than protectiveness per se in Bradley's (1969b) study. Weidman (1970) also found that more protective gloves cause more decrement to performance than less protective gloves when a task demands fine finger movements.

Bradley (1969b) concedes that none of the four glove measures are "pure" measures. For example, a glove that is high in protectiveness is more likely to be thicker and therefore less supple. Measuring these characteristics in these ways did allow quantifiable descriptions of gloves, which Bradley has shown is related to performance.

Specific Effects of Different Glove Types

Various gloves and glove assemblies are discussed in reviewed literature. The glove types fall into nine categories. First, the butyl rubber glove is a thin, smooth, supple glove used primarily for nuclear, chemical, and biological (NBC) protection in the military. In the studies reviewed, the butyl glove is always worn over a very thin cotton glove, which absorbs perspiration. Second, the neoprene type glove is also an NBC protective glove used by the military, but this material is less supple and less smooth than the butyl rubber. Neoprene gloves are sometimes worn over a thin cotton inner glove. Third, the wool gloves discussed in literature are simple, thin wool gloves. Fourth, several types of leather gloves have been studied including work, air crew, cape, and winter leather gloves. The various leather gloves are not described well in literature to differentiate them, so they are discussed as one glove type in this report. The next three glove types are double glove assemblies. These are made of the butyl, neoprene, and wool gloves worn as liners under leather shells. The eighth glove type is a chemical and biological (CB) protective glove that is composed of a chemically impregnated cotton. This glove was formerly used by the military. The last glove type is a mitten which is examined in only one study. Even though many of the studies reviewed for this report examined more than one glove type, each of the glove types is discussed separately to show the effects of each glove type across studies.

Butyl

Bensel (1980) compares the butyl glove, currently used by the military, to a neoprene glove that serves the same NBC protective functions. The gloves were tested with and without the standard U.S. Army leather glove worn over them, always with the thin cotton inner glove worn under them.

Angular force (torque) exerted with the butyl gloves without the leather was superior to all other hand-wear conditions, even bare hands. Since force was exerted on a brass cylinder, the superiority of the butyl glove was probably because of the high tenacity of the material. Performance during dexterity tests with the butyl was no different from the tests with bare hands. The other hand-wear conditions were significantly worse than bare hands. The butyl gloves were also superior to the neoprene gloves in ease of donning, fit, and resistance to tearing. The superiority of fit may have accounted for some of the butyl advantage because better fit meant the butyl gloves had the advantages given by snugness. The superiority of the butyl glove in exerting angular force (torque) is also shown by McGinnis, Bensel, and Lockhart (1973).

Johnson and Sleeper (1986) tested finger dexterity bare-handed and with butyl gloves, with and without the M17A1 gas mask. The mask with a hood, gloves with inserts, a charcoal foam jacket and trousers, and rubber boots make the mission-oriented protective posture level IV (MOPP IV) ensemble. This ensemble is worn by soldiers in a chemically contaminated environment. Wearing the mask had no effect on the dexterity performance; however, subjects needed significantly more time to complete the task when wearing the butyl gloves than when bare-handed, even after a third test day. McGinnis, Bensel, and Lockhart (1973) also found that performance with the butyl glove during dexterity tasks was significantly worse than with bare hands.

Fine (1987) and Fine and Kobrick (1985) tested soldiers during cognitive tasks while wearing the MOPP IV ensemble. The chemical-protective clothing had a detrimental effect on cognitive performance in the heat. The effects of the gloves alone were not examined.

Neoprene

In all but one dexterity task in the Bensel study (1980), the neoprene glove performed about as well as the butyl glove. The test in which the neoprene glove did not perform as well was a test that measured finger dexterity. Since the test required fine finger manipulation, the fit of the glove was very important. Since the neoprene glove in this study did not fit as well as the butyl glove, the findings cannot generalize all neoprene gloves; however, the butyl glove performed much better during the torque test so the butyl material is probably better for this type of task.

Taylor and Berman (1982a) tested neoprene "inner" gloves in their study, but enough information is not available to determine how different these gloves were from those in the Bensel study. Performance of the neoprene glove in operating a joystick for a tracking task was superior to two different leather gloves and those two leather gloves over the neoprene inner gloves. The authors concluded that the higher tenacity (coefficient of kinetic friction) of the neoprene caused the superior performance because all other glove ensembles tested used leather shells with less tenacity.

Wool

Bradley (1969a) tested the MA-1 flying glove assembly, which consisted of a wool inner glove and a leather shell. The author also examined the wool inner gloves alone. The wool gloves were inferior to the wool and leather assembly and bare hands in operating a push button, which required tenacity because of the button's smooth, convex surface. The wool glove was inferior to the combination glove in operating a toggle switch. The author concludes that the lack of protection of the wool glove causes the difference. Also, the wool glove is inferior to bare-handed operation of a vertically operated lever.

Rogers and Noddin (1984) tested a wool insert glove in several tasks. The results showed that the gloves were detrimental to performance in tests of finger dexterity, manual dexterity, and tapping. Performance in tests of rotary pursuit, of steadiness, of choice reaction time, of aiming, and of another tapping test was unaffected by the gloves.

Leather

Leather gloves are usually used as an outer shell in a glove assembly, but a few studies have examined the effects of leather gloves alone. Meredith (1978) (cited in Taylor & Berman, 1982a) shows that air-crew cape-leather gloves are only marginally inferior to bare hands in several dexterity tests. Taylor and Berman (1982a) found that the cape-leather glove and a winter leather glove with a waterproof seal significantly impaired a tracking task that involved manipulating a joystick. During this task, the leather gloves alone impaired performance as much as the leather gloves over neoprene gloves.

Leather and Butyl

Other studies have tested the effects of leather gloves only as part of glove assemblies, with the leather gloves over butyl rubber, neoprene rubber, or wool gloves. As previously referenced, Bensel (1980) tested the standard Army leather glove in assemblies with butyl and neoprene. The leather and rubber assemblies were consistently inferior in performance to bare hands, to the butyl glove alone, and to a lesser extent the neoprene glove alone. This inferiority showed during the torque test and manual dexterity tasks. McGinnis, Bensel, and Lockhart (1973) also examined the effects of the leather and butyl assembly on torque and dexterity. Performance of this assembly was so poor that the authors suggested that it no longer be considered for use as an Army CB protective glove. The authors believe soldiers might discard the leather shell out of frustration in training and in chemically contaminated environments; however, the authors suggest no alternative to protecting the butyl glove from puncture during conditions hazardous to the butyl material.

Adams and Peterson (1988) tested handgrip torque for circular electrical connectors with the leather and butyl assembly (along with the thin cotton insert) and with a leather and wool work glove assembly. The glove assemblies allowed subjects to exert more torque on the connectors than with bare hands. The authors believe this is because of the protection from discomfort caused by tightly grasping the knurled surface of the simulated connector rings. The advantage is about the same for both glove assemblies.

Leather and Neoprene

As previously discussed, Taylor and Berman (1982a) found that a leather and neoprene glove assembly was detrimental to performance with a joystick during a tracking task. The authors also showed that the assembly was detrimental to reaction time in a key pressing task in one experiment. In another experiment in the same study, the leather and neoprene assembly slightly improved reaction time in key pressing but only when a high force was required to press the keys. The final experiment in this study tested the same glove assembly without the fingertips of the assembly, with the fingertips only, without the fingers of the assembly, with the fingers only, and with the complete assembly. These hand-wear conditions were tested during a keying task and during dexterity tasks to determine how tactility and mobility affected performance. These factors were reduced and confounded when subjects wore complete gloves. The authors conclude that tactility in the fingertips seems to be the main factor in manual dexterity performance, while mobility seems to be the main factor in keying performance. The authors also suggest that except for a positioning test, the dexterity tests used measured different factors than those related to keying performance.

Leather and Wool

As previously mentioned, Adams and Peterson (1988) found that a leather and wool assembly increased the maximum torque subjects could apply to electrical connectors because of the protection offered by the assembly. Bradley (1969a) showed that a leather and wool assembly had the following effects: it improved performance on a toggle switch with a high actuation force because of the glove's protective factor; it allowed performance superior to a wool glove on a smooth, convex push button because of the assemblies higher tenacity; and it was detrimental to performance, relative to bare hands, on a vertically operated lever, perhaps because the glove lacked the suppleness needed for fine adjustments. Swain, Shelton, and Rigby (1970) found that a leather and wool glove assembly reduces the maximum torque that subjects can apply to three sizes of knobs.

Cotton CB

One study (McGinnis, Bensel, & Lockhart, 1973) examined the effects of a cotton CB protective glove on ability to apply torque and during four dexterity tasks. Because of the low tenacity of cotton, the glove was detrimental to applying torque to a smooth cylindrical handle. The cotton glove was equal to the butyl glove during the dexterity tasks. This cotton glove is no longer used as a CB protective glove by the Army.

Mitten

The final "glove" was a mitten that was compared to 17 other gloves by Bradley (1969b). The mitten was inferior to the five-fingered glove that was similar in operating a push button, a rotary knob, and a horizontally operable lever. Only a few of the gloves used in this study are described in detail because the main purpose of the study was to determine the effects of Bradley's four glove characteristics, not the gloves themselves.

Learning Effects

Several studies have shown that wearing gloves causes differential learning effects depending on whether gloves are worn, what types of gloves are worn, and what task is performed. Bensel (1980) tested subjects during five dexterity tests and a torque test. Subjects performed all tasks in each of 14 sessions on 14 different days. Performance improved significantly during the first seven sessions in all six tasks and continued during the last seven sessions in three of the dexterity tests. Learning effects were particularly pronounced for the more bulky glove types, the leather and neoprene and the leather and butyl assemblies. Learning effects for the butyl glove and bare hands were less pronounced. McGinnis, Bensel, and Lockhart (1973) show a similar effect for the leather and butyl assembly.

Bradley (1969a) provided subjects with a limited amount of practice during a less complex task and found a strong learning effect in the first half of the experimental data and a small learning effect in the second half. The author does not indicate whether the gloves cause differential learning. Bradley doubled the practice time for a similar experiment (1969b) but did not report whether a learning effect occurred.

Johnson and Sleeper (1986) found different learning effects for butyl gloves and bare hands during two dexterity tests. Subjects performed both tests on each of the five days. Subjects ceased showing improvement during the O'Connor Finger Dexterity Test on Day 4 when gloved and on Day 3 when bare-handed. Subjects ceased showing improvement during the Purdue Pegboard Manual Dexterity Test on Day 3 when gloved and on Day 1 when bare-handed.

The differential learning effect seems to be more pronounced with bulky gloves and complex tasks. Two consequences result from the differential learning effect. First, people who must wear gloves in real-life tasks must be given more time to practice these tasks than is needed with bare hands. The second consequence is that when researchers examine glove effects, extra practice time must be given to subjects, especially when the gloves that they wear are bulky or when the task is complex. Data must also be analyzed to check for a differential learning effect because early performance during a task may not indicate performance after subjects become more accustomed to performing with the gloves. If the learning effect is not the same for groups who wear gloves and for groups who do not, then statistical correction will not allow the same valid conclusions that can be made when learning effects are similar for both groups.

Use of Manual Dexterity Tests

Many studies that examined the effect of gloves on performance used manual dexterity tests to measure performance. Rogers and Noddin (1984) argued for use of dexterity tests to measure "pure" manual ability deficits caused by the cold. The authors state that since research has been so task specific, new studies must be performed to determine the effect of cold during each task if a similar task has not already been tested. While these tests may determine whether a glove will cause a decrement in certain types of hand and finger movement and manipulation, they do little to indicate how much space is needed between push buttons, which is the behavior of interest in this study. The keys used in Taylor and Berman's study (1982a) were actually push buttons, and the authors stated that five of the six manual dexterity tests used in their study seemed to measure factors other than those involved in keying. The positioning test, which is related to keying performance, did not help in specifying minimum distances between controls. Because the glove effect varies by control type, glove type, and task type, the task used to determine something as specific as push-button separation must involve pushing buttons. Dexterity tasks do not always generalize to real-life activities. Adolfson and Berghage (1974) discuss manual-dexterity tasks in measuring effects of the cold.

A very simple dexterity test was used in the development of criteria for fire-fighters' gloves. The dexterity requirement was that the wearer of the glove be able to pick up a simulated pencil, wet or dry, with each of the four combinations of thumb and finger. The authors thought that this task was representative of fine grip manipulations and took into account glove fit, finger construction, and material bulk (Coletta, Arons, Ashley, & Brennan, 1976a & 1976b). The authors did not indicate how or why these particular criteria were chosen. They offered nothing to support the assertion that this task is a valid indicator of the degree of overall dexterity. Even if the task were a valid indicator of dexterity, the authors offer no evidence that the dexterity needed to pick up a simulated pencil is the amount of dexterity needed for a fire glove.

Fleishman and Hempel (1954) discussed five different factors that dexterity tests measure. Hines and O'Connor (1926) provided an example of a dexterity task that helped predict which applicants were not well suited for small assembly work. The task involved placing small pins in small holes, so the task was relevant to small assembly.

Grip strength is sometimes discussed with dexterity although they are very different constructs. Hertzberg (1955) describes grip strength losses of about 20% at various distances between the palm and fingers (i.e., different grip sizes). A 6.35 cm (2.5-in.) grip size allowed subjects to produce a higher mean grip strength than grip sizes of 12.70, 10.16, and 3.81 cm (5, 4, and 1.5 in.) Without gloves, mean grip strength was 65.77 kg (145 lb) for the 6.35 cm grip. With gloves (which were not described), the mean was 48.99 kg (108 lb). Tichauer (1978) explains the cause of grip loss when wearing gloves. Nerve endings located on the inside of the fingers give feedback to the brain about the degree of closure of the hand. Thick gloves can cause the nerves to provide the feedback too early by producing pressure on the interdigital surfaces before the hand is really closed. This may cause heavy objects to be dropped from a gloved hand and may have an effect on operation of controls that must be gripped.

Glove Fitting

Even though the importance of glove fit or snugness has been shown in many of the studies previously described, none of the studies in the area of glove effects describe rigorous methods for assigning glove sizes to subjects. Bensel (1980) states simply that "each subject was fitted" (p. 17) for one size of each type of glove and that the leather shell gloves were fitted over the gloves to be worn under them. The author did state mean hand measures for subjects assigned to each glove, which is more information than any other study has given. Bradley (1969b) used only one size of each of 18 gloves that fit himself best and only used subjects "whose hands fitted snugly in the tightest glove" (p. 22). Bradley used two sizes in another study (1969a) in which subjects were male college students "whose hands fitted comfortably (with one exception) into one of the two glove sizes available" (p. 15). Taylor and Berman (1982a) stated only that each subject was fitted with the glove needed for the particular session. Since glove fit is important, the method used for fitting should be described whenever possible.

Related to glove size is the anthropometry measures of the population to which a study's results are supposed to generalize. The ranges of hand dimensions of the population of interest are of particular importance when determining minimum distances between controls since large hands and fingers require more room than small ones. The MIL-STD-1472D and Diffrient, Tilley, and Harman (1981) provide percentile measures of hand circumference, hand length, and finger lengths which are relevant to glove size. Diffrient, Tilley, and Harman stated that glove size is hand girth measured around the metacarpals, excluding the thumb. Gordon et al. (1989) provided an anthropometric survey of U.S. Army soldiers, which is a good source of percentile data for hand measures and includes data for males and females.

Push Buttons

Push buttons and keys are essentially the same type of control. The difference between the two is primarily in their uses. The control is usually called a key when a group of push buttons is used in a data entry task, for example on an alphanumeric keyboard or a numeric ten-key pad. The control is usually called a push button when it is used for a more discontinuous task, such as switching a device on and off. Despite the difference that often exists between tasks performed by push buttons and keys, some of the research in the area of keyboards are relevant to characteristics of push buttons. This section will review sources that have examined the effects of varying certain push-button characteristics, sources that offer general guidelines for desirable characteristics of push-button switches, and sources that offer guidelines about optimum spacing between push buttons during bare-hand conditions.

In a key-pressing task, Taylor and Berman (1982a) tested two levels of actuation force, 1 N (3.5 oz) and 15 N (55 oz), and two levels of key or push-button travel, 2 mm and 10 mm. Three keys were used side by side. The key size was 15 mm by 15 mm, and the key separation was 13 mm edge to edge. The authors suggest that high actuation force is important in reducing error while low travel is important in increasing speed. Conclusions from this study are limited since the two levels of each independent variable left large intermediate areas untested. Taylor and Berman (1982b) provided a detailed discussion of the mechanical characteristics of keys, including displacement, detent, resistance to actuation, dip, and feedback parameters.

Deininger (1960) studied four variables in key design: size, force, displacement, and feedback. The author found that increasing the square button-top size from 9.6 mm to 12.7 mm improved keying time and reduced errors. Results of the study also showed that varying the actuating force from 1 N (3.5 oz) to 4 N (14.1 oz) and varying the maximum displacement from 0.8 mm to 4.8 mm produced no significant performance differences. In addition, auditory and kinesthetic feedback added to push buttons with 3.2 mm travel and 1 N (3.5 oz) force caused no significant differences in speed or error performance.

Chase, Rapin, Gilden, Sutton, and Guilfoyle (1961) showed that decreased auditory feedback, decreased proprioceptive feedback (induced by applying vibration to the forearm), and a combination of these with decreased visual feedback caused impairment in a key-tapping ask. The dependent variables were the degree to which subjects could tap at a specific rate and tap with a specific amount of force. The artificiality of the task makes generalization to push-button switches tenuous at best. Other studies have shown the importance of feedback while operating controls but only with bare hands (Bahrick, Bennett, & Fitts, 1955; Briggs, Fitts, & Bahrick, 1957; Gibbs, 1954).

Kinkead and Gonzalez (1969) (cited in Taylor and Berman, 1982a) found that snap-action detents increased errors with experienced typists. Taylor and Berman (1982a) found that the presence or absence of auditory feedback made no difference in a keying task with and without gloves; however, kinesthetic feedback of movement and force and visual feedback were still present. Also, the detent of the push buttons was probably not completely masked by the gloves.

Chapanis and Kinkade (1972) offer three recommendations for push buttons. One, resistance of the switch should start low, build up rapidly, then drop suddenly to indicate actuation. Two, the push button should have either a concave surface or a rough surface to prevent slipping. Three, an audible click should be provided to indicate that the switch has been actuated. Ivergard (1989) offers similar suggestions.

Several sources offer specifications for push-button resistance (actuation force), travel (displacement), button-top size, and spacing between buttons. For using a single finger to press buttons, which is the type of button pushing with which this study is concerned, Chapanis and Kinkade (1972) and Ivergard (1989) recommend the same specifications. Chapanis and Kinkade stated that these specifications were adapted from MIL-STD-803A-3 (USAF). That reference is now superseded by MIL-STD-1472D (1989). The new specifications hold two changes for single-finger operation of push buttons. One, the old range of acceptable displacement was 3 mm to 38 mm; the new one is 2 mm to 6 mm. Two, the old minimum button-top diameter was 13 mm; the new standard provides a range, 9.5 mm to 25 mm. The range of acceptable resistance is 2.8 N (10 oz) to 11 N (40 oz). The range of spacing is a minimum of 13 mm to a preferred 50 mm. The upper boundary of spacing is the only upper boundary called a preferred measure. The other upper bounds are simply maximums. The MIL-STD-1472D also requires that the push button switches have positive indication (e.g., snap feel or audible click) and either a concave surface or a surface with a high degree of frictional resistance to prevent slipping.

Bullinger, Kern, and Muntzinger (1987) offer different specifications. They recommend the following: a minimum button diameter of 15 mm, resistance of 1 N (3.5 oz) to 8 N (29 oz), and minimum and optimum spacing of 20 mm and 50 mm, respectively. No displacement recommendations were offered. Even though the minimum spacing is significantly higher than the MIL-STD-1472D recommends, the authors state that provisions would have to be made for gloved operation.

This study is to determine if the wearing of gloves while operating push-button switches requires greater minimum spacing between the push buttons. Subjects operated push-button switches bare-handed and while wearing five different glove types, which vary in bulk. The buttons were placed in three different densities (i.e., buttons will be placed at three specific distances from one another, one distance in each of three groups).

The alternative hypotheses were (a) that gloved subjects would not be able to perform as well as bare-handed subjects during the button-pushing task, (b) that the performance difference would decrease as the spacing became wider, and (c) that the bulkier gloves would cause higher performance decrement than the less bulky gloves, particularly with narrower spacing.

METHOD

Subjects

Seventy-two undergraduate psychology students attending the University of South Dakota served as subjects. All subjects were tested to ensure that they had corrected or uncorrected visual acuity no worse than 20/30 for near vision. Visual acuity of 20/30 was more than adequate to perceive the visual stimulus for the experiment. Subjects were given extra credit points in exchange for serving as subjects.

Subjects were chosen from a pool of volunteers. Since it is possible that males and females may perform differently during the experimental tasks, each of the six experimental conditions had the same ratio of males to females. Also, since it was suspected that hand size had an important effect on determining optimal spacing between push buttons, subjects were chosen so that each of the six experimental conditions had the same proportion of subjects with each of the three ranges of hand girth for each gender. Hand girth traditionally determines glove size, so it was chosen as the critical dimension for fitting gloves. Volunteers whose hand girth did not fall in the range of the Army's anthropometric survey (Gordon et al., 1989) were not included in the subject pool.

The following procedure ensured that each group had the same gender ratio and the same proportion of hand sizes. The subject pool was first split by gender. Then, within each gender, subjects were divided into three equal groups (plus or minus one) based on hand girth. Cutoff values for hand girth for each group were chosen so that each group was of equal size. Essentially, subjects were matched by hand girth within gender. Two subjects from each of the three hand-girth groups for each gender were randomly assigned to each of the six experimental conditions, filling six groups of twelve. If a subject from one hand-girth or gender group did not participate or complete the experiment, another subject from that group was used. When more subjects were needed than the number in the original subject pool, the same hand-girth cutoff values were used to assign additional subjects to hand-girth or gender groups. For males, the hand-girth ranges were 190 mm through 212 mm, 213 mm through 222 mm, and 223 mm through 237 mm for small, medium, and large groups, respectively. For females, the hand-girth ranges were 167 mm through 182 mm, 183 mm through 190 mm, and 191 mm through 207 mm for small, medium, and large groups, respectively.

A comparison between hand-girth measures of subjects in this study and hand-girth measures of Army soldiers in Gordon et al. (1989) is of interest for generalization of results from this study. Table 1 presents percentile information and means for hand-girth measures from subjects in both studies. As shown in Table 1, subjects from the two studies match rather closely in hand girth.

Since this study was to test gloves used in the armed forces, the generalization of subjects in this study to soldiers in the Gordon et al. study is important. At present, most soldiers are not college educated, so generalization of students' tasks results would not be valid; however, the tasks performed in this study did not involve a large cognitive component. It is possible that a student would have more experience with calculators and typing than the typical person entering the military; however, any soldier whose duties included button-pushing tasks would soon become proficient with these tasks.

Only right-handed subjects were used in this study because equal representation of right- and left-handed people in the six hand-girth/gender groups would be extremely difficult to achieve. Unequal assignment of left-handed subjects to various experimental conditions might have confounded experimental effects. All subjects signed an informed consent form (see Appendix A). Deception was not used, and subjects were fully debriefed.

Table 1

A Comparison of Percentile Information and Means for Hand-Girth Measurements

Group	Mean	SD	Percentile 25th	50th	75th
Army soldiers					
Males	213.8	9.7	207.2	213.4	220.1
Females	186.2	8.5	180.4	186.0	191.6
Students					
Males	215.2	10.6	208.3	215.0	224.0
Females	187.9	10.3	180.3	188.5	195.0

Apparatus

Push-Button Panels

This study used three panels of nine buttons each, each mounted in a 3 by 3 matrix. This matrix was chosen so that buttons could be presented in different positions relative to other buttons (e.g., a button surrounded on four sides by other buttons; a button with another button above, another below, another to the left, but not to the right; a button with another to the left and another below but none above or to the right; etc.).

Each panel held buttons, which were spaced at a specific distance from each other, with distances different on each panel. The panel with the shortest distance (SD) between edges of buttons (the SD panel) contained push buttons spaced 13 mm apart. This is the minimum distance allowed by the MIL-STD-1472D for placement of push buttons.

The panel with the medium distance (MD) between buttons (the MD panel) contained push buttons spaced 19 mm apart, which was 0.64 cm (0.25 in.) greater than the distance allowed by MIL-STD-1472D. This value was chosen for three reasons. First, the MIL-STD-1472D spacing for controls generally tend to vary in increments of 0.64 cm. Second, 6 mm was a large enough distance to allow expectations for some difference in performance, yet small enough not to leave a great range of distances unaccounted for between SD and MD panel distances. Third, the 19-mm distance was also close to the 20-mm minimum distance recommended by Bullinger, Kern, and Muntzinger (1987) for bare-handed push-button operation.

The panel with the longest distance (LD) between buttons (the LD panel) contained push buttons spaced 25 mm apart, 0.13 cm (0.5 in.) greater than the minimum distance allowed by MIL-STD-1472D. This value was approximately double the 13-mm minimum spacing distance allowed for bare-handed operation. Increasing the minimum spacing for push buttons beyond this value was probably not practical because space available for controls is usually limited when minimum values are used. Also, the additional space needed to operate push buttons while a subject wore gloves was limited primarily by the extra bulk that gloves add to the fingers. No evidence existed to suggest that gloved operation (at least for the types of gloves used in this study) would require more than 25 mm separation between buttons since the extra bulk added to the fingers was far less than 25 mm in each direction. Considering that Garrett (1968) suggested only an extra 6 mm between control buttons when a pressurized glove was worn, the 12-mm increase in spacing, which the 25-mm spacing allowed, was certainly adequate to allow for operating with the gloves in this study. In addition, the 25-mm spacing distance allowed the difference between the SD and MD panels and the difference between the MD and LD panels to be equal.

The push-button switches that were used in this study were chosen to meet the MIL-STD-1472D criteria previously discussed. Very few push buttons are manufactured that meet the specifications needed for this study. Most push buttons that are commercially available are either too small or have no detent click. Manufacturers' catalogs rarely list all the relevant specifications, especially resistance. The model used in this study was manufactured by Schurter Incorporated, part number 041.2311 (Schurter, 1990). The button top was square. A square button was needed because most push buttons used on modern weapon systems are rectangular or square. A square button was chosen over a rectangular button because using rectangular buttons would not allow equal center-to-center distances between buttons horizontally and vertically placed on panels.

The push buttons were fitted with nonslip rubber adhesive surfaces. This made the button surfaces rough and resistant to slippage. The top surfaces of the buttons lay approximately 9 mm above the panel surfaces.

The operating travel distance of the buttons was approximately 3.2 mm. This satisfied the MIL-STD-1472D specification for travel distance between 2 mm and 6 mm for a fingertip-actuated push button. A detent that gave a "snap action" and an "audible click" was activated approximately half way through the travel distance. The electrical circuit of the switch was actuated at the same time as the detent. Since the switch was momentary, actuation continued only as long as the button was held at or below the point at which the detent sounded. When pressure was removed from the button, the electrical circuit of the switch went back to an unactuated state.

The MIL-STD-1472D required that push buttons have a diameter between 9.5 mm and 25 mm for fingertip actuation; however, the push buttons on most current control panels are square or rectangular, not round. The push buttons used for this study were 15 mm by 15 mm.

The operating resistance of the switches ranged from approximately 2 N to 2.3 N (7 to 8.5 oz). This resistance was slightly below the MIL-STD-1472D specification range of 2.8 N (10 oz) to 11 N (40 oz). Resistance of the switches in this study being near the low end of the MIL-STD-1472D range was appropriate because switches with a higher actuation force might have offered an advantage to the gloved operator. This advantage would have been because of the protection that the gloves would have offered from hard contact with the buttons (Bradley, 1961, 1969b). Also, the switches were somewhat sensitive, though not overly sensitive, to accidental actuation.

These switches also met the recommendations of Chapanis and Kinkade (1972) and Ivergard (1989) previously mentioned. The resistance of the switches started low, built rapidly, then dropped suddenly to indicate actuation. The buttons had rough surfaces that helped prevent slipping. An audible click sounded to indicate actuation.

The Switch-Computer Interface

The push-button switches were interfaced with the computer through an AT compatible keyboard. Wires lead from the circuits for individual characters on the keyboard to the push-button switches on the three panels. Instead of completing a circuit at the keyboard by pressing a key, the circuit was completed at the switch by pressing the push button. A computer program simply read each character signal as an individual switch actuation.

Even though the electric signal had to travel an extra distance from the switches, the electrical signal traveled fast enough and the computer read the signal fast enough so the reaction times for activating the switches were legitimately scored with millisecond resolution. The computer did not read more than one signal from a push button until after the button was held in actuating position for 0.5 s or longer. The computer that was used was an CSS PC-AT™ compatible computer with a processing speed of 10 megahertz.

Gloves

This study examined the effects of five glove types, three of which are used by the Army and have some use in other military branches. The U.S. Army Human Engineering Laboratory chose these three glove types for this study. The other two glove types are commercially available fire glove and a thin vinyl glove.

The military glove types were representative of the more bulky glove types used in the Army. Less bulky types were used by the Army, but if control spacing were specified to accommodate operation with the more bulky glove types, these specifications would also accommodate less bulky gloves.

The NBC protective glove was made from butyl rubber. The sizes available for this study were small, medium, and large. An extra large size exists but was not available; however, the large size covered the upper range of hand sizes rather well. The material was very pliable, and the same type of glove used in a previous study ranged in thickness from 0.508 mm to 0.813 mm (Bensel, 1980). The surface texture of the butyl glove was very smooth. Since the material was rubber, the gloves had less tendency to slip off surfaces than materials such as wool or cotton. The butyl glove covered the hand, wrist, and most of the forearm.

The butyl gloves are issued to military troops with a pair of cotton gloves that are worn under the butyl gloves. These cotton gloves absorb moisture from the hands, which perspire in the moisture-impermeable butyl gloves. The cotton gloves in this study were lightweight, stretchable, and very thin so they added a negligible volume to the hands which fit in the butyl gloves. The cotton gloves were worn under the butyl gloves during this study except when the nomex glove was worn under the butyl. This assembly is discussed in this report.

The next glove type was the leather and wool glove assembly. The assembly was made of a leather shell worn over a wool liner. The wool and leather gloves can be worn separately, but they were worn only as an assembly in this study. The surface of the leather shells was smooth and like the butyl glove, resistant to slipping. The wool and leather gloves covered the hand and wrist.

The leather and wool gloves were sized 2 through 5, and a size 3 wool glove was worn with a size 3 leather glove (likewise for the other sizes). Size 2 of the leather and wool glove assembly was not available for this study, so size 3 was substituted for the low end of the hand size range. The thickness of the leather and wool assembly was approximately 2 mm.

The next glove type was a butyl and nomex glove assembly. Nomex is a thin, pliable, fire-resistant material. The nomex glove covered the hand and wrist. The nomex gloves fit snugly on most hands and were available in sizes 9 through 11. The thickness of this assembly was approximately 1.5 mm. The surface of the nomex glove that covers the ventral side of the hand and wrist is covered with a layer of smooth leather.

The fire-fighting glove was composed of three layers: a tough leather outer shell; a thin, waterproof vapor barrier; and a heat-resistant inner liner. It was available in sizes small to extra large. It was approximately 2 mm thick and covered the hand and wrist.

The final glove type was a vinyl glove that was very thin, much like a surgical glove. One size fit all hands snugly. It covered the entire hand, none of the wrist.

The Self-Paced Task

Each subject used one panel of nine buttons at a time. A computer-generated diagram appeared on a monitor to indicate to the subjects which four of the nine buttons to push. The diagram also indicated the order in which to push them. After the subject pushed the four buttons indicated in the correct order, one trial was complete. A tone sounded immediately after the fourth button was pushed to inform the subject that the buttons were pushed correctly. This tone also indicated that a new diagram would appear in 1 s.

If the subject pushed a button or buttons incorrectly, one of two outcomes occurred. First, if the subject pushed a button incorrectly but realized the mistake before pushing a fourth button, then the subject could push a cancel button. After pushing the cancel button, the subject started over pushing the same four buttons indicated by the diagram. This cancel button lay to the right of the panel of nine buttons. Second, if the subject pushed a button incorrectly and did not realize the mistake or realized the mistake only after pushing a fourth button, an error tone sounded. The error tone was easily distinguishable from the tone for a correct trial. The error tone informed the subject of the error and directed the subject to start over, pushing the same four buttons indicated by the diagram. Subjects continued with the same diagram until all four buttons were pushed correctly.

The diagrams that appeared on the monitor were highly compatible with nine-button panels. The diagram contained a rectangle with nine smaller rectangles in a 3 by 3 matrix. The nine rectangles on the screen were this shape even though the buttons were square because the same diagrams will be used to examine toggle switches in a future study. Using the same diagrams will allow performance comparisons between push button and toggle switches.

The rectangle that holds the nine smaller ones was 120 mm by 73 mm. The small rectangles were 21 mm by 9 mm. Numbers one through four within four of the small rectangles indicated the order in which to push four buttons on the corresponding panel. The numbers were approximately 4 mm by 3 mm. The numbers were white, highly contrasting with their small rectangular backgrounds which were black. The small rectangles highly contrasted with their light green background.

Subjects performed 18 trials with each of the three differently spaced panels in the self-paced task. Eighteen different diagrams were created to indicate 18 different button-pushing sequences. Eighteen trials were used so that each of the nine buttons were pushed the same number of times. Each button was pushed eight times, and each button was first, second, third, and fourth in the sequence twice.

The 18 sequences of the 18 diagrams were pseudo-randomly generated. The sequences appeared random to the subjects, but certain sequences were avoided so that trials were similar in difficulty. For example, a trial that required pushing the top three buttons in sequence left to right with the fourth button right below the third would be very easily performed. It would be much easier than a trial which required a more random sequence. Such extreme of difficulty was avoided. In a pilot study, reaction times from subjects did not indicate any sequences that were obviously different in difficulty. The same 18 sequences were used for each of the three panels, but the order of the sequences was randomized for each subject using each panel.

A sequence of four buttons was chosen instead of a higher or lower number to make the task as challenging as possible without taxing the ability of short-term memory. The diagram remained on the screen while subjects pushed the buttons, but some subjects were able to push all four buttons without looking back at the screen. Subjects had to remember each button position and the order in which each button should be activated. This could be considered eight bits of information, which falls in the seven plus or minus two range, which is considered the standard limit of short-term memory. Subjects may, however, have remembered the sequence as a pattern, which would probably require fewer than eight bits. Subject performance in a pilot study helped determine that a sequence of four buttons was acceptable.

Subject performance in a pilot study helped determine criterion performance. By the end of practice time, subjects who began with the self-paced task had to achieve times of 3 s or less on at least half of the 18 correct responses for at least one of the practice panels.

The Machine-Paced Task

The same diagrams and button panels were used in the machine-paced task as the self-paced task. No cancel button was available during the machine-paced task.

The machine-paced task started by allowing the subject more than enough time to push the four buttons in the first trial. The diagram remained on the screen until the time allowed expired. When time expired, the diagram disappeared and a tone sounded. The tone informed the subject that no further button pushes were acknowledged for that trial. It also signaled that a new diagram would appear in about 1 s.

The same tone sounded regardless whether the buttons were pushed correctly. If all four buttons were not pushed in correct sequence, the trial was considered an error trial. If a sequence was entered correctly, a new diagram appeared allowing less time to respond than in the previous trial. Response time continued to decrease after each correct trial. If a subject made an error, a new diagram appeared, but the response time allowed was the same as in the previous trial. A subject was allowed to make three errors at one level within the time allowed. After the third error, subjects were considered to have reached their best-time score with the panel they were using.

The amount of time allowed at which subjects began the machine-paced task and the rate at which time allowed was decreased was a compromise. The time allowed decreased quickly enough so that subjects did not spend much time performing the task; however, the time allowed decreased slowly enough so that a rate of performance could be determined. Time allowed for the first diagram was 5 s. When subjects responded correctly to the first four diagrams, time decreased by 0.5 s. Time allowed decreased by 0.1 s after correct responses to subsequent diagrams.

After subjects went through the 18 diagrams, the same 18 were used again. The 18 diagrams were randomized again to be ready when subjects required more than the original 18 diagrams to reach their highest rate of performance.

Subject performance during a pilot study helped determine criterion performance. Subjects who began with the machine-paced task had to perform at 3 s or less on at least one panel during practice trials for their data to be included in the analysis. The criterion level of performance was not extremely challenging. The level was high enough to eliminate two subjects who had difficulty with this task. Since no subjects were aware of the criteria and since it would have served no purpose to tell those who did not meet the criteria, these two subjects finished the experiment and were not informed that they had not met the criteria.

Procedure

Measuring Hand Size

First contact with potential subjects was made when the students volunteered to participate in the study. At that time, each volunteer had one hand measurement (hand girth) taken. This measurement was hand girth. With the hand held straight, fingers together and thumb apart, the girth around the hand was measured at the knuckles of the second through fifth digits. The thumb was not included in the girth measure. As previously discussed, this girth measurement constitutes a first approximation to glove size; therefore, volunteers not within the range found in the Army anthropometric survey (Gordon et al., 1989) were not included in this study.

When subjects arrived for the experiment, they read and signed a consent form. Then two more hand measurements were taken. The finger-length measurement is the length of the third digit, from the crotch of the second and third digits to the tip of the third digit. The hand-length measurement is the length from the first fold of the wrist nearest to the palm to the tip of the second digit. These measurements along with the girth measurement allowed subjects' glove sizes to be determined.

Glove-Fitting Protocol

Since the inside measurements of a glove are smaller than the outside measurements, a smaller hand would fit the glove than it would seem from the outside measurements. At the same time, since all these gloves stretch to a certain extent, a larger hand would fit the glove than it would seem from the inside measurements; therefore, to estimate a range of fit for each military glove, 5% of a given glove measurement was subtracted from that measurement to estimate the low end of the range. To estimate the high end of the range, 5% of that measured was added to the measurement.

Estimating a range of fit for each size of the fire glove was more complex because of the thickness of the glove. To determine the girth range, the girth measurement of the glove was multiplied by 0.82. This value was obtained by fitting gloves to subjects in a pilot study and functioned well in creating size ranges. To determine the end of the range, 5% of this product was added and subtracted from itself. For the finger length and hand length ranges, a constant of 4 mm was subtracted from the glove measures, and 5% of this remainder was added and subtracted from itself to determine the ends of the range. The thin vinyl glove came in one size and stretched to fit all sizes of hands. The hand dimension ranges used to fit subjects with gloves appear in Appendix B. These ranges were based on actual measurements of the gloves (see Appendix C). To fit the butyl glove over the nomex, the three hand dimensions were measured over the nomex glove. For the leather and wool assembly, subjects were fit with a wool glove and wore the corresponding leather shell. Almost all subjects were comfortable with the size of glove assigned to them, and only two requested a different size. These two were given gloves one size larger.

The highest priority dimension is hand girth. If a subject's hand girth falls within the range of more than one glove size, then the second priority dimension, third digit length, will determine the subject's glove size. If the subject still falls within the ranges of more than one glove, then the third priority dimension, wrist to second digit length, will determine the glove size.

Hand girth is the highest priority dimension because it traditionally determines glove size. Also, if hand girth were too large for a glove, it may not be possible to get the hand in the glove. Even if a glove's middle finger length were perfect for a certain hand, it will not mean very much if the glove can not be placed on the hand.

Third digit length is the second priority dimension because the longest digit of the hand is usually the third digit. Being the longest digit, it may determine how well other digits fit into the glove. For example, if a glove's middle finger were too short for a hand's middle finger, the other glove fingers can only be pulled over the other fingers of the hand if the middle finger allows.

The length from the wrist to the tip of the second digit is the third priority dimension because it represents other aspects of the hand not measured with the first two dimensions. This is because length of the palm is included in this dimension as well as length of the index finger.

Subjects who participated in the bare-hands condition did not need to be fitted for gloves. Hand dimension data for bare-handed subjects as well as the gloved subjects were recorded.

After subjects were fitted for gloves, their near vision was tested with a Snellen chart. They were then ready to begin the tasks.

Practice Trials

Subjects practiced while wearing their assigned gloves unless they were in the bare-handed group. Because of the possibility of a differential learning effect for performance with gloves versus bare hands, practice was allowed until subjects became proficient. Subjects practiced until they achieved 18 correct practice trials with each of the three differently spaced panels for the self-paced task. Subjects performed the machine-paced task previously described for each of the three panels for practice.

The tasks were explained well to the subjects before they began the practice trials (see Appendices D & E for self-paced and machine-paced instructions to subjects). Subjects were allowed to ask questions during self- and machine-paced practice.

Half of the subjects performed the self-paced test trials first, preceded by self-paced practice. Half performed the machine-paced test trials first, preceded by machine-paced practice. During each task, all three panels were used.

Test Trials

As in practice, subjects performed 18 correct test trials on each panel in the self-paced task. Also in practice, subjects completed testing on each of the three panels in the machine-paced task.

Two unforeseen problems presented themselves during testing of subjects for this experiment. One problem was that some of the push-button switches would occasionally malfunction because of contact bounce, sending a double signal. The computer program interpreted this as an error since no one diagram indicated the same button twice. Approximately one malfunction would occur on one panel during testing for each of the first 18 subjects. When a button seemed to be malfunctioning, it would be replaced, but it soon became apparent that the supply of extra buttons would run out. After the 18th subject, the program was changed so that it would not read two signals in a row (for the same diagram) from the same button. To count legitimate error totals for data before and after the programming change, trials were only counted as error trials when a wrong button was pushed and the same button was not pushed immediately for that given diagram.

Since the machine-paced task allowed two errors in a row and since button malfunctions occurred rarely, the malfunctions probably had little or no effect on machine-paced best-time scores. Since correct trials in the self-paced task were separately analyzed from error trials, the malfunctions could not have had a direct effect on self-paced times. Even if the response to an occasional diagram were affected, the effect would be diluted when the mean was taken for total response times in all 18 correct trials. This mean of correct response times in the 18 diagrams was a subject's score for a given panel.

The second problem involved only the machine-paced task. Each time a subject performed on a panel, 36 diagrams were available for stimuli. Most subjects did not need nearly this many diagrams; however, for one of the three test panels for each of three subjects, 36 diagrams were used before three mistakes in a row were made. Fortunately, these subjects were very close to their best-time score. In the last few trials, they had made tw errors, responded correctly to one panel, made two more errors, then ran out of stimuli. Their best-time score was the time allowed for the last diagram to which they responded correctly. It is possible, though not likely, that one or more of these subjects would have improved their best-time score by 0.1 s. It is improbable that a difference greater than that would have occurred.

Design

A 6 (hand-wear condition) by 3 (spacing between push buttons) by 2 (task order) by 2 (gender) split-plot design was used to examine the effects of wearing gloves, button spacing, gender, and task order during performance in each of two button-pressing tasks. Hand-wear condition was a between-groups independent variable (IV), and spacing between buttons was a within-subjects IV. Subjects in each of the six hand-wear conditions were tested in all three conditions of button spacing. Task order, a blocking variable, refers to the order in which subjects performed the machine and self-paced tasks. Half of the subjects performed the machine-paced task first and the self-paced task second (the machine-self group). The other half of the subjects performed the self-paced task first and the machine-paced task second (the self-machine group). Gender was also a blocking variable.

This design was chosen because a completely randomized factorial design would require 216 subjects to have 12 subjects in each condition. This number of subjects would have been prohibitive. Also, having spacing between buttons as a within-subjects IV prevents individual differences among the subjects from being attributed to error for this IV. A completely randomized block factorial design would require each subject to participate in 12 experimental conditions for each of the two tasks. This would have required too much time from each subject. Even if fatigue effects were prevented by having experimental sessions over a period of days, any unreliability in the subjects would be difficult to comprehend. Also, counterbalancing for learning effects with hand girth and [illegible] would have been complex and would have required many subjects, which would have defeated a main advantage of a randomized block factorial design.

The order in which subjects completed the self- and machine-paced tasks was counterbalanced, half of the subjects in each of the six hand-wear conditions completing each of the tasks first. This allowed conclusions to be made about whether performance, measured during the various conditions of hand wear and space between buttons, was consistent in both tasks.

The order in which subjects practiced and tested each of the three differently spaced panels was also balanced for learning effects. Each of the 72 subjects performed tasks four times: the self-paced task in practice, the machine-paced task in practice, the self-paced task in testing, and the machine-paced task in testing. There were six different panel orders possible. To spread the learning effects evenly over the three panels, each subject was randomly assigned four of the six possible panel orders to use in the four task performances. Each subject was presented with the three panels in a different order each of the four times they performed a task.

The learning effects were also spread evenly over performance with each of the 18 diagrams. For each time the 18 diagrams appeared, a computerized random number generator determined a pseudo-randomized order of diagram presentation.

Data Collection

Self-Paced Task

For the 18 trials on each panel, in which the subject responded correctly in the self-paced task, the total time to respond with four button pushes was recorded. The mean of these 18 totals was the subject's time score for a given panel. Each subject produced three time scores, one for each of the SD, MD, and LD panels. Time was recorded in milliseconds using a timer developed by Granaas (1989).

Each trial in which a subject pushed a wrong button or buttons was an error trial. This was true except for the event in which the subject pushed the same button twice in a row. This exception was previously explained. Each subject produced an error total, which was the total number of error trials, one for each of the SD, MD, and LD panels.

Machine-Paced Task

The time allowed for each trial in the machine-paced task was recorded. The amount of time allowed immediately before the time which the following occurred was a dependent variable: (a) three consecutive trials resulted in errors, (b) three consecutive trials resulted in incomplete responses before the time limit, or (c) a mixture of a and b. This amount of time allowed was named the subject's best-time score. Each subject produced a best-time score for each of the three panels.

One of the 72 subjects scored 5.0 s on the SD panel in the machine-paced task. The next highest score was 2.4 s, which indicated 5.0 was an outlier. Also, the subject scored 2.0 s in practice on the SD panel, indicating 5.0 s was not a valid score. All other scores from this subject seemed valid. Since removing all of this subject's data would have resulted in an unbalanced design, the 5.0 s data point was replaced. To attain an estimate of what a valid score would have been, test scores on the SD panel from the remaining 71 subjects were regressed on their respective practice scores. The following regression equation resulted:

$$\text{Test score} = 0.273(\text{practice score}) + 1.081.$$

The 2.0 s practice score was plugged into the equation, resulting in an estimate of 1.629 s. This value was rounded to 1.6 s and replaced 5.0 s in the data set.

Each trial in which a subject pushed a wrong button or buttons was an error trial in the machine-paced task. Each subject produced an error total, which was the total number of error trials, for each of the three panels. Trials in which time expired were not counted as error trials unless an incorrect button was pushed.

Data Analysis

Each of the four dependent measures, time data from the self-paced task, error data from the self-paced task, time data from the machine-paced task, and error data from the machine-paced task, resulted in 216 data points for each measure. An analysis of variance (ANOVA) was performed on each of these dependent variables separately.

Multivariate analysis was not performed on time data or the error data across the two tasks because the tasks were so different. Multivariate analysis was not performed on the time and error data within each task because high correlations between time data and error data were not expected. Table 2 shows that the data confirmed this expectation. The table presents pairwise correlations between time and error data in each task collapsed across all variables except spacing. The first matrix in Table 2 shows correlations between best-time scores on each panel and error totals on each panel for the machine-paced task. The correlations along the diagonal, upper left to lower right, are most important because they represent the relation between time and error data collected simultaneously on the same panel. Though the correlations are all negative, suggesting a consistent relation, they are low and not significant. The same situation exists in the second matrix, which contains correlations between the time and error data from the self-paced task.

Table 2

Correlations Between Time Data and Error Data in the Machine-Paced Task

			Best-Time Score		
			Panel		
			Small	Medium	Large
Error Total	Panel	Small	-.15	-.15	-.14
		Medium	-.24*	-.11	-.15
		Large	-.25*	-.23	-.18

* *p* < .05

Correlations Between Time Data and Error Data in the Self-Paced Task

			Response Time		
			Panel		
			Small	Medium	Large
Error Total	Panel	Small	-.13	-.12	-.14
		Medium	-.05	-.05	-.15
		Large	-.35*	-.34*	-.22

* *p* < .05

RESULTS

Primary Analyses

Self-Paced Task Time Analyses

A 6 (hand-wear condition) by 3 (button spacing) by 2 (gender) by 2 (task order) split-plot ANOVA was performed on the self-paced time scores. The main effect for task order was significant (F (1,48) = 21.37, p < .0001). The mean of the group that performed the machine-paced task first was lower than the group that performed the self-paced task first. The main effect for button spacing was also significant (F (2,96) = 22.83, p < .0001). The other main effects and all interactions were not significant.

A test for the assumption of sphericity (using Mauchly's criteria) was performed on these data. A significant chi-square indicated that the assumption was not met. The probability of the F-value, corrected by a Huynh-Feldt epsilon of 1.305, was not changed (at least not above the fourth decimal place).

A post hoc analysis using Tukey's honestly significant difference (HSD) test was performed on the time scores for the three button-spacing levels. The analysis showed that the mean time for the panel with the longest distance between push buttons was significantly higher than the means for the SD and MD panels. The means for the SD and MD panels were not significantly different from each other. Table 3 presents the means and standard deviations of the time scores for each level of spacing, hand wear, task order, and gender (i.e., the data were collapsed across all variables except spacing, then across all variables except hand wear, etc.). Appendix F contains the ANOVA tables for the self-paced time analysis.

Self-Paced Task Error Analysis

A 6 (hand-wear condition) by 3 (button spacing) by 2 (gender) by 2 (task order) split-plot ANOVA was performed on the error totals. The main effect for task order was significant (F (1,48) = 4.43, p < .05). The mean error total for the group that performed the self-paced task first was lower than the group that performed the machine-paced task first. No other main effects and no interactions were significant for these data. Table 4 presents the means and standard deviations of error totals for each level of spacing, hand wear, task order, and gender. Appendix G contains the ANOVA tables for the self-paced error analysis.

Machine-Paced Task Time Analysis

A 6 (hand-wear condition) by 3 (button spacing) by 2 (gender) by 2 (task order) split-plot ANOVA was performed on the best-time scores. The main effect for task order was significant (F (1,48) = 5.86, p < .05). The group that performed the self-paced task first obtained the lower mean best-time score. Other main effects and all interactions were not significant. Table 5 presents the means and standard deviations of best-time scores for each level of spacing, hand wear, task order, and gender. Appendix H contains the ANOVA tables for the machine-paced time analysis.

Table 3

The Means and Standard Deviations of Time Scores for Each Level of Spacing, Hand Wear, Task Order, and Gender for the Self-Paced Time Data

Variable	N	Mean (in seconds)	SD
Spacing			
Small	72	1.919	.404
Medium	72	1.945	.414
Large	72	2.040	.405
Hand wear			
Bare hand	36	1.871	.302
Vinyl	36	2.202	.527
Butyl and cotton	36	2.063	.356
Butyl and nomex	36	1.968	.398
Leather and wool	36	1.814	.444
Fire fighter	36	1.889	.267
Task order[a]			
Self paced first	108	2.161	.398
Self paced second	108	1.775	.320
Gender			
Female	108	1.946	.329
Male	108	1.991	.476

[a] These are the mean times for the self-paced task for those subjects who performed the self-paced task first (self-paced first), and the machine-paced task second or vice versa (machine-paced first and self-paced second).

Machine-Paced Error Analysis

A 6 (hand-wear condition) by 3 (button spacing) by 2 (gender) by 2 (task order) split-plot ANOVA was performed on the error totals from the machine-paced task. There were no significant interactions or main effects for these data. Table 6 presents the means and standard deviations of the error totals for each level of spacing, hand wear, task order, and gender. Appendix I contains the ANOVA tables for the machine-paced error analysis.

Exploratory Analyses

Hand Measures

Pairwise correlations were performed between the three hand measures (girth, finger length, and hand length) and time and error data from the machine- and self-paced tasks (see Table 7). Though most of the correlations were not significant, they showed a tendency in the machine-paced data. The hand measures consistently correlated positively with machine-paced error data and negatively with machine-paced time data. This suggests that larger-handed subjects had a slight tendency to perform the machine-paced task faster and with more errors relative to smaller-handed subjects. Correlations between the hand measures and the self-paced measures were all low and not significant. Hand measures correlated highly positively and significantly with each other.

Table 4

The Means and Standard Deviations of Error Totals for Each Level of Spacing, Hand Wear, Task Order, and Gender for the Self-Paced Error Data

Variable	N	Mean error total	SD
Spacing			
Small	72	.847	1.296
Medium	72	.597	.744
Large	72	.847	1.206
Hand wear			
Bare hand	36	.722	.974
Vinyl	36	.555	1.107
Butyl and cotton	36	.583	.770
Butyl and nomex	36	.555	.877
Leather and wool	36	1.083	1.228
Fire fighter	36	1.083	1.481
Task order[a]			
Self paced first	108	.583	.877
Self paced second	108	.944	1.281
Gender			
Female	108	.731	1.157
Male	108	.796	1.066

[a] These are the mean errors for the self-paced task for those subjects who performed the self-paced task first (self-paced first), and the machine-paced task second or vice versa (machine-paced first and self-paced second).

Gender Analysis

In the primary analyses, gender and hand girth were confounded because male subjects tended to have larger hands. To examine the relation between gender (separate from girth) and performance, seven male subjects, whose hand-girth measures overlapped with the female subjects' girth range, were matched with seven female subjects. The two groups of seven were matched by hand wear and pace order. This resulted in one group of males and one group of females, each with a similar range of hand girth and each with the same number of subjects with each task order and hand-wear condition. Table 8 presents a profile of the two groups.

Using data only from these 14 subjects, a 3 (button spacing) by 2 (gender) split-plot ANOVA was performed on each of the four dependent variables: the self-paced times, the self-paced errors, the machine-paced times, and the machine-paced errors. Only the analysis of the self-paced time data showed a statistically significant result. The main effect for spacing was significant ($F(2,24) = 8.34$, $p < .01$). There were no other significant effects.

Table 5

The Means and Standard Deviations of Best-Time Scores for Each Level of Spacing, Hand Wear, Task Order, and Gender for the Machine-Paced Time Data

Variable	N	Mean (in seconds)	SD
Spacing			
Small	72	1.582	.389
Medium	72	1.542	.311
Large	72	1.599	.345
Hand wear			
Bare hand	36	1.514	.273
Vinyl	36	1.728	.440
Butyl and cotton	36	1.619	.355
Butyl and nomex	36	1.594	.360
Leather and wool	36	1.422	.233
Fire fighter	36	1.561	.339
Task order[a]			
Machine paced first	108	1.667	.396
Machine paced second	108	1.481	.265
Gender			
Female	108	1.630	.315
Male	108	1.517	.373

[a] These are the mean times for the machine-paced task for those subjects who performed the machine-paced task first (machine-paced first), and the self-paced task second or vice versa (self-paced first and machine-paced second).

A post hoc analysis using Tukey's HSD test was performed on the time scores for the three button-spacing levels. The analysis showed that the mean time for the panel with the longest distance between push buttons was significantly higher than the means for the SD and MD panels. The means for the SD and MD panels were not significantly different from each other. This was consistent with the primary analysis of the self-paced time data. Table 9 presents means by gender and spacing for all four gender analyses. Appendices J through M contain the ANOVA tables for the self-paced time, self-paced error, machine-paced time, and machine-paced error analyses.

Hand-Girth Analysis

Since gender and hand girth were confounded in the primary analyses, an exploratory analysis was conducted to determine the relation between hand girth and performance. To accomplish this, analyses were done separately for males and females. The small, medium, and large hand-girth ranges were different for each gender, but each gender group was composed of an equal number of small, medium, and large girth subjects according to the range of that gender. Each gender group was also completely balanced for hand-wear condition, spacing, and task order.

Table 6

The Means and Standard Deviations of Error Totals for Each Level of Spacing, Hand Wear, Task Order, and Gender for the Machine-Paced Error Data

Variable	N	Mean error total	SD
Spacing			
Small	72	1.639	1.271
Medium	72	1.792	1.463
Large	72	1.583	1.431
Hand wear			
Bare hand	36	1.333	1.265
Vinyl	36	1.694	1.411
Butyl and cotton	36	1.417	1.317
Butyl and nomex	36	1.944	1.548
Leather and wool	36	1.917	1.628
Fire fighter	36	1.722	1.059
Task order[a]			
Machine self	108	1.898	1.380
Self machine	108	1.444	1.363
Gender			
Female	108	1.454	1.195
Male	108	1.889	1.531

[a] These are the mean error for the machine-paced task for those subjects who performed the machine-paced task first (machine-paced first), and the self-paced task second or vice versa (self-paced first and machine-paced second).

A 6 (hand-wear condition) by 3 (button spacing) by 3 (hand girth) split-plot ANOVA was performed on each of the four dependent variables: the self-paced times, the self-paced errors, the machine-paced times, and the machine-paced errors. These analyses were performed once for males and once for females.

For the female subjects, the self-paced time analysis showed a significant main effect for spacing (F (2,36) = 16.77, $p < .0001$). The means for the three levels of spacing were consistent with previous analyses of self-paced time data. The means are presented in Table 10 with means and standard deviations for the other variables in the self-paced data analyses for female subjects. There were no significant interactions or other significant main effects for the self-paced time data, and there were no significant interactions or main effects for the self-paced error data from female subjects. Appendices N and O contain the ANOVA tables for the self-paced time and self-paced error analyses for females.

Table 7

Intercorrelations Among the Hand-Measure Variables and Between the Hand-Measure Variables and the Self- and Machine-Paced Data

Task/ variable	Panel size	Hand girth	Finger length	Hand length
1. Mach Error	(Small)	.26*	.11	.13
2. Mach error	(Medium)	.24*	.14	.16
3. Mach error	(Large)	.21	.07	.05
4. Self error	(Small)	.05	.03	.00
5. Self error	(Medium)	.11	.05	.08
6. Self error	(Large)	.17	.07	.16
7. Mach time	(Small)	-.15	-.24*	-.36*
8. Mach time	(Medium)	-.04	-.07	-.23
9. Mach time	(Large)	-.14	-.13	-.27*
10. Self time	(Small)	.05	.03	.00
11. Self time	(Medium)	.03	.02	-.05
12. Self time	(Large)	.05	-.04	-.03
13. Hand girth			.63*	.74*
14. Finger length				.81*

* $p < .05$

Table 8

Hand-Girth Measures for Subjects in Each Gender Matched by Hand-Wear Condition and Task Order

Hand wear	Task order	Hand girth (mm) Male	Female
1. Butyl and cotton	Self machine	200	195
2. Butyl and nomex	Self machine	200	190
3. Butyl and nomex	Machine self	198	197
4. Leather and wool	Self machine	201	197
5. Leather and wool	Machine self	190	205
6. Fire fighter	Self machine	205	204
7. Fire fighter	Machine self	198	203

Table 9

The Means and Standard Deviations by Gender and by Spacing for all Four Gender Analyses

Variable	N	Mean	SD
Self-paced time data (in seconds)			
Spacing			
Small	14	1.778	.263
Medium	14	1.814	.291
Large	14	1.911	.292
Gender			
Male	21	1.888	.347
Female	21	1.781	.189
Self-paced error data (error total)			
Spacing			
Small	14	.714	1.139
Medium	14	.571	.513
Large	14	1.074	1.492
Gender			
Male	21	.476	.813
Female	21	1.095	1.300
Machine-paced time data (in seconds)			
Spacing			
Small	14	1.450	.352
Medium	14	1.493	.395
Large	14	1.557	.420
Gender			
Male	21	1.505	.484
Female	21	1.495	.258
Machine-paced error data (error total)			
Spacing			
Small	14	1.714	1.069
Medium	14	1.571	1.222
Large	14	1.571	1.342
Gender			
Male	21	1.429	1.207
Female	21	1.809	1.167

Table 10

Means and Standard Deviations of Self-Paced Data by Spacing, Hand Wear, and Girth Size from Female Subjects

Variable	N	Mean	SD
	Self-paced time data (in seconds)		
Spacing			
Small	36	1.892	.333
Medium	36	1.933	.333
Large	36	2.009	.320
Hand wear			
Bare hand	18	1.887	.137
Vinyl	18	1.990	.367
Butyl and cotton	18	2.161	.279
Butyl and nomex	18	1.885	.274
Leather and wool	18	1.847	.478
Fire fighter	18	1.896	.275
Girth size			
Small	36	2.008	.413
Medium	36	1.947	.321
Large	36	1.879	.221
	Self-paced error data		
Spacing			
Small	36	.917	1.519
Medium	36	.555	.558
Large	36	.722	1.186
Hand wear			
Bare hand	18	.611	.698
Vinyl	18	.444	.983
Butyl and cotton	18	.666	.840
Butyl and nomex	18	.778	1.114
Leather and wool	18	.778	1.215
Fire fighter	18	1.111	1.811
Girth size			
Small	36	.444	.652
Medium	36	.972	1.521
Large	36	.778	1.098

The machine-paced time analysis for the female subjects showed a significant interaction for spacing by hand wear (F (10,36) = 2.38, $p < .05$) and a significant main effect for spacing (F (2,36) = 3.78, $p < .05$). There were no other significant interactions or main effects for the machine-paced time data, and there were no significant interactions or main effects for the machine-paced error data from female subjects.

Figure 1 illustrates the spacing by hand-wear interaction from the analysis of the female subjects' machine-paced time data. There seems to be a tendency for most of the hand-wear conditions to require less time for the MD panel than for the SD and LD panels. The pattern for the butyl and cotton hand wear shows an opposite trend, which may account for the interaction. The interaction may also be because of the extremely slow mean time for the fire-fighter hand wear on the SD panel; however, the trend for the butyl and cotton condition was probably because of error, since there is no reason to suspect that this glove assembly would cause such an effect. The fire-fighter glove may have hindered female subjects on the SD panel in particular; however, the interaction was discovered in an exploratory analysis with an inflated Type I error rate. The interaction should be viewed skeptically, especially without confirmatory evidence.

A post hoc analysis using Tukey's HSD was performed on the means from the main effect for spacing, which was found in the analysis of the machine-paced time data for females. The post hoc test showed that the mean for the SD panel was significantly higher than the mean for the MD panel. The mean for the LD panel was not significantly different from the other two panels. Table 11 presents the means and standard deviations of the variables in the machine-paced data analysis for female subjects. Appendices P and Q contain the ANOVA tables for the machine-paced time and machine-paced error analyses for females.

For the male subjects the self-paced time analysis showed a significant main effect for spacing (F (2,36) = 9.93, $p < .001$). The means for the three levels of spacing were consistent with previous analyses of self-paced time data. There were no other significant effects in the analysis of the self-paced time data for male subjects. The means are presented in Table 12 with means and standard deviations for the other variables in the self-paced time analysis for male subjects.

The self-paced error analysis for males showed a significant main effect for girth size (F (2,18) = 4.81, $p < .05$). A post hoc analysis using Tukey's HSD showed that the mean of the large girth group was significantly higher than that of the small girth group. The medium group was not significantly different from either of the other two groups. Table 12 presents the means from this analysis. Appendices R and S contain the ANOVA tables for the self-paced time and self-paced error analyses for males.

The machine-paced time analysis for the male subjects showed a significant interaction for spacing by girth size (F (4,36) = 2.93, $p < .05$). There were no other significant interactions or main effects for the machine-paced time data, and there were no significant interactions or main effects for the machine-paced error data from male subjects.

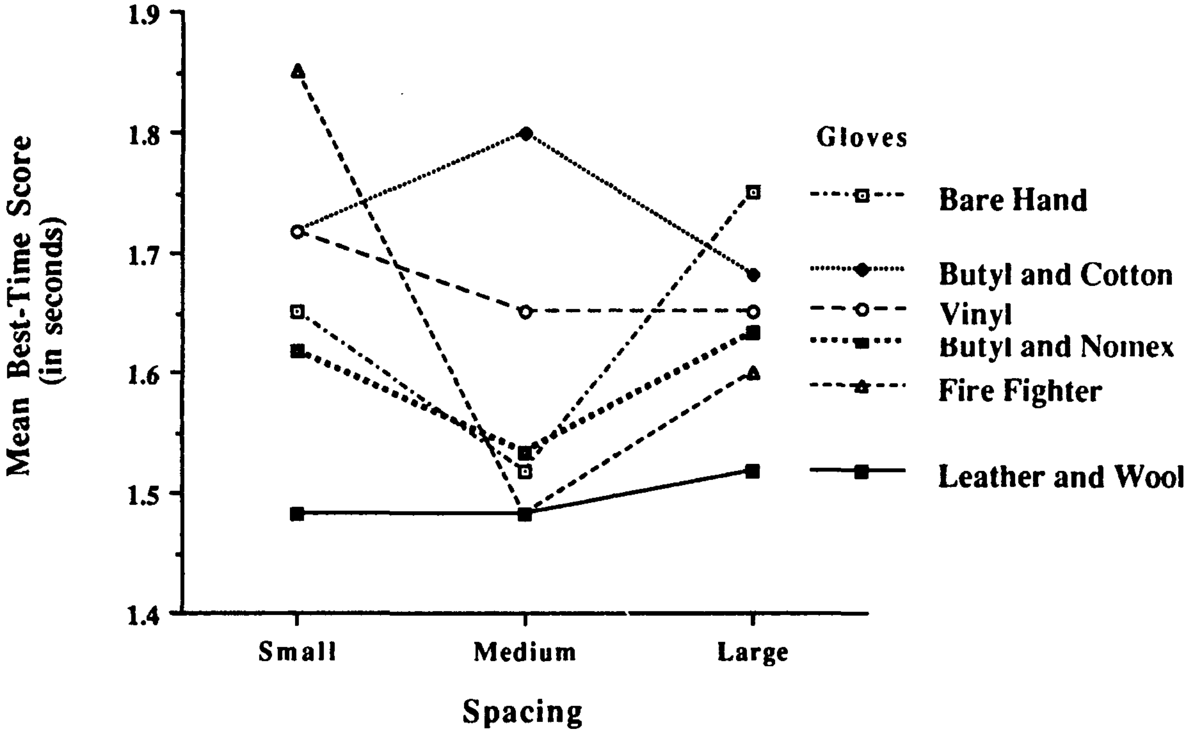

Figure 1. Mean best-time score for each hand-wear condition by each level of spacing for machine-paced data for female subjects (each data point is the mean of six subjects).

Taɔle 11

Means and Standard Deviations of Machine-Paced Data by Spacing, Hand Wear, and Girth Size from Female Subjects

Variable	N	Mean	SD
Machine-paced time data (in seconds)			
Spacing			
Small	36	1.672	.366
Medium	36	1.578	.301
Large	36	1.639	.270
Hand wear			
Bare Hand	18	1.639	.279
Vinyl	18	1.672	.346
Butyl and cotton	18	1.733	.361
Butyl and nomex	18	1.594	.170
Leather and wool	18	1.494	.234
Fire fighter	18	1.644	.420
Girth size			
Small	36	1.600	.167
Medium	36	1.694	.329
Large	36	1.594	.400
Machine-paced error data			
Variable	N	Mean	SD
Spacing			
Small	36	1.444	1.229
Medium	36	1.528	1.183
Large	36	1.388	1.201
Hand wear			
Bare hand	18	1.055	1.110
Vinyl	18	1.500	1.098
Butyl and cotton	18	1.333	1.237
Butyl and nomex	18	1.667	1.455
Leather and wool	18	1.555	1.293
Fire fighter	18	1.611	.979
Girth size			
Small	36	1.055	1.013
Medium	36	1.611	1.153
Large	36	1.694	1.327

Table 12

Means and Standard Deviations of Self-Paced Data by Spacing, Hand Wear, and Girth Size from Male Subjects

Variable	N	Mean	SD
Self-paced time data (in seconds)			
Spacing			
Small	36	1.946	.467
Medium	36	1.957	.485
Large	36	2.070	.479
Hand wear			
Bare hand	18	1.856	.411
Vinyl	18	2.413	.585
Butyl and cotton	18	1.966	.404
Butyl and nomex	18	2.050	.486
Leather and wool	18	1.781	.418
Fire fighter	18	1.882	.267
Girth size			
Small	36	1.922	.404
Medium	36	2.066	.461
Large	36	1.986	.555
Self-paced error data			
Spacing			
Small	36	.778	1.045
Medium	36	.639	.899
Large	36	.972	1.230
Hand wear			
Bare hand	18	.833	1.200
Vinyl	18	.666	1.237
Butyl and cotton	18	.500	.707
Butyl and nomex	18	.333	.485
Leather and wool	18	1.389	1.195
Fire fighter	18	1.055	1.109
Girth size			
Small	36	.361	.683
Medium	36	.805	.822
Large	36	1.222	1.396

Figure 2 illustrates the spacing by girth-size interaction from the analysis of the male subjects' machine-paced time data. It appears that the interaction is because of a tendency for large girth males to operate faster on the LD panel, while the medium and small girth subjects operated faster on the MD or SD panels. The interaction was discovered in an exploratory analysis with an inflated Type I error rate, so the interaction should be viewed skeptically, especially without confirmatory evidence. Table 13 presents the means and standard deviations of the variables in the machine-paced data analysis for male subjects. Appendices T and U contain the ANOVA tables for the machine-paced time and machine-paced error analyses.

DISCUSSION

Hypotheses

The first null hypothesis that gloved and bare-handed subjects will perform no differently on the button-pushing task can not be rejected by these results. There are no significant main effects for hand-wear condition in any of the analyses.

The second null hypothesis that the performance differences among hand-wear conditions will not decrease as the spacing between buttons becomes wider can not be rejected. An interaction involving spacing and hand wear would be necessary to reject this null hypothesis. The interaction between hand wear and spacing in the data from female subjects (see Figure 1) does not supply adequate evidence to reject the null hypothesis. Performance differences do not appear in the figure to decrease as the spacing becomes wider.

The third null hypothesis that the degree of bulk in the gloves will not cause performance differences can not be rejected. This hypothesis is not rejected for two reasons. First, there are no significant main effects for hand-wear condition. Second, the hand wear by spacing interaction in the data from females was discovered in an analysis with an inflated Type I error rate. Only the fire-fighting glove shows the effect predicted by the alternative hypothesis, and the extreme score for that glove in the small-space condition can be because of error variance.

Task-Order Effect

In the primary analysis, the self-paced time results and the machine-paced time results show significant main effects for task order. Subjects who perform the machine-paced task first are faster during the self-paced task than subjects who perform the self-paced task first. Likewise, subjects who perform the self-paced task first are faster during the machine-paced task than subjects who perform the machine-paced task first. This probably occurred because subjects who perform the opposite task first had more practice pushing buttons than the other group.

The error analysis for the self-paced task in the primary analysis shows a significant main effect for task order. The main effect for task order in the machine-paced error analysis is nearly significant ($p < .09$). In both sets of results, the groups that perform the self-paced task first obtain lower mean error totals. The group that started with the machine-paced task committed more errors in the self-paced task and in the machine-paced task than the group that started with the self-paced task.

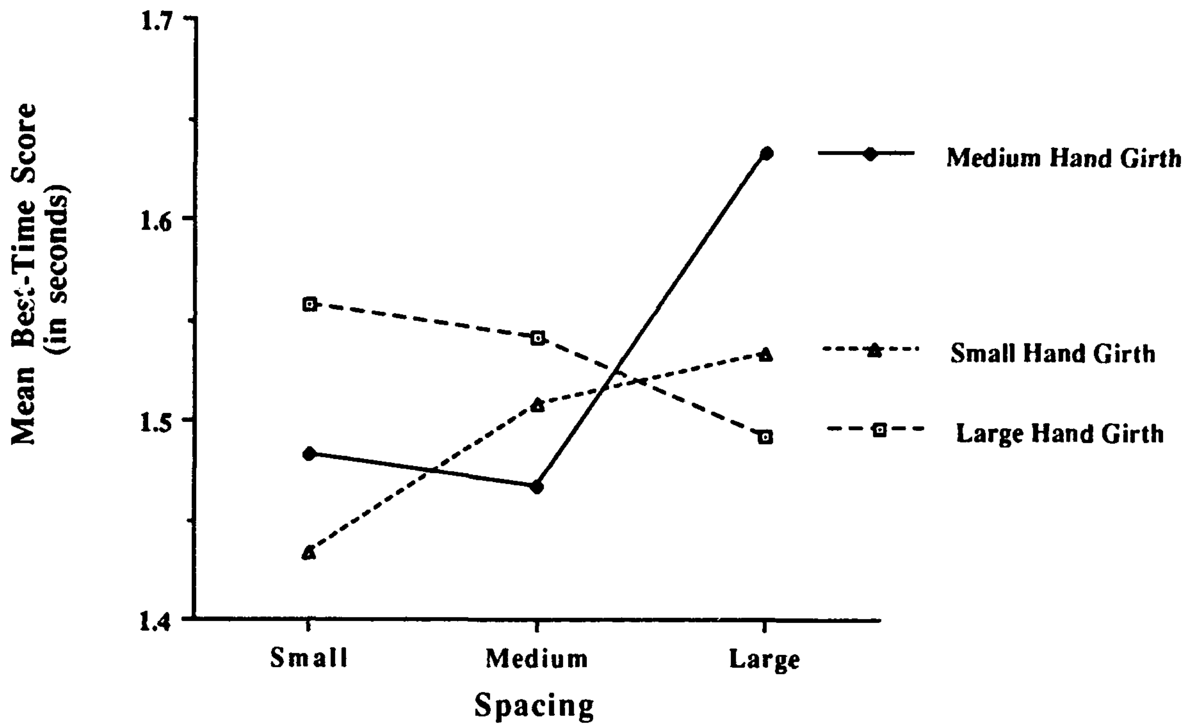

Figure 2. Mean best-time score for each hand-girth size by each level of spacing for male subjects (each data point is the mean of 12 subjects).

Table 13

Means and Standard Deviations of Self-Paced Data by Spacing, Hand Wear, and Girth Size from Male Subjects

Variable	N	Mean	SD
Machine-paced time data (in seconds)			
Spacing			
Small	36	1.491	.395
Medium	36	1.505	.320
Large	36	1.553	.406
Hand wear			
Bare hand	18	1.389	.205
Vinyl	18	1.783	.521
Butyl and cotton	18	1.505	.319
Butyl and nomex	18	1.594	.488
Leather and wool	18	1.350	.215
Fire fighter	18	1.477	.213
Girth size			
Small	36	1.492	.386
Medium	36	1.528	.384
Large	36	1.531	.358
Machine-paced error data			
Spacing			
Small	36	1.833	1.298
Medium	36	2.055	1.672
Large	36	1.778	1.623
Hand wear			
Bare hand	18	1.611	1.378
Vinyl	18	1.889	1.676
Butyl and cotton	18	1.500	1.425
Butyl and nomex	18	2.222	1.629
Leather and wool	18	2.278	1.873
Fire fighter	18	1.833	1.150
Girth size			
Small	36	1.444	1.107
Medium	36	2.000	1.493
Large	36	2.222	1.838

It is possible that exposure to the self-paced task before the machine-paced task tended to help subjects make fewer errors because the self-paced task gave more direct feedback about accuracy. Subjects who performed the machine-paced task first may have tended to sacrifice accuracy for speed; therefore, when they performed the self-paced task, they performed more quickly and less accurately. Subjects who performed the self-paced task first may have tended to place more importance on accuracy; therefore, when they performed the machine-paced task, they performed faster than the other group because they had extra practice but made fewer errors because of the feedback they received during the self-paced task.

Since none of the Task-Order x Hand-Wear interactions are significant, it can be concluded that no strong differential learning effects took place. If strong differential learning effects did exist in the data, it would show more in data from the tasks that were performed first than tasks performed second. This would have resulted in the interaction. As previously discussed, differential learning effects caused by wearing gloves are more prevalent in complex tasks and performance without adequate practice. Since the tasks in this study were rather simple and since a fair amount of practice was allowed, the lack of strong differential learning effects is not surprising.

Gender and Hand-Girth Effects

The exploratory analysis in which the performance of seven male subjects and seven female subjects are compared show no significant effects. It is suspected that male subjects may tend to operate faster and with more errors. This is suspected because hand measures consistently correlate positively with machine-paced error data and negatively with machine-paced time data in the exploratory analysis, and male subjects have larger hands than female subjects on the average.

Though the gender analyses showed no statistically significant results, the actual means suggested the females performed faster and with more errors than males (see Table 9). Also, the main effect for gender was nearly significant ($p < .11$) for all of the dependent measures except machine-paced error totals. Since the females in this comparison were the females with the largest hands and the males were the males with the smallest hands, the comparison does not generalize to all the subjects in this study. The comparison does, however, provide evidence that correlations between hand measures and performance are not because of gender differences.

The exploratory analyses in which the male and female data were examined separately show some evidence of a hand-girth size effect. In the analysis of machine-paced error data for females, the main effect for hand girth was nearly significant ($p < .06$). The mean error totals for the large and medium girth females were larger than that for the small girth females (see table 11). In the analysis of self-paced error data for males, the main effect for hand girth was significant. The mean error total increased with girth size. In the analysis of machine-paced error data for males, the Spacing x Hand-Girth interaction was significant. As Figure 2 shows, large girth males performed faster on the LD panel while the medium and small girth males performed slower on the LD panel.

Taken individually, these results do not provide strong support for a girth effect because these results were obtained with an inflated Type I error rate. Taken together, however, they suggest that hand girth does affect performance. Subjects with hand girths that are larger than others in their gender may tend to commit more errors, and large girth males may perform better on panels with wide spacing. This is particularly important to know when forming experimental groups for studies such as this study.

Glove Effect

The lack of a glove effect is surprising. Figure 3 presents the mean times for each glove at each spacing level in the self-paced task. It appears from the figure that enough consistency exists to rank order the hand-wear conditions by best to worst performance: leather and wool, bare hands, fire fighter, butyl and nomex, butyl and cotton, and vinyl. However, the entire range of means by hand-wear condition (i.e., collapsed across all variables except hand-wear condition) is only about 0.4 s. The range was even smaller in the machine-paced time data. Figure 4 presents the mean times for each hand-wear condition at each spacing level in the machine-paced task.

In all the ANOVAs, the mean sum of squares for the glove effect or the glove by spacing effect was either smaller than the mean square error or only slightly larger. When the sum of squares for these treatment effects was only slightly larger than the mean square error, power was too low to estimate using charts of the function of power for ANOVA tests. This suggests that glove effects are a possibility, but only strong glove effects would have shown in this study. It is clear from the tables of means that differences among means for the time data were not great. Differences among means by hand-wear condition in the time data were small. Even if an increased sample size showed that such small differences were statistically significant, they would have limited practical significance.

If any substantial hand-wear differences existed in the error data, they were concealed by a great deal of extraneous variance. In some applications, the differences in means by hand-wear condition in error data found in this study would be of some concern. For example, entering coordinates for the firing of a weapon requires very high accuracy. Since the error variance in the error data is high, concluding that gloves cause no increase in errors would be erroneous.

Results from some studies noted in the introduction are consistent with the lack of glove effects in this study. Rogers and Noddin (1984) found that a wool glove caused no detriment to performance in tests of aiming and key tapping. Bradley (1969a) found a glove effect for a wool glove in operating a push button, but the button type used in that study had a convex, slippery surface. Since that button type is much different from the one used in this study, the results do not conflict. Bradley (1961, 1969b) also found that gloves with a higher coefficient of sliding friction, such as butyl and leather, are better for operation of push-button controls.

Bradley (1969b) stated snugness is important for operation of push buttons because the finger had to occupy the part of the glove striking the button surface. The gloves used in this study varied in snugness, the butyl and cotton glove often fit loosely; however, the buttons used in this study provide a fairly large target for the gloved finger. Since the buttons used in this study were large and did not require a very high actuating force, snugness may not have been an important factor.

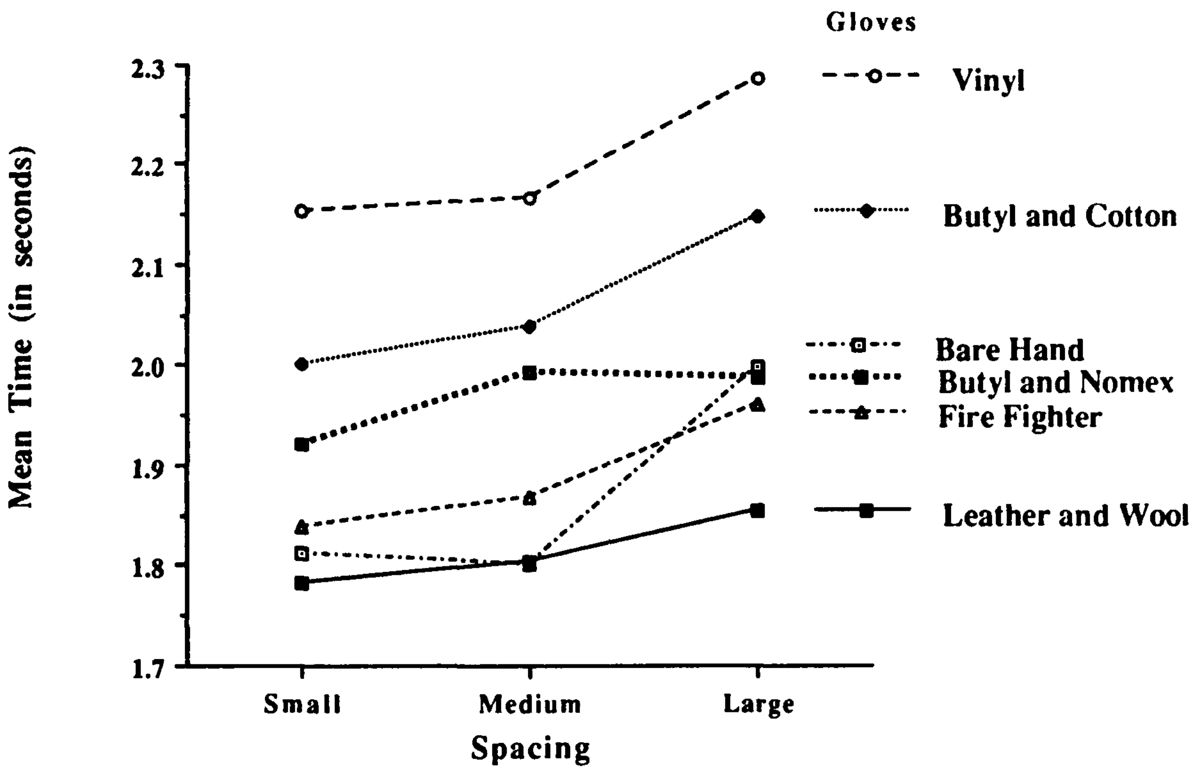

Figure 3. Mean times for each hand-wear condition by each level of spacing for the self-paced data (each data point is the mean of 12 subjects).

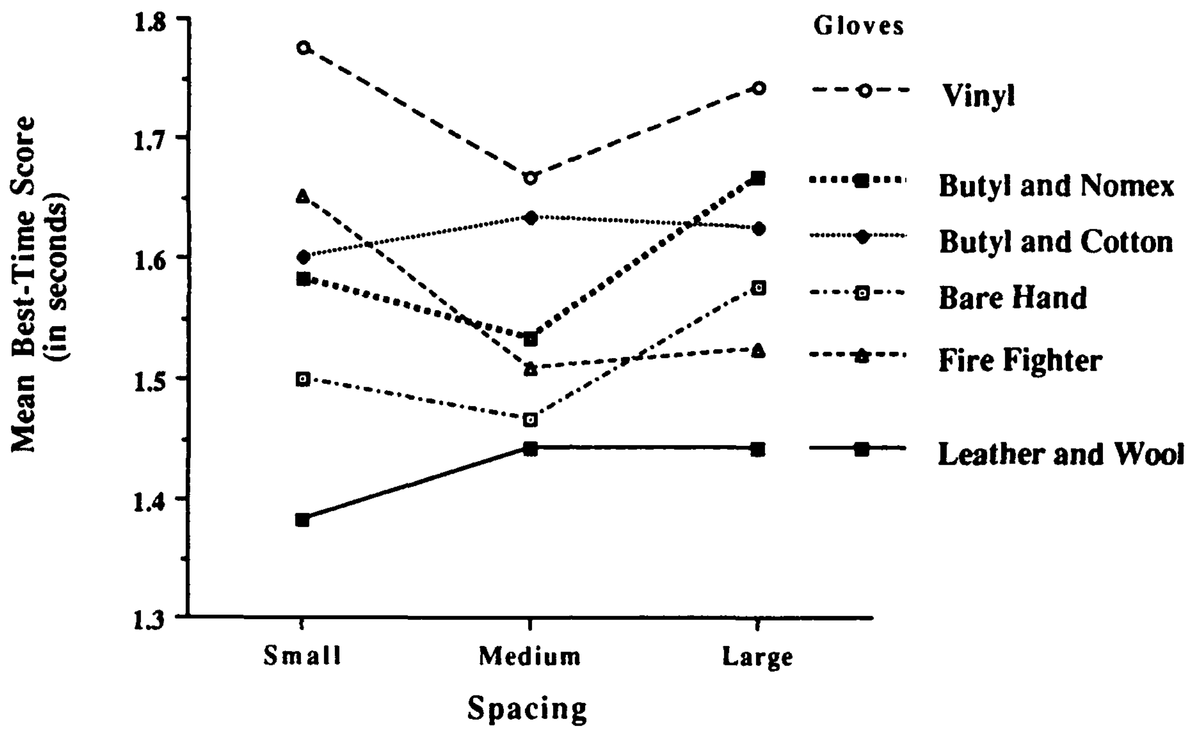

Figure 4. Mean best-time score for each hand-wear condition by each level of spacing for the machine-paced data (each data point is the mean of 12 subjects).

Some of Boff and Lincoln's observations (1988) are not consistent with the results of this study. They concluded that keyboard data entry was not affected by gloves unless the keys were slippery or rapid entry was required. Rapid entry was required in the machine-paced task, but speed of performance showed no decline with gloves. They also stated performance time was increased when gloves are cumbersome, loose fitting, or sloppy to wear. It may be that the gloves used in this study were not too cumbersome, loose fitting, or sloppy.

Spacing Effect

The most strongly supported result of this study is the spacing effect. It seems that allowing more space between push buttons, such as the ones used in this study, actually slows performance at some point, at least for a self-paced task. Evidence of the effect is shown in Figure 3. For all hand-wear conditions, except the butyl and nomex glove, time of operation is similar for the SD and MD panels but increases for the LD panel.

Even though the methodology is not sensitive enough to detect small glove effects, the majority of the subjects wore gloves and the spacing effect is still found. The significance of this fact is that if the small and medium spacing were not adequately wide for gloved operation, the mean time for operation of the LD panel probably would not have been significantly higher.

The results from the exploratory analyses show evidence that during some circumstances, the MD panel may be optimal. The main effect for spacing in the machine-paced time analysis for females is significant. The mean time for the MD panel is less than that for the SD panel. This result is exploratory and may be because of particularly high scores for one glove type with the small spacing. Also, male subjects with large hand girths seem to perform faster with wider spacing.

The results of the analyses of error totals fail to show the spacing effect found in the time data. Means of the three spacing levels in the error data differ from one another, but standard deviations are very high relative to the means.

Any errors caused by the gloves were not distinguished from errors committed for other reasons. In the self-paced task, the mean error total for the leather and wool hand-wear condition was higher than the mean error totals for all the other hand-wear conditions. In the machine-paced task the mean error total for the leather and wool hand-wear condition was higher than most of the other hand-wear conditions. Also, the mean times for the leather and wool condition were lower than almost all the other hand-wear conditions in both tasks. This suggests that subjects in the leather and wool condition may tend to perform quickly at the expense of making more errors. If this is true, it negates the idea that some aspect of the leather and wool assembly is the reason for the faster performance.

The error data do not offer support for or against the conclusion that the SD and MD panels were superior to the LD panel. Figure 5 presents the machine-paced mean error total for each hand-wear condition at each spacing level. Figure 6 presents the same information for the self-paced error data. The appearance of Figure 5 suggests the medium spacing causes more errors; however, the effect is not significant, and there is no reason to expect such a relation between spacing and performance. Considering the high error variance of both groups of error data and considering Figures 5 and 6 together, error results offer little information on spacing.

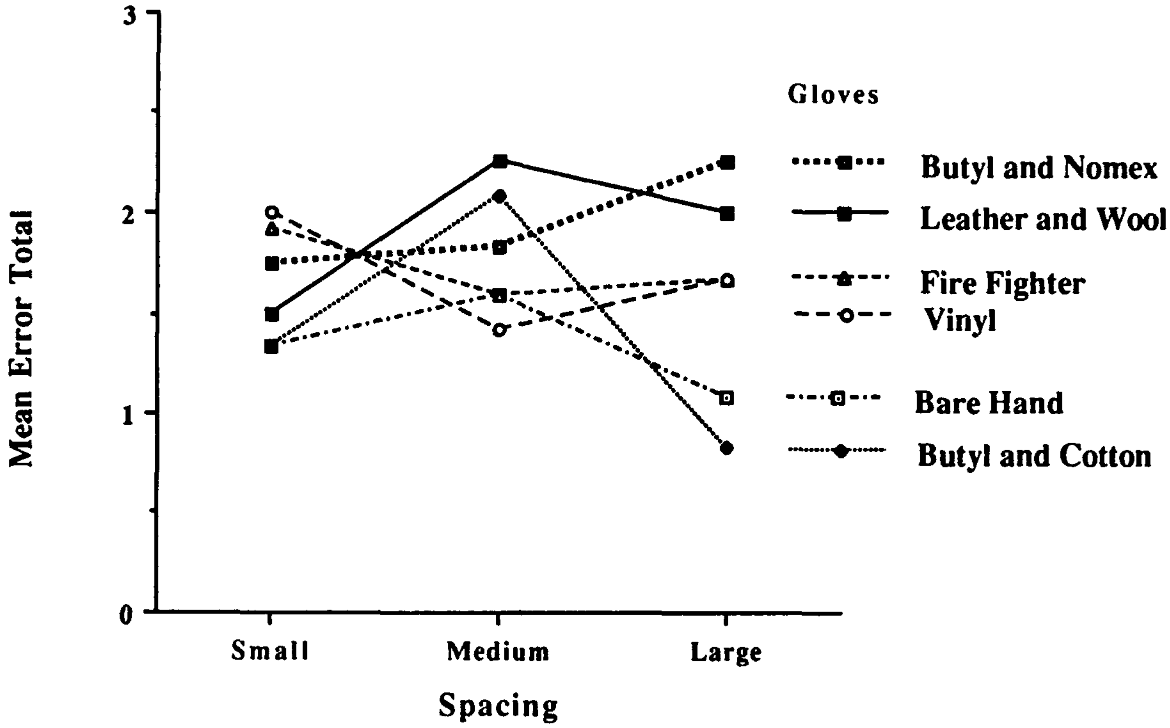

Figure 5. Mean error total for each hand-wear condition by each level of spacing for the machine-paced data (each data point is the mean of 12 subjects).

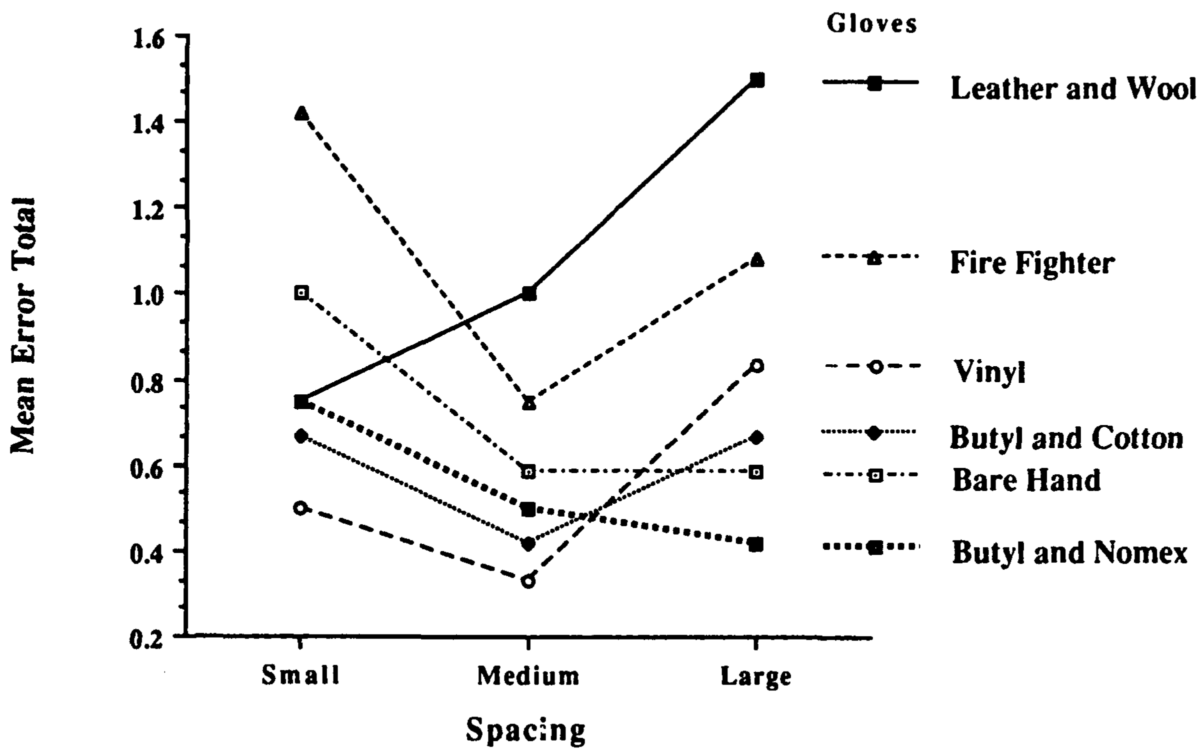

Figure 6. Mean error total for each hand-wear condition by each level of spacing for the self-paced data (each data point is the mean of 12 subjects).

The reason slightly more time was needed in operating the LD panel may be because of the need for positioning the hand in various spots over a larger area. Virtually all aiming movements proceed in two phases (Woodworth [1899], cited in Rosenbaum, 1991), a ballistic phase followed by a corrective phase. Ballistic movements are rapid and cover most of the distance to a target, and corrective movements minimize the distance between the effector (the finger) and the target (the button).

In the button-pushing task used in this study, the positioning of the finger over the individual buttons is an aiming movement consisting of a ballistic and corrective phase. The actual pushing of the button after the finger is already positioned probably does not vary when the panel is larger. The extra time is needed for positioning the finger. The ballistic movement must be greater for a larger panel than a smaller panel; however, since ballistic movements are rapid, most of the extra time is probably because of a longer corrective phase. A longer ballistic movement is probably more prone to error; therefore, it requires a longer corrective phase. This explanation is also consistent with Fitt's Law which states that time to acquire a target is a function of the size and distance of the target, the smaller the target and the greater the distance, the more time needed (Rosenbaum, 1991).

Bullinger, Kern, and Muntzinger (1987) assert that 50 mm is the "optimum" spacing between push buttons. The MIL-STD-1472D states that 50 mm is the "preferred" spacing for push buttons. Perhaps this is true to prevent errors or to perform a different kind of task. The two sources do not specify. The 50-mm spacing would probably slow performance in tasks like the ones in this study.

The small differences in mean times in the self-paced task, which ranged from about 0.03 s to 0.12 s among the three panels, may not make enough difference in some applications to be practically significant. Sometimes, however, space is limited and there is concern that the 13-mm minimum distance between buttons, allowed by the MIL-STD-1472D or other standards, will not be sufficient for gloved operators. In this case, the results are useful in indicating that 13 mm is wide enough for the gloves examined in this study and for similar gloves that are equally or less bulky.

If a decision were made to go with spacing wider than the 13-mm minimum distance, evidence from this study indicates that a 19-mm spacing between buttons would allow the same level of performance (perhaps better in some circumstances) and that a drop in performance could be expected at 25 mm.

One limitation of this study is that the push-button switches used were only one size of button cap, one level of resistance, and one type of button surface. Any large difference in any of these factors might change the effect of spacing. For example, very small button caps would probably require more distance between buttons. Deininger (1960) found one button size (12.7 mm) improved performance over a smaller size (9.6 mm). These factors might also interact with glove type. For example, a surface less resistant to slipping than the one in this study might cause more difficulty with a leather glove than a butyl glove.

It should be remembered that the buttons used in this study met suggestions by Chapanis and Kinkade (1972) and many of the requirements of the MIL-STD-1472D. Simply meeting these requirements may have prevented some glove effects.

CONCLUSIONS

1. When push buttons, gloves, and tasks, such as the ones in this study, are used, the 13-mm minimum spacing required by the MIL-STD-1472D does not hinder speed of performance.

2. When circumstances allow, the 19-mm spacing may be optimal since this study shows it does not hinder speed of performance and since the extra room may prevent accidental actuation of switches during some circumstances. Also, for certain populations, such as large handed males, the 19-mm spacing may allow faster operation.

3. Spacing of 25 mm between buttons seems to hinder speed of performance.

4. Time data from both the machine- and self-paced tasks indicate subjects who perform a task second (machine- or self-paced) have a performance advantage over subjects who performed that task first. This advantage is mainly because of the extra practice gained in the other task. Error data from both tasks indicate that performing the self-paced task first tends to allow lower error rates; perhaps this is because of the feedback given in the self-paced task.

5. Evidence from the separate analyses of male and female data, from correlations and informal comparisons of means, indicates a general girth effect. Subjects with larger hands tended to score faster times and more errors. This girth effect does not appear to be because of gender differences.

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APPENDIX A

INFORMED CONSENT FORM

INFORMED CONSENT FORM

You are invited to participate in the Gloved Operator Performance study at the USD Human Factors Laboratory. Your participation is voluntary. You must be over 18 years old.

The purpose of this study is to measure how much interference is caused by wearing a glove when operating certain kinds of machinery and control panels. If you agree to take part, you will go through a training period without wearing gloves, and then a further training and test period while wearing gloves. The results will provide information on the amount of skill lost when wearing gloves, and will provide some suggestions for designing machines and gloves so that there is as little loss as possible.

The study will require about two hours of your time. There is no risk involved, and you will not be asked to work at full strength, or in a fatigued condition.

You will be awarded extra credit in your psychology class for participating. The number of extra credit points will be determined by the class professor.

You may stop working in this study any time and leave. If you don't finish the two hour assignment, the extra credit will be pro-rated.

Your scores will be kept confidential, and your name will not be associated in any way with the results.

You may ask questions about the study at any time. We appreciate your taking part. If you agree to do so, please sign this form. You will be given a copy for your own records.

Jan Berkhout
Principal Investigator
677-5295

______________________________ __________ __________
Subject Signature   Age   Date

______________________________ __________
Researcher   Date

APPENDIX B

HAND DIMENSIONS FOR GLOVE FITTING

Table B-1

Hand Dimensions for Glove Fitting

Glove type and size	Hand circumference	Third digit length	Wrist to second digit
Butyl and cotton			
Small	-244	-82	-191
Medium	221-245	71-79	185-205
Large	238-	76-	190-
Nomex			
8	-210	-95	-206
9	190-210	86-95	191-211
10	200-221	90-100	197-217
11	209-	90-	203-
Leather and wool			
3	-200	-84	-173
4	192-212	81-89	163-181
5	209-	83-	177-
Fire fighter			
Small	-204	-93	-203
Medium	205-228	86-95	183-203
Large	213-235	87-97	198-218
X-large	217-	90-	200-

APPENDIX C

GLOVE DIMENSIONS

Table C-1

Glove Dimensions

Glove type and size	Hand circumference	Third digit length	Wrist to second digit
Butyl and cotton			
Small	232	78[a]	182
Medium	233	75	195
Large	250	80	200
Nomex			
8	200	90	196
9	200	90	201
10	210	95	207
11	220	95	211
Leather and wool			
3	190	80	165
4	202	85	172
5	220	87	186
Fire fighter[b]			
Small	235	93	197[c]
Medium	265	94	196
Large	273	96	212
X-large	278	99	215

a This measure is larger for the small size than the medium.

b These are the unadjusted measures.

c This measure is larger for the small size than the medium.

APPENDIX D

SELF-PACED INSTRUCTIONS FOR SUBJECTS

SELF-PACED INSTRUCTIONS FOR SUBJECTS

The monitor in front of you will present diagrams like this one (a hard copy of an example diagram was shown to the subject). These diagrams will show nine buttons that correspond to the panel of nine buttons in front of you. As soon as a diagram appears, push the four buttons indicated by the diagram. Push the buttons in the order indicated by the numbers on the diagram, the button labelled "1" fist, "2" second, "3" third, and "4" fourth. If you push a wrong button, push the cancel button to the right of the panel, then start over. If the fourth button you push is wrong, it will be too late to push the cancel button. When this happens, or when you push a wrong button without realizing it, an error tone will sound and you will start over, pushing the same four buttons.

When you push the buttons, push them as quickly as you can without making a mistake. Be sure to push the buttons all of the way down so that each button activation will be recognized, but do not keep the button held down as that will cause an error.

After you push four buttons correctly, a "correct tone" will sound, and a new diagram will appear on the screen 1 second later. After you respond correctly to 18 diagrams with one panel of nine buttons, you will perform the task five more times with various panels of nine buttons. This will allow you to have practice with each of three different panels, then to be tested on each of the three different panels. Do you have any questions?

APPENDIX E

MACHINE-PACED INSTRUCTIONS FOR SUBJECTS

MACHINE-PACED INSTRUCTIONS FOR SUBJECTS

The monitor in front of you will present diagrams like this one (a hard copy of an example diagram was shown to the subject). These diagrams will show nine buttons that correspond to the panel of nine buttons in front of you. As soon as a diagram appears, push the four buttons indicated by the diagram. Push the buttons in the order indicated by the numbers on the diagram, the button labelled "1" fist, "2" second, "3" third, and "4" fourth. If you push a wrong button, ignore the mistake and push the next button in the sequence of four.

After you push four buttons, wait for a new diagram to appear on the screen. A certain amount of time will be allowed to push the four buttons, and the diagram will remain on the screen even if you have already pushed four buttons. When time has expired for a diagram, a tone will sound and the diagram will disappear, and no more button pushes will be recognized for that diagram. If you are not finished pushing buttons for the previous diagram, leave it unfinished and wait for the next diagram. A new diagram will appear 1 second after the tone.

When you push the buttons, push them as quickly as you can without making a mistake. Be sure to push the buttons all of the way down so that each button activation will be recognized, but do not keep the button held down as that will cause an error.

Each time you push four buttons correctly, the time limit for the following diagram will be slightly less than the previous one. If you make a mistake, a new diagram will appear with the same time limit as the previous one. Eventually you will not have enough time to push four buttons correctly. After you make three mistakes in a row at the same time limit, you will be finished with the task. This will allow you to have practice with each of three different panels, then to be tested on each of the three different panels. Do you have any questions?

APPENDIX F

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED TIME DATA

Table F-1

Analysis of Variance Table for Self-Paced Time Data

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	3.7075	0.7415	1.97	0.0999
T-O	1	8.0368	8.0368	21.37	0.0001
H-wear*T-O	5	0.5995	0.1199	0.32	0.8992
Gender	1	0.1191	0.1191	0.32	0.5762
H-wear*gender	5	2.1271	0.4254	1.13	0.3568
T-O*gender	1	0.2224	0.2224	0.59	0.4457
H-wear*T-O*gender	5	0.8120	0.1624	0.43	0.8241
Error	48	18.0512	0.3761		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.5830	0.2915	22.83	0.0001
Spacing*H-wear	10	0.1482	0.0148	1.16	0.3269
Spacing*T-O	2	0.0115	0.0005	0.45	0.6376
Spacing*H-wear*T-O	10	0.0823	0.0008	0.64	0.7718
Spacing*gender	2	0.0144	0.0072	0.56	0.5704
Spacing*H-wear*gender	10	0.0953	0.0095	0.75	0.6794
Spacing*T-O*gender	2	0.0018	0.0009	0.07	0.9314
Spacing*H-wear*T-O*gender	10	0.1675	0.0167	1.31	0.2353
Error (spacing)	96	1.2257	0.0128		

APPENDIX G

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED ERROR DATA

Table G-1

Analysis of Variance Table for Self-Paced Error Data

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	11.7083	2.3417	1.47	0.2156
T-O	1	7.0417	7.0417	4.43	0.0405
H-wear*T-O	5	5.1528	1.0306	0.65	0.6636
Gender	1	0.2269	0.2269	0.14	0.7071
H-wear*gender	5	6.0787	1.2157	0.77	0.5791
T-O*gender	1	0.3750	0.3750	0.24	0.6292
H-wear*T-O*gender	5	10.1528	2.0306	1.28	0.2886
Error	48	76.2222	1.5880		
Univariate tests of hypotheses for within subject effects					
Spacing	2	3.0000	1.5000	1.38	0.2568
Spacing*H-wear	10	7.3333	0.7333	0.67	0.7459
Spacing*T-O	2	2.1111	1.0556	0.97	0.3827
Spacing*H-sear*T-O	10	13.4444	1.3444	1.24	0.2785
Spacing*gender	2	1.3704	0.6852	0.63	0.5349
Spacing*H-wear*gender	10	8.0741	0.8074	0.74	0.6832
Spacing*T-O*gender	2	4.7778	2.3889	2.20	0.1168
Spacing*H-wear*T-O*gender	10	3.4444	0.3444	0.32	0.9751
Error (spacing)	96	104.4444	1.0880		

APPENDIX H

ANALYSIS OF VARIANCE TABLE FOR THE MACHINE-PACED TIME DATA

Table H-1

Analysis of Variance Table for the Machine-Paced Time Data

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	1.9059	0.3812	1.21	0.3208
T-O	1	1.8519	1.8519	5.86	0.0193
H-wear*T-O	5	0.9798	0.1960	0.62	0.6852
Gender	1	0.6891	0.6891	2.18	0.1464
H-wear*gender	5	0.8893	0.1779	0.56	0.7281
T-O*gender	1	0.0267	0.0267	0.08	0.7727
H-wear*T-O*gender	5	0.6150	0.1230	0.39	0.8539
Error	48	15.1733	0.3161		
Univariate tests of hypotheses for within subject effects					
Spacing	2	0.1139	0.0570	2.10	0.1275
Spacing*H-wear	10	0.3210	0.0321	1.19	0.3104
Spacing*T-O	2	0.0123	0.0061	0.23	0.7971
Spacing*H-wear*T-O	10	0.1660	0.0166	0.61	0.7994
Spacing*gender	2	0.1251	0.0625	2.31	0.1048
Spacing*H-wear*gender	10	0.4366	0.0437	1.61	0.1146
Spacing*T-O*gender	2	0.1219	0.0610	2.25	0.1108
Spacing*H-wear*T-O*gender	10	0.1363	0.1364	0.50	0.8837
Error (spacing)	96	2.6000	0.0271		

APPENDIX I

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED ERROR DATA

Table I-1

Analysis of Variance Table for Machine-Paced Error Data

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	11.4120	2.2824	0.64	0.6713
T-O	1	11.1157	11.1157	3.11	0.0842
H-wear*T-O	5	3.0787	0.6158	0.17	0.9716
Gender	1	10.2269	10.2269	2.86	0.0972
H-wear*gender	5	2.0787	0.4157	0.12	0.9882
T-O*Gender	1	0.1157	0.1157	0.03	0.8579
H-wear*T-O*gender	5	6.0787	1.2157	0.34	0.8860
Error	48	171.5556	3.5741		
Univariate tests of hypotheses for within subject effects					
Spacing	2	1.6759	0.8380	0.55	0.5777
Spacing*H-wear	10	17.3241	1.7324	1.14	0.3406
Spacing*T-O	2	5.1759	2.5880	1.70	0.1874
Spacing*H-wear*T-O	10	9.3796	0.9380	0.62	0.7954
Spacing*gender	2	0.2315	0.1157	0.08	0.9267
Spacing*H-wear*gender	10	12.5463	1.2546	0.83	0.6044
Spacing*T-O*gender	2	0.0648	0.0324	0.02	0.9789
Spacing*H-wear*T-O*gender	10	5.8241	0.5824	0.38	0.9511
Error (spacing)	96	145.7778	1.5185		

APPENDIX J

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED TIME DATA FROM THE GENDER ANALYSIS

Table J-1

Analysis of Variance Table for Self-Paced Time Data from the Gender Analysis

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
Gender	1	0.1189	0.1189	0.51	0.0972
Error	12	2.8014	0.2335		
Univariate tests of hypotheses for within subject effects					
Spacing	2	0.1327	0.0664	8.34	0.0018
Spacing*gender	2	0.0011	0.0005	0.07	0.9326
Error (spacing)	24	0.1910	0.0079		

APPENDIX K

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED ERROR DATA FROM THE GENDER ANALYSIS

Table K-1

Analysis of Variance Table for Self-Paced Error Data from the Gender Analysis

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
Gender	1	4.0238	4.0238	3.07	0.1051
Error	12	15.7143	1.3095		
Univariate Tests of Hypotheses for Within Subject Effects					
Spacing	2	1.8571	0.9286	0.80	0.4627
Spacing*gender	2	1.4762	0.7381	0.63	0.5398
Error (spacing)	24	28.0000	1.1667		

APPENDIX L

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED TIME DATA FROM THE GENDER ANALYSIS

Table L-1

Analysis of Variance Table for Machine-Paced Time Data from the Gender Analysis

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
Gender	1	0.0009	0.0009	0.00	0.9648
Error	12	5.6190	0.4683		
Univariate tests of hypotheses for within subject effects					
Spacing	2	0.0814	0.0407	3.19	0.0593
Spacing*gender	2	0.0119	0.0059	0.47	0.6332
Error (spacing)	24	0.3067	0.0128		

APPENDIX M

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED ERROR DATA FROM THE GENDER ANALYSIS

Table M-1

Analysis of Variance Table for Machine-Paced
Error Data from the Gender Analysis

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
Gender	1	1.5238	1.5238	0.87	0.3697
Error	12	21.0476	1.7540		
Univariate tests of hypotheses for within subject effects					
Spacing	2	0.1905	0.0952	0.07	0.9348
Spacing*gender	2	1.3333	0.6667	0.47	0.6287
Error (Spacing)	24	33.8095	1.4087		

APPENDIX N

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED TIME DATA FROM FEMALE SUBJECTS

Table N-1

Analysis of Variance Table for Self-Paced Time Data from Female Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	1.2119	0.2424	0.62	0.6882
Girth	2	0.2992	0.1496	0.38	0.6885
H-wear*girth	10	2.2557	0.2256	0.57	0.8137
Error	18	7.0654	0.3925		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.2537	0.1268	16.77	0.0001
Spacing*H-wear	10	0.0491	0.0049	0.65	0.7620
Spacing*girth	4	0.0271	0.0067	0.90	0.4755
Spacing*H-wear*girth	20	0.1704	0.0085	1.13	0.3673
Error (spacing)	36	0.2723	0.0076		

APPENDIX O

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED ERROR DATA FROM FEMALE SUBJECTS

Table O-1

Analysis of Variance Table for Self-Paced Error Data from Female Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	4.4907	0.8981	0.49	0.7777
Girth	2	5.1296	2.5648	1.41	0.2708
H-wear*girth	10	9.4259	0.9426	0.52	0.8565
Error	18	32.8333	1.8241		
Univariate tests of hypothesis for within subject effects					
Spacing	2	2.3519	0.1759	0.82	0.4488
Spacing*H-wear	10	7.8704	0.7870	0.55	0.8437
Spacing*girth	4	1.4815	0.3704	0.26	0.9028
Spacing*H-wear*girth	20	27.9630	1.3981	0.97	0.5111
Error (spacing)	36	51.6667	1.4352		

APPENDIX P

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED TIME DATA FROM FEMALE SUBJECTS

Table P-1

Analysis of Variance Table for Machine-Paced Time Data from Female Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	0.5830	0.1166	0.36	0.8684
Girth	2	0.2274	0.1137	0.35	0.7080
H-wear*girth	10	1.6548	0.1655	0.51	0.8596
Error	18	5.8133	0.3230		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.1652	0.0826	3.78	0.0324
Spacing*H-wear	10	0.5204	0.0520	2.38	0.0277
Spacing*girth	4	0.1376	0.0344	1.57	0.2022
Spacing*H-wear*girth	20	0.6969	0.0348	1.59	0.1091
Error (spacing)	36	0.7867	0.0218		

APPENDIX Q

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED ERROR DATA FROM FEMALE SUBJECTS

Table Q-1

Analysis of Variance Table for Machine-Paced Error Data from Female Subjects

Source	DF	Type III SS	MS	F	PR>F
		Tests of hypotheses for between subjects effects			
H-wear	5	4.6019	0.9204	0.72	0.6202
Girth	2	8.6852	4.3426	3.37	0.0570
H-wear*girth	10	18.9815	1.8981	1.47	0.2272
Error	18	23.1667	1.2870		
		Univariate tests of hypothesis for within subject effects			
Spacing	2	0.3519	0.1759	0.12	0.8903
Spacing*H-wear	10	14.9815	1.4981	0.99	0.4675
Spacing*girth	4	5.1481	1.2870	0.85	0.5014
Spacing*H-wear*girth	20	22.5185	1.1259	0.75	0.7540
Error (spacing)	36	54.3333	1.5093		

APPENDIX R

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED TIME DATA FROM MALE SUBJECTS

Table R-1

Analysis of Variance Table for Self-Paced Time Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
		Tests of hypotheses for between subjects effects			
H-wear	5	4.6227	0.9245	1.21	0.3450
Girth	2	0.3761	0.1881	0.25	0.7847
H-wear*girth	10	3.9506	0.3951	0.52	0.8569
Error	18	13.7750	0.7653		
		Univariate tests of hypothesis for within subject effects			
Spacing	2	0.3437	0.1718	9.93	0.0004
Spacing*H-wear	10	0.1943	0.1943	1.12	0.3724
Spacing*girth	4	0.0793	0.1982	1.15	0.3510
Spacing*H-wear*girth	20	0.3170	0.0158	0.92	0.5721
Error (spacing)	36	0.6229	0.0173		

APPENDIX S

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED ERROR DATA FROM MALE SUBJECTS

Table S-1

Analysis of Variance Table for Self-Paced Error Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	13.2963	2.6593	1.91	0.1417
Girth	2	13.3519	6.6759	4.81	0.0213
H-wear*girth	10	13.2037	1.3204	0.95	0.5140
Error	18	25.0000	1.3889		
Univariate tests of hypothesis for within subject effects					
Spacing	2	2.0185	1.0093	1.10	0.3435
Spacing*H-wear	10	7.5370	0.7537	0.82	0.6099
Spacing*girth	4	1.1481	0.2870	0.31	0.8673
Spacing*H-wear*girth	20	12.9630	0.6481	0.71	0.7930
Error (spacing)	36	33.0000	0.9167		

APPENDIX T

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED TIME DATA FROM MALE SUBJECTS

Table T-1

Analysis of Variance Table for Machine-Paced Time Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	2.2122	0.4424	1.03	0.4280
Girth	2	0.0339	0.0169	0.04	0.9613
H-wear*girth	10	3.2105	0.3211	0.75	0.6720
Error	18	7.7067	0.4281		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.0739	0.0369	1.95	0.1575
Spacing*H-wear	10	0.2372	0.0237	1.25	0.2945
Spacing*girth	4	0.2222	0.0555	2.93	0.0341
Spacing*H-wear*girth	20	0.5110	0.0255	1.34	0.2152
Error (spacing)	36	0.6833	0.0190		

Table P-1

Analysis of Variance Table for Machine-Paced Time Data from Female Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	0.5830	0.1166	0.36	0.8684
Girth	2	0.2274	0.1137	0.35	0.7080
H-wear*girth	10	1.6548	0.1655	0.51	0.8596
Error	18	5.8133	0.3230		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.1652	0.0826	3.78	0.0324
Spacing*H-wear	10	0.5204	0.0520	2.38	0.0277
Spacing*girth	4	0.1376	0.0344	1.57	0.2022
Spacing*H-wear*girth	20	0.6969	0.0348	1.59	0.1091
Error (spacing)	36	0.7867	0.0218		

APPENDIX Q

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED ERROR DATA FROM FEMALE SUBJECTS

Table Q-1

Analysis of Variance Table for Machine-Paced Error Data from Female Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	4.6019	0.9204	0.72	0.6202
Girth	2	8.6852	4.3426	3.37	0.0570
H-wear*girth	10	18.9815	1.8981	1.47	0.2272
Error	18	23.1667	1.2870		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.3519	0.1759	0.12	0.8903
Spacing*H-wear	10	14.9815	1.4981	0.99	0.4675
Spacing*girth	4	5.1481	1.2870	0.85	0.5014
Spacing*H-wear*girth	20	22.5185	1.1259	0.75	0.7540
Error (spacing)	36	54.3333	1.5093		

APPENDIX R

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED TIME DATA FROM MALE SUBJECTS

Table R-1

Analysis of Variance Table for Self-Paced Time Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	4.6227	0.9245	1.21	0.3450
Girth	2	0.3761	0.1881	0.25	0.7847
H-wear*girth	10	3.9506	0.3951	0.52	0.8569
Error	18	13.7750	0.7653		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.3437	0.1718	9.93	0.0004
Spacing*H-wear	10	0.1943	0.1943	1.12	0.3724
Spacing*girth	4	0.0793	0.1982	1.15	0.3510
Spacing*H-wear*girth	20	0.3170	0.0158	0.92	0.5721
Error (spacing)	36	0.6229	0.0173		

APPENDIX S

ANALYSIS OF VARIANCE TABLE FOR SELF-PACED ERROR DATA FROM MALE SUBJECTS

Table S-1

Analysis of Variance Table for Self-Paced Error Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
		Tests of hypotheses for between subjects effects			
H-wear	5	13.2963	2.6593	1.91	0.1417
Girth	2	13.3519	6.6759	4.81	0.0213
H-wear*girth	10	13.2037	1.3204	0.95	0.5140
Error	18	25.0000	1.3889		
		Univariate tests of hypothesis for within subject effects			
Spacing	2	2.0185	1.0093	1.10	0.3435
Spacing*H-wear	10	7.5370	0.7537	0.82	0.6099
Spacing*girth	4	1.1481	0.2870	0.31	0.8673
Spacing*H-wear*girth	20	12.9630	0.6481	0.71	0.7930
Error (spacing)	36	33.0000	0.9167		

APPENDIX T

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED TIME DATA FROM MALE SUBJECTS

Table T-1

Analysis of Variance Table for Machine-Paced Time Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	2.2122	0.4424	1.03	0.4280
Girth	2	0.0339	0.0169	0.04	0.9613
H-wear*girth	10	3.2105	0.3211	0.75	0.6720
Error	18	7.7067	0.4281		
Univariate tests of hypothesis for within subject effects					
Spacing	2	0.0739	0.0369	1.95	0.1575
Spacing*H-wear	10	0.2372	0.0237	1.25	0.2945
Spacing*girth	4	0.2222	0.0555	2.93	0.0341
Spacing*H-wear*girth	20	0.5110	0.0255	1.34	0.2152
Error (spacing)	36	0.6833	0.0190		

APPENDIX U

ANALYSIS OF VARIANCE TABLE FOR MACHINE-PACED ERROR DATA FROM MALE SUBJECTS

Table U-1

Analysis of Variance Table for Machine-Paced Error Data from Male Subjects

Source	DF	Type III SS	MS	F	PR>F
Tests of hypotheses for between subjects effects					
H-wear	5	8.8889	1.7778	0.50	0.7704
Girth	2	11.5555	5.7778	1.63	0.2229
H-wear*girth	10	65.8889	6.5889	1.86	0.1204
Error	18	63.6667	3.5370		
Univariate tests of hypothesis for within subject effects					
Spacing	2	1.5555	0.7778	0.54	0.5902
Spacing*H-wear	10	14.8889	1.4889	1.02	0.4432
Spacing*girth	4	3.5555	0.8889	0.61	0.6571
Spacing*H-wear*girth	20	52.3333	1.4167	0.97	0.5108
Error (spacing)	36	52.3333	1.4537		