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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

**THE EFFECTS OF SITE CONFIGURATION ON A TACTILE
INFORMATION DISPLAY FOR THE HUMAN HEAD**

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

By

MARIE E. LAMBERT

Norman, Oklahoma

1990

**THE EFFECTS OF SITE CONFIGURATION ON A TACTILE
INFORMATION DISPLAY FOR THE HUMAN HEAD**

A THESIS

APPROVED FOR THE SCHOOL OF INDUSTRIAL ENGINEERING

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ABSTRACT

This research investigated the feasibility of using a tactile display to transmit information via the scalp. The purpose of the study was to compare performance for various stimulus site configurations. The first phase of the study investigated the number of sites that could be reliably detected and identified for the front section and the rear section of the scalp. Also during this phase, a multi-position array condition was investigated to determine target identification performance at twelve dispersed sites on the head. The results indicated that stimulus detection and localization were possible for 6, 8, 10, and 12 sites in a linear configuration for the front and the back of the scalp. However, response time and accuracy performance measures deteriorated significantly at the 12-site condition for both the front and back configuration. In addition, a high level of performance was achieved for the array condition.

The second phase of the study determined whether target identification was possible under conditions of high mental workload. During this phase, the target identification task was conducted while performing the Criterion Task Set (CTS) Memory

Search and Unstable Tracking dual-task to simulate the memory and motor output tasks encountered in a flying situation. Although it took significantly longer to respond to the target identification task, accuracy was not significantly affected under conditions of high mental workload. Performance on the CTS dual-task declined significantly when performed with the target identification task.

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THE EFFECTS OF SITE CONFIGURATION ON A TACTILE INFORMATION DISPLAY FOR THE HUMAN HEAD

CHAPTER I

INTRODUCTION

Situation awareness has become a key concept in the aerospace community. A pilot's knowledge of the events of the environment has recently been recognized as "crucial to mission success and survivability" (Endsley, 1988). Situation awareness in aviation is the pilot's perception and comprehension of elements in the environment at any point in time (Endsley, 1988; Harwood, Barnett, and Wickens, 1988 as cited by Fracker 1988; and Kuperman and Wilson, 1988). The increased interest in situation awareness is due primarily to advances in technology which have allowed the design of displays and devices to improve pilot performance.

The technological revolution has heralded an era of accessibility to large amounts of information. Electronic and computer wizardry have enabled information and capabilities previously unimaginable to be at our fingertips within seconds. The aero-

space industry has been and continues to be on the leading edge of this great technology boom.

In the past twenty years, the aerospace industry has witnessed numerous advances designed to improve pilot performance. As the technology became available, various devices and displays were added to the cockpit to give the pilot an 'edge'. Unfortunately, although these devices are instrumental in improving pilot performance in and of themselves, collectively they may actually saturate the pilot with information and consequently impair performance. This occurs primarily because the pilot is forced to attend to several displays to extract pieces of information and then assimilate and integrate this information to gain a true picture of the environment. The problem is magnified due to increased aircraft speeds which have lessened the time available to process information. Consequently, the pilot's immediate grasp and knowledge of the situation in a combat environment is crucial because the difference between success and failure can be determined in seconds.

The heightened interest in improving situation awareness has prompted researchers to explore new methods of presenting information so that it can be processed rapidly and easily. The focus of this research centers on utilizing the unexploited tactile

sense through tactile stimulation as a means to convey information.

The helmet-mounted tactile target display is a device that attempts to use the tactile sense not to replace but to augment the visual and auditory senses and consequently aid pilot performance. The concept, which was originally designed by an Israeli research group (U.S. Patent Number 4,713,651; issued to Meir Morag, Dec. 15, 1987), is based on the premise that this 'extra' sense can be used as an additional channel of information to preclude overloading a pilot's visual and auditory senses. This will increase the pilot's situation awareness and improve overall performance. Tactile point stimulators are located inside the pilot's helmet and used to signal spatial events. The specific point stimulated represents the angular position of an event and amplitude and/or frequency modulations could be used to represent parameters of the event (distance, urgency, etc.).

The helmet-mounted tactile display meets the design guidelines (Endsley, 1988) for maximizing situation awareness. Primarily, the tactile display uses the pilot's head as the display surface allowing an egocentric view of the environment which is rapidly relatable to the pilot's cognitive map and his orientation in it. In addition, since the tactile helmet would be used along

with visual tactical displays already in the cockpit, it emphasizes the status of the threat environment.

CHAPTER II

PROBLEM DEFINITION

The pilot's ability to cope with today's sophisticated, multi-capability aircraft has recently become a topic of great concern. The initial remedy to this problem was to provide the pilot with as much information about the status of the aircraft and the environment as possible. As technology advanced and more and more systems were added to the aircraft, more and more displays were also added to the cockpit. The current aircraft cockpit is a mosaic of dials, switches and displays. Looking at today's cockpit, it is hard to believe that the pilot's primary task is flying the aircraft. Today's aircraft severely limit the pilot's situation awareness because they seriously tax his/her cognitive abilities.

The current approach to the problem is to design the cockpit to enhance situation awareness. Endsley (1988) compiled a list of design guidelines to maximize situation awareness. One of the design guidelines proposed utilizing additional modes of information input to provide information simultaneously with the visual channel.

The purpose of this thesis was to investigate the use of a tactile helmet display and evaluate target identification performance for various stimulus site configurations. A tactile target identification task was used to evaluate the number and location of tactile stimuli presented to the front and rear sections of the head using a modified automobile racing helmet and push-type solenoids. In addition, target stimuli were configured in an array of twelve sites dispersed symmetrically on the head to study identification performance when targets are presented to multiple planes of the head. The target identification task was also conducted while performing memory and motor output tasks to determine the cognitive effects of the tactile display and the effects of task loading on target identification performance.

In summary, the goal of this study was to determine the effects of site configuration on target identification performance with a helmet-mounted tactile display in the presence of additional dual-task loading.

CHAPTER III

LITERATURE REVIEW

3.1 Tactile Stimulation

The tactile sense has long fascinated mankind. Some of the earliest recorded studies were conducted by E.H. Weber from 1830 to 1850. Weber attempted to map the tactile sensitivity and two-point discrimination threshold for forty-four sites on the human body starting from the top of the head to the dorsal side of the foot. Although his experimental methodology is unknown and translations of the results of his work indicate that his procedures and controls were somewhat crude, his data on the sensitivity of the head and face area have been shown to be fairly accurate (Weinstein, 1968). Consequently, Weber's work paved the way for future research on tactile sensitivity.

As more information was gathered on tactile sensitivity, it was hypothesized that the tactile sense could be used as a means of communication. Early tests of this hypothesis attempted to transmit the spoken word directly to the skin (Gault, 1924; Gault and Crane, 1928 as cited by Goff, 1967). Although these early

tests failed to support the hypothesis, they did aid in defining the characteristics necessary to perceive tactile stimulation and to determine performance. These characteristics are frequency, amplitude (intensity), duration and contactor area (Goff, 1967).

3.2 Parameters of Tactile Perception

If a tactile display is to be successful, the tactile information must first be perceived before it can be processed and utilized by the operator. To insure that the information is sensed, it must possess the characteristics that will ensure stimulus detection. Those characteristics include:

Frequency - Mere contact with the skin may not convey enough information to elicit a response. Propagation of vibratory disturbances and repeated impacts have been shown to yield a higher degree of sensitivity than a single contact (Sherrick and Craig, 1982). In fact, earlier researchers believed that there might be a separate vibratory sense (Geldard, 1940 as cited by Sherrick and Craig, 1982). The vibratory disturbances and repeated impacts must be set at a level that will exploit their capability to generate higher degrees of sensitivity.

Amplitude - The intensity with which the contactor impacts the skin is vital to stimulus detection. If the intensity is too low,

contact may not be perceived, but if it is too high, contact may cause pain and discomfort.

Duration - The length of time that the stimulus is presented will determine whether or not the stimulus is detected and provide a means to vary the amount of information available.

Contact Area - The stimulus must contact the skin in such a way that sufficient surface area is depressed to yield sensation. If the contact area is too large, point localization may be ambiguous and if it is too small, detection may not occur.

3.2.1 Frequency

The range of frequencies that can be perceived by the skin is an important factor in determining the amount of information that can be processed by the tactile sense. Frequency can be used to communicate information to the skin in much the same way it is used to convey information to the ears. To provide this information and ensure an accurate measure of frequency discrimination, subjective intensity of the stimulus must be eliminated as a factor (Goff, 1967). Equal subjective intensity curves, much like equal loudness contour curves for audition, must be used to ensure accurate data representation and to provide reliable results.

Goff (1967) examined frequency discrimination at low frequency values. The subject's task was to compare mechanical vibrations on the basis of frequency. Goff used a contactor that

was 6.5 mm in diameter attached to a Goodman Model V-47 vibrator to stimulate the subject's right index finger. The vibrator, which was secured to the end of a balance arm, exerted a constant pressure of 8 grams on the skin. Equal subjective intensity curves were then established using the method of limits with a standard of 100 Hz and attenuation settings of 20 and 35 dB. Goff found that at the 35 dB level, the differential frequency threshold increased (got worse) from approximately 4 to 110 Hz as the vibrator frequency increased from 25 to 200 Hz.

Franzen and Nordmark (1975) studied thresholds for vibrotactile discrimination of pulse frequencies between 1 and 384 Hz and recorded slightly better results than Goff. Franzen and Nordmark mechanically stimulated the fleshy pad of the middle finger at a 30 dB sensation level. The stimulus contactor was a 2 mm probe mounted on the cone of a moving-coil loudspeaker. The probe was controlled by a micro-manipulator which was set to contact the skin at 500 microns. The task consisted of presenting the subject with a target stimulus frequency for 0.5 second followed by a 0.4 second break interval. After the break, the subject adjusted a control to locate the target frequency again. The results showed that the differential threshold, measured as the least discriminable change in period, improved from approximately 10 msec to 0.1 msec as pulse rate increased from 1 to 256 Hz. Franzen and Nordmark concluded that higher frequencies improve

stimulus detection and discriminability. However, a slight deterioration in performance was noted at 384 Hz.

These results suggest that higher frequencies tend to improve performance in frequency discrimination tasks but this improvement begins to taper off at approximately 380 Hz. Consequently, when frequency discrimination is a factor, tactile displays should utilize frequencies that will enhance performance. Craig and Sherrick (1982) recommended that frequencies around 250 Hz be used in vibro-tactile displays because according to Bliss (1974 as cited by Craig and Sherrick, 1982), these frequencies "permit finer spatial discrimination and maximal absolute sensitivity".

3.2.2 Amplitude

The intensity of the stimulus must be at a level that allows the signal to be received but is not uncomfortable. Individual sensitivity is a factor that must be measured and a level may then be used that will accommodate most individuals. Gilson (1968) compared the discriminability of vibro-tactile patterns applied to the fingers with the discriminability of patterns applied to 10 parts of the body from the shoulder to the ankle. Subjects were asked to report whether the patterns were perceived as the same or different. A Goodman Model V-47 vibrator was used to present a 200 msec burst of 60 Hz vibration to the right index finger at a rate of 1 burst per second. Gilson varied the amplitude of the stimuli

from 3 to 28 dB. The results showed that amplitude did not affect the subject's ability to discriminate the patterns.

Goff (1967) and Franzen and Nordmark (1975) used 35 and 30 dB respectively in their experiments. This may be considered an acceptable level to insure stimulus perception by most individuals.

The Optacon, which stands for optical-to-tactile conversion, is a reading aid for the blind that uses vibro-tactile stimulation to transmit written material to the finger of the user. Tests conducted with the Optacon instruct subjects to adjust the intensity to a comfortable level because differences in amplitude have not been shown to affect performance (Craig and Sherrick, 1982).

3.2.3 Duration

The length of time that the stimulus is presented will determine whether or not the stimulus is detected and will also provide a means to vary the amount of information available. The duration of the stimulus should be long enough to insure detection but short enough to preclude information overload or desensitization. Generally, increasing the duration increases recognition and discrimination (Craig and Sherrick, 1982). The shortest duration at which stimuli can be identified and discriminated was determined by Cohen and Kirman (1986) to be 50 msec. A Good-

man Model V-47 vibrator was fitted with a 6.35 mm diameter, cylindrical, brass rod contactor that was slightly beveled at the edge. The method of limits was used to determine the subject's threshold for a 100 Hz stimulus which occurred in 200 msec bursts applied to the subject's index finger. After the threshold was determined, the intensity of the stimulus was raised 30 dB to insure that it was clearly perceived. The intensities of all other stimuli were matched to this level. The method of constants with forced choice was used to determine the difference limen for frequency discrimination. The duration of stimulation was varied from 200 msec down to 30 msec to determine the effect on frequency recognition. The task consisted of: a warning light for 500 msec; a fixed foreperiod for 100 msec; presentation of the first stimulus; an interstimulus interval of 500 msec; presentation of the second stimulus; subject response; and an intertrial interval for 10 seconds. Results showed that frequency discrimination did not decline over the range of 200 msec to 50 msec but did decline substantially at 30 msec.

3.2.4 Contactor Area

Verrillo (1963) studied the effects of contactor area, contactor configuration and frequency on vibro-tactile thresholds. The site of stimulation was the fleshy pad of the palm over the first metacarpal of the right hand. The vibrator was mounted to the platten of a drill-press assembly so that it could be lowered and

raised within 1/1000 of an inch. Frequency thresholds were determined for three subjects at 25 and 30 dB intensity levels with the contactor located 0.5 mm and 1.0 mm above minimum contact with the skin. A sine wave generator was modulated by an electronic switch so that the signal was on for 1 second and off for 1 second. Three different contactors (convex, concave, and an annulus) were used to compare their effect on sensitivity thresholds. The results indicated that contactor area was a significant parameter in vibro-tactile stimulation. However, at low frequencies the absolute threshold was independent of contactor size and for very small contactors the threshold was independent of frequency.

Rabinowitz, Houtisima, Durlach, and Delhorne (1987) found that contactor area did not significantly affect performance. Rabinowitz et. al used a Goodman type vibrating disk assembly to activate one of eight contactors on the distal pad of the middle finger. The assembly could be rotated to any one of the eight positions by a stepper motor and lifted vertically by a solenoid. The stimulus presentation consisted of a 500 msec vibratory interval surrounded by a 400 msec fringe during which the contactor was in contact with the finger but not vibrating. Frequency and intensity parameters were varied between 50 and 530 Hz and 3 and 30 dB respectively. The subjects were required to identify which position was stimulated and then respond via a keycard. The results indicated that intensity had the greatest effect on

recognition performance followed by frequency. Contactor area had the least effect.

3.3 Tactile Sensitivity at Various Body Loci

Sensitivity of the skin to vibro-tactile stimulation varies from one location to another on the body. Most vibro-tactile sensitivity research has focused on the fingers as the site of stimulation. The fingers offer many advantages in that they are highly sensitive to small amplitudes of vibration and are capable of sharp spatial acuity (Craig and Sherrick, 1982). The tongue also possesses a great deal of sensitivity and has also been used extensively in research on tactile communication of speech. In general, the frontal facial region, especially the lip area and the nose, and the fingertips are the areas of the greatest absolute sensitivity and highest accuracy of localization and acuity (Craig and Sherrick, 1982).

Although the previously mentioned areas offer many advantages, it may not be convenient to have these sites connected to a tactile display. In addition, many times the information required of the tactile display may not require the high degree of sensitivity that these sites offer. Consequently, other sites may be more suitable. The suitability of alternate loci was demonstrated in a study where subjects, who were trained to recognize patterns presented on their backs, had very little trouble transferring their

learning to recognizing patterns presented on the thigh and abdomen (Scadden, 1973 as cited in Craig and Sherrick, 1982).

In another experiment, Gilson (1968) compared the discriminability of vibro-tactile patterns applied to the fingers with the discriminability of patterns applied to ten parts of the body from the shoulder to the ankle. All ten vibrators were adjusted for equal sensation. Subjects reported more errors with the fingers than at other sites on the body. In a related study, Cholewiak and Craig (1984) examined vibro-tactile pattern recognition and discrimination at the finger, palm, and thigh. The apparatus used to generate the patterns was adapted from the Optacon. The system used a 144 element tactile array that vibrated at 230 Hz. Pattern durations were fixed at either 4 msec or 52 msec and were presented at a stimulus onset asynchrony (SOA) of 10, 17, 26, 56, 96, and 300 msec. The results showed that longer separation times and longer durations improved both recognition and discrimination performance especially for the thigh.

The suitability of the head as a site for a tactile display has not been the focus of extensive research. This may be due in part to its decreased sensitivity and limited accessibility because of hair. Early research has shown that the sensitivity of the scalp varies (Weber as translated by Ross and Murray, 1978). Weber found that the crown possessed the area of least sensitivity followed by the lower part of the back of the head while the area of greatest

sensitivity was near the forehead. Weber used the points on the legs of an adjustable compass to stimulate the scalp in order to determine the minimum perceptible distance between the two points and the minimum distance for identifying their orientation. He found that the minimum perceptible distance between the points was approximately 2.25 cm for the lower part of the forehead, 3.4 cm for the top of the head, and 3.2 cm for the back of the head. The minimum distance to determine the orientation of the two points was approximately 2.7 cm for the center of the forehead, and 4.05 cm for the back of the head. Data were not available for the crown. Weber ranked the 44 body locations according to their sensitivity. The forehead ranked 24th, the top of the head ranked 29th, and the back of the head ranked 26th.

Weinstein (1968) conducted a study to verify Weber's results. Weinstein tested only 17 sites and the forehead was the only area of the head included in the study. Weinstein ranked the forehead 4th for pressure sensitivity, 10th for localization and 11th for discrimination.

In a more recent study, Shimizu and Wake (1982) stimulated the middle of the forehead with either a continuous or discrete stream from a water jet to determine the effect of presentation rate on a subject's ability to detect stimulus shifts. Subjects were seated with their faces held longitudinally in a chin rest. Each trial consisted of: a 2.5 sec warning signal (buzzer); a 200 msec test

stimulus to the middle of the forehead; an interstimulus interval which varied from 100 to 3200 msec; the target stimulus. The subjects were required to respond verbally as to whether the target stimulus was to the left, right, up, down or in one of the four oblique directions. The stimulus was 1.0 mm in diameter and operated at a force of .065N at 230 cc/min. The results indicated that the differential threshold for physical separation was lower for the continuous condition. Subjects could better perceive physical separation when the stimulus presentation was continuous as opposed to discrete. In addition, it took more time to detect the separation along oblique directions than along horizontal and vertical directions. The discrete stimulation took more time to detect changes in all directions. Shimizu and Wake concluded that the sensitivity of the forehead is much better than Weinstein indicated.

3.4 Processing and Attending to Vibro-Tactile Stimulation

The success of a tactile display depends a great deal on the operator's ability to attend to and process the stimulus information. The extent to which vibro-tactile stimulation can be used as a viable method of communication and information presentation depends on determining 'what' and 'how much' information can be perceived through the skin.

Bliss, Crane, Mansfield, and Townsend (1966) conducted two experiments to determine the amount of information available in

brief tactile presentations. Jets of air were used to stimulate the interjoint regions of the fingers. In the first experiment, they investigated the span of immediate memory for brief point stimulation. Subjects were asked to identify which locations were stimulated. On any one trial, stimulation points were randomly chosen and the corresponding stimulators were activated for 100 msec. The results showed that two of the three subjects possessed a span of immediate memory of about 4.5 stimulus positions. The third subject however, continued to increase the number of positions correctly reported until he reached an average span of immediate memory of about 7.5 stimulus positions. It appeared that the third subject was able to 'chunk' the information in a manner similar to the phenomena that occurs in visual memory tasks.

In the second experiment, subjects were required to give whole or partial reports of the points stimulated (an example of a partial report would be to report only those stimulations on the distal interjoint regions). The results showed that slightly more information is available in partial reports (immediate memory) than in whole reports (short term memory). In addition, the accuracy of the partial report was superior to the whole report only when the report was solicited within 0.8 sec of stimulus termination. When the subjects waited 2.0 sec after stimulus termination to give partial reports, there was no difference between partial report and whole report accuracy.

Franzen, Markowitz and Swets (1970) studied the spatial limitations of attention to vibro-tactile stimuli. Vibrating disks .25" in diameter were used to stimulate the fingers at a frequency of 222 Hz for a duration of 500 msec. Subjects were required to respond to the recognition of a stimulus. In the first condition, subjects knew exactly which finger or fingers would be stimulated. The results showed that detection performance for two fingers was no better than detection for one finger. No spatial summation was evident. In the second condition, subjects did not know which finger or fingers would be stimulated and the results indicated that detection performance when two fingers were stimulated was much better than when only one of the fingers was stimulated. The single channel attention model suggests that when a subject is uncertain of the location of stimulation, detection performance for two fingers will be greater than that of either single finger. Franzen, Markowitz and Swets attributed the greater performance for the two finger condition to a decrement in the performance of the single finger condition not to spatial summation.

Shiffrin, Craig and Cohen (1973) studied attention limitations in tactile processing and presented findings that disputed the work by Franzen, Markowitz and Swets (1970). A single Goodman V-47 vibrator presented a stimulus to either the thenar eminence of the right hand, the left index finger, or the volar surface of the forearm. Subject's were asked to identify the site stimulated. The stimulus parameters were 160 Hz and 200 msec. Stimuli were pre-

sented either simultaneously, where the subjects were given one brief time interval in which to monitor all three sites for the presence of a signal, or sequentially, where the subjects were given three successive time intervals, one of which contained the signal. The results indicated that there was no significant difference in the number of correctly identified stimuli at any of the sites and that sequential performance was nearly identical to simultaneous performance. This last point disputes the single channel theory because the simultaneous performance should have been less than the sequential performance since it forced the subject to attend to more than one stimulus site at a time.

Craig (1985) conducted a series of experiments to explore this question of attention and whether or not information from more than one site could be combined. Craig was primarily interested in determining the circumstances under which subjects could attend to more than one site of stimulation, the cost of this attention, how rapidly attention could be switched from one site to another, and how spatial separation between two sites affects attention. Tactile displays similar to those used in the Optacon were used to stimulate the middle and index fingers of the left hand. The first experiment established a baseline for discriminating and identifying vibro-tactile patterns presented at one or two sites when the site of stimulation was known (directed attention) and unknown (divided attention). The stimuli were the 26 upper case letters of the alphabet. In the recognition task, subjects responded via a

keyboard with the letter corresponding to the stimulus. In the discrimination task, subjects were presented with two letters and responded whether they were the same or different. Also, this experiment examined the effect of pattern difficulty on discrimination and identification. The results of this experiment showed that performance on divided attention tasks was below directed attention tasks even at a stimulus onset asynchrony (SOA) of 400 msec. Additional temporal separation was required in order to process two tactile patterns independently. The results also suggested that it did not take longer to switch attention between complex patterns. The same amount of temporal separation (approximately 50 - 100 msec) was required for both simple and complex patterns.

The second experiment compared performance in identifying a pattern presented to one finger with performance when the pattern extended over two fingers. Subjects were asked to identify which one of nine patterns had been presented. The results showed that subjects could attend to more than one finger but at a lower level of performance.

The third experiment attempted to determine if subjects split their attention from one finger to the other and then combine the two when presented the stimuli across two fingers. If this were the case, it would take more time to process this information. The task was the same as that described in the second experiment ex-

cept this time the subjects were told to respond as quickly as possible. The results confirmed the hypothesis as it took a significantly longer period of time to respond correctly to a pattern split between two fingers than to a pattern presented to a single finger.

The final experiment examined whether bilateral presentation of patterns improved overall performance as compared to ipsilateral performance as the time between stimuli (SOA) increased. Patterns were presented to the left and right index fingers and subjects were required to respond whether they were the same or different. The results confirmed that bilateral presentation improved the overall performance.

The primary conclusion drawn from these experiments was that attention deficits could be reduced and in some cases eliminated for certain tasks if the patterns were presented bilaterally.

3.5 Masking

It is impossible to talk about tactile stimulation without including a brief discussion on masking. Masking is the phenomenon that exists when one stimulus interferes with the detection of another stimulus. Forward masking occurs when the stimulus to be identified (the target) is preceded by a non-target stimulus. Backward masking occurs when the target stimulus is followed by a non-target stimulus. Many studies have been conducted to deter-

mine the conditions under which masking is prevalent. It appears that masking is more prevalent when the two sites are very close together or when the interstimulus interval (ISI) or stimulus onset asynchrony (SOA) is very small.

Gilson (1969) measured the detectability of a test vibrator located on the upper thigh in the presence of masking vibrators located at other sites on the body. He found that as the distance between the test site and the masking site increased, masking decreased. In addition, he found that this occurrence could be offset by changing the time interval between the activation of the test site and the activation of the other body site to compensate for neural conduction time. For instance, delaying the activation of a vibrator located on the upper arm by 10 msec relative to the onset of the test vibrator on the upper thigh produced nearly as much masking as a vibrator located next to the test vibrator.

Kirman (1984) studied the effect of target and mask duration and temporal separation on recognition. He found that ISI provided a significant main effect and that when the target and the masker occur for the same duration, forward masking was greater than backward masking. Evans (1987) studied the persistence of vibro-tactile stimuli and found that vibro-tactile patterns persist for some time following the cessation of stimulation. Evans also found that two stimuli presented in close spatial and temporal (SOA) proximity will be integrated into a composite representation

and that the spatial location of the target and masker is preserved during this integration process. In addition, the last pattern presented is more strongly represented in the composite.

Although masking can be a problem in vibro-tactile displays that require information to be presented rapidly to sites that are in close proximity, it can also be beneficial to the display. Kirman (1973 as cited by Craig and Sherrick, 1982) pointed out that "masking is an indication of interactions among stimuli that might produce new spatiotemporal patterns through mechanisms of integration that may lead to better information transmission". If this is indeed the case, masking could be an asset which will allow more information to be transferred and processed through the skin.

3.6 Criterion Task Set (CTS)

To determine the effectiveness of a tactile display, tests must be conducted under circumstances that provide demanding mental workload. The U.S. Air Force Criterion Task Set (CTS), which was developed at the Armstrong Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, was chosen in this study to provide realistic secondary tasks that best relate to the mental processing and motor output tasks encountered in a flying situation.

The CTS is a battery of nine basic human performance tasks designed to place selective demands on the elementary mental

resources and information processing functions of the human operator (Shingledecker, 1984). The CTS model is based on Wicken's (1981) multiple resource theory and Sternberg's (1966) processing stage theory of human performance. The three primary stages of processing and associated resources are perceptual input, central processing, and motor output. The CTS model not only provides a means to assess the effects of treatment conditions on human performance, but also allows comparisons of workload effects on specific types of information processing functions. The current version of the CTS consists of nine tasks, but only the Memory Search and Unstable Tracking tasks were used in this study. The dual-task version of the CTS provides the ability to combine two CTS tasks for simultaneous presentation.

3.6.1 Memory Search (MS)

The Memory Search task is based on Sternberg's (1969) additive-factor method which states that factors influencing different processing stages will have an additive effect on mean reaction times (RT). The MS task is designed to place demands on a subject's short term memory retrieval function. This relates to resource behaviors that involve keeping track of and recalling recent events (Shingledecker, 1984). In the Memory Search task, a small set of items (the positive set) is presented to the subject for memorization. After memorizing the set, the subject initiates the first trial by pressing a button on the response keypad. A series of

test items is then presented to the subject one at a time, and the subject must respond positively or negatively as to whether the test item was contained in the positive set. Response time is measured from the onset of the test item to the response. Accuracy of response is also recorded.

Stimulus items in the CTS Memory Search task are visually presented characters from a restricted alphabet. Due to the acoustic confusability of certain letters, only 17 of the 26 letters of the alphabet are used (ABCEFGHIJLOQRSXYZ). Positive set items are randomly selected and the remaining items form the negative set. A new positive set is selected at the beginning of each 3-minute trial. Test items are generated with the restriction that positive and negative set items are drawn with equal probability.

Subjects are encouraged to respond as rapidly and accurately as possible. Response deadlines of 3 seconds are imposed and stimuli are presented at short random interstimulus intervals. Responses are entered using a pushbutton keypad. Subjects are given feedback concerning their performance after each test period to ensure that an acceptable speed-accuracy trade-off is maintained. In the CTS, there are three difficulty levels of the task, generated by positive sets of one, four, or six items. The most difficult level (a positive set containing 6 letters) was used in the current study.

3.6.2 Unstable Tracking (UT)

The CTS Unstable Tracking task is similar to the critically unstable tracking task developed by Jex, McDonnell, and Phatak (1966). The Jex task requires a subject to stabilize the movement of an increasingly unstable cursor. Eventually, the instability increases to the point of loss of control. This point is termed the critical point. The results of Jex et al. (1966) show that this task does indeed constrain the operator's behavior and that the critical instability performance is directly related to the operator's effective time delay while tracking.

The CTS version of the task places selected demands on the human information processing resources dedicated to the execution of rapid and accurate manual responses (Shingledecker, 1984). The associated resource behaviors that result from these demands are continuous control, error correction, and control actuation. In the CTS Unstable Tracking task, subjects view a CRT displaying a fixed target area centered horizontally on the screen. A cursor moves horizontally on the screen, and the subject attempts to keep the cursor centered over the target area by rotary movements on a control knob.

The control system represented by the task is an inherently unstable one. The subject's actions (input) introduce error that is magnified by the system so that it becomes increasingly difficult to

respond to the velocity of the cursor movements as well as cursor position. If the subject loses control and the cursor reaches either edge of the display, an edge violation is recorded, and the cursor is automatically reset to the center of the display and the subject continues tracking. Performance is scored in terms of the root mean square (RMS) of the error deviations from the center target and the number of control losses or edge violations.

Levels of demand can be varied by adjusting the instability factor λ to either low ($\lambda = 1$), moderate ($\lambda = 2$), or high ($\lambda = 3$). Jex et al. (1966) found the upper limit of λ to be between 4 and 5 at which point cursor control could not be maintained. For the current study, the CTS dual-task version paired the most difficult level of the Memory Search task (positive set = 6) with the most difficult level of Unstable Tracking ($\lambda = 3$).

CHAPTER IV

EXPERIMENTAL METHODOLOGY

This research to determine the feasibility of using tactile stimulation of the scalp as a means of conveying information was conducted in two parts. Study 1 examined the number of sites that could be reliably identified for the front section and the rear section of the scalp. Study 2 evaluated the ability to detect and localize stimuli for three different site configurations under conditions of high mental workload.

4.1 Equipment

Guardian tubular solenoids (Model TP4x16, intermittent duty, 24-volts DC) were used to provide the tactile stimuli. The body of each solenoid was 5.0 cm long and 1.3 cm in diameter. The external shaft of the solenoid was 3.1 cm long with a diameter of 1.3 mm at the tip. For the specific equipment configuration used in this research, the impact force of the solenoids was approximately 13 grams at 17.5 volts. The tips were coated with silicon rubber to provide a modest amount of padding for impact with the subject's scalp.

The control box for the system consisted of a relay that was pulsed by a BK Precision Model 3011 function generator set at approximately 4 Hz. As the relay pulsed, it completed a circuit from a 24-volt Acopian Model 51212T9A power supply, through a variable resistor that controlled the solenoid force, and a multi-position switch to select the desired solenoid site. A slide switch allowed the experimenter to manually initiate and end a pulse sequence to the preselected solenoid location. An additional circuit attached to the slide switch was used to initiate subject response timing using a Commodore 64 microcomputer. The computer recorded the subject's stimulus location response and the response time. The Commodore keyboard was used as the response device. A Commodore 1541 disk drive was used to store subject responses and response time data.

The tactile stimulation helmet used in this research was constructed from a modified automobile racing helmet. Large portions of the anterior and posterior sections of the helmet were removed, leaving a strip of helmet material running from ear to ear (roughly along the coronal suture) to support the helmet while it was in place on the head.

Three aluminum bands (each 61.5 cm long, 2.5 cm wide, and 0.3 cm thick) served as anchoring platforms for the solenoids. These bands were bent to approximate the outer shape of the helmet and were attached with bolts at the ear positions on the

and backward to provide front-to-back adjustment of the solenoids along the sagittal plane of the skull. One of the metal bands was situated over the anterior cut-out section and the other two bands were positioned over the upper and lower posterior section (see Figure 1).

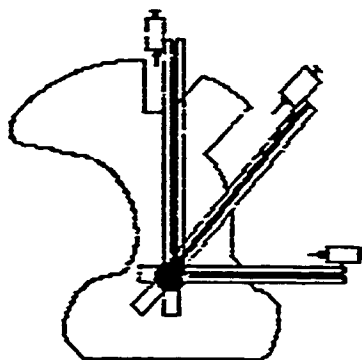


Figure 1. Helmet and Solenoid Anchoring Bands.

A slot (40 cm long and 0.6 cm wide) was milled down the center of each band. For each solenoid, a bolt was extended up through the milled channel, through the base of an L-bracket and secured with a wing nut. Loosening the wing nut allowed the L-bracket to be moved from side to side along the channel. Attached to the vertical leg of the L-bracket (perpendicular to the surface of the helmet) was a short (3.0 cm) section of PVC tubing (1.4 cm ID). The PVC tubing sections served as mounting sleeves for the sole-

noids, which were held in place by set screws tapped through the wall of the tubing. Loosening the hand-tightened set screws allowed rapid inward/outward adjustment of the solenoids for proper contact with the scalp. (Refer to Figure 2 for a complete sketch of the solenoid mounting and adjustment assembly.)

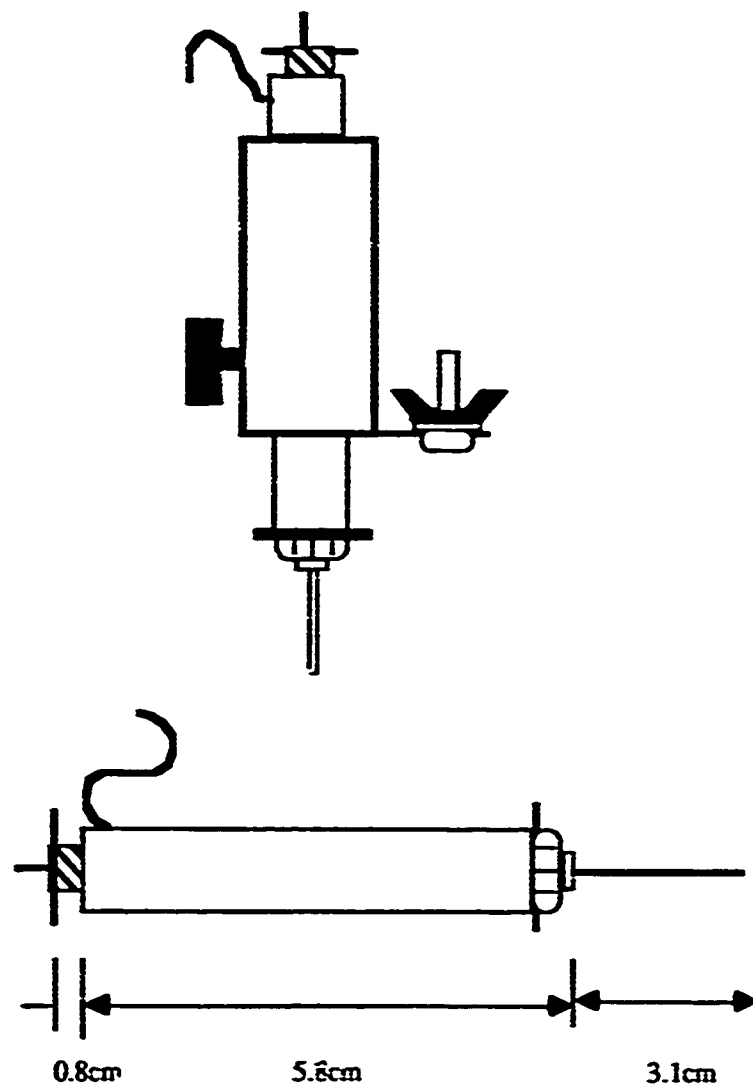


Figure 2. Solenoid and Mounting Assembly

4.2 General Test Procedure

On each stimulus trial, the experimenter selected the desired solenoid site and then activated the slide switch to initiate the solenoid pulses and the response timer. After the desired stimulus ontime (about one second or approximately four solenoid pulses), the experimenter returned the slide switch to the off position.

Subjects were instructed to respond to the pulses as quickly as possible by pressing a labeled key on the Commodore 64 keyboard. The correct key corresponded spatially with the solenoid position that had been stimulated. The number row keys were used for the front and back linear configurations and the R, T, Y, U / F, G, H, J / V, B, N, M keys were used for the array configuration. The letter keys were marked with numbered pieces of tape that corresponded to sites 1 through 12. The subject's response stopped the response time clock, and both the response location and response time were recorded in a data file stored on disk. Along with their manual responses, the subjects gave verbal confidence ratings concerning their identification of the stimulus position. These ratings were on a three-point scale as follows:

- 1 - unsure of the location
- 2 - moderately sure of the location
- 3 - very sure of the location.

The ratings were transcribed to a data collection form for later incorporation into the response database. The response data were transferred to a mainframe IBM 3081 for summary and statistical analysis using the Statistical Analysis System (SAS).

4.3 Study 1 - Detection and Localization

Study 1 was designed to evaluate the number of sites that could be identified for the front section and the rear section of the scalp. The front and rear sections of the scalp were stimulated separately at 6, 8, 10 or 12 sites by solenoids mounted in the helmet. Between sessions, subjects were trained on the CTS Memory Search and Unstable Tracking tasks that were used for the dual-task loading in Study 2. Also during this phase of the research, a 12-site array condition was investigated to determine performance when targets were positioned at twelve dispersed sites on the head. Four sites were stimulated at the front, middle (top), and back planes of the head.

4.3.1 Subjects

Eight subjects (four women and four men) were employed for this portion of the study. All subjects were volunteers recruited from the University of Oklahoma campus. Subject age ranged from 19 to 42 years with a mean age of 23 years. Subjects were

screened to ensure that they did not have any major visual or auditory dysfunction. Approval for the use of human subjects was obtained from the Institutional Review Board - Norman Campus. Each subject's informed consent was obtained.

4.3.2 Experimental Design

4.3.2.1 Independent Variables

The independent variables for this study were

- (1) the configuration of target stimuli (front plane, back plane, array), and
- (2) the number of stimulus sites.

The configuration of target stimuli was either (1) across the front plane of the scalp (approximately 18 cm from the external occipital inion), (2) across the back plane of the scalp (approximately 3.0 cm from the external occipital inion) or (3) the array described in the next paragraph.

The number of stimulus sites consisted of either 6, 8, 10 or 12 for the front and back linear configurations and 12 sites for the array configuration with four sites on each of the front, middle (top) and rear sections of the scalp.

The total number of stimuli presented during a given session was dependent on the number of sites for that session. Each site

received ten stimuli per session (e.g., a total of 60 stimuli were presented for the 6-site condition).

4.3.2.2 Dependent Variables

The dependent variables for this study included the following:

- (1) absolute accuracy for site identification
- (2) relative accuracy for site identification
- (3) response time, and
- (4) confidence rating.

Absolute accuracy was the exact measure of the subject's ability to identify which solenoid was activated. The subject scored '1' for a correct response and '0' for an incorrect identification. Absolute accuracy is summarized as the percentage of correct responses.

Relative accuracy measured the subject's closeness to the correct site. The subject scored a correct response ('1') if the response was no more than one site away from the actual stimulated location. This dependent measure was not used for the array condition due to the configuration of stimuli. For example, site 5 was on the opposite side of the head and displaced from site 4. In addition, the proximity of stimuli was relevant not only in the transverse plane, but in the sagittal and diagonal planes as well.

Response time provides a good measure of workload because as workload increases, subjects take more time to respond to stimuli (Schlegel, 1986). Response time in milliseconds was measured by the Commodore 64 from the onset of the stimulus until the subject's response. The confidence ratings were obtained as outlined in Section 4.2.

4.3.2.3 Control Variables

Control variables for this study included the following:

- (1) environmental factors
 - (a) noise
 - (b) temperature
 - (c) lighting levels
 - (d) layout of the workstation
- (2) subject perceived intensity level of the stimuli
- (3) subject instructions
- (4) subject training, and
- (5) subject motivation.

The laboratory was an isolated room in the basement of Dale Hall at the University of Oklahoma. The room was carpeted to eliminate external noise and reduce the internal sound level. Temperature was maintained at approximately 70 degrees Fahrenheit.

For each subject, adjustment of the solenoid contact with the scalp was performed for each site to insure that the stimulus intensity was at a comfortable level and that all stimuli were perceived with equal subjective sensation.

Subjects were given a brief overview of the study and oral instructions for the task. Subjects were encouraged to do their best at the start of each trial. The task itself and performance feedback at the end of each trial produced a high level of self-motivation.

4.3.3 Procedure

Before any testing began, fixed endpoints were established on the aluminum bands. The endpoints were approximately 17 cm on either side of the midline for the front band and 16 cm on either side of the midline for the back band. The endpoints encompassed a total of approximately 180 degrees on the stimulus plane. By fixing the endpoint spacing on the aluminum band, the sites were fixed at the same angular separation for each subject. The physical spacing of the stimulation sites varied slightly depending on each subject's head size and shape. The range was set and marked prior to testing for all test levels and configurations. As the number of sites changed from one test condition to another, the interstimulus distance also changed (i.e., decreased with increases in the number

of stimuli). The interstimulus distance for the various levels and configurations are presented in Tables 1 and 2.

Table 1. Mounting and Nominal Tip-to-Tip Spacing of Solenoids for the Front and Back Configurations.

Location of Solenoid	Number of Sites	Mounting Spacing	Tip-to-Tip Spacing
Front	6	6.8 cm	4.0 cm
	8	4.9 cm	3.0 cm
	10	3.8 cm	2.5 cm
	12	3.1 cm	2.0 cm
Back	6	6.4 cm	3.5 cm
	8	4.6 cm	2.8 cm
	10	3.6 cm	2.3 cm
	12	2.9 cm	1.7 cm

Table 2. Mounting and Nominal Tip-to-Tip Spacing of Solenoids for the Array Configuration.

Solenoid Position	Number of Sites	Mounting Spacing	Tip-to-Tip Spacing
Front	4	11.3 cm	6.8 cm
Top	4	11.5 cm	5.8 cm
Back	4	10.7 cm	5.8 cm

Subjects were briefed on the general nature of the experiment. Subjects were then instructed to place the helmet on their head in a comfortable position and secure it firmly with the chin strap and additional padding. Once the helmet was in place, the solenoids were individually adjusted to contact the subject's scalp and provide approximately equal subjective intensities of stimulation.

Once the helmet was properly adjusted and calibrated, the subjects were given either 36, 48, 60 or 72 practice trials (depending on the number solenoid positions) to familiarize them with the task and the solenoid locations. Practice trials consisted of first running through all solenoid positions sequentially in ascending order and then in descending order, followed by two sequences of random trials, and then a final sequential set in ascending and descending order immediately prior to the start of the session. Trials were administered such that the sequence of presentation of the solenoid locations was block randomized. Each block presented the 6, 8 10 or 12 solenoid locations once (depending on the number of sites for that session). Ten blocks of trials were presented for each session. The sets of 6, 8, 10 and 12 solenoids were tested for each of the band locations (front and back). The sequence of set size presentation was determined by a 4 x 4 Latin Square with half of the subjects starting with the front configuration and the other half starting with the back configuration. The array configuration was tested once at the end of the four sessions for the front

configuration and once following the sessions for the back configuration.

Subjects were seated at a workstation with a response keyboard and fitted with the tactile helmet (see Figure 3).

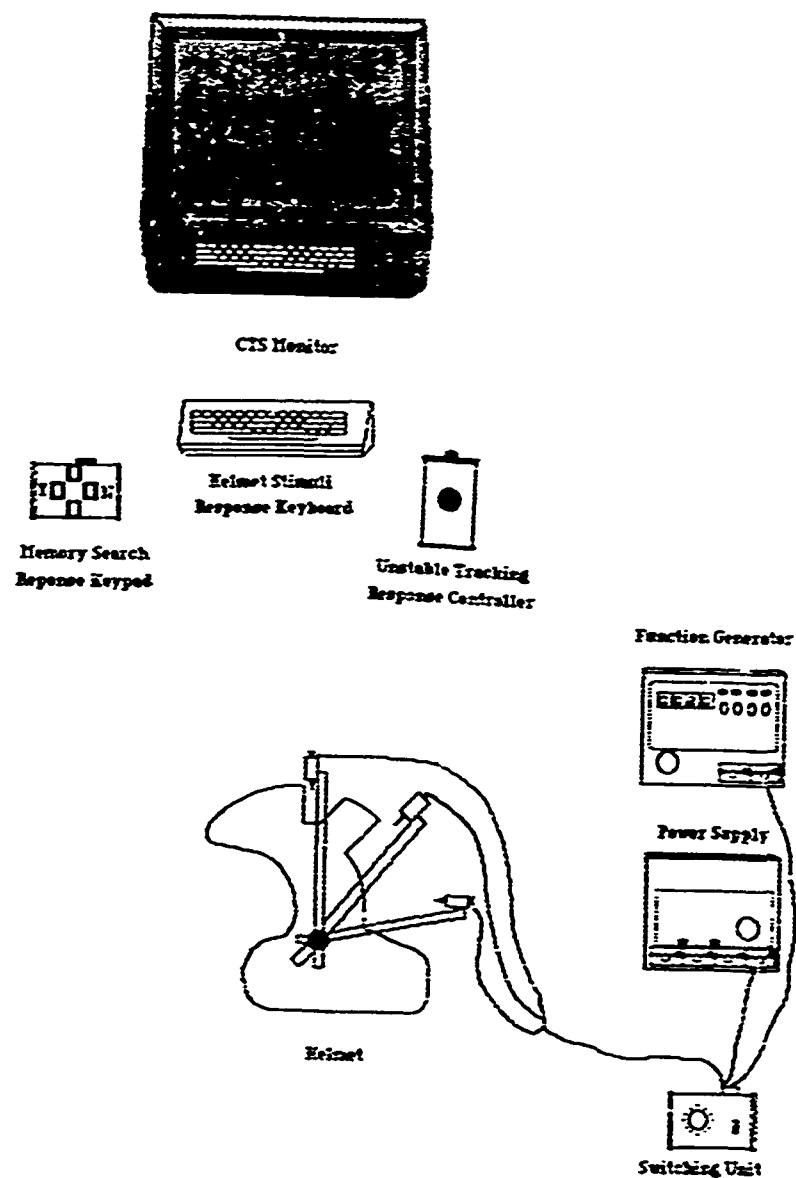


Figure 3. Workstation Layout.

A small partition separated the experimenter from the subject to ensure that the subject did not receive cues from the experimenter. The experimenter sat behind the partition and selected the sites to be stimulated from a computer generated list of random numbers.

Following each session, the subject removed the helmet so that it could be reconfigured for the next session. During this time, the subject performed a practice/training trial on the Criterion Task Set (CTS). Each subject performed a total of seven training trials which included one trial of the Memory Search task alone, one trial of the Unstable Tracking task alone, and five trials of the combined Memory Search and Unstable Tracking tasks. The standard CTS trial length of three minutes was used.

After the CTS trial was completed, the subject was instructed to once again secure the helmet. The experimenter readjusted and recalibrated the solenoids for the next test session. Total test time for each subject in Study 1 was approximately four hours.

4.4 Study 2 - Demanding Workload

The results of Study 1 indicated that target detection and localization were possible for the front, rear, and array conditions under non-distracting conditions. Study 2 investigated whether detection and localization were possible under conditions of high mental workload.

Subjects were required to perform the standard dual task version of the U.S. Air Force Criterion Task Set (CTS) while attending to helmet tactile stimuli. The dual task consisted of the Memory Search and the Unstable Tracking tasks described in Section 3.6. The helmet task consisted of identifying target stimuli for the front, back, and array conditions as in Study 1. Eight solenoid sites were used for the front and back conditions, with the same twelve sites used for the array condition.

4.4.1 Subjects

Twelve volunteers (7 women and 5 men) were recruited from the University of Oklahoma campus for this study. Subject age ranged from 19 to 42 years with a mean age of 25 years. All subjects were required to have normal or corrected vision. Eight of the subjects had participated in Study 1. The remaining four had participated in other tactile helmet studies.

4.4.2 Experimental Design

The experimental design used in this study was similar to that described for Study 1 except for the additional inclusion of the Criterion Task Set (CTS) task loading.

4.4.2.1 Independent Variables

The independent variables for Study 2 were

- (1) the configuration of target stimuli, and
- (2) the level of task loading.

The configurations of target stimuli were the front (8 sites), the back (8 sites) and the array (12 sites). Task loading consisted of the helmet task alone, or the helmet task along with the CTS dual-task.

4.4.2.2 Dependent Variables

The dependent variables for the helmet task were the same as those used in Study 1 and defined in Section 4.3.2.2. The dependent variables that provide measures of performance for the CTS tasks are as follows:

- (1) Memory Search (MS) Response Time
- (2) Memory Search (MS) Percentage Correct
- (3) Unstable Tracking (UT) Root Mean Square (RMS), and
- (4) Unstable Tracking (UT) Edge Violations.

Response time for the Memory Search task is recorded from the onset of the test item to the response. Accuracy of response is measured as the percent of correct responses. RMS measures the error deviations from the center target for the Unstable Tracking

task. Edge Violations provide a count of the number of control losses that result when the cursor hit the sides of the target area.

4.4.3 Equipment

The helmet was instrumented for Study 2 in the same manner as for Study 1 (Section 4.1), except only 8 solenoids were mounted on the aluminum anchoring bands for the front and back configurations. To accomplish the CTS dual task loading required in this study, the following equipment was added to the workstation:

- (1) additional Commodore 64 microcomputer
- (2) two Commodore 1541 disk drives (one to run CTS software, one for CTS data storage)
- (3) Commodore 1702 color monitor (for CTS tasks)
- (4) two subject response devices (rotary control for UT task, keypad for MS task).

4.4.4 Procedure

Subjects received training on the CTS tasks during Study 1. The CTS tasks used in both the training and the actual study were set at the most difficult level of the Memory Search task (positive set = 6) and the most difficult level of Unstable Tracking ($\lambda = 3$). The Memory Search stimuli were presented immediately above the Unstable Tracking display which eliminated gaze aversion and allowed both tasks to be performed simultaneously. The subject responded to the tasks by controlling the rotary knob for the

tracking task with the preferred hand and depressing the Yes/No buttons on the keypad for the memory task with the non-preferred hand.

On the day of the test trials, subjects were given an orientation to the experimental procedure. Subjects then performed a total of six baseline CTS trials: two Memory Search trials, two Unstable Tracking trials and two dual-task Memory Search and Unstable Tracking trials. The actual test began after the subject secured the helmet and the experimenter adjusted and calibrated it as described in Study 1.

Subjects performed a total of six sessions. Three sessions required subjects to respond to the tactile stimuli alone for the front, back, and array configurations, and three sessions required the subjects to respond to the tactile helmet stimuli for the front, back, and array configurations while performing the CTS Memory Search and Unstable Tracking dual-task. Subjects provided verbal confidence ratings during all test sessions.

The increased task loading presented the subjects with a dilemma when the presentation of stimuli overlapped and required two or sometimes three responses at once. Subjects were forced to schedule responses, typically retaining continuous control of the Unstable Tracking task control knob and trading off responses on the Memory Search keypad and the tactile helmet response keyboard.

Approximately two CTS trials were required to complete the 8-site front and back conditions and three CTS trials were required to complete the 12-site array condition. Total test session time for each subject was approximately two and a half hours.

CHAPTER V

RESULTS

5.1 Study 1 Results

Means and standard deviations for the dependent variables described in Section 4.3.2.2 are presented in Tables 3, 4, and 5 for the front, back and array configurations respectively.

Table 3. Means (Standard Deviations) for Response Measures for the Front Configuration.

Number of Sites	All Trials				Correct Trials	
	Absolute Accuracy	Relative Accuracy	Response Time	Confidence Rating	Response Time	Confidence Rating
6	95%	100%	1546 (376)	2.8 (0.2)	1533 (848)	2.8 (0.4)
8	79%	99%	1897 (488)	2.5 (0.4)	1818 (778)	2.6 (0.6)
10	65%	96%	2138 (717)	2.4 (0.3)	2126 (1132)	2.5 (0.6)
12	57%	94%	2254 (558)	2.2 (0.3)	2167 (798)	2.3 (0.5)
Mean	74%	97%	1959	2.5	1911	2.6

Table 4. Means (Standard Deviations) for Response Measures for the Back Configuration.

Number of Sites	All Trials				Correct Trials	
	Absolute Accuracy	Relative Accuracy	Response Time	Confidence Rating	Response Time	Confidence Rating
6	85%	99%	1726 (634)	2.6 (0.4)	1652 (836)	2.7 (0.5)
8	72%	97%	1894 (642)	2.5 (0.3)	1851 (902)	2.6 (0.5)
10	67%	93%	2122 (644)	2.2 (0.4)	2061 (974)	2.6 (0.6)
12	50%	84%	2115 (672)	2.1 (0.5)	2025 (844)	2.3 (0.7)
Mean	69%	93%	1964	2.4	1897	2.6

Table 5. Means (Standard Deviations) for Response Measures for the Array Configuration.

Session	All Trials			Correct Trials	
	Absolute Accuracy	Response Time	Confidence Rating	Response Time	Confidence Rating
Array 1st Trial	81%	1962 (675)	2.6 (0.3)	1938 (1367)	2.7 (0.7)
Array 2nd Trial	84%	1964 (673)	2.6 (0.4)	1948 (1050)	2.7 (0.5)
Mean	83%	1963	2.6	1943	2.7

The means are plotted in Figures 4 through 9. In the tables and figures, response times and confidence ratings for "correct" trials refer to only those trials in which the site was correctly identified by the subject. "Overall" trials refer to all trials, whether accurate or inaccurate.

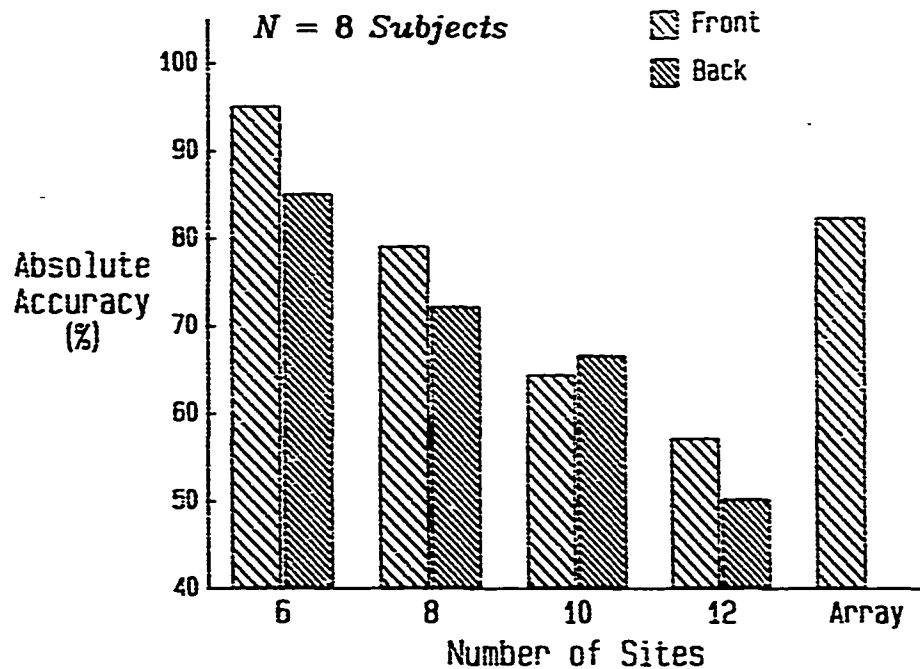


Figure 4. Mean Absolute Accuracy for 6, 8, 10, and 12 Sites Plus the Array Configuration.

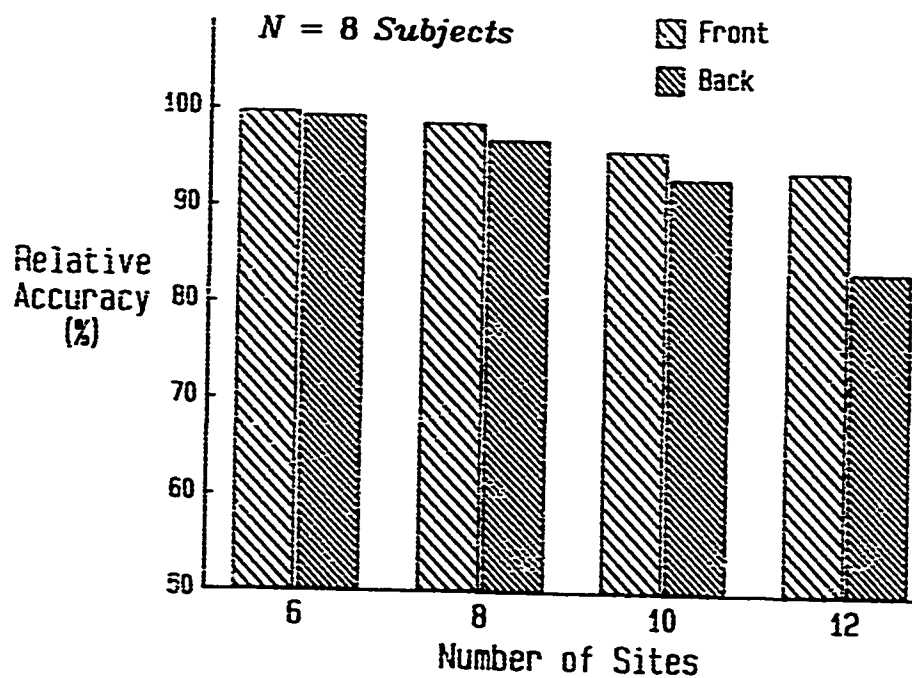


Figure 5. Mean Relative Accuracy for 6, 8, 10, and 12 Sites.

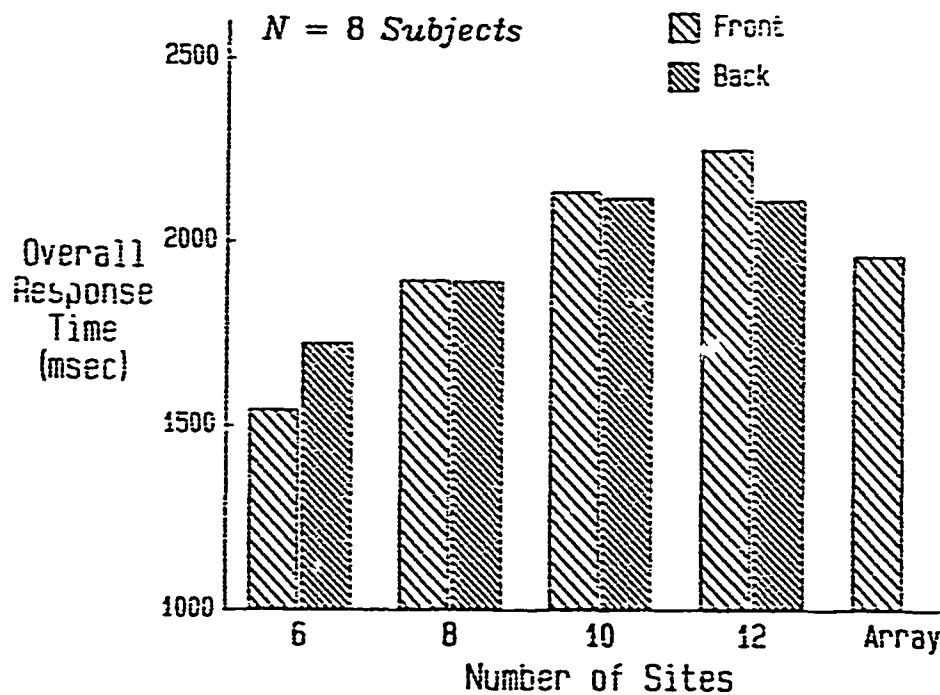


Figure 6. Mean Response Time for 6, 8, 10, and 12 Sites Plus the Array Configuration.

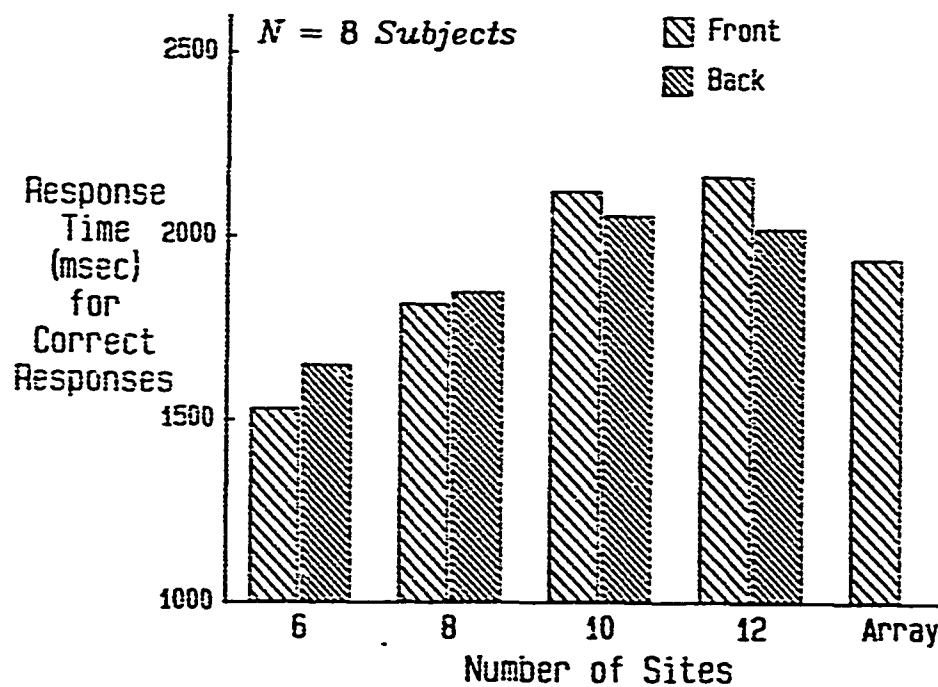


Figure 7. Mean Response Time for Correct Responses for 6, 8, 10, and 12 Sites Plus the Array Configuration.

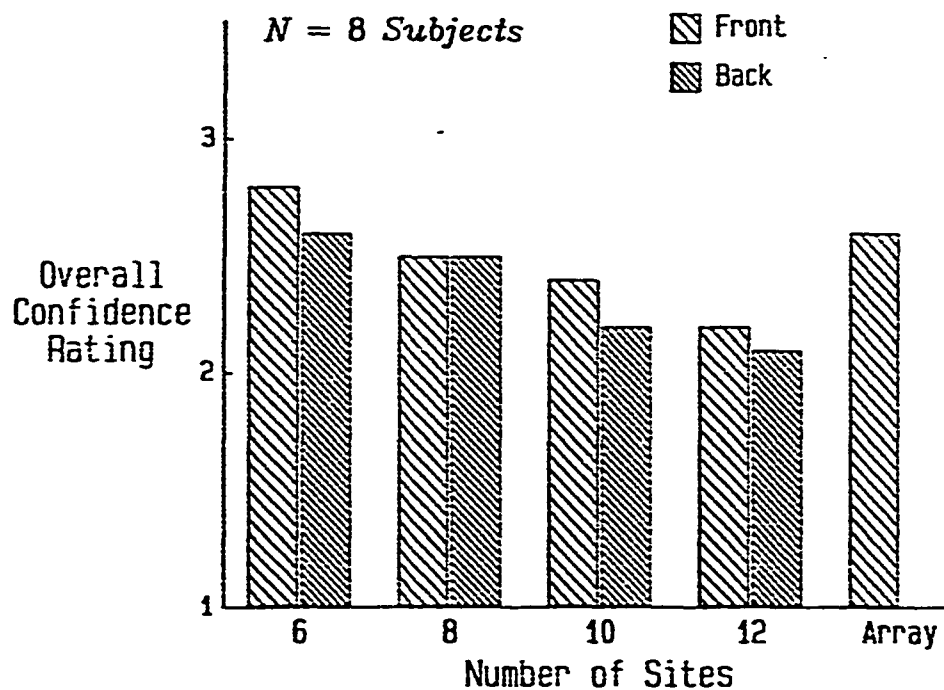


Figure 8. Mean Confidence Rating for 6, 8, 10, and 12 Sites Plus the Array Configuration.

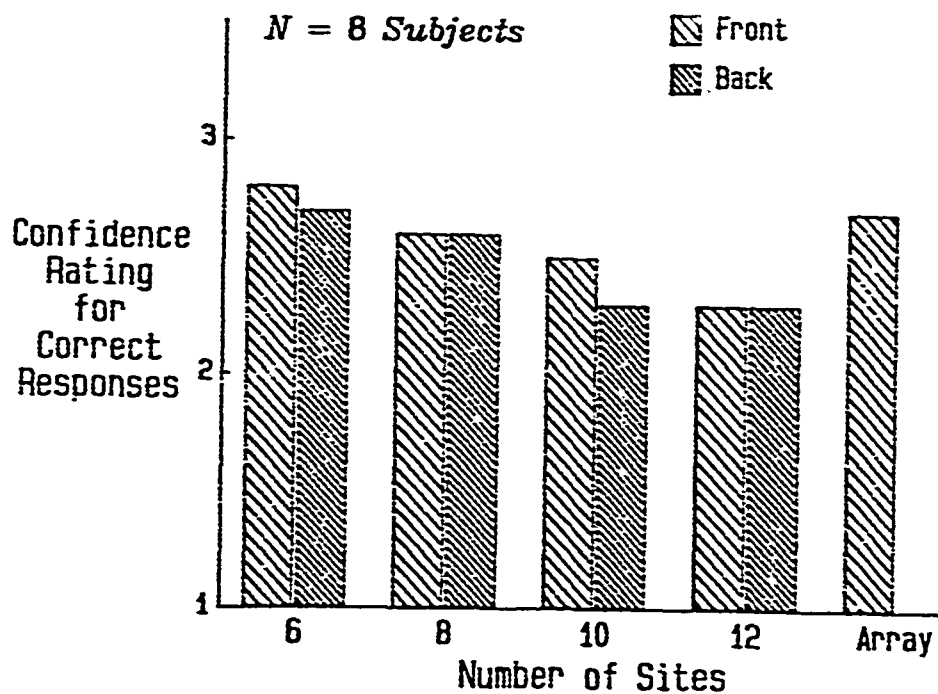


Figure 9. Mean Confidence Rating for Correct Responses for 6, 8, 10, and 12 Sites Plus the Array Configuration.

A repeated measures analysis of variance was conducted to examine the effects of configuration (front, back), number of sites (6, 8, 10, 12), and their interaction.

Performance differences between the front and the back configurations for the various number of sites were not statistically significant for the dependent measures accuracy and response time. Absolute accuracy for the front configuration (69%) was better than for the back (64%) but the difference was not significant ($F(1,7) = 2.35, p > 0.1689$). However, there was a significant difference in the relative accuracy scores for the two configurations ($F(1,7) = 36.58, p < 0.0001$). The average relative accuracy score for the front was 96.5% compared to 91.9% for the back.

Response times did not differ significantly between the two configurations ($F(1,7) = 1.13, p > 0.2874$). The overall average time for the front (2024 msec) was approximately equal to the overall time for the back (2003 msec).

Differences in confidence ratings were highly significant ($F(1,7) = 37.58, p < 0.0001$) with ratings for the front configuration (2.5) being slightly higher than those for the back (2.4).

Performance differences among the various number of sites for the front and back configurations were highly significant for all dependent measures (See Table 6).

Table 6. Performance Analysis for the Front and Back Configurations.

Dependent Variables	F(3,21)	<i>p</i>	Number of Sites
Absolute Accuracy	48.92	0.0001	6 8 10 12
Relative Accuracy	40.41	0.0001	<u>6</u> 8 10 12
Response Time	18.64	0.0001	6 8 <u>10</u> 12
Confidence Rating	28.66	0.0001	6 8 <u>10</u> 12

There was a significant difference between all site conditions for absolute accuracy ($F(3,21) = 48.92, p < 0.0001$). Scores ranged from 90% for the 6-site condition to 54% for the 12-site condition. There was no statistical significance between the 6-site and the 8-site conditions for relative accuracy, but both the 10-site condition and the 12-site condition were significantly different from all other conditions.

Response time was also significant ($F(3,21) = 40.41, p < 0.0001$). There was no statistical difference between the 10-site condition and the 12-site condition, but both the 6-site condition

and the 8-site condition were significantly different from all other conditions. Confidence ratings ($F(3,21) = 18.64, p < 0.0001$) followed the same trend. There was no significant difference between the 10-site condition and the 12-site condition. The 6-site condition and the 8-site condition were both significantly different from all other conditions.

The correlation between absolute accuracy and confidence ratings decreased from $r = 0.60$ ($p < 0.0001$) for 6 sites to $r = 0.48$ ($p < 0.0001$) for 12 sites. The correlation between response times and confidence ratings went from $r = -0.25$ ($p = 0.0091$) for the 6-site condition to $r = -0.12$ ($p = 0.1720$) for the 8-site condition. A moderately strong negative correlation was again evident ($r = -0.28, p = 0.0004$) for the 10-site condition and $r = -0.26$ ($p = 0.0002$) for the 12-site condition. The correlation between absolute accuracy and response time followed a similar trend. The correlation for the 6-site condition was $r = -0.32$ ($p = 0.0014$), but again there was not a significant correlation for the 8-site condition. The correlation for the 10-site condition was also not significant but for the 12-site condition was moderately significant ($r = -0.21, p = 0.0041$).

In general, subjects were faster and more confident when making correct identifications (1904 msec and 2.6 vs 2143 and 2.2 for average scores of the front and back conditions combined). This means that subjects were aware of their errors and relayed their

uncertainty through the verbal ratings. This is also apparent from the correlations of the dependent measures. As absolute accuracy increased, so did the confidence rating ($r = 0.28, p < 0.0001$). In addition, shorter response times were accompanied by higher confidence ratings ($r = -0.28, p < 0.0001$). A faster response time was also accompanied by higher accuracy ($r = -0.15, p < 0.0001$) although the effect was not very strong in this case.

The response and confidence rating data were also averaged by solenoid site for each subject and each session. Correlations computed using these means indicated even stronger relationships across sessions for absolute accuracy and confidence rating ($r = 0.54, p < 0.0001$), for response time and confidence rating ($r = -0.35, p < 0.0001$), and response time and absolute accuracy ($r = -0.28, p < 0.0001$). The correlations computed in this fashion reflect individual differences in subject performance.

The interaction between configuration (front, back) and the number of sites (6, 8, 10, 12) was only significant for the dependent measure relative accuracy ($F(3,21) = 16.84, p < 0.0001$).

Analyses were performed to examine the effects of the number of sites for the front and back configurations separately. Performance differences among the various number of sites were highly significant for all dependent measures for the front configuration. The absolute accuracy score for 6 sites (95%) was significantly higher ($F(3,21) = p < 0.0001$) than all other site

levels. The absolute accuracy for 8 sites (79%) was significantly higher than for 10 sites (65%) and for 12 sites (57%). The relative accuracy score followed the same trend and was surprisingly high for all levels (from 100% for 6 sites to 94% for 12 sites) with fewer statistically significant differences.

Response times also differed significantly among the various number of sites ($F(3,21) = 15.44, p < 0.0001$), with the time for 6 sites (1546 msec) being substantially shorter than for 8 sites (1897 msec), 10 sites (2138 msec) or 12 sites (2254 msec). Although the difference in response time between 8 and 10 sites was not statistically significant, there was a substantial decline (14%) in accuracy between these two levels.

Differences in confidence ratings were highly significant ($F(3,21) = 31.60, p < 0.0001$) and followed the same pattern as response time. Ratings for 6 sites (2.8) differed significantly from those for 8 sites (2.5), 10 sites (2.4), and 12 sites (2.2).

The correlations using session means indicated a moderately strong positive correlation ($r = 0.59, p < 0.0001$) between accuracy and confidence rating and a negative correlation between response time and confidence rating ($r = -0.39, p < 0.0001$) and between response time and accuracy ($r = -0.30, p < 0.0001$).

Performance differences for the back configuration were significant with respect to all dependent variables. Absolute

accuracy differed significantly ($F(3,21) = 20.29, p < 0.0001$) with the 12-site condition (50%) being significantly worse than 6 sites (85%), 8 sites (72%), and 10 sites (67%). Absolute accuracy for 6 and 8 sites did not differ significantly. Relative accuracy was also significant ($F(3,21) = 41.94, p < 0.0001$) and followed a similar pattern. The 12-site level (84%) was significantly different from all other levels.

Response times differed significantly different ($F(3,21) = 4.88, p = 0.0100$) for the various number of sites. The 6-site (1726 msec) and 8-site (1894 msec) configurations were significantly different from 10 sites (2122 msec) and 12 sites (2115 msec).

Ratings differed significantly ($F(3,21) = 11.15, p < 0.0001$) and followed the same trend as response time with the faster responses coinciding with the higher confidence ratings. The ratings for 6 sites (2.6) and for 8 sites (2.5) differed significantly from the ratings for 10 sites (2.2) and 12 sites (2.1).

Correlations for the back configuration tended to follow the general trend. The correlation between accuracy and confidence rating was moderately positive ($r = 0.50, p < 0.0001$) and the correlations between response time and confidence rating and response time and accuracy were negative ($r = -0.31, p < 0.0001$ and $r = -0.27, p < 0.0001$).

Results of the ANOVA and Tukey tests comparing the various number of sites within the front and back configurations are summarized in Tables 7 and 8 respectively.

Table 7. Performance Analysis for the Front Configuration.

Dependent Variable	F(3,21)	p	Number of Sites
Absolute Accuracy	29.09	0.0001	6 8 <u>10</u> 12
Relative Accuracy	11.18	0.0001	<u>6</u> <u>8</u> <u>10</u> 12
Response Time	15.44	0.0001	6 <u>8</u> <u>10</u> 12
Confidence Rating	31.60	0.0001	6 <u>8</u> <u>10</u> 12

Table 8. Performance Analysis for the Back Configuration.

Dependent Variable	F(3,21)	p	Number of Sites
Absolute Accuracy	20.09	0.0001	<u>6</u> <u>8</u> 10 12
Relative Accuracy	41.94	0.0001	<u>6</u> <u>8</u> 10 12
Response Time	4.88	0.0100	<u>10</u> <u>12</u> <u>8</u> 6
Confidence Rating	11.15	0.0001	<u>6</u> <u>8</u> <u>10</u> 12

Performance differences between the first and second array sessions were not statistically significant. Although there was an improvement in accuracy from session 1 (81%) to session 2 (84%), the increase was not significant ($F(1,7) = 2.24, p > .1781$). Due to the special configuration of the array condition, relative accuracy was inappropriate as a measure of performance.

Overall, subjects were very consistent and confident in their responses for the array configuration. Correlations using data for the individual sessions were not significant. However, a low positive correlation was evident when data from the two array sessions were combined. The correlation between accuracy and confidence rating was $r = 0.24$ ($p < 0.0001$). The correlation between response time and confidence rating was not significant ($r = -0.05, p > 0.0364$).

An analysis that included all of the configurations (front, back and array) was conducted (See Table 9).

Table 9. Performance Analysis for All Configurations.

Dependent Variables	Configurations
Absolute Accuracy	F06 B06 A02 A01 F08 B08 B10 F10 F12 B12
Confidence Rating	F06 A02 A01 B06 F08 B08 F10 B10 F12 B12

Configuration was significant ($F(9,70) = 14.34$ $p < 0.0001$) for absolute accuracy. The front configuration with 6 sites was the most accurate (95%). Mean accuracy scores and confidence ratings for all configurations in the study are presented in Figures 10 and 11.

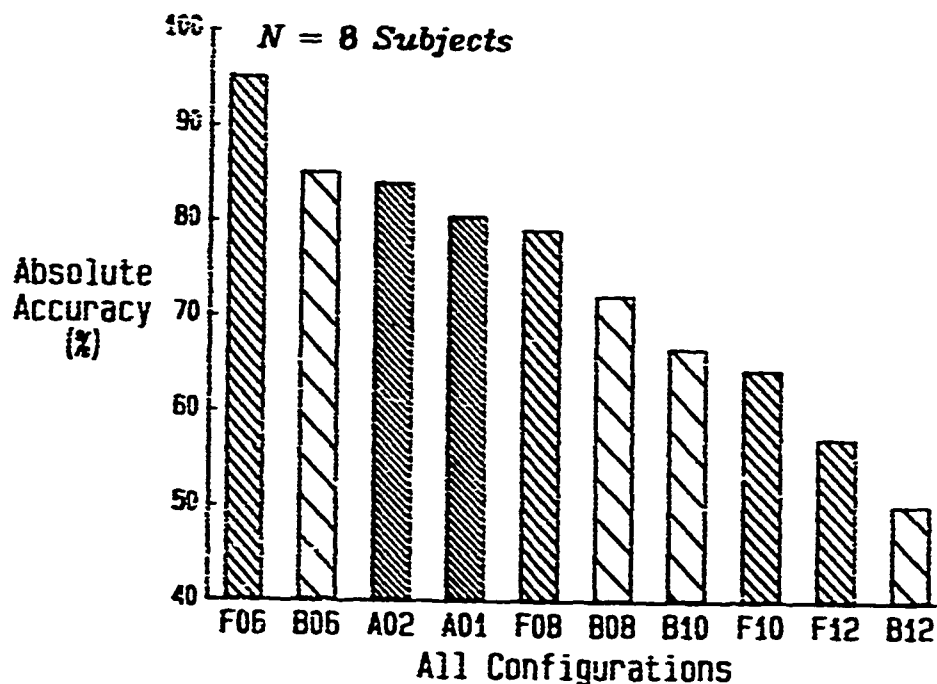


Figure 10. Mean Absolute Accuracy for All Configurations.

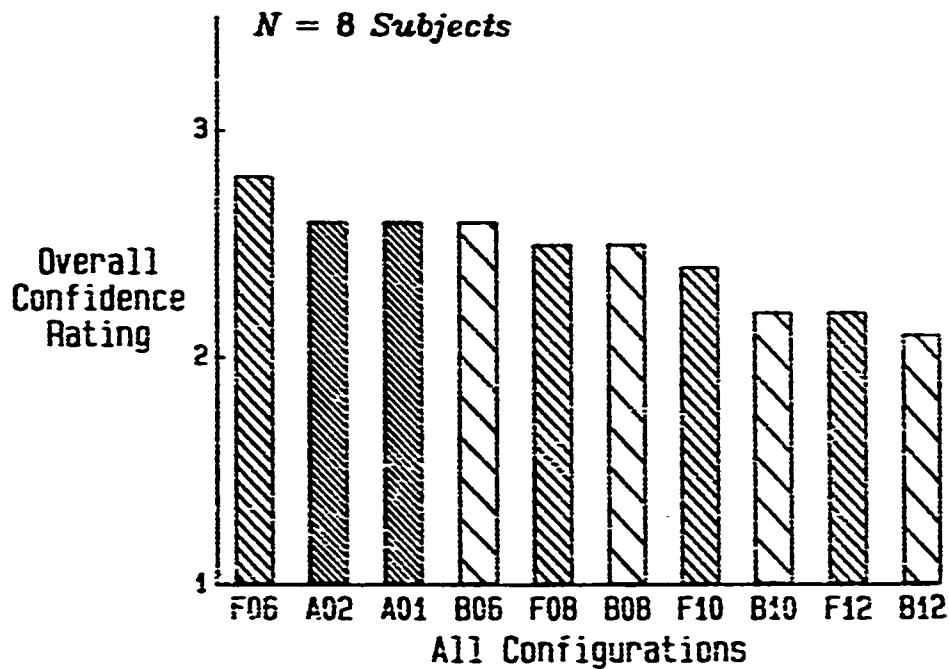


Figure 11. Mean Confidence Rating for All Configurations.

Response time was not significant ($F(9,70) = 0.99, p > 0.4546$) but rating was significant ($F(9,70) = 5.23, p < 0.0001$). The front configuration with 6 sites (2.8) differed significantly from the back configuration with 12 sites (2.1).

Correlations for the overall study followed the general trend. The correlation between absolute accuracy and confidence rating was moderate ($r = 0.29, p < 0.0001$) and the correlations between response time and rating and response time and accuracy were

slightly negative ($r = -0.23$, $p < 0.0001$ and $r = -0.12$, $p < 0.0001$) respectively.

Separate analyses of individual site differences for 6, 8, 10 and 12 sites were conducted for both the front and the back configurations. For the front plane, response times were faster for the extreme ends and center positions (e.g., for the 12-site condition, site 1 (2107 msec), site 12 (1977 msec), and site 6 (1922 msec) provided the fastest response times). This pattern occurred at all levels but was not significant for 6 sites. Confidence ratings followed the same pattern with the center and end sites receiving the highest ratings.

Although a similar trend was evident for the back plane (except that the center position was not as fast for the 8- and 10-site levels), the differences between response times were not significant. Confidence ratings followed the same pattern as the response times.

The tendency for better performance for the center and extreme end sites was also evident for the front and the back planes with respect to absolute accuracy. However, the differences were not significant at any level except for the 12-site front plane ($F(11,77) = 3.55$, $p = 0.0005$). Under this condition, site 6 had the highest accuracy (93%) followed by site 12 (69%). The high accuracy score achieved for site 6 and the drastic drop in accuracy

for the next highest site was an interesting but unexplainable occurrence.

An analysis of individual site differences was also conducted for the array configuration. Accuracy differed significantly for the different stimuli ($F(11,77) = 7.3, p < 0.0001$). Stimulus 10 was correctly identified only 43% of the time which was significantly lower than all other stimuli (ranging from 94% for site 3 to 65% for site 12). Response times and confidence ratings did not vary significantly across individual sites.

5.2 Study 2 Results

The same dependent measures of performance that were used in Study 1 and described in Section 4.3.2.2 were used in this study. Means and standard deviations for the dependent variables are presented in Table 10.

Table 10. Means (Standard Deviations) of Helmet Response Measures for Study 2.

Condition	All Trials				Correct Trials	
	Absolute Accuracy	Relative Accuracy	Response Time	Confidence Rating	Response Time	Confidence Rating
Front Helmet-Only	84%	100%	1559 (613)	2.6 (0.5)	1490 (580)	2.7 (0.5)
Front CTS	81%	99%	2194 (1061)	2.5 (0.6)	2105 (1019)	2.5 (0.5)
Back Helmet-Only	82%	99%	1754 (639)	2.4 (0.6)	1704 (630)	2.5 (0.5)
Back CTS	75%	97%	2357 (990)	2.3 (0.6)	2245 (911)	2.4 (0.6)
Array Helmet-Only	92%	---	1671 (873)	2.7 (0.5)	1616 (624)	2.8 (0.4)
Array CTS	87%	---	2222 (1238)	2.5 (0.6)	2197 (1260)	2.6 (0.4)

The data for each measure are based on 40 trials per subject for the front and back configurations and 60 trials per subject for the array configuration (5 trials per solenoid site). The means for the various dependent measures with and without CTS loading are plotted in Figures 12 through 17.

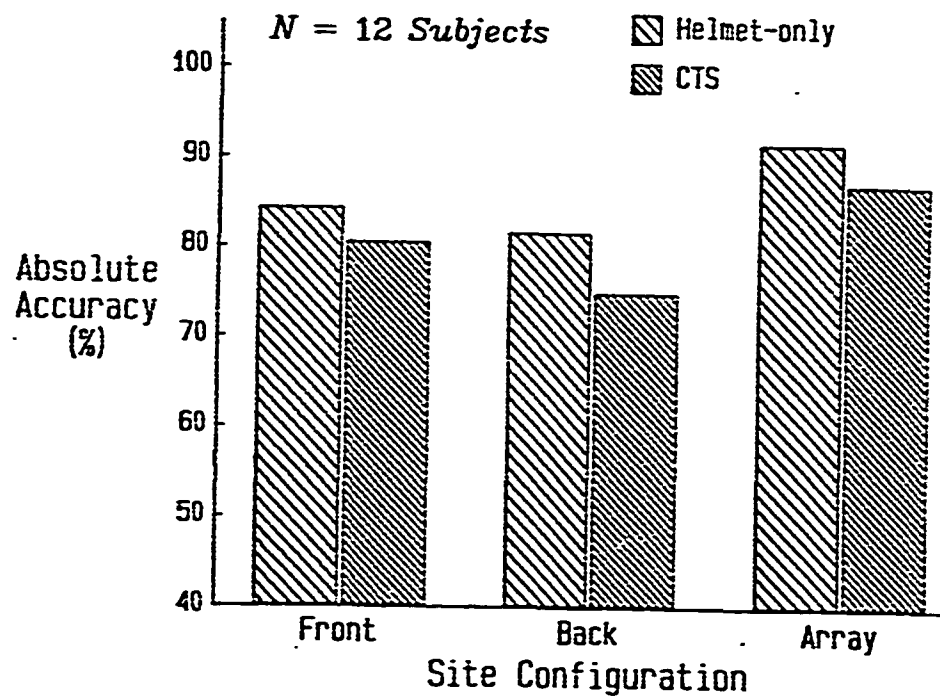


Figure 12. Mean Absolute Accuracy for Task Loading Condition.

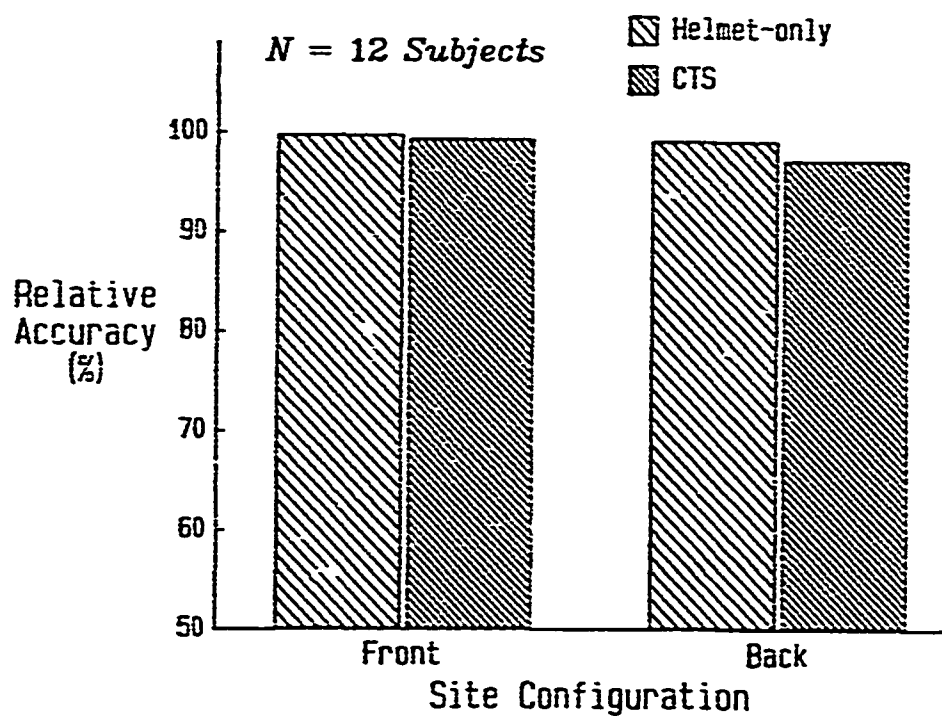


Figure 13. Mean Relative Accuracy for Task Loading Condition.

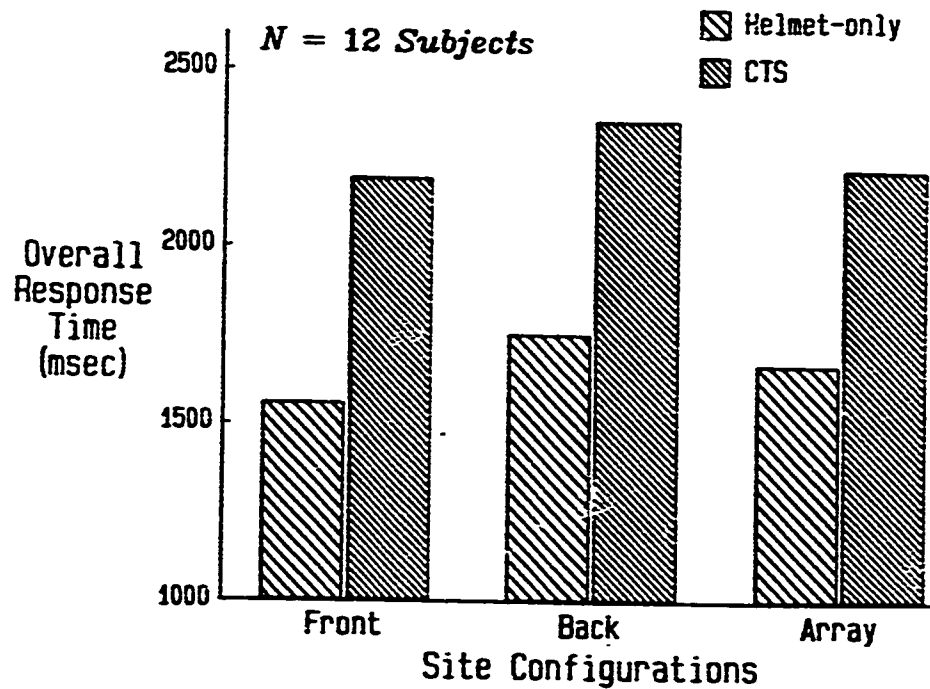


Figure 14. Mean Response Time for Task Loading Condition.

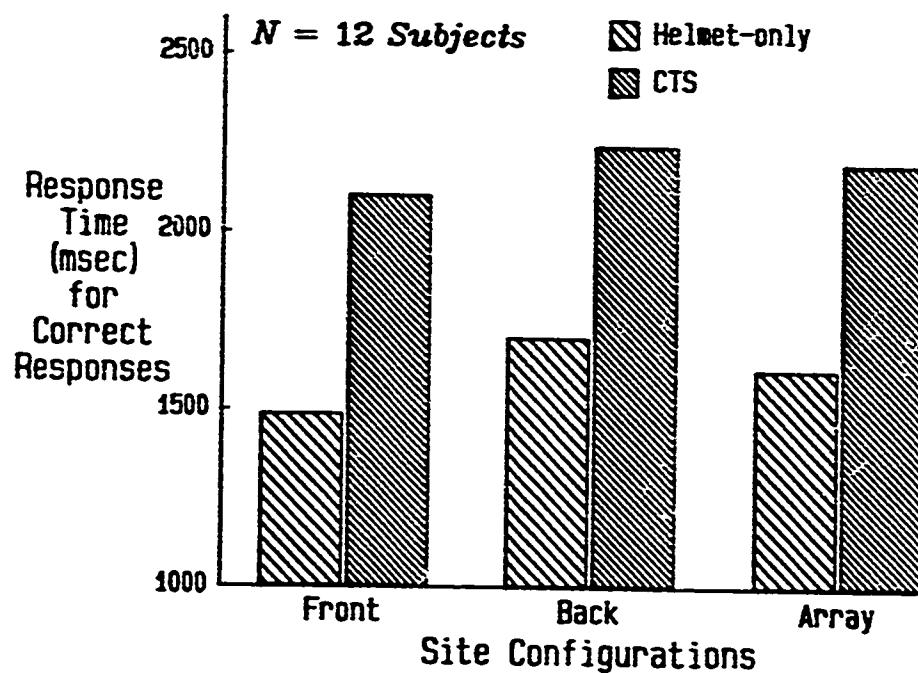


Figure 15. Mean Response Time for Correct Responses for Task Loading Condition.

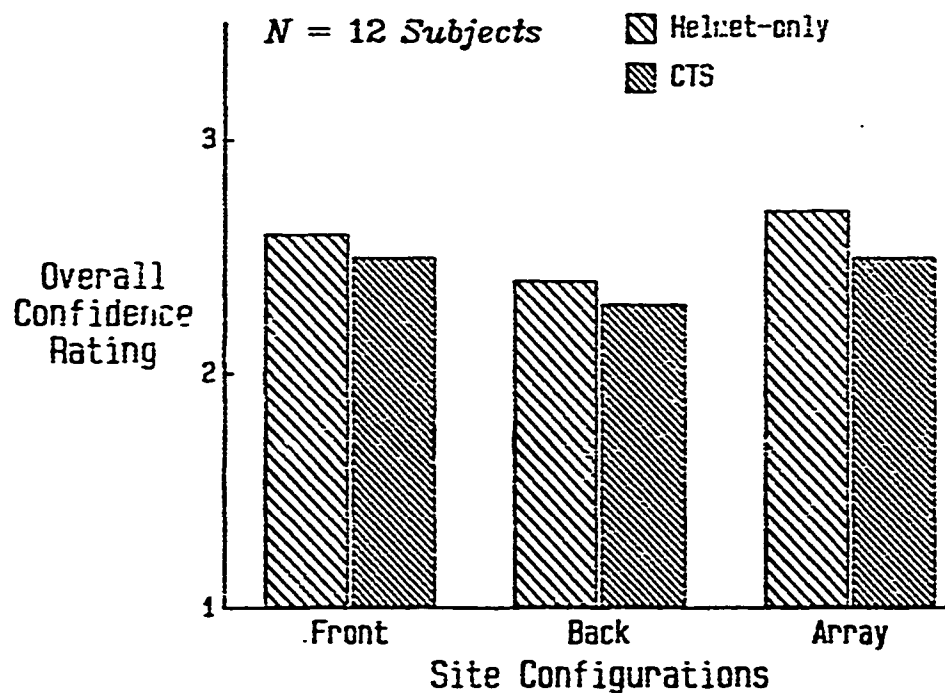


Figure 16. Mean Confidence Rating for Task Loading Condition.

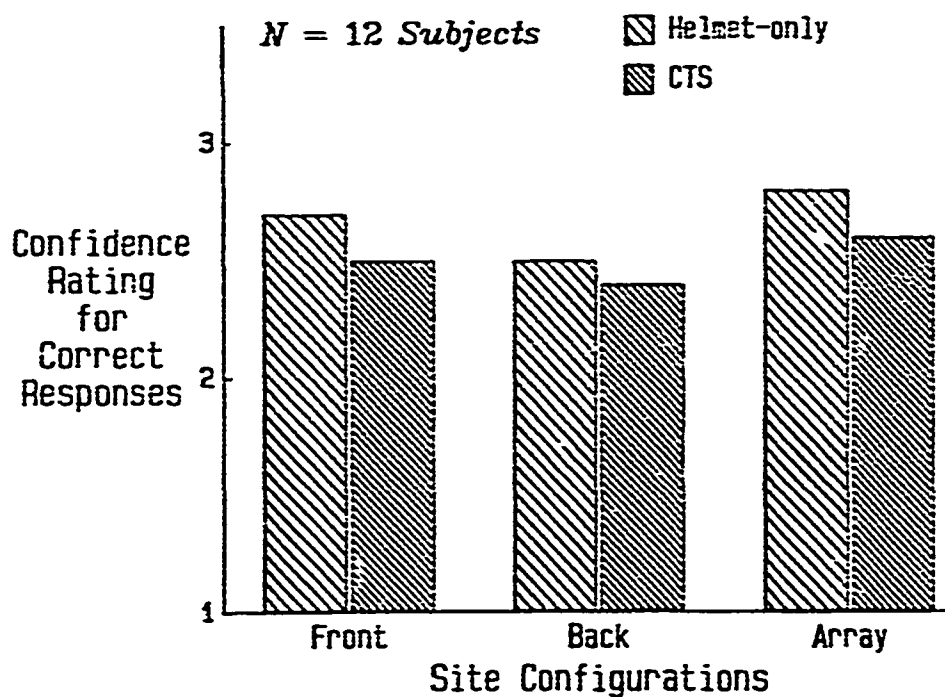


Figure 17. Mean Confidence Rating for Correct Responses for Task Loading Condition.

There were no significant interactions between configuration and task loading for any of the dependent measures. Performance differences among the various helmet configurations were significant only for absolute accuracy and confidence rating. For the absolute accuracy score ($F(2,22) = 12.28, p = 0.0003$), the array configuration was significantly better than the front and back configurations. Relative accuracy was not evaluated because it was inappropriate in scoring the array condition.

Confidence ratings differed significantly ($F(2,22) = 18.74, p < 0.0001$) with the back configuration being significantly lower than the front and the array configuration. This coincides with the results of Study 1.

Performance differences for the task loading conditions (helmet alone vs. helmet with CTS) were significant for all dependent measures. In all cases, performance on the helmet-only task was significantly better than for the helmet with CTS loading. For absolute accuracy, there was a relatively weak level of significance ($F(1,11) = 8.56, p = 0.0138$). This indicates that although there was a difference between the helmet-only condition (87%) and the helmet with CTS condition (82%), the differences in accuracy were slight. Performance under the task loading condition was still very good with respect to absolute accuracy.

Response times for the helmet with CTS condition were significantly longer than for the helmet-only condition ($F(1,11) =$

Response times for the helmet with CTS condition were significantly longer than for the helmet-only condition ($F(1,11) = 16.22, p = 0.0020$). This was at least partially caused by the task configuration which required that subjects move their hands from one control device to another and schedule manual responses between the CTS Memory Search task and the helmet identification task. A verbal response to the tactile stimulation or a multi-function control device would probably reduce this response time decrement.

Differences in confidence ratings were significant ($F(1,11) = 9.78, p = 0.0096$) with an overall lower confidence for the helmet with CTS condition.

As in Study 1, subjects were faster and more confident when making correct localizations. The correlation between absolute accuracy and confidence rating for the front plane, helmet-only task ($r = 0.37, p < 0.0001$) was greater than for the helmet with CTS loading task ($r = 0.27, p < 0.0001$) for the helmet with CTS condition. Subjects were less sure of themselves when making correct responses under conditions of high workload. This pattern occurred but was less pronounced for the back and array configurations. Subjects tended to be more comfortable and more confident of their responses with the array configuration regardless of the task loading condition.

Correlations between response times and ratings followed a similar but more pronounced trend. Correlations were higher for the helmet-only condition than for the helmet with CTS condition. The correlation for the front configuration was $r = -0.37$ ($p < 0.0001$) for the helmet-only task vs. $r = -0.21$ ($p < 0.001$) for the helmet with CTS task. The correlation for the back was $r = -0.32$ ($p < 0.0001$) for the helmet-only task but there was no significant correlation for the helmet with CTS task. The correlation for the array was $r = -0.34$ ($p < 0.0001$) for the helmet-only task and $r = -0.21$ ($p < 0.0001$) for the helmet with CTS task.

Analyses for individual site differences followed the same pattern as previously described in Study 1. Response times and ratings differed significantly for the extreme ends for both the front and back configurations. Subjects were faster and more confident in responding to sites 1 and 8. Site 10 continued to have the lowest accuracy for the array condition, but the difference was not significant for this study.

5.3 CTS Performance

To assess the possible influence (or intrusion) of the helmet task on operational performance, CTS performance was examined across all testing conditions. Means and standard deviations for the dependent variables are presented in Table 11.

Table 11. Means (Standard Deviations) of CTS Response Measures.

Response Measure	Baseline		With Helmet		
	Single Task	Dual Task	Front	Back	Array
Memory Search Response Time	740 (127)	828 (176)	1230 (243)	1214 (197)	1174 (169)
Memory Search Percentage Correct	97 (0.03)	95 (0.06)	88 (0.11)	90 (0.09)	89 (0.08)
Unstable Tracking RMS Error	34 (7.6)	34 (8.1)	41 (3.7)	41 (4.2)	42 (4.2)
Unstable Tracking Edge Violations	33 (31)	30 (25)	99 (45)	108 (61)	120 (56)

The performance measures for the CTS tasks were described in Section 4.4.2.2. The means are plotted in Figures 18 through 21. The single and dual task summaries are each based on two baseline trials per subject (without the helmet in place).

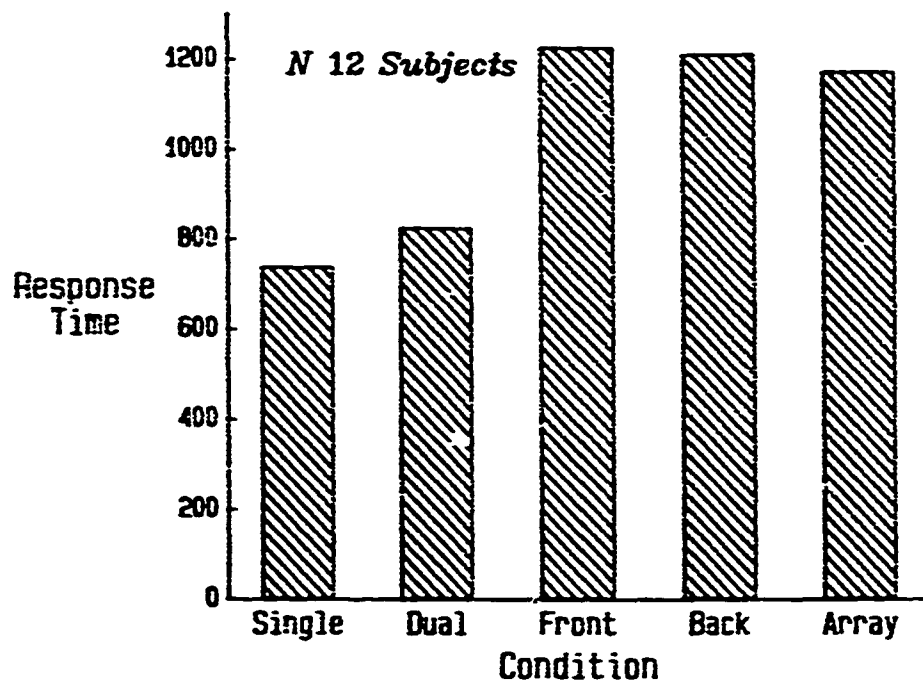


Figure 18. Mean Response Time for Memory Search.

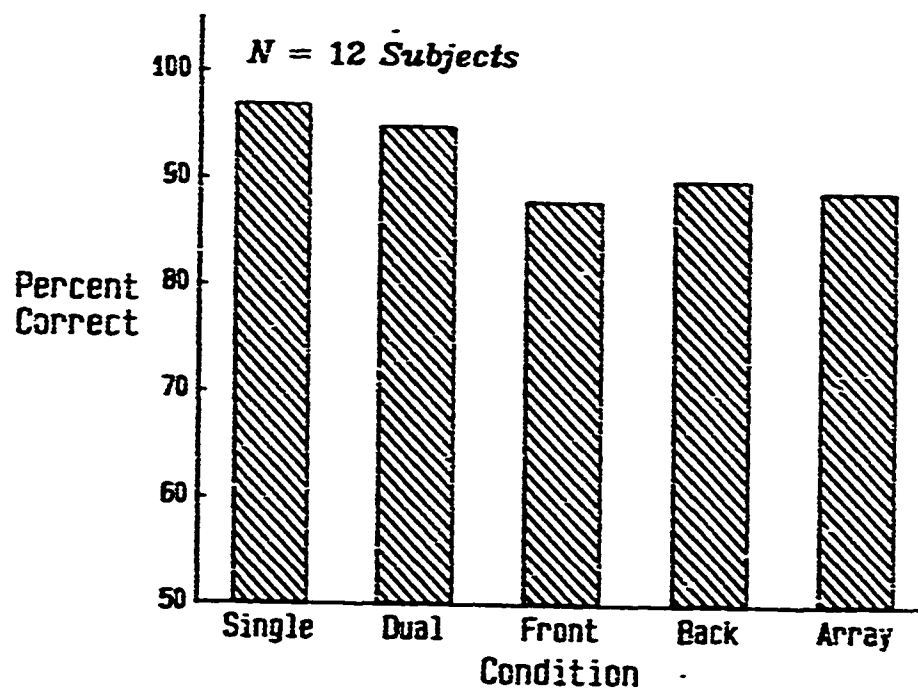


Figure 19. Mean Percentage Correct for Memory Search.

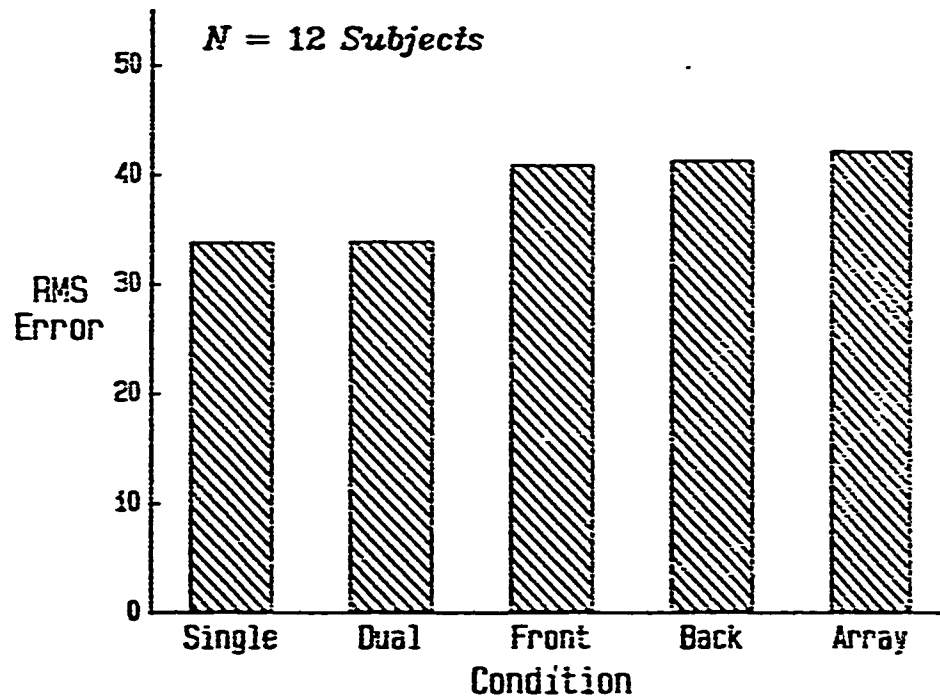


Figure 20. Mean RMS for Unstable Tracking.

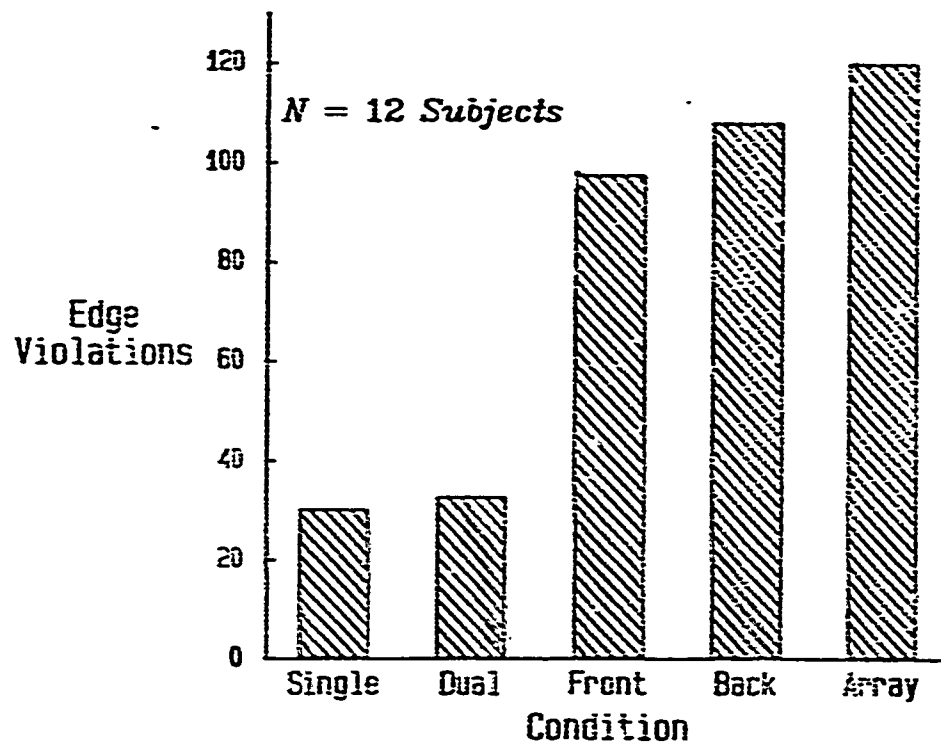


Figure 21. Mean Number of Edge Violations for Unstable Tracking.

Performance on CTS tasks in conjunction with the helmet task was significantly worse than under baseline conditions. This was true for all four dependent measures.

Memory Search response times were approximately 45% slower under the helmet conditions ($F(4,43) = 67.62, p < 0.0001$). Again, this was at least partially due to the scheduling of limited manual response resources. The percentage of correct responses dropped from 95% under baseline conditions to a low of 88% for the front plane. Thus, subjects took longer and were less accurate in their responses.

Unstable Tracking performance was significantly worse in terms of the RMS Error score ($F(4,40) = 28.46, p < 0.0001$) and the number of Edge Violations ($F(4,40) = 38.34, p < 0.0001$). Performance differences were particularly evident with the Edge Violation score which went from 32 under the baseline condition to 98 for the front, 108 for the back, and 120 for the array configurations. Part of this difference could be attributed to the visual demands of responding to the helmet stimulus. Due to the task requirements, subjects were forced to direct their hands from the Memory Search response keypad to the helmet response keyboard, search for the appropriate response, and then return their hand to the MS keypad while simultaneously maintaining control of the tracking task with the other hand. As previously

stated, this problem could be reduced with alternate response modes for the helmet stimuli.

CHAPTER VI

SUMMARY

6.1 Conclusions

Based on the results of this research, the configuration of tactile stimuli on the human head did affect detection and localization performance. Study 1 revealed that subjects were able to detect and localize 6, 8, 10, and 12 tactile stimuli configured on the front and rear planes of the scalp. Performance began to deteriorate at 10 sites and subjects had considerable trouble identifying and localizing stimuli at 12 sites for both the front and the back configurations. Although there were no differences between the front and the back configurations with respect to accuracy and response time, lower relative accuracy and confidence ratings indicated that subjects experienced difficulty localizing target stimuli for the back configuration.

The high scores achieved for the array configuration provided favorable results for the feasibility of a tactile helmet display since this configuration was the most realistic. Subjects were very confident in their responses for the array configuration.

Accuracy performance for the array configuration was comparable to the much lower 6- and 8-site configurations. but response times were closer to the 10-site configuration.

Subjects were typically faster and more confident in their responses when they were responding correctly. As expected, performance was better for the smaller number of stimulus sites (6 and 8). Subjects responded faster and were more accurate for the outermost sites for the front and back linear configurations. The center site was also significantly better on the 10-site and 12-site conditions. Subjects remarked that the center site provided an additional point of reference when a larger number of sites were stimulated.

The results of Study 2 revealed that target detection and identification were possible under conditions of high mental workload. There appeared to be no significant difference in accuracy between high mental workload and non-distracting conditions. The only significant difference between the two conditions was with respect to response time. Unfortunately, the effect of the helmet task on the concurrent human performance tasks was significant. Ongoing task performance was degraded in comparison with baseline conditions. The CTS performance suffered the most for the array configuration. The need for more time to respond to stimuli for this configuration may have contributed to the lower CTS performance.

6.2 Additional Observations

There were several observations that were made during the investigation. Some of these were experimenter observations and others were observations made by subjects (usually by several subjects). These observations were not scientifically documented nor explored. The observations are as follows:

1. Uniform stimulation was difficult to control. Because the "throw" of the solenoid was only 4 to 5 mm, the alignment of the solenoids with the scalp had to be fairly exact. In addition, because the helmet was 'one-size fits-all', it was harder to align the solenoids with the scalp of subjects with small heads. This was especially true for the back of the head. It was difficult to control contact for this region of the scalp for subjects with small heads. As the helmet began to settle, it shifted backward increasing contact for the front solenoids and decreasing contact for the back solenoids. This occurrence and even slight head movements would require helmet re-adjustment.

2. The time between trials was an important variable in response accuracy. Many subjects noted that if a site was not stimulated for a fairly long time, it was more difficult to be accurate in localization of that site. Subjects had to be re-familiarized with stimulus site

locations whenever pauses in testing lasting more than 30 seconds to 1 minute occurred.

3. Occasionally subjects would get displaced one solenoid position and carry that displacement through a series of trials. This indicated that some subjects relied more on previously stimulated solenoid positions than they relied on the point that was actually stimulated on their head.

4. Subjects noted distinct and interesting reactions to the condition involving both the helmet task and the CTS dual-task. As noted previously, subjects were literally saturated with simultaneous activities in this condition. Subjects responded to the tracking task with the preferred hand and the memory task and the helmet task with the non-preferred hand. During this condition, subjects noted that they first had to derive a way to schedule their responses. Several subjects complained of getting confused and responding to the helmet task on the Memory Search keypad.

6.3 Recommendations for Future Research

A great deal of research is still needed to answer many questions of interest regarding the feasibility of using tactile stimuli to provide situation information to pilots. Among the more basic issues is the question of the need to re-familiarize operators to respond to specific sites after relatively short interstimulus breaks.

The necessary frequency of this recalibration in an operational setting is a question that must be addressed.

Another important issue that should be explored is whether some of the response time decrements observed in this study can be reduced by using verbal response time measures to the helmet stimuli or by providing a device that permits responses to more than one event.

It is also important to determine the costs vs. the benefits of a tactile device with respect to other tasks. The disruptive effects of the helmet must be evaluated and compared with alternative methods of providing the same information to the operator.

Overall, the tactile helmet appears to have potential for providing pilots with important information about their environment. However, considerable research is still needed to explore the effectiveness of this new device.

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