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UNIVERSITY OF ALBERTA

SPATIOTEMPORAL FACTORS AND TACTILE MOTION DIRECTION DISCRIMINATIONS

BY ©

KARSTEN A. LOEPELMANN

A THESIS SUBMITTED TO THE
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Spatiotemporal factors and tactile motion direction discriminations," submitted by Karsten A. Loepelmann in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Various spatiotemporal patterns were delivered to the distal pad of the left index fingertip via an OPTACON, a tactile reading aid for the visually impaired. Patterns consisted of bars, meaningless shapes, and Roman alphabetic letters. These patterns were moved across the fingertip along one of two axes: proximal-distal or laterally left-right. The rate of pattern motion was also varied. Observers attempted to discriminate which one of two pairs contained patterns moving in opposite directions. Results are analyzed in terms of masking and temporal integration; and alternate explanations are given. Implications for the design of tactile visual-substitution systems are discussed.

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INTRODUCTION

Imagine living in a world devoid of books, newspapers, and street signs. Such everyday things are often taken for granted—until they are gone or inaccessible. Among the losses experienced by the visually impaired, the loss of access to visual information is probably the most pervasive. The problem is one of finding an alternate means of obtaining information, which would otherwise be inaccessible. One (at least partial) solution is "sensory substitution": the use of one of the remaining intact senses as a substitute or adjunct for the impaired modality. Sensory substitution can provide greater interaction with the environment in two important ways. First, when the primary sense relied on for navigation (i.e., vision) is impaired, the ancillary modality can supply a means of obstacle avoidance, making locomotion through the environment safe and effective. Second, signals and symbolic information (i.e., printed text) in the environment may be extracted by the auxiliary modality and utilized, allowing one to maintain ties with greater society. However, the use of direct sensory substitution creates its own unique set of problems.

The first question that must be addressed is: Which modality should be used as the substitute? The tactile modality has been suggested as a feasible substitute for vision, for several reasons (Geldard, 1977; Lechelt, 1978). First, the skin is able to detect several different types of physical energies and is well-suited to respond to a wide range of spatiotemporal stimulation (Lechelt, 1986a). Second, the skin can process information over a spatially extended area, similarly to vision (Geldard, 1970). Thus it appears that the skin is able to process a variety of stimuli, and it can do so efficiently.

The next important question is: What is the best way of delivering information to the substitute or auxiliary modality? An early method of sensory substitution to assist in symbol processing was Braille, which uses a pattern of up to six raised dots to represent the letters of the alphabet, instead of the usual Roman characters. However, Braille reading is slower than visual reading (Loomis, 1981), and the source material must be converted to tactile form before it can be accessed. More recently, the TVSS, a video-to-skin system, was designed to capitalize on the skin's ability to process spatial information by presenting an isomorphic representation of the visual stimulus to the tactile modality (see Bach-y-Rita, 1972). However, Craig and Sherrick (1982) concluded that performance did not live up to expectations, in part because the skin cannot process information to the same extent as the visual system.

It is clear that the skin is not the retina, and as such, cannot process information in the same way. Past attempts at sensory substitution have revealed that not enough was known about the skin's ability to process information to provide an optimal solution (Kirman, 1973). The skin's information processing capacity must first be determined (Bach-y-Rita, 1980; Lechelt, 1984; Sherrick, 1982). In order to enable the skin to meaningfully process impinging stimulus patterns, we must first learn its "language." The ultimate goals of research into sensory substitution are to find the most efficient means of transmitting information. Specifically, the objectives are: a) to provide the skin with stimuli that it is eminently capable of discriminating and processing, and b) to provide a high fidelity in the tactile world with changes in the visual world; that is, to maximize the utility of sensory substitution systems by minimizing the time lag between onset of the visual stimulus and presentation of the transmogrified stimulus to the skin.

These findings can then be applied to existing sensory substitution systems, or can provide the basis for the design of future systems.

The Importance of Motion

Motion appears to be an important component in obtaining tactile information. "Merely resting the hand on a material may suffice to evoke a simple impression of surface-touch, but to feel modifications of the surface (hardness, graininess, etc.) and thus to recognize the specific material, movement is necessary," (Krueger, 1970; p. 339). There is evidence that stimuli moving across the skin activate motion-sensitive neurons in the primary somatosensory cortex (e.g., Warren, Hamalainen, & Gardner, 1986).

However, motion has not always been found to be beneficial. The OPTACON, a tactile reading aid for the visually impaired, can present moving stimuli to the distal pad of the left index fingertip; the tactile stimuli are isomorphic with digitized visual stimuli. In the so-called "Times Square" or "scan" mode, letters emerge from the right side of the display and appear to move leftward across it, disappearing at the left edge of the display. The illusion of movement is created by presenting a succession of "frames" of static images, much like a movie. In "static" mode, letters do not move, but appear in their entirety on the display for a certain period of time before they vanish. At the lower "display times," defined as the length of time any given part of the pattern is presented on the display, it has been found that performance in static mode is superior to scan mode (Craig, 1980; 1983a; reviewed in Loomis, 1981; Loomis & Lederman, 1986; and Sherrick, 1982). Craig (1980) has suggested that, "This result might be explained by forward and backward masking effects that could occur as the scanned pattern was being centered on the array" (p. 157). In the experimental paradigm of masking, forward masking occurs when a masking stimulus that precedes a target stimulus degrades the target; backward masking occurs when a masker follows the target and degrades it. Thus, in this mode of presentation it may be that the target essentially masks itself. A conclusive explanation has not yet been obtained.

This study investigates low-level information-processing of moving stimuli: What is the maximum rate of motion at which discriminations of motion direction can reliably be made? Although higher-level processes such as pattern identification provide more information about the stimulus, they also require more time to extract this information. This study, however, is designed to determine the limits at which motion direction discriminations can be made.

By examining the issues associated with moving stimuli, knowledge about the processes underlying tactile perception may be extended. Also, because the OPTACON is typically used in scan mode, the findings of this study may contribute to data which can be applied to existing and future tactually based vision sensory substitution systems.

Temporal Factors

Currently, there is no consensus on the critical temporal variable(s) affecting moving vibrotactile stimuli. Loomis (1981) and Taenzer (1970) posit that display time (the total time that the pattern is presented) is the most important variable. On the other hand, Gardner and Palmer (1989a) and Kirman (1974) concluded that onset asynchrony between elements of the pattern was the most significant factor, and Craig (1983b) found that stimulus onset asynchrony (SOA) predicted performance better than other temporal indices.

The current study is intended to shed some light on this issue by investigating the relative efficacy of display time and SOA in describing performance. For example, why is SOA thought to be the critical variable?

Craig (1982a; 1982b; Horner & Craig, 1989) suggested that masking degrades performance at brief SOAs. Masking is presumed to be a result of temporal integration (Craig, 1981; Craig & Evans, 1987; Evans & Craig, 1986). Evans (1987) suggested that a tactile stimulus creates a trace that is kept in a sensory store, from which it immediately begins to deteriorate. If a second stimulus is presented in sufficiently close temporal contiguity with the preceding stimulus—such that the first trace has not sufficiently deteriorated—then the two traces will combine, effectively masking each other.

As noted above, Craig (1980) suggested that forward and backward masking between the elements that comprise motion may be responsible for the poorer performance of scan mode, as opposed to static mode. Although this study does not employ a masking paradigm, this issue will be explored.

Spatial Factors

One of the goals of sensory substitution is to determine what constitutes a "good" tactile stimulus pattern, and what characteristics make stimuli maximally discriminable. According to Sherrick (1982), "We must seek a small set of features that appear to be elemental to the recognition process in current tactile displays. These may be actual patterns themselves. . .or they may be the relations among these patterns" (p. 36).

Spatial complexity of the stimulus (roughly correlated with the number of component line segments in a pattern) appears to affect performance. For example, Gardner and Palmer (1990) found a significant negative correlation between the total number of line segments in an alphabetic character and the probability of correct tactile identification. Also, Lechelt (1986b) found that "simpler" letters such as *I* and *L* produced more correct tactile identifications than the more complex letters *G* and *B*.

In the above studies, the observers' task was to identify the letters, which requires high-level cognitive processing such as feature analysis or template matching. Little research has been done examining the effects of spatial complexity on low-level discriminations. Characters contain features that may differentially aid in extracting information from the pattern of stimulation. It may be that more complex patterns are harder to identify because of a difficulty in extracting *any* information from them.

The current study investigates the effects of spatial complexity on discriminations of motion direction in order to determine if stimulus complexity affects stimulus motion information extraction. Also, the effects of higher-order information (i.e., the meaningfulness of the stimuli) on this low-level task will be examined by presenting observers with stimulus patterns ranging from lines to alphabetic letters.

EXPERIMENT 1

This experiment focused on the effects of SOA between successive presentations of the stimulus patterns comprising motion in Times Square mode on the observers' ability to discriminate the direction of simple, moving stimuli. Bars of vibrotactile stimulation were moved along different axes (i.e., up-down, and left-right), but across equal areas of the index fingertip pad.

The questions addressed in this experiment included: a) How does the SOA between frames affect discriminations of motion direction? b) Is knowing the SOA sufficient for predicting this discrimination, or is knowing display time also necessary?

Method

Subjects

Four sighted volunteer observers participated in Experiment 1: three males and one female. Two of the male observers had participated in several previous sensory-perceptual experiments employing the equipment used in this research. The remaining two observers had no prior experience with this apparatus system. All observers participated in all conditions of the experiment.

Apparatus

An OPTACON (OPtical-to-TACtile CONverter) tactile display unit (TeleSensory; Mountain View, California) interfaced with an IBM PC XT microcomputer was used to deliver tactile stimuli (Loepelmann & Lechelt, 1991). The OPTACON's display consists of a matrix of 144 (6 column × 24 row array) piezoelectric bimorph reeds or "pins" vibrating at 230 Hz. Each pin is under computer control, and may be activated individually. The computer provides complete control over temporal and spatial aspects of the vibrotactile pattern. The user rests his or her fingertip in a "cradle," having 144 small holes (see Figure 1). When an element of the matrix is activated, the corresponding pin emerges from the hole, contacts and indents the skin.

By pressing one of five pushbuttons on a keypad, observers were able to initiate trials and make responses.

Stimuli

In Experiment 1-A, stimuli consisted of vertical bars 1 column wide by 10 rows high. Each bar was "scrolled" or moved right or left across the width of the matrix (6 pins). Note that the bars were scrolled along the 10 uppermost rows of the tactile display. In Experiment 1-B, stimuli were horizontal bars 6 columns wide by 1 row high, and were scrolled up or down across the upper 10 rows of the matrix.

The motion achieved on the OPTACON display was not continuous across the matrix, but rather was accomplished by presenting the stimuli in a sequence of discrete steps or "frames." After onset of a stimulus frame, there existed a brief temporal delay before this extant frame was replaced by the succeeding frame, in which the relative position of the bar was changed by a small amount (i.e., by one row or column in the desired direction of motion) from the previous position. The result of consecutive presentations of these display frames was a percept of motion. This delay between successive frame onsets represents the stimulus onset asynchrony (SOA) between frames. The same five SOA values were used for both the horizontal and vertical motion conditions: 5, 10, 15, 20, and 25 ms.

Presentation of moving stimuli via the OPTACON is conventionally described in terms of display time, defined as beginning when an element of the stimulus pattern appears on one side of the matrix, and as ending when that element exits the opposite side of the matrix (see Craig, 1981). However, because the pins on the tactile matrix are spaced closer vertically than horizontally, the display times for vertical and horizontal motion across the same amount of physical space differ. That is, although both horizontal and vertical motion occurred across the same amount of physical space (about 11 mm), a greater number of steps was required to scroll the bars vertically, which resulted in a longer display time in comparison to horizontal motion. Thus, at the same SOA between frames, there existed differences in display time between horizontal and vertical motion conditions. Display times for the moving bars in Experiment 1-A were 30, 60, 90, 120, and 150 ms, whereas in Experiment 1-B, display times were 50, 100, 150, 200, and 250 ms. Although it is possible to change the SOA so that the display times in the horizontal and vertical motion conditions are equal, this manipulation would result in a difference between conditions in the total amount of energy delivered to the skin.

Attempts were made to minimize any differences between Experiments 1-A and 1-B. First, the number of pins activated by stimuli in Experiment 1-A (10 × 1 pin stimulus, scrolled horizontally by 6) was equal to that in Experiment 1-B (1 × 6 pin stimulus, scrolled vertically by 10). As a result, the total amount of energy delivered to the skin was the same across experimental conditions. Second, horizontal and vertical motion occurred across approximately equal physical areas on the skin (11.0 vs. 11.25

mm, respectively). Thus, the main differences between Experiments 1-A and 1-B were in display times and axis of motion.

Procedure

Each participant sat in front of the OPTACON and placed the pad of the distal phalange of his or her left index finger on the tactile matrix. The left hand was used because: a) the OPTACON is designed to accommodate the left hand, and b) previous studies (Benton, Levin, & Varney, 1973; Benton, Varney, & Hamsher, 1978) found that the left hand was superior to the right in determining the direction of moving tactile stimuli.

The amplitude of pin vibration was kept at a constant, comfortable level that was maintained throughout the experiment. To reduce distractions and auditory cues produced by the vibrotactile matrix, observers wore headphones that delivered white noise.

Trials were self-paced, and employed a two-alternative forced choice procedure. In Experiment 1-A, four vertical bars were scrolled right-to-left or left-to-right across the matrix. In each trial, three of the bars moved in the same direction; one bar always moved in the opposite direction of the other three. This "opposite motion" bar was systematically varied to appear in all possible temporal positions (i.e., first, second, third, and fourth). The stimuli were temporally grouped into two pairs of two bars each, with a temporal gap of 100 ms within pairs and 250 ms between pairs. Because of this grouping, one stimulus pair contained two bars moving in the same direction, whereas the other pair contained two bars moving in opposite directions. The observers' task was to identify the pair of bars (i.e., first or second) that contained the opposite motion bar.

Observers pressed a pushbutton on a keypad to indicate their responses. The direction of motion of the opposite motion bar was balanced across trials: in half the trials, three bars moved right and the opposite motion bar moved left; in the other half, three bars moved left, and the opposite motion bar moved right. No trial-by-trial feedback was given.

The procedure employed in Experiment 1-B was identical with that of Experiment 1-A, except that horizontal bars scrolled up or down across the fingertip, instead of right or left. Participants were again required to select the pair of bars that moved in opposite directions.

Each observer participated in all conditions of the experiment, which was run in 25 blocks of 80 trials each. Each experimental condition (five SOAs by two directions of opposite motion) was presented 200 times, for a total of 2,000 trials in Experiment 1-A, and another 2,000 trials in Experiment 1-B. The order of presentation of conditions in each block was randomized. Experiments 1-A and 1-B were alternated every five blocks to reduce any practice effects.

Results and Discussion

Mean percent correct discriminations of motion direction were calculated for each experimental condition. These results are shown in Figure 2. It is evident that as SOA increased, observer performance improved appreciably in both parts of Experiment 1, and approached asymptote at the larger SOAs. These observations were confirmed by statistical analysis. Correct discriminations of motion direction were examined in Experiments 1-A and 1-B using a two-way (direction of opposite motion and SOA between frames) fixed-factor repeated-measures analysis of variance (ANOVA).

As expected, there was a statistically significant main effect of SOA in Experiments 1-A (F [4, 12] = 50.76, $p < 0.001$) and 1-B (F [4, 12] = 49.16, $p < 0.001$). Specifically, as SOA increased, percent correct discriminations increased. Post hoc analysis employing Scheffé's procedure revealed that in Experiment 1-A there were significantly fewer correct discriminations at the 5 ms SOA than at the three longest SOAs ($S^2 = 16.02$, $p < 0.05$). In Experiment 1-B, performance in the 5 ms SOA condition was significantly lower ($p < 0.05$) than at all other SOA levels; also, direction discriminations at 10 ms SOA were significantly poorer ($p < 0.05$) than in the 25 ms SOA condition. It was also found that performance in both Experiments at 5 ms SOA was at chance level.

A main effect of opposite motion direction was obtained (F [1, 3] = 37.67, $p < 0.01$). Observer performance was better when the opposite motion bar moved left than when it moved right. The observers may be more sensitive to stimuli moving left because English-reading people typically scan visual information from left to right; as a result, the stimuli "move" left across the field of view. It may be that the observers are better able to process left-moving stimuli across modalities. However, it should be noted that no differential direction sensitivity effect was obtained in the succeeding experiments, in which more complex tactile patterns were used (see below).

An additional two-way (axis of motion, SOA between frames) fixed-factor repeated-measures ANOVA was performed to determine whether Experiments 1-A and 1-B differed. As may be expected from the above results, there was again a significant main effect of SOA: percent correct discriminations increased as SOA increased (F [4, 12] = 58.94, $p < 0.001$). No axis of motion × SOA interaction was obtained; that is, there were no differences between Experiments 1-A and 1-B at any SOA level. However, when the results are shown in terms of display time, some differences emerge from the data (see Figure 3). The differences between the Experiments were significant at display times of 50 ms ($t = 3.49, p < 0.05$) and 100 ms ($t = 2.83, p < 0.05$). These differences became smaller as display time increased, and in fact were nonsignificant at the 125 ms and 150 ms display times. (Note that the *t* tests were based on linear interpolation of Experiment 1-A scores at 50 ms and 100 ms display times, and linear interpolation of 1-A and 1-B at 125 ms display time.)

Because the same amount of energy was delivered on trials in each experimental condition, these differences could not have been caused by differential amounts of energy delivered to the skin. Likewise, because the motion occurred over approximately the same area of skin, the distance across which the bars moved cannot account for the results. Thus, it seems most likely that the differences between Experiments 1-A and 1-B were effected by display time. Specifically, the longer the display time, the more accurate discriminations of motion direction will be (until performance reaches asymptote). This issue will be further examined in the General Discussion.

EXPERIMENT 2

Experiment 2 further examined the effects of manipulating spatial and temporal variables on discriminations of motion direction. However, compared with Experiment 1-B, the up-down motion in Experiment 2-B occurred across a larger tactile surface area so that there existed a point at which the entire, more spatially complex symbol would be displayed on the tactile matrix. This manipulation resulted in the symbols being presented in a rectangular area across the fingerpad—as opposed to the square area employed in Experiment 1. It was deemed necessary to present the entire symbol on the display in both parts of Experiment 2 so that the motion produced would simulate and have greater generalizability to OPTACON reading. Because of this manipulation, the display times in Experiment 2-B were greater at each SOA than in Experiment 1-B: 90, 180, 270, 360, and 450 ms. The display times in Experiment 2-A were the same as those in Experiment 1-A.

Another consequence of presenting the stimuli over a larger, rectangular tactile surface area was that more energy was presented to the skin on trials in Experiment 2-B than in Experiment 2-A. Moving a given stimulus over a greater area requires producing more frames of motion, resulting in a longer display time and thus a greater amount of energy. In light of the finding in Experiment 1 that changing the temporal parameters had an effect on motion direction discriminations despite holding the energy constant, it was not deemed necessary to control the amount of energy in Experiment 2. As a result, energy varied with display time. Also, unequal amounts of energy were delivered by the different stimulus symbols in Experiment 2, due to the different number of pins activated by each symbol (the more pins activated, the greater the energy produced by the tactile matrix). Although it is possible to construct symbols delivering equal amounts of energy, it was convenient to adapt existing symbols from a previous study (Lechelt & Loepelmann, 1990) for use in this experiment.

The questions addressed in Experiment 2 included: a) Does manipulating the display time overshadow the effects of SOA on motion direction discriminability? b) Are certain symbols more discriminable than others, and if so, what features of these symbols are responsible for these differences in discriminability? c) How does motion direction discriminability of complex stimuli compare to that of simpler stimuli?

Method

Subjects

Four sighted observers participated in Experiment 2. None of the three female observers had any prior experience with the apparatus. The male observer was the only one to participate in Experiments 1 and 2. Again, all observers participated in all conditions of the experiment.

Apparatus

The apparatus was the same as in Experiment 1.

Stimuli

Stimuli consisted of 10 non-alphanumeric symbols, comprised of three to five connected lines which were spatially arranged to form different features (see Figure 4). These symbols were constructed to conform to several limiting parameters. For example, some symbols were constructed of orthogonal lines, whereas others contained diagonal lines. When centred on the matrix, all symbols were a maximum of 6 columns wide.

Also, all the symbols occupied the upper 18 rows of the matrix so that they appeared only on the highly sensitive tip of the distal finger pad. As well, a fundamental characteristic applied to these "nonsense" symbols was that they were to have no intrinsic semantic value to the observers (Lechelt & Loepelmann, 1990).

Procedure

As in Experiment 1 above, the observers' task was to decide which pair of symbols contained the opposite motion symbol. In Experiment 2-A, symbols moved left or right across the width of the tactile matrix. In Experiment 2-B, the symbols moved up or down across the upper 18 rows of the matrix so that for one frame, each symbol would be displayed in its entirety on the matrix (as in Experiment 2-A). The increased scrolling distance in Experiment 2-B produced a longer display time at each SOA than in Experiment 1-B; the effects of this greater display time could be compared to the results of Experiment 1-B. Note that the energy transmitted to the fingertip in Experiment 2-A was different from that in Experiment 2-B, due to the longer display time required for vertical motion.

The temporal gap between symbols was increased to 200 ms; the gap between pairs of symbols was increased to 350 ms. Pilot studies indicated that these longer temporal gaps precluded any interference from stimulus aftereffects or aftersensations. The SOAs used were the same as those employed in Experiment 1: 5, 10, 15, 20, and 25 ms.

As in Experiment 1, a completely-crossed design was employed: 10 symbols by 5 SOAs by 2 directions of motion, for a total of 100 conditions in each of Experiment 2-A and 2-B. Each observer participated in 13 blocks of 400 trials each, for a total of

5,200 trials in each part of Experiment 2. Experiments 2-A and 2-B were alternated every block to reduce any practice effects.

Results and Discussion

Mean percent correct discriminations of motion direction were calculated. These results are shown in Figure 5. It is evident that at the briefer SOAs, performance in Experiment 2-B surpassed that in Experiment 2-A; these differences disappeared as SOA increased. Also, as in Experiment 1, observer performance approached asymptote at the larger SOAs.

These observations were confirmed by statistical analysis. Discriminations of motion direction were examined in Experiments 2-A and 2-B using a three-way (symbol, direction of opposite motion, and SOA between frames) fixed-factor repeated-measures ANOVA. As expected, there were statistically significant main effects of SOA in Experiments 2-A (F [4, 12] = 102.56, $p < 0.001$) and 2-B (F [4, 12] = 7.40, $p < 0.01$). Specifically, percent correct discriminations increased with increasing SOA. Post hoc analysis using Scheffé's procedure showed that the means of all SOA conditions in Experiment 2-A differed significantly from each other, with the exception of the two greatest SOAs, 20 ms and 25 ms ($S^2 = 13.8$, $p < 0.05$). As in Experiment 1, performance in the 5 ms SOA condition was at chance. In Experiment 2-B, the 5 ms SOA condition contained fewer correct discriminations than at the other four SOA levels.

There was a significant main effect of symbols in Experiment 2-B (F [9, 27] = 4.34, $p < 0.01$). Post hoc analysis using Scheffé's procedure ($S^2 = 17.46$, $p < 0.05$) showed that motion discriminations of symbol 3 were poorer than those of symbols 1, 2, 7, and 9. Symbol 3 was worst at indicating upward or downward movement probably because it has the smallest horizontal "limbs" of this symbol set. These limbs provide the most information on motion direction. The only other features that could indicate direction are the leading and trailing edges of the long vertical line down its centre, which is otherwise ineffective for indicating up-down motion. In comparison, symbols 1, 2, 7, and 9 all contained diagonals and horizontal lines. It is not clear which one of these features is responsible for the better performance with these symbols; it may be that both are required. Note, however, that when aggregated over all SOA conditions, performance was above 90% for all symbols (see Figure 7). It seems likely that these results are indicative of ceiling effects.

The only significant interaction obtained in Experiment 2-B was symbol × SOA (F [36, 108] = 3.48, $p < 0.001$). Due to the difficulty associated with calculating the Scheffé criterion for interactions, Tukey's HSD, another relatively conservative post hoc procedure, was employed. It was found that at the briefest SOA, differences between all symbols in direction discriminability were found; and at the 10 ms SOA, performance with symbol 5 was poorer (HSD between means = 2.99, $p < 0.05$). At longer SOAs, the differences between symbols were nonsignificant. Thus it seems that the various component features of the symbols may have differential effects on direction discriminability only at briefer SOAs. Further research is needed to determine which features contribute to this phenomenon, and why.

Another three-way (symbol, axis of motion, and SOA between frames) fixed-factor repeated-measures ANOVA was carried out to examine if any differences existed between the two parts of Experiment 2. Again, an overall main effect of SOA was obtained (F [4, 12] = 86.65, $p < 0.001$). In contrast to the results in Experiment 1, there was a difference between the two parts of Experiment 2: performance in Experiment 2-B was found to be superior to that in Experiment 2-A ($F = 99.46$, $p < 0.01$). Furthermore, there was an axis of motion × SOA interaction (F [4, 12] = 34.50, $p < 0.001$), as is clear from Figure 5. Individual post hoc comparisons between means demonstrated that the differences between Experiments 2-A and 2-B at SOAs of 5, and 10 ms were statistically significant (HSD between means = 4.82, $p < 0.05$). At the longer SOAs, these differences disappear.

Figure 6 shows that the differences between the two parts of Experiment 2 can be partially accounted for by the variable of display time. Performance in Experiment 2-A was better than that in Experiment 2-B at display times of 90 ms ($t = 8.15$, $p < 0.05$) and 150 ms ($t = 5.90$, $p < 0.05$). (Note that the latter t test was based on linear interpolation of Experiment 2-B results at 150 ms.) At any given display time, the main difference between Experiments 2-A and 2-B is the SOA between frames. It is clear that neither SOA nor display time alone is sufficient to characterize the results.

Significant symbol × SOA (F [36, 108] = 2.08, $p < 0.01$) and axis × symbol × SOA (F [36, 108] = 1.60, $p < 0.04$) interactions were found. Both of these interaction effects are products of the symbol × SOA interaction obtained in Experiment 2-B, discussed above.

Finally, an F test was performed to determine whether any overall difference existed between Experiments 1 and 2. No significant difference was found. Although intuitively it may seem easier to discriminate motion direction of simple stimuli, it may be that temporal factors are more important than spatial factors in the low-level task of determining the direction of motion.

EXPERIMENT 3

This experiment examined the effects of semantically meaningful stimuli on discriminations of motion direction. Because the spatial features of the alphabetic letters employed are (visually) familiar, it is expected that performance will be better than with nonsense symbols.

Experiment 3 investigated the following questions: a) Do the letters differ in their discriminability, and if so, what features set these particular letters apart from the others? b) How does motion direction discriminability of semantically meaningful stimuli compare to that of the nonsense stimuli of Experiment 2?

Method

Subjects

The same observers that participated in Experiment 2 also participated in Experiment 3.

Apparatus

The apparatus was the same as in Experiments 1 and 2.

Stimuli

Stimuli consisted of 10 upper-case Roman alphabetic letters. Of these 10 letters, 5 were the poorest-identified letters presented via and OPTACON (Lechelt, 1986b): *L*, *O*, *I*, *C*, and *U*. The other five were the best-identified letters: *Z*, *S*, *B*, *X*, and *G* (Lechelt, 1986b). All letters were presented in an approximation of IBM Standard Gothic sans-serif typeface.

When centred on the tactile matrix, all letters occupied the upper 18 rows of the display, and had a maximum width of 6 columns (except the letter *I*, which had a maximum width of 3 columns).

Procedure

The procedure was the same as in Experiment 2. In Experiment 3-A, letters scrolled left and right; in Experiment 3-B, they scrolled up and down.

Results and Discussion

Mean percent correct discriminations of motion direction were calculated. These results are shown in Figure 8. The results parallel those in Experiment 2: at the briefer SOAs, observer performance in Experiment 3-B was better than that in Experiment 3-A; as SOA increased, these differences disappeared. Again, performance reached asymptote at the larger SOAs. These observations were confirmed by statistical analysis. A three-way (letter, direction of opposite motion, and SOA between frames) fixed-factor repeated-measures ANOVA was used to examine discriminations of motion direction in Experiments 3-A and 3-B.

A statistically significant main effect of SOA was obtained in Experiment 3-A (*F* [4, 12] = 132.58, $p < 0.001$) and (albeit a much smaller effect) in Experiment 3-B (*F* [4, 12] = 4.59, $p < 0.02$). As in the previous experiments, percent correct discriminations increased with increasing SOA. Post hoc analysis using Scheffé's procedure showed that the means of the two smallest SOA conditions in Experiment 3-A differed significantly from each other, and also from the three largest SOAs ($S^2 = 13.8, p < 0.05$). As in Experiment 1 and 2-A, performance in the 5 ms SOA condition was at chance.

Differences in direction discriminability were found between letters in Experiment 3-A (F [9, 27] = 2.81, $p < 0.02$). Specifically, direction discriminations for *S* were poorer than for *X*, *Z*, *G*, *C*, and *L*; whereas performance for *L* was superior to that for *S*, *O*, *U*, *I*, and *B* (Scheffé criterion $S^2 = 17.46, p < 0.05$). These results are comparable to those found by Lechelt (1986b), despite the differences in the task (i.e., Lechelt [1986b] required observers to identify letters). Specifically, the letter *L* was found to produce the best performance. and *S* effected one of the poorest results of all letters.

A main effect of letters was also found in Experiment 3-B (F [9, 27] = 2.43, $p < 0.04$). Performance for letters *I*, *U*, and *B* was poorer than for *Z*, *S*, and *X* (Scheffé criterion $S^2 = 17.46, p < 0.05$). Lechelt's (1986b) opposite results (i.e., *I* and *U* produced better performance; and *Z*, *S*, and *X* produced poorer performance) can again be accounted for by task differences. That is, Lechelt (1986b) used left-moving letters whereas Experiment 3-B used up- or down-moving letters. The available motion direction cues are different when a letter is moving along a difference axis. For example, the letter *I* provides a better percept of motion when moving right or left than it does moving up or down, due to its long vertical line component.

A significant interaction between letter and SOA was found in Experiment 3-A (F [36, 108] = 1.60, $p < 0.04$) and Experiment 3-B (F [36, 108] = 2.14, $p < 0.01$). Individual post hoc comparisons between means revealed that differences between all letters existed at the 5 ms SOA value, and that performance with the letter *U* was poorer at the 10 ms SOA in both parts of Experiment 3 (HSD between means = 3.76, $p < 0.05$). This result is similar to the symbol × SOA interaction obtained in Experiment 2.

In Experiment 3-B, significant direction × SOA (F [4, 12] = 4.62, $p < 0.02$) and letter × direction × SOA (F [36, 108] = 1.80, $p < 0.02$) interactions were obtained. Once again, the nature of these interactions is that differences exist only at the briefest SOA value (HSD between means = 1.07 and 3.33, for each interaction respectively; $p < 0.05$). However, it is not clear why these latter two complex interactions were not obtained in Experiment 3-A. As noted above, further research is needed to clarify the nature of the relation between the spatially complex features found in letters and SOA.

An additional three-way (letter, axis of motion, and SOA between frames) fixed-factor repeated-measures ANOVA was carried out to determine if any differences existed between the two parts of Experiment 3. As may be expected from the above results, overall main effects of letters (F [9, 27] = 2.31, $p < 0.05$) and SOA (F [4, 12] = 104.56, $p < 0.001$) were found in Experiment 3. As in Experiment 2, performance on all letters exceeded 90% correct, indicating possible ceiling effects. See Figure 10 for letter results aggregated over all conditions.

Performance in Experiment 3-B was found to be superior to that in Experiment 3-A (F [1, 3] = 50.71, $p < 0.01$). As in Experiment 2, a significant axis of motion × SOA interaction was obtained (F [4, 12] = 63.71, $p < 0.001$); this interaction can be seen in Figure 8. Individual post hoc comparisons between means using Tukey's HSD procedure showed that the differences between Experiments 3-A and 3-B at the SOA of 5 ms were statistically significant (HSD between means = 3.82, $p < 0.05$).

Figure 9 provides further evidence to support the idea that display time can help account for the differences between Experiments 3-A and 3-B. As in Experiment 2, however, display time cannot account for all the differences. Performance in Experiment

3-A was significantly better than that in Experiment 3-B at display times of 90 ms (t = 5.91, $p < 0.05$) and 150 ms ($t = 3.62$, $p < 0.05$). (Again, the latter t test was based on linear interpolation of Experiment 3-B results at 150 ms.) It is clear that both SOA and display time are necessary to fully describe the results.

An axis of motion × letter interaction for Experiment 3 overall was obtained (F [9, 27] = 3.07, $p < 0.02$). Specifically, individual post hoc comparisons between means revealed that performance was better for all letters in Experiment 3-B (HSD between means = 1.76, $p < 0.05$). This result is most likely due to the greater display times. It may also be that the features contained in the letters allow for better determination of motion direction (although this factor may also be affected by variations in display time).

A significant letter × SOA interaction for Experiment 3 overall was obtained (F [36, 108] = 2.49, $p < 0.001$), as may be expected from similar results in Experiments 3-A and 3-B. Once again, the interaction followed the same pattern as before: differences in direction discriminability between letters existed only at the briefest SOA and disappeared at the longer SOAs (HSD between means = 2.78, $p < 0.05$).

Lastly, an F test was performed to confirm if any overall difference between Experiments 2 and 3 existed. No significant difference between the two experiments was found. Also, no differences in discriminability were found to exist between letters. These results will be examined in greater detail in the next chapter.

Craig (1979) constructed a confusion matrix for tactually presented letters that was highly correlated with a visual confusion matrix ($r = 0.88$), suggesting that similar processes are involved in identifying letters across the two modalities. However, there are at least two important differences between Craig's (1979) study and this project.

First, Experiment 3 did not require observers to discriminate between letters; rather, the task was merely to discriminate the motion direction of the *same* letter. Second, this project used moving letters. There may be little transfer from the visual modality because letters (and words) are fixated upon visually, thus are not read while moving. There is no question that the component features of letters affect their identification (e.g., see Craig, 1976), but when it comes to motion direction discriminations, it appears that spatial features have little effect.

GENERAL DISCUSSION

The results of the above experiments and their implications are reviewed with respect to temporal and spatial factors. Issues of a basic and theoretical nature will be examined, as well as brief references to practical applications.

Temporal Factors

Although this study did not employ a masking paradigm—and indeed was not specifically designed to examine masking effects—it is apparent that the pattern of results obtained is inconsistent with a masking explanation. The results of Experiments 1, 2-A, and 3-A cohere with Craig's (1980a) conception of masking in that SOAs of less than 10 ms between frames produced poor (chance level) performance. Performance improved as SOA increased, as predicted by a masking account. Each frame comprising motion might mask the preceding and succeeding frames via forward and backward masking, as suggested by Craig (1980). Yet the results of Experiments 2-B and 3-B contradict the masking explanation. In these conditions, the SOA values are the same as in Experiments 2-A and 3-A, but because the stimuli travel across a larger area, the display times are longer. Under these conditions, there is no degradation of performance at brief SOAs; the function is almost constant across SOAs.

Masking should not be affected by display time or area of motion; rather, it should be a function of SOA alone. It is concluded that masking is not responsible for all the results obtained in the three experiments that make up this study.

There are several reasons why masking does not appear to affect the results of this study. First, research has shown that if a target and a masker are spatially identical, the masker will not interfere with the percept of the target (Craig, 1982b; 1983b; Craig & Evans, 1987; Evans, 1987; Evans & Craig, 1986; 1991). Although it may be argued that each frame is spatially different from the preceding and succeeding frames, they are sufficiently similar to be considered virtually identical. Second, it has been determined that vibrotactile masking is a product of temporal integration of stimuli at SOAs of less than about 10 ms (Craig, 1982a; Evans & Craig, 1986). That is, because a second stimulus is presented before the preceding one has sufficiently decayed, they are integrated, making it more difficult to identify either stimulus, causing masking. Thus, masking exists only at brief SOAs due to the nature of the underlying integration function: if the first stimulus has decayed by the time the second is presented, there is no integration, and thus there is no masking. However, the fact that performance was not poor in all brief SOA conditions casts doubt on the possibility that temporal integration effected limits on motion discrimination performance in this study.

On the other hand, it cannot be concluded that temporal integration does not play a role in the perception of moving tactile stimuli. Kirman (1973) reasoned that to create the percept of a coherent, unitary figure moving across the skin, the components of tactile apparent motion must, to some extent, be integrated. That is, instead of diminishing performance, temporal integration may be essential to the perception of moving tactile patterns.

As the masking/temporal integration account provides at best only a very limiting explanatory basis for the obtained results in the present research, an examination of the underlying physiological factors involved in tactile pattern perception is required.

Recent electrophysiological studies using OPTACON pulses delivered to the hand have produced results that may help explain some psychophysical findings. Peripheral neurons sensitive to motion in one direction have been found by numerous investigators (Gardner & Palmer, 1989a; Goodwin & Morley, 1987; Warren, Hamalainen, & Gardner, 1986; Whitsel, Roppolo, & Werner, 1972), which suggests that the direction of movement of tactile patterns is extracted not just peripherally, but automatically: that is, without expenditure of higher-order cognitive resources, such as attention. If this is so, the failure to discriminate the direction of moving tactile patterns may be a result of the neurons' inability to adequately process the information being delivered to the skin.

Gardner & Palmer (1989a) found that RAs (rapidly adapting mechanoreceptors, also known as Meissner's afferents) were the receptors most activated by the OPTACON's tactile matrix. They noted that when high frequency stimuli (i.e., patterns presented at a rapid rate: less than 10 ms SOA between frames) are employed, the mechanical limits of the skin may be reached (Gardner & Palmer, 1989b). That is, when stimulated by impulses in such rapid succession, the skin has insufficient time to recover to its resting state between pulses. As a result, RA responsiveness will be reduced.

Most RAs signal motion via a uniform spike train; velocity of spatial motion of the stimulus is represented by the frequency and duration of the spikes (Gardner & Palmer, 1989a). RAs code faster rates of motion by decreasing the duration and increasing the frequency of their firing. But there is an upper limit to the response rate; at an SOA of around 10 ms between frames, some RAs fail to fire (Gardner and Palmer, 1989a). It is not clear whether this result was due to the aforementioned mechanical limits of the skin, or because the afferents' upper rate of responding was reached. The axonal refractory period for RAs is less than 10 ms, and may even be as short as 5 ms (Freeman and Johnson, 1982a; 1982b, cited in Gardner & Palmer, 1989a), which would mean that the receptors could respond to even the most rapid stimulus presentation rates in Experiments 1, 2, and 3.

However, neither the mechanical nor the refractory period explanations can account for the superior performance in the brief SOA/long display time conditions (Experiments 2-B and 3-B) over the brief SOA/brief display time conditions (Experiments 1, 2-A, and 3-A). The patterns scroll across the fingertip at the same rate as in the brief SOA/brief display time conditions, albeit across a greater area. It does not seem likely that the greater area traversed by the patterns in these conditions would produce better performance by affecting the mechanical properties of the skin.

Likewise, the minimum refractory period account cannot explain why performance is superior at brief SOAs in Experiments 2-B and 3-B. If the RAs cannot handle stimuli moving at a rapid rate (i.e., a brief SOA), the length of the display time or distance of motion should not have any effect on performance. Gardner and Palmer (1989a) determined that Pacinian corpuscles (PCs), which have larger receptive fields than RAs, are also affected by OPTACON stimulation. Like RAs, PCs signal motion by a spike train that increases in frequency as the stimulus moves more rapidly across the skin. Although PCs also have axonal refractory periods of less than 10 ms, their larger receptive fields may make them better suited to detecting motion in some conditions. Perhaps stimuli moving across a larger area allow PCs to signal motion direction, thereby making up for the overwhelmed RAs.

It is possible that other, perhaps higher-level processes are responsible for the differences between the brief SOA/brief display time and brief SOA/long display time conditions. In the latter condition, the greater length of time available for processing tactile information may enable a more cognitive process to compensate for the reduced efficacy of the peripheral motion direction sensors.

It is suggested that, under certain conditions, observers may monitor where the stimulus pattern emerges and exits from the tactile matrix. From this information, the direction of motion can be ascertained. For example, if the pattern is determined to emerge from the top of the matrix and exit out the bottom, the direction of motion can be inferred as "downward." This strategy may compensate for automatic processes, when those processes are unable to signal motion direction (e.g., because the rate of motion is too rapid). However, it must be noted that there are limitations to the above strategy; it may be employed only under certain temporal conditions.

There is evidence to suggest that central factors affect temporal processing. Lechelt (1979) found that central, attentional factors were involved in temporal discriminations, in that discriminations of stimulus aperiodicity were a function of the temporal patterning. Results indicating that central processes may limit temporal resolution were obtained by Loomis (1981); specifically, accurate judgments of temporal order (a central process) require at least 26 ms between stimuli. Evans (1987) noted that observers made errors in judging the order of two events at SOAs up to 106 ms, due to temporal integration. Thus, at brief SOAs, errors in judgments of temporal order of stimulus frames may cause difficulty in motion direction inferencing. However, it should be noted that the threshold of temporal acuity was found to be lower for multiple pulses (which may correspond to the multiple-frame presentation mode of the above Experiments) than in a simple two-pulse condition (Uttal & Krissoff, 1966). Thus, in this study, the threshold for making accurate temporal order judgments may be even lower than the intervals indicated above. The above findings may provide at least a partial explanation of the pattern of results obtained in this study.

When motion occurs across a short distance (e.g., in Experiments 1, 2-A, and 3-A) and the SOA between frames is relatively long, performance is good, perhaps because the RA or PC afferents are able to handle the slow rate of motion. However, when stimuli traverse a short distance but have a brief SOA, performance is poor for two reasons. First, the afferents are unable to deal with information presented at such a rapid rate. Second, because of the brief time between pattern onset and offset (well under 100 ms), observers are unable to make a correct temporal order judgment between the two events, resulting in poor performance.

In conditions where stimuli move across a relatively large distance (e.g., in Experiments 2-B and 3-B) and are presented at long SOAs, RAs or PCs again may signal motion direction. But when motion is produced over a large distance with a brief SOA between frames, there is sufficient time between pattern onset and offset (over 100 ms) to produce correct temporal order judgments (and thusly, correct motion direction inferences). As a result, motion direction discrimination performance is good—and not dependent on SOA.

Note that the above account is only a tentative explanation of the results obtained in this study. Further research is necessary to adequately test the assertions made. For example, it may be determined if the proposed pattern onset/offset monitoring process uses attention by presenting moving stimuli to multiple sites on the skin (see Craig & Evans, 1991).

Most of the interactions obtained in this study had the same general property: at brief SOAs there were wide (within-observer) variations in scores that were reduced as SOA increased. The most likely explanation of this phenomenon is that a ceiling effect existed at the longer SOAs, which attenuated the variability of the scores and thereby produced an interaction effect. Note that this explanation can only account for the results when they are expressed in terms of SOA, not display time.

Motion direction discrimination performance can be adequately described by SOA when the stimuli move across the same distance and the display times do not vary a great deal (i.e., as in Experiment 1). But when the stimuli traverse areas of different size and the display times encompass a wider range of values, SOA does not provide an adequate description of performance. Instead, display time allows for a more stable characterization of the results when SOA and distance of motion are varied. It should be noted that display time alone may be insufficient to fully describe the results, because SOA (or distance of motion) can still produce differences at a given display time (e.g., see the differences between graphs in Figures 3, 6, and 9).

Spatial Factors

Although Gardner and Palmer (1990) found that the number of line segments in a letter was negatively correlated with letter identification performance, the spatial complexity of the stimulus had no significant effect on discriminations of motion direction in this study (i.e., no differences were obtained between Experiments 1 and 2), despite the fact that display times were longer in Experiment 2-B than 1-B. It should be noted, though, that some features of complex patterns do have effects—albeit small—on performance. For example, lines perpendicular to the direction of motion appeared to provide better motion direction cues than lines parallel to the direction of motion. Thus, in this low-level task at least, the spatial arrangement of the component lines appears to have been more important than the quantity of lines in a pattern.

In studies employing the OPTACON, observers are typically required to identify different patterns (e.g., see Craig, 1976; Lechelt, 1986b). However, in this study, the task was merely to discriminate motion direction of spatially identical patterns. Horner and Craig (1989) determined that vibrotactile patterns need not be identified to be discriminated. It did not appear that observers in Experiment 3 were spontaneously identifying the letters, or at least they were not conscious of doing so. Although the observers knew that letters were being presented, when informally asked to identify them, they could only hazard tentative guesses regarding which particular letters were employed. It is apparent that the observers treated all stimuli (bars, symbols, and letters) simply as moving "patterns," and did not extract any further information from them. The meaningfulness of the patterns would likely have had a greater effect had the task required identification of different letters.

The inability of observers to identify letters may be due to the fact that they were unfamiliar with the tactual presentation of letters, and did not experience any transfer from the visual modality. For example, it is difficult to see a letter visually and *not* automatically identify it. However, novice OPTACON users (visually impaired or sighted), usually require a great deal of training to recognize letters.

CONCLUSIONS AND IMPLICATIONS

It is not possible to conclude why presenting stimuli on the OPTACON in scan mode produces better performance than static mode, or what factor is responsible for the limits of motion discrimination performance. As noted above, masking and temporal integration do not seem to be likely causes. It may be that performance is limited by mechanical or physiological factors of the tactile modality, but this possibility has yet to be clearly established. Perhaps the direction of motion is signalled by more cognitive processes, as suggested above.

The basis of the limits of motion direction discrimination performance is not clear. Further experimentation to determine whether masking or temporal integration play any role in the perception of moving stimuli is a natural extension of the present study. Clearly, the physiological processes underlying motion detection need to be further investigated. Future research should also examine whether motion is signalled automatically, or if, under certain conditions, it depends upon processes that draw attentional resources.

It is apparent that the spatial complexity and meaningfulness of stimuli have little effect on the performance of a low-level task such as motion direction discrimination. However, the finding that the arrangement of line segments of moving tactile patterns affected motion discriminability more than the quantity of segments has implications for tactile reading. Although it is difficult to change the number of line segments comprising an alphabetic letter without negatively affecting identifiability, it is relatively easy to manipulate their arrangement, to some extent. For example, parallel lines may be changed to oblique lines. Large changes may not be required (and may even be detrimental): Heller (1987, 1992) found that the tactile modality is highly sensitive to the orientation of patterns. The identifiability and discriminability of the modified letters would need to be established to determine their viability, but it is hoped that they would constitute an improvement over unmodified letters.

As noted in the Introduction, opinions regarding the critical temporal variable for stimuli presented to the skin have been divided between display time and stimulus onset asynchrony. Based on the evidence presented above, it is clear that, for motion direction discriminations at least, display time provided a better delineation of performance. That is not to say that SOA is without descriptive power, but the picture painted by SOA was incomplete. The best description of performance is one that utilizes both display time and SOA.

For moving stimuli, it is apparent that the skin does not have a maximum speed limit (represented by a brief SOA), but rather has a minimum time limit for processing information (represented by a brief display time). Display time provides a means of describing the lower limit at which information about motion can be extracted from the stimulus. Increasing display time improved performance, but was unfortunately counter to the goal of presenting information as rapidly as possible. For designers of future tactile sensory substitution systems, the goal remains to attempt to maximize the amount of discriminable and meaningful information delivered in this minimum time span.

Figure 1: Close-up of OPTACON display.

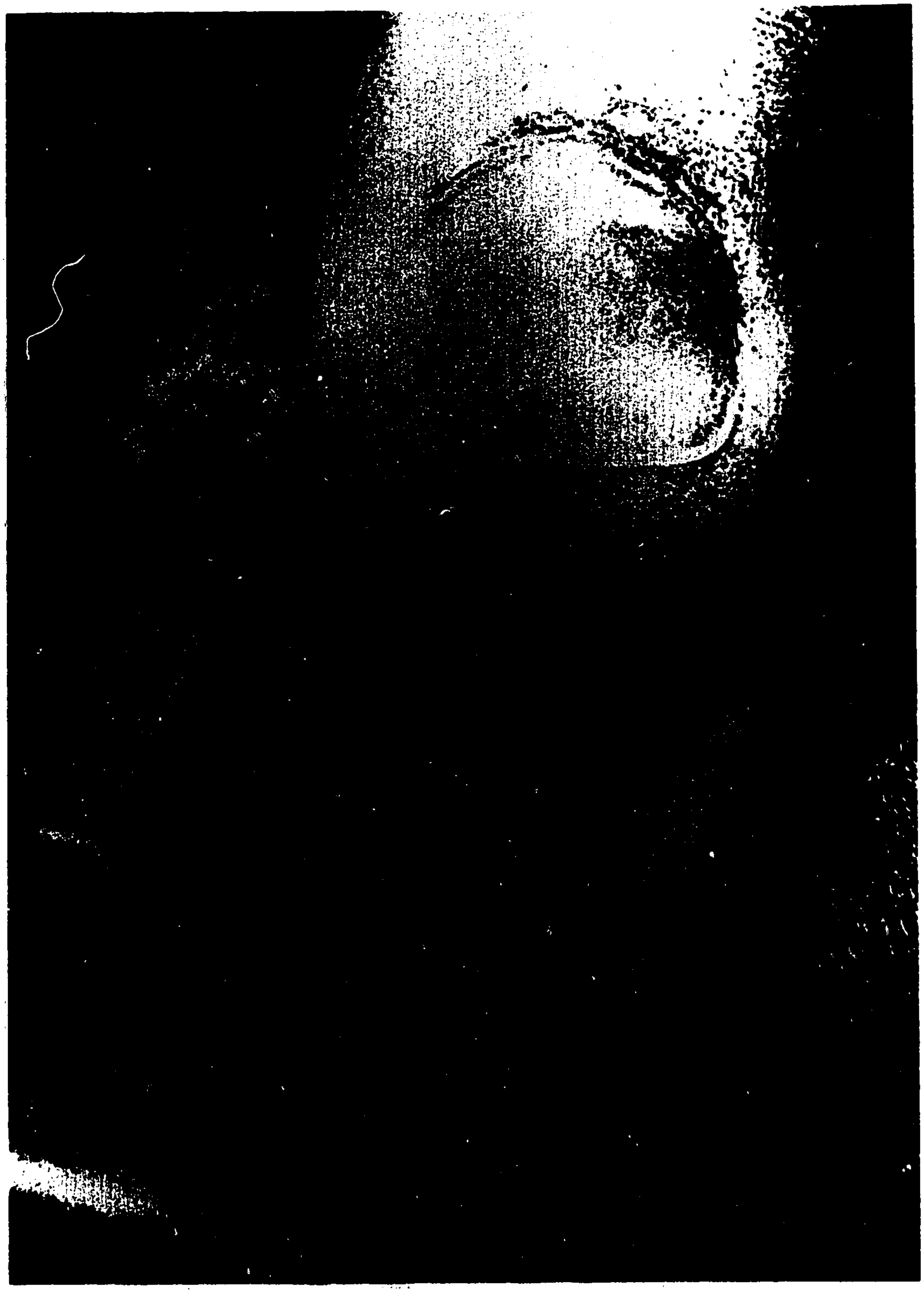


Figure 2: Motion direction discriminations as a function of SOA in Experiment 1. Note: motion is lateral in Expt. 1-A, and vertical in Expt. 1-B.

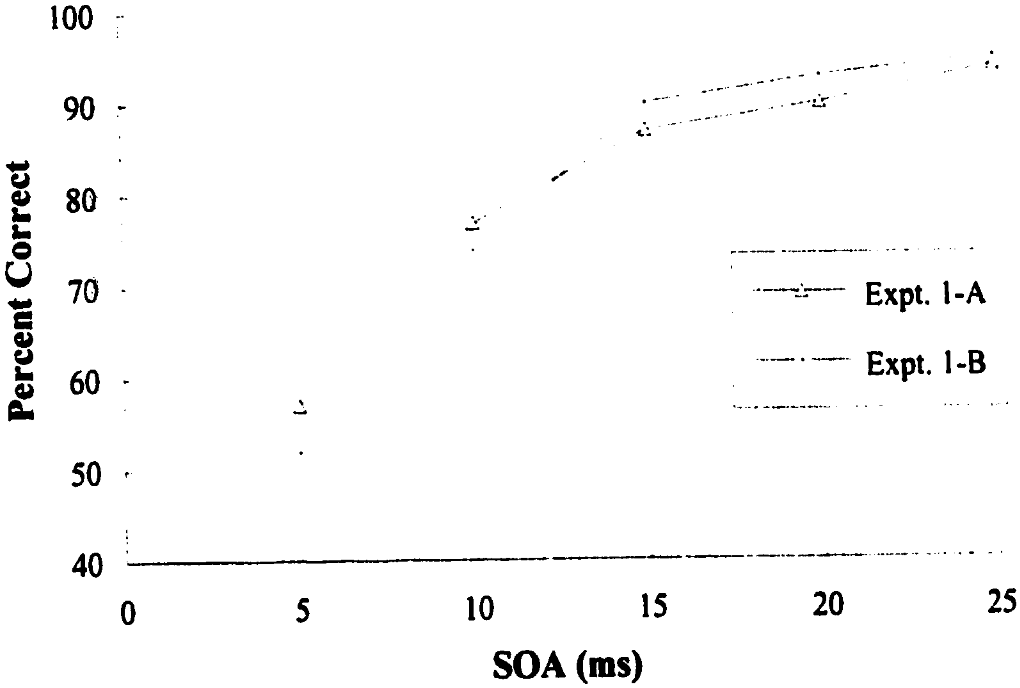


Figure 3: Motion direction discriminations as a function of display time in Experiment 1. Note: motion is lateral in Expt. 1-A, vertical in Expt. 1-B.

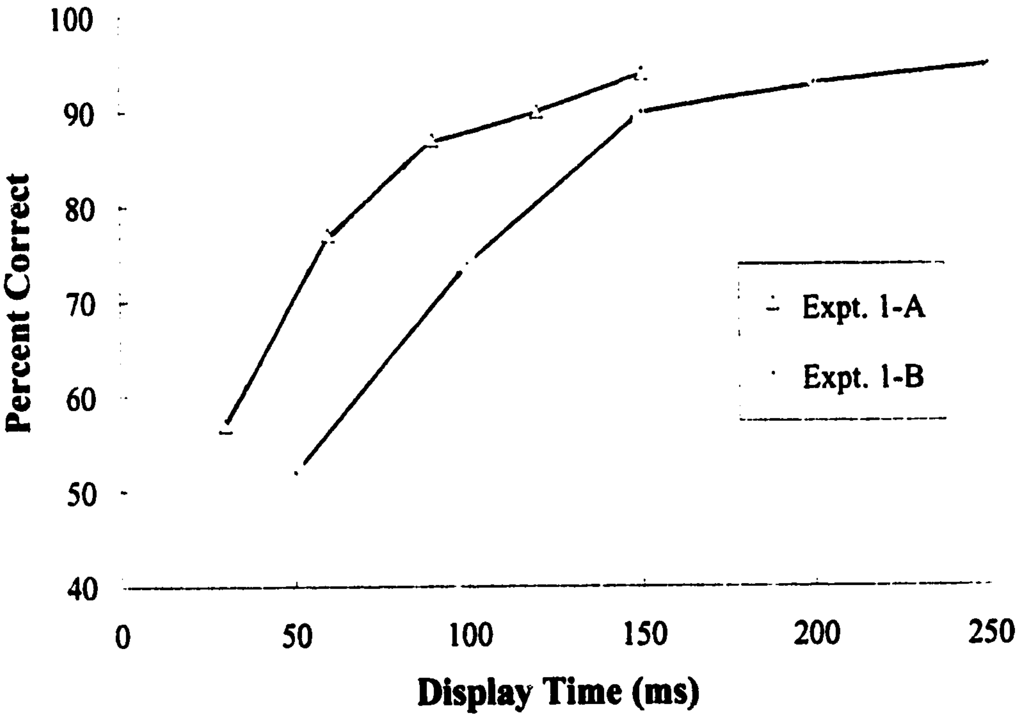


Figure 4: Experiment 2 symbols.

Symbol 1	Symbol 2	Symbol 3	Symbol 4	Symbol 5
○○○●○○	●○○○○○	●●●●○○	●●●●●●	○○○○○●
○○○●○○	○●○○○○	○○○●○○	●○○○○●	○○○○○●
○○○●○○	○○●○○○	○○○●○○	●○○○○●	○○○○○●
○○○●○○	○○●○○○	○○○●○○	●○○○○●	○○○○○●
○○○●○○	○○○●○○	○○○●○○	●○○○○●	○○○○○●
○○○●○○	○○○○●○	○○○●○○	○○○○○●	○○○○○●
○○○●○○	○○○○●○	○○○●○○	○○○○○●	○○○○○●
○○○●○○	○○○○○●	○○○●○○	○○○○○●	○○○○○●
○○○●○○	●●●●●●	○○○●●●	○○○○○●	○○○○○●
○○○●○○	●○○○○○	○○○●○○	○○○○○●	○○○○○●
○○○●○○	○●○○○○	○○○●○○	○○○○○●	○○○○○●
○○○●○○	○●○○○○	○○○●○○	○○○○○●	○○○○○●
○○●○○○	○○●○○○	○○○●○○	●●●●●●	○○○○○●
○○●○○○	○○○●○○	○○○●○○	●○○○○○	○○○○○●
○●○○○○	○○○●○○	○○○●○○	●○○○○○	○○●○○●
○●○○○○	○○○○●○	○○○●○○	●○○○○○	○●○●○●
●○○○○○	○○○○○●	○○○●○○	●○○○○○	●○○○●●
●●●●●●	○○○○○●	○○○●○○	●○○○○○	●○○○○●

Symbol 6	Symbol 7	Symbol 8	Symbol 9	Symbol 10
●○○○○○	●○○○○○	●○○○○●	●●●●●●	○○○○○●
●○○○○○	●○○○○○	○●○○○●	●○○○○○	○○○○○●
●○○○○○	○●○○○○	○○●○○●	●○○○○○	○○○○○●
●○○○○○	○○●○○○	○○○●○●	●○○○○○	○○○○○●
●○○○○○	○○●○○○	○○○○●●	●○○○○○	○○○○○●
●○○○○○	○○○●○○	●●●●●●	●○○○○○	○○○○○●
●○○○○○	○○○○●○	○○○○○●	●○○○○○	●○○○○●
●○○○○○	○○○○●○	○○○○○●	○●○○○○	○●○○○●
●●●●●●	○○○○○●	○○○○○●	○○●○○○	○○●○○●
○○○○○●	○○○○○●	○○○○○●	○○○●○○	○○○●○●
○○○○○●	○○○○●○	○○○○○●	○○○○●○	○○○○●●
○○○○○●	○○○○●○	○○○○○●	○○○○○●	●●●●●●
○○○○○●	○○○●○○	○○○○○●	○○○○○●	○○○○○●
○○○○○●	○○●○○○	○○○○○●	○○○○○●	○○○○●○
○○○○○●	○○●○○○	○○○○○●	○○○○○●	○○○●○○
○○○○○●	○●○○○○	○○○○○●	○○○○○●	○○●○○○
○○○○○●	●○○○○○	○○○○○●	○○○○○●	○●○○○○
○○○○○●	●●●●●●	○○○○○●	○○○○○●	●○○○○○

Figure 5: Motion direction discriminations as a function of SOA in Experiment 2. Note: motion is lateral in Expt. 2-A, vertical in Expt. 2-B.

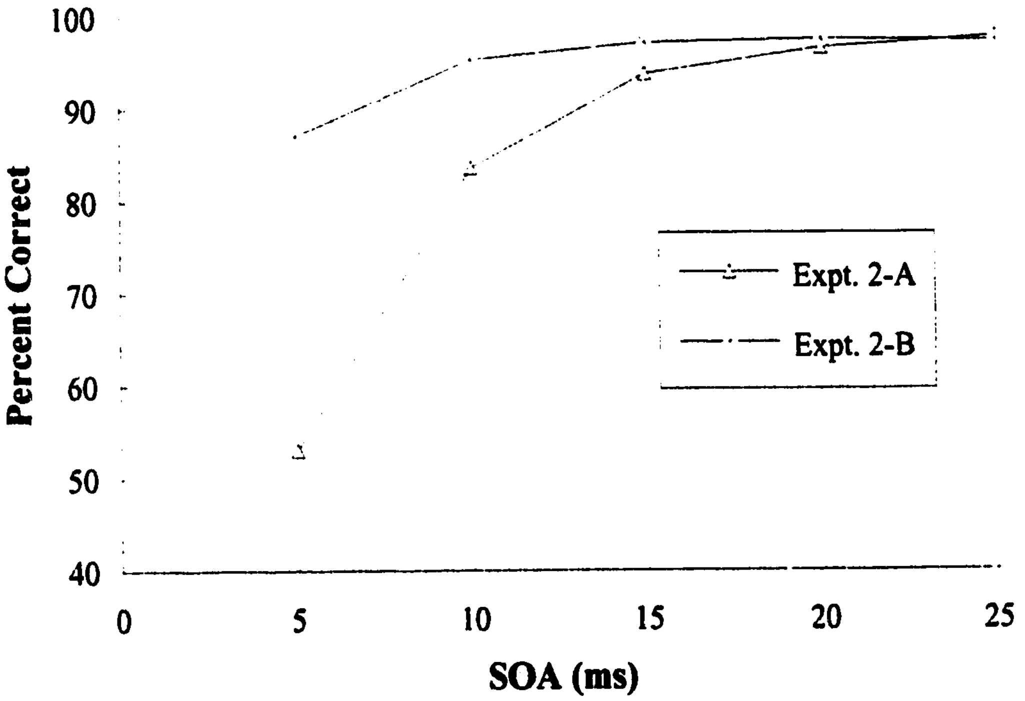


Figure 6: Motion direction discriminations as a function of display time in Experiment 2. Note: motion is lateral in Expt. 2-A, vertical in Expt. 2-B.

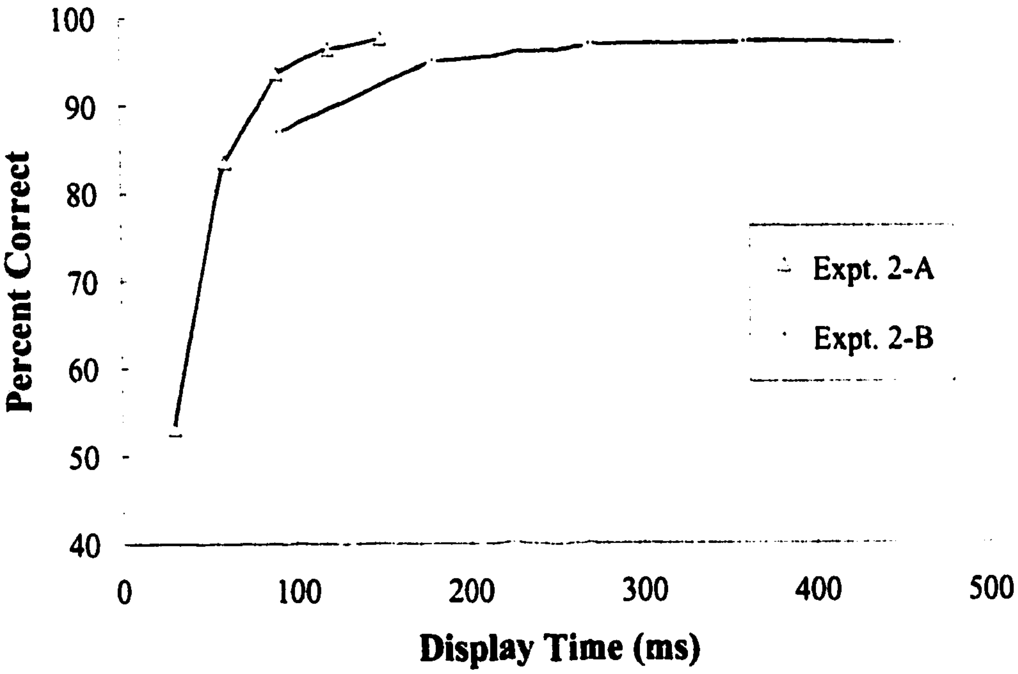


Figure 7: Motion direction discriminations for each symbol in Experiment 2 (see Figure 4).

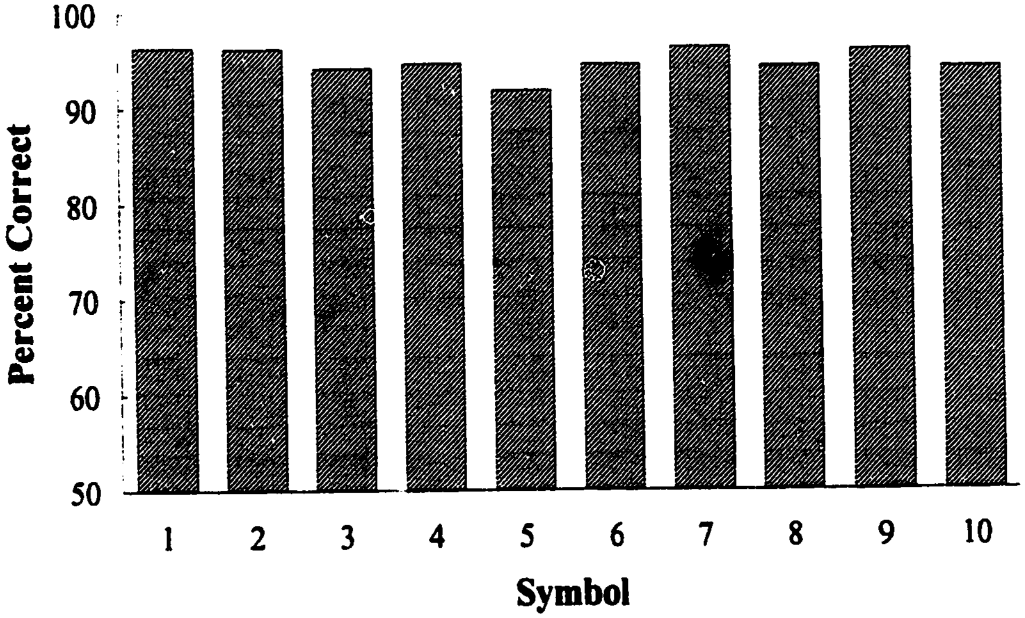


Figure 8: Motion direction discriminations as a function of SOA in Experiment 3. Note: motion is lateral in Expt. 3-A, vertical in Expt. 3-B.

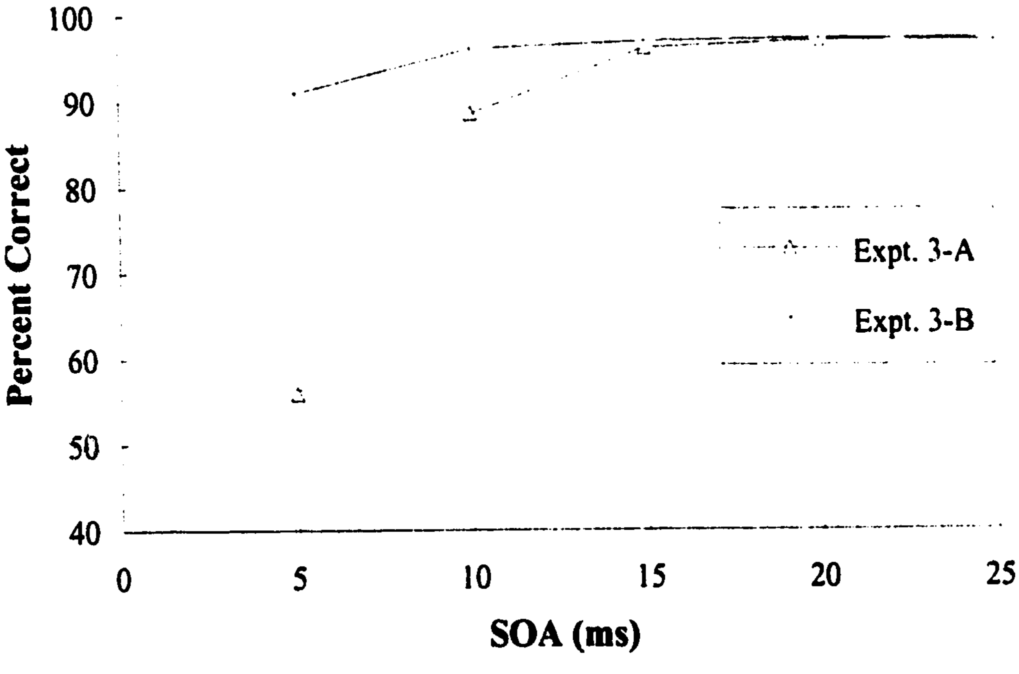


Figure 9: Motion direction discriminations as a function of display time in Experiment 3. Note: motion is lateral in Expt. 3-A, vertical in Expt. 3-B.

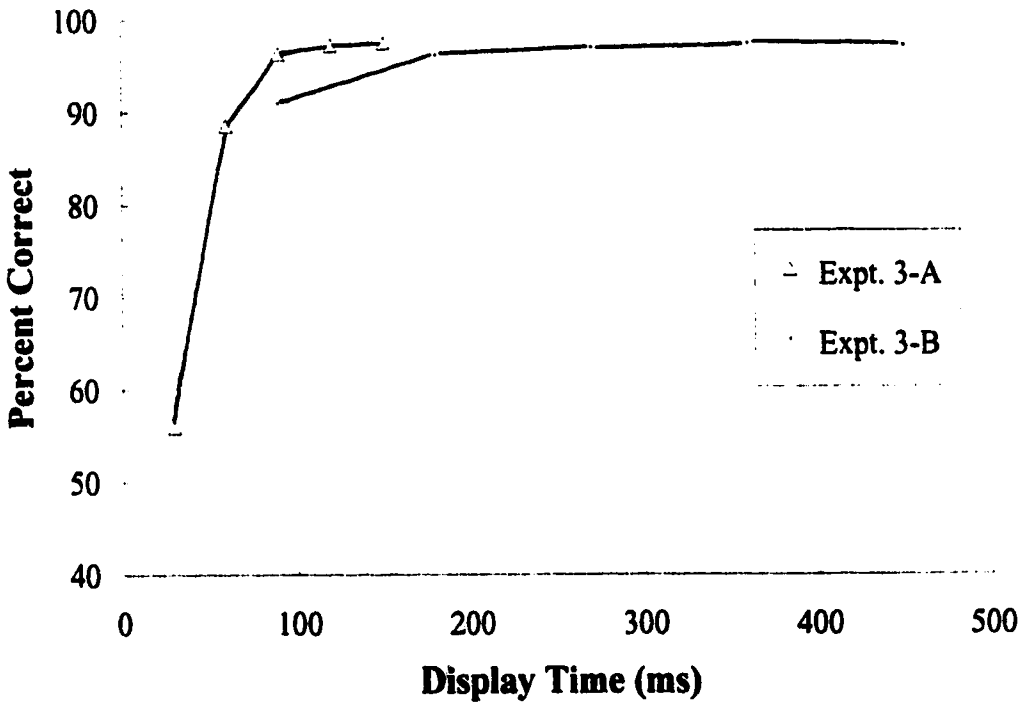
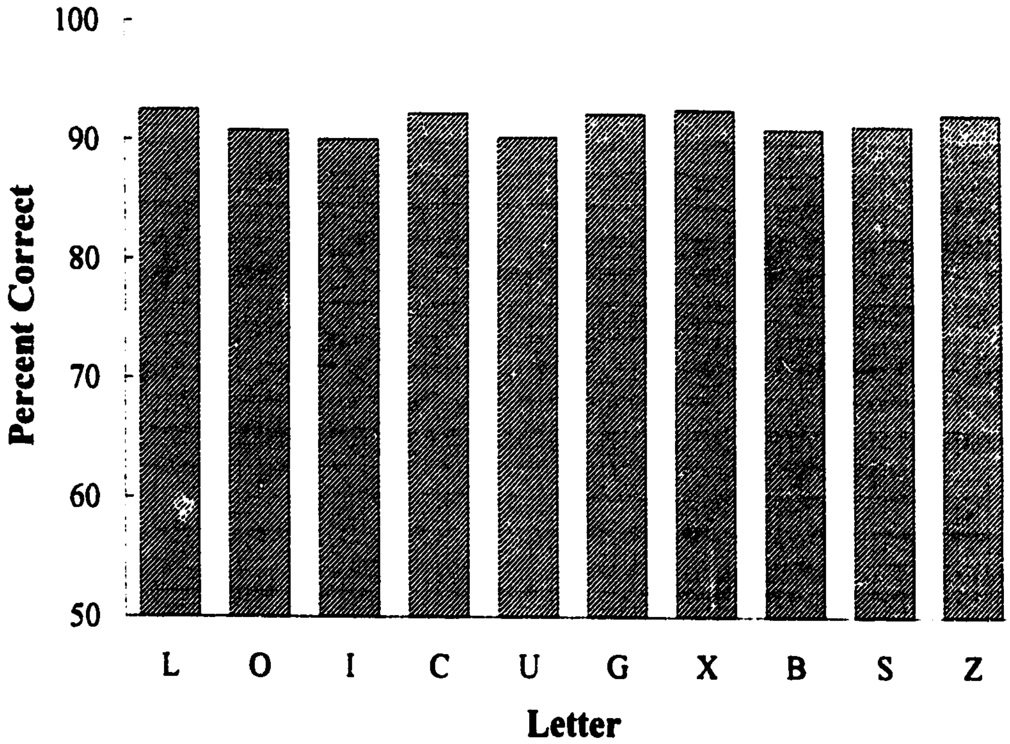


Figure 10: Motion direction discriminations for each letter in Experiment 3.



BIBLIOGRAPHY

Bach-y-Rita, P. (1972). Brain mechanisms in sensory substitution. New York: Academic Press.

Bach-y-Rita, P. (1980). Sensory substitution in rehabilitation. Sensory World, 39, 12-19.

Benton, A. L., Levin, H. S., & Varney, N. R. (1973). Tactile perception of direction in normal subjects. Neurology, 23, 1248-1250.

Benton, A. L., Varney, N. R., & Hamsher, K. DE S. (1978). Lateral differences in tactile directional perception. Neuropsychologia, 16, 109-114.

Craig, J. C. (1976). Vibrotactile letter recognition: The effects of a masking stimulus. Perception & Psychophysics, 20, 317-326.

Craig, J. C. (1979). A confusion matrix for tactually presented letters. Perception & Psychophysics, 26, 409-411.

Craig, J. C. (1981). Tactile letter recognition: Pattern duration and modes of pattern generation. Perception and Psychophysics, 30, 540-546.

Craig, J. C. (1982a). Temporal integration of vibrotactile patterns. Perception & Psychophysics, 32, 219-229.

Craig, J. C. (1982b). Vibrotactile masking: A comparison of energy and pattern maskers. Perception & Psychophysics, 31, 523-529.

Craig, J. C. (1983a). Some factors affecting tactile pattern perception. International Journal of Neuroscience, 19, 47-58.

Craig, J. C. (1983b). The role of onset in the perception of sequentially presented vibrotactile patterns. Perception & Psychophysics, 34, 421-432.

Craig, J. C., & Evans, P. M. (1987). Vibrotactile masking and the persistence of tactual features. Perception & Psychophysics, 42, 309-317.

Craig, J. C., & Evans, P. M. (1991). Tactile attention and the perception of moving tactile stimuli. Perception & Psychophysics, 49, 355-364.

Craig, J. C., & Sherrick, C. E. (1982). The psychophysics of touch. In W. Schiff & E. Foulke (Eds.), Tactual perception: A sourcebook (pp. 55-81). Cambridge: Cambridge University Press.

Evans, P. M. (1987). Vibrotactile masking: Temporal integration, persistence, and strengths of representations. Perception & Psychophysics, 42, 515-525.

Evans, P. M., & Craig, J. C. (1986). Temporal integration and vibrotactile backward masking. Journal of Experimental Psychology: Human Perception and Performance, 12, 160-168.

Evans, P. M., & Craig, J. C. (1991). Tactile attention and the perception of moving tactile stimuli. Perception & Psychophysics, 49, 355-364.

Gardner, E. P., & Palmer, C. I. (1989a). Simulation of motion on the skin: I. Receptive fields and temporal frequency coding by cutaneous mechanoreceptors of OPTACON pulses delivered to the hand. Journal of Neurophysiology, 62, 1410-1436.

Gardner, E. P., & Palmer, C. I. (1989b). Simulation of motion on the skin: II. Cutaneous mechanoreceptor coding of the width and texture of bar patterns displaced across the OPTACON. Journal of Neurophysiology, 62, 1437-1460.

Gardner, E. P., & Palmer, C. I. (1990). Simulation of motion on the skin: III. Mechanisms used by rapidly adapting cutaneous mechanoreceptors in the primate hand for spatiotemporal resolution and two-point resolution. Journal of Neurophysiology, 63, 841-859.

Geldard, F. A. (1970). Vision, audition, and beyond. In W. D. Neff (Ed.), Contributions to sensory physiology, Vol. 4 (pp. 1-17). New York: Academic Press.

Geldard, F. A. (1977). Tactile communication. In T. A. Sebok (Ed.), How animals communicate (pp. 211-232). Bloomington, IN: Indiana University Press.

Goodwin, A. W., & Morley, J. W. (1987). Sinusoidal movement of a grating across the monkey's fingerpad: Effect of contact angle and force of the grating on afferent fiber responses. The Journal of Neuroscience, 7, 2192-2202.

Heller, M. A. (1987). The effect of orientation on visual and tactual braille recognition. Perception, 16, 291-298.

Heller, M. A. (1992). The effect of orientation on tactual braille recognition: Optimal touching positions. Perception & Psychophysics, 51, 549-556.

Horner, D. T. & Craig, J. C. (1989). A comparison of discrimination and identification of vibrotactile patterns. Perception & Psychophysics, 45, 21-30.

Kirman, J. H. (1973). Tactile communication of speech: A review and an analysis. Psychological Bulletin, 80, 54-74.

Kirman, J. H. (1974). Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration. Perception & Psychophysics, 15, 1-6.

Krueger, L. E. (1970). David Katz's Der aufbau der Tastwelt (The world of touch): A synopsis. Perception & Psychophysics, 7, 337-341.

Lechelt, E. C. (1978). Research strategies and processing capacities of the skin as they relate to the development of sensory aids (sensory substitution systems) for the sensorily handicapped. International Journal of Rehabilitation Research, 1, 378-380.

Lechelt, E. C. (1979). Discrimination of stimulus aperiodicity as a function of temporal patterning: A discrepancy between psychophysical and sensory-neural assessments. Perception, 8, 217-224.

Lechelt, E. C. (1984). Sensory substitution: "Seeing with the skin." Alberta Psychology, 13, 18-20.

Lechelt, E. C. (1986a). Sensory-substitution systems for the sensorily impaired: The case for the use of tactile-vibratory stimulation. Perceptual and Motor Skills, 62, 356-358.

Lechelt, E. C. (1986b, June). Laterality and gender effects in tactile letter recognition. Paper presented at The American Association for the Advancement of Science Meeting: Pacific Division, Vancouver, BC.

Lechelt, E. C., & Loepelmann, K. A. (1990). Effect of presentation rate in tactile discrimination of dynamically presented symbols. Canadian Psychology, 31, 206.

Loepelmann, K. A., & Lechelt, E. C. (1991). A modular software system for controlling an OPTACON-computer interface. In J. Presperin (Ed.), Proceedings of the RESNA 14th Annual Conference (pp. 326-327). Washington, DC: RESNA Press.

Loomis, J. M. (1981). Tactile pattern perception. Perception, 10, 5-27.

Loomis, J. M., & Lederman, S. J. (1986). Tactual perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), Handbook of Perception and Performance, Vol. 1: Cognitive Processes and Performance (pp. 31·1-31·41). New York: John Wiley and Sons.

Sherrick, C. E. (1982). Cutaneous communication. In W. D. Neff (Ed.), Contributions to sensory physiology, Vol. 6 (pp. 1-43). New York : Academic Press.

Taenzer, J. C. (1970). Visual word reading. IEEE Transactions on Man-Machine Systems, MMS-11, 11-53.

Uttal, W. R., & Krissoff, M. (1966). Effect of stimulus pattern on temporal acuity in the somatosensory system. Journal of Experimental Psychology, 71, 878-883.

Warren, S., Hamalainen, H. A., & Gardner, E. P. (1986). Objective classification of motion- and direction-sensitive neurons in primary somatosensory cortex of awake monkeys. Journal of Neurophysiology, 56, 598-622.

Whitsel, B. L., Roppolo, J. R., & Werner, G. (1972). Cortical information processing of stimulus motion on primate skin. Journal of Neurophysiology, 35, 691-717.

APPENDIX
ANOVA Tables

Experiment 1-A

Main Effects

1. Direction of opposite motion (L vs. R) $[F(1, 3) = 37.67, p < 0.01]$
2. SOA between frames $[F(4, 12) = 50.76, p < 0.001]$

Interactions

1. Direction × SOA $[F(4, 12) = 0.98, p < 0.46]$

Experiment 1-B

Main Effects

1. Direction of opposite motion (U vs. D) $[F(1, 3) = 0.05, p < 0.85]$
2. SOA between frames $[F(4, 12) = 49.16, p < 0.001]$

Interactions

1. Direction × SOA $[F(4, 12) = 0.12, p < 0.98]$

Experiment 1 (Overall)

Main Effects

1. Axis of motion (L/R vs. U/D) $[F(1, 3) = 0.02, p < 0.91]$
2. SOA between frames $[F(4, 12) = 58.94, p < 0.001]$

Interactions

1. Axis × SOA $[F(4, 12) = 3.17, p < 0.06]$

Experiment 2-A

Main Effects

1. Symbol $[F(9, 27) = 1.71, p < 0.14]$
2. Direction of opposite motion (L vs. R) $[F(1, 3) = 2.42, p < 0.22]$
3. SOA between frames $[F(4, 12) = 102.56, p < 0.001]$

Interactions

1. Symbol × direction [$F(9, 27) = 0.77, p < 0.65$]
2. Symbol × SOA [$F(36, 108) = 1.09, p < 0.36$]
3. Direction × SOA [$F(4, 12) = 1.23, p < 0.35$]
4. Symbol × direction × SOA [$F(36, 108) = 1.06, p < 0.40$]

Experiment 2-B

Main Effects

1. Symbol [$F(9, 27) = 4.34, p < 0.01$]
2. Direction of opposite motion (U vs. D) [$F(1, 3) = 0.93, p < 0.41$]
3. SOA between frames [$F(4, 12) = 7.40, p < 0.01$]

Interactions

1. Symbol × direction [$F(9, 27) = 2.15, p < 0.07$]
2. Symbol × SOA [$F(36, 108) = 3.48, p < 0.001$]
3. Direction × SOA [$F(4, 12) = 0.59, p < 0.68$]
4. Symbol × direction × SOA [$F(36, 108) = 0.92, p < 0.61$]

Experiment 2 (Overall)

Main Effects

1. Axis of motion (L/R vs. U/D) [$F(1, 3) = 99.46, p < 0.01$]
2. Symbol [$F(9, 27) = 1.20, p < 0.34$]
3. SOA between frames [$F(4, 12) = 86.65, p < 0.001$]

Interactions

1. Axis × symbol [$F(9, 27) = 0.62, p < 0.10$]
2. Axis × SOA [$F(4, 12) = 34.50, p < 0.001$]
3. Symbol × SOA [$F(36, 108) = 2.08, p < 0.01$]
4. Axis × symbol × SOA [$F(36, 108) = 1.60, p < 0.04$]

Experiment 1 vs. Experiment 2

Main Effect

1. Bars vs. symbols [$F(1,3) = 4.32, p < 0.13$]

Experiment 3-A

Main Effects

1. Letter [$F(9, 27) = 2.81, p < 0.02$]
2. Direction of opposite motion (L vs. R) [$F(1, 3) = 0.19, p < 0.70$]
3. SOA between frames [$F(4, 12) = 132.58, p < 0.001$]

Interactions

1. Letter × direction [$F(9, 27) = 0.59, p < 0.80$]
2. Letter × SOA [$F(36, 108) = 1.60, p < 0.04$]
3. Direction × SOA [$F(4, 12) = 0.16, p < 0.96$]
4. Letter × direction × SOA [$F(36, 108) = 0.57, p < 0.98$]

Experiment 3-B

Main Effects

1. Letter [$F(9, 27) = 2.43, p < 0.04$]
2. Direction of opposite motion (U vs. D) [$F(1, 3) = 3.61, p < 0.16$]
3. SOA between frames [$F(4, 12) = 4.59, p < 0.02$]

Interactions

1. Letter × direction [$F(9, 27) = 0.64, p < 0.76$]
2. Letter × SOA [$F(36, 108) = 2.14, p < 0.01$]
3. Direction × SOA [$F(4, 12) = 4.62, p < 0.02$]
4. Letter × direction × SOA [$F(36, 108) = 1.80, p < 0.02$]

Experiment 3 (Overall)

Main Effects

1. Axis of motion (L/R vs. U/D) [$F(1, 3) = 50.71, p < 0.01$]
2. Letter [$F(9, 27) = 2.31, p < 0.05$]
3. SOA between frames [$F(4, 12) = 104.56, p < 0.001$]

Interactions

1. Axis × letter [$F\,(9, 27) = 3.07, p < 0.02$]
2. Axis × SOA [$F\,(4, 12) = 63.71, p < 0.001$]
3. Letter × SOA [$F\,(36, 108) = 2.49, p < 0.001$]
4. Axis × letter × SOA [$F\,(36, 108) = 1.12, p < 0.33$]

<u>Experiment 2 vs. Experiment 3</u>

Main Effect

1. Symbols vs. Letters [$F\,(1,3) = 0.79, p < 0.45$]