Improving Selection Performance on Pen-Based Systems: A Study of Pen-Based Interaction for Selection Tasks

XIANGSHI REN
Kochi University of Technology
and
SHINJI MORIYA
Tokyo Denki University

Two experiments were conducted to compare pen-based selection strategies and their characteristics. Two state transition models were also formulated which provide new vocabulary that will help in investigating interactions related to target selection issues. Six strategies, which can be described by the state transition models, were used in the experiments. We determined the best strategy of the six to be the "*Slide Touch*" strategy, where the target is selected at the moment the pen-tip touches the target for the first time after landing on the screen surface. The six strategies were also classified into strategy groups according to their characteristics. We determined the best strategy group to be the "*In-Out*" strategy group, where the target is selected by contact either inside or outside the target. Analyses show that differences between strategies are influenced by variations in target size; however, the differences between strategies are not affected by the distance to the target (i.e., pen-movement-distance) or the direction of pen movement (i.e., pen-movement-direction). We also found "the smallest maximum size" of five pixels, i.e., the boundary value for the target size below which there are significant differences, and above which there are no significant differences between the strategies in error rate. Relationships between interaction states, routes, and strategy efficiency were also investigated.

Categories and Subject Descriptors: D.2.1 [**Software Engineering**]: Requirements/Specifications—*Methodologies*; D.2.2 [**Software Engineering**]: Design Tools and Techniques—*User interfaces*; H.1.2 [**Models and Principles**]: User/Machine Systems—*Human factors*; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Evaluation/methodology*; *Input devices and strategies*; *Interaction styles*; *Screen design* (e.g., text, graphics, color);

This work was done while the first author was an instructor in the Department of Information and Communication Engineering at Tokyo Denki University. The authors were assisted in conducting the experiments by Erei Miyajima, Masaya Hagihara, and Kunio Sato.

Authors' addresses: X. Ren, Department of Information Systems Engineering, Kochi University of Technology, 185 Miyanokuchi, Tosayamada-cho, Kami-gun, Kochi, 782-8502, Japan; email: ren@info.kochi-tech.ac.jp; S. Moriya, Department of Information and Communication Engineering, Tokyo Denki University, 2-2 Kanda-Nishikicho, Chiyoda-ku, Tokyo, 101-8457, Japan; email: moriya@c.dendai.ac.jp.

Theory and methods; I.3.6 [**Computer Graphics**]: Methodology and Techniques—*Interaction techniques*

General Terms: Design, Experimentation, Human Factors, Measurement, Theory

Additional Key Words and Phrases: Mobile computing, pen-based systems, pen-based input interfaces, small targets, state-transition models, target selection strategies, classifications of selection strategies

1. INTRODUCTION

Pen-based systems (incorporating a small touch-sensitive screen) have emerged as an important access technology having carved out a large niche in the computer market. Pen-based input is well suited to jotting down text and accessing information in mobile computing situations. "Notepads" made pen-based systems more popular a few years ago; however, not enough empirical tests have been performed to determine how we can improve their usage and efficiency. Goldberg and Richardson [1993], MacKenzie et al. [1994], Venolia and Neiberg [1994], and MacKenzie and Zhang [1999] are a few exceptions.

In small pen-based systems, accessing information by the selection of a target is more often attempted than by inputting handwritten data. Common targets are menus, data (one character of the text or graphic segment, etc.), ranges etc., and the selection of keys on a software keyboard displayed on a screen. As the amount of information displayed on the screen is increasing, users have to select smaller targets. The trade-off between the size and accessibility of targets and the amount of information presented on the screen is a fundamental problem in human-computer design. This is especially obvious in mobile products, such as personal digital assistants (PDAs), personal information managers (PIMs), and other mobile pen-based applications.

In order to solve the problem, some leading studies have developed a variety of relatively efficient selection strategies for the touch-screen [Potter et al. 1988; Sears and Shneiderman 1991; Sears et al. 1992], the mouse [Kabbash and Buxton 1995; MacKenzie et al. 1991],[1] and 3D input systems [Zhai et al. 1996]. Potter et al. [1988] conducted an empirical experiment to compare three selection strategies for touch-screens; however, only one target size was used, and finger-movement-distance and finger-movement-direction were not considered. Sears and Shneiderman [1991] tested three selection devices; touch-screen, touch-screen with stabilization, and mouse. The task was the selection of rectangular targets of 1, 4, 16, and 32 pixels per side. Their results showed that a stabilized touch-screen was effective for reducing the error rates when selecting a target. Kabbash and Buxton [1995] developed an area cursor which is larger than normal in order to improve target selection. Moreover, Worden

---

[1] MacKenzie et al. [1991] also used a stylus but with an *indirect* tablet.

et al. [1997] have provided a study of the effectiveness of two strategies for target selection: "area cursors" and "sticky icons." Zhai et al. [1994] designed and demonstrated the effectiveness of the "silk cursor" which provided the volume/occlusion cues for target selection.

However, current target selection strategies for pen-based systems are mostly only imitations of selection techniques for mouse and touch-screen devices. Investigations aimed at improving selection strategies for pen-based input devices have been neglected. This article looks at selection strategies suitable for selecting small targets, and identifies and quantifies the influential factors that make strategies more or less efficient with a view to improving selection performance on pen-based systems.

This article is organized as follows. Section 2 introduces two interaction models for describing and designing 2D and 3D target selection strategies. It also describes and evaluates six strategies and six strategy groups which were tested in the experiments. Section 3 presents the experiment which determined the best individual strategy and the best strategy group. We explore the effect of target size, pen-movement-distance, and pen-movement-direction on the differences between selection strategies. We also investigate the relationships between interaction states, routes, and strategy efficiency. Section 4 presents another experiment for determining "the smallest maximum size," i.e., the boundary value of the target size below which the degree of difficulty was significantly affected when selecting targets on pen-based systems. Section 5 gives a conclusion and directions for future research.

2. CHARACTERISTICS OF SELECTION STRATEGIES

2.1 State Transition Models for Selecting a Target with a Pen

State transition models are very useful for describing and designing pointing/selecting interactions. Buxton [1990] suggested a state transition model to help characterize graphical input. However models for target selection have not been considered in detail. Chen [1993] proposed a state transition diagram for describing interactions with a target, but 3D targets have not been reported. Our models shown in Figure 1 and Figure 2 may expand and refine their research on target selection using a pen.

2.2.1 *A State Transition Model Describing Two-Dimensional Selection Strategies*. Figure 1 shows a simple state transition model which elucidates a number of properties for selecting two-dimensional (2D) targets. This model can describe target selection not only on electromagnetic type tablets but also on touch-sensitive type tablets (touch-screens) which are used in general-purpose pen-based systems. The tip of the stylus pen interacts with the electromagnetic tablet so that it switches on when in contact with the screen surface. The pen switches off when the pen-tip is not in contact with the screen surface.

The state transition model (Figure 1) shows an interaction with a 2D target. The model shows the target and the status and position of the

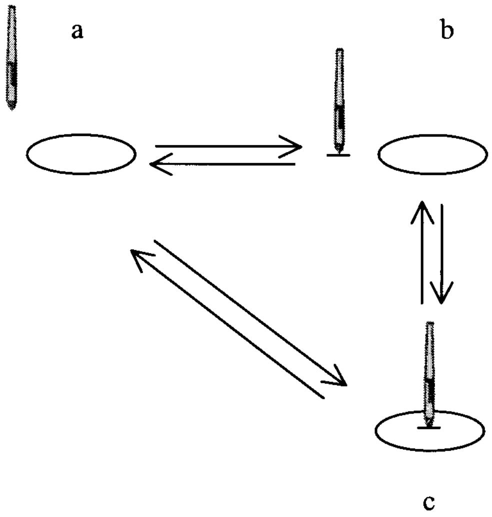

Fig. 1. A state transition model describing 2D target selection with a stylus pen. The ellipses illustrate 2D targets. The line arrows show the transition between two states which may be in either direction. The short lines under the pen-tip (in *b* and *c*) show the pen-tip in contact with the screen (the pen is switched on by contact with the screen). State *a*: pen outside/above the 2D plane, pen-tip switched off (pen not in contact with the screen); state *b*: outside the target, switched on (pen in contact with the screen); state *c*: inside the target, switched on (pen in contact with the screen). If we assume for example that state *a* is an initial state and *c* is a final state, the state transition route may be either $a \rightarrow b \rightarrow c$ or $a \rightarrow c$.

pen-tip. The ellipses represent 2D targets on the screen. The line arrows show the transition between two states. The short lines under the pen-tip show that the pen-tip is in contact with the screen (the pen is switched on). State *a* shows the pen outside/above the 2D plane, pen not in contact with the screen (the pen-tip switched off). State *b* shows the pen in contact with the screen (and therefore switched on) but outside the target area. State *c* represents the pen in contact with the screen (therefore switched on) inside the target. In state *a* the pen is approaching the 2D screen surface from above, in 3D space. In states *b* and *c* the pen is in contact with the screen (the pen is dragged over the 2D plane). Thus there are three states: state *a*: outside/above the 2D plane, not in contact with the screen (switched off); state *b*: outside the target, in contact with the screen (switched on); state *c*: inside the target, in contact with the screen (switched on).

2.2.2 *A State Transition Model Describing Three-Dimensional Selection Strategies*. Figure 2 shows a state transition model which elucidates a number of properties for selecting three-dimensional (3D) targets. We used an electromagnetic tablet in the experiments. This type of tablet also allowed us to trial 3D selection strategies, because when the pen-tip is above the tablet screen surface (within a height of 1 cm), the computer can recognize the coordinates (x, y) of the pen-tip. Thus, even though the bottom of a target (e.g., a menu or a button) on the screen is 2D, it can be highlighted or selected when the pen is above the tablet surface (within 1 cm). This means that the target can also be expressed as a 3D target.

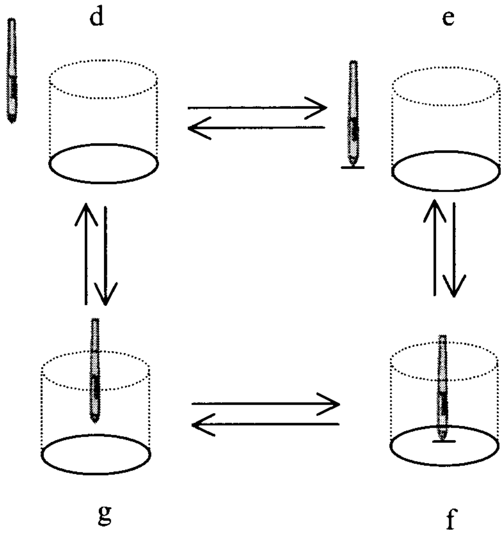

Fig. 2. A state transition model describing 3D target selection with a stylus pen. The cylinders with dashed lines show the body of a 3D target. The ellipses with a solid line illustrate the bottom of 3D targets on the tablet screen surface. The short lines under the pen-tip (in *e* and *f*) show the pen-tip in contact with the tablet surface. State *d*: the pen-tip is outside the 3D target, pen-tip switched off (pen not contact with the screen); state *e*: the pen-tip is outside the 3D target, switched on (the pen is in contact with the screen); state *f*: the pen-tip is inside the 3D target, switched on (pen in contact with the screen); state *g*: inside the 3D target but not in contact with the screen and therefore switched off.

The state transition model in Figure 2 showing an interaction with a 3D target consists of the target and the status and position of the pen-tip. The ellipses with a solid line illustrate the bottom of the 3D targets on the screen surface. The cylinders show the body of the 3D target. Some responses (e.g., highlighting) will take place when the pen is in the cylinder even though the pen-tip is not in contact with the screen surface. The short lines under the pen-tip show that the pen-tip is in contact with the screen surface. States *d* and *e* represent the pen outside the target. State *f* and state *g* represent the pen inside the target. States *e* and *f* represent the pen in contact with the screen surface (the pen is dragged over the 2D plane). States *d* and *g* represent the pen as not in contact with the screen surface. In this model we considered the two pen positions above and beside the 3D target as the same in effect. There may, however, be some design value in considering the implied approach paths as offering different selection options. Thus there are four states: state *d*: pen not in contact with the screen, outside the target (before or after entering the 3D target sensitive zone); state *e*: in contact with the screen surface, outside the target; state *f*: in contact with the screen, inside the target; and state *g*: approach or removal from the 2D plane inside the 3D target sensitive area (3D cylinder).

It should be noted that although the illustrations show ellipses in Figure 1 and cylindrical targets in Figure 2, the shape of the target has no definitive bearing on this discussion. Our focus here is on the description of selection strategies using the state transition models. For example, we shall describe 2D target selection strategies using the state transition model in Figure 1. Here assume state a is an initial state, and state c is a final state. The states and transitions used to select a target can be expressed as $a \rightarrow b \rightarrow c$ or $a \rightarrow c$. In other words, new strategies may be designed using these state transition models. The state transition models representing the manipulation of a pen from an arbitrary initial state to an arbitrary final state can become a strategy. For example, in the "*Slide Touch*" strategy the initial state is a, and the final state is c (see Section 2.2); in the "*Direct Off*" strategy, the initial state is a, and the final state is a (see Section 2.2). Theoretically, an infinite range of selection strategies exists.

We consider that these states are an adequate basis for 2D (a, b, and c in Figure 1) and 3D target design (d, e, f, and g in Figure 2) because they include all the normal conditions for these types of pen-based systems (pen in contact with the screen, pen not in contact with the screen; pen switched on, pen switched off; pen inside the target area, and pen outside the target area). Furthermore, the models may be modified to include other conditions such as pen side switches.

2.2 Six Strategies Used in Two Experiments

The six strategies for selecting a target in the two experiments (see Sections 3 and 4) are illustrated in Figure 3. The arrows show the direction of pen-tip movement. The dashed lines indicate that the pen-tip is not in contact with the screen surface (either before or after contact), and the solid lines (in *Slide Touch*, *Direct Off*, and *Slide Off*) show that the pen-tip is in contact with the screen surface. The pen-tip is automatically switched on by contact with the screen surface. The dark points show where target selection is affected in the strategy process. Here, we explain the six strategies and show how these strategies fit into the state transition models (Figures 1 and 2). Assume I is a collection of initial states, described as I = {}; F is a collection described as F = {}; M is a collection of middle states, described as M = {}; R is a collection of routes, described as R = {}. An arrow "→" means that a state changes to another state. "↔" means the changes between two states may be in either direction. Table I shows initial states (I), middle states (M), final states (F), and routes (R) for the six strategies.

—*Direct On* strategy: the pen approaches from above. The target is selected only momentarily at the time the pen makes contact with the screen in the target area. Here, I (Initial state) = $\{a\}$, F (Final state) = $\{c\}$, R (Route) = $\{a \rightarrow c\}$, and there is no middle state (M) (see Figures 1 and 3).

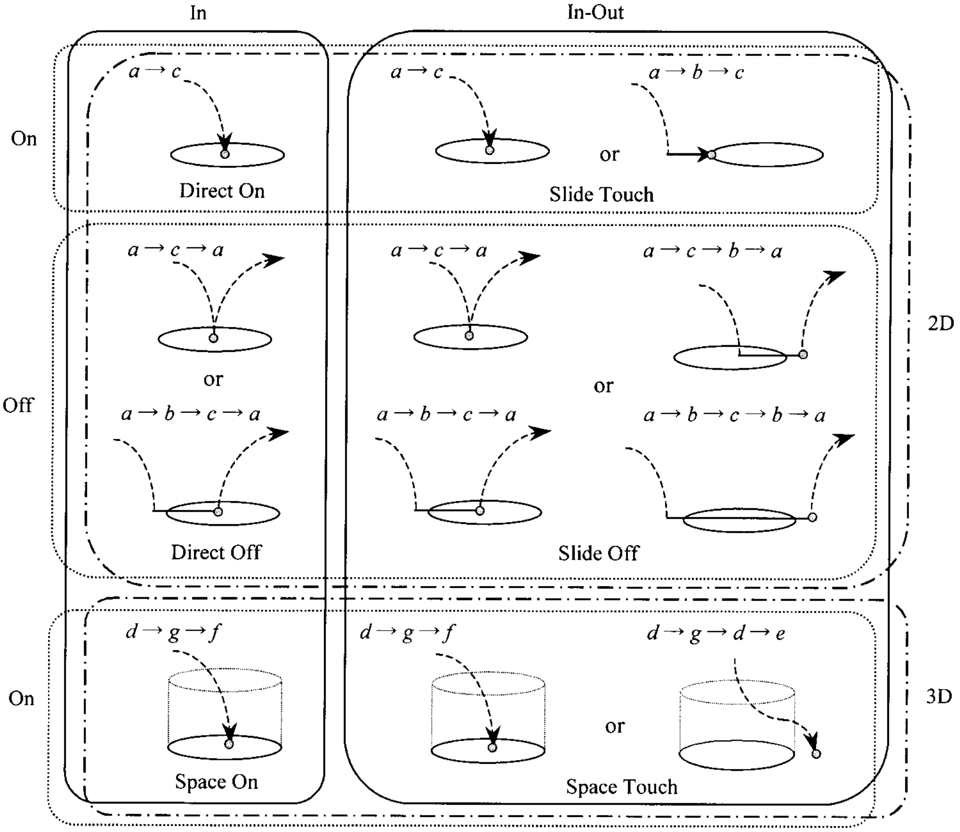

Fig. 3. This figure represents the six strategies (*Direct On,*, *Slide Touch*, *Direct Off*, *Slide Off*, *Space On*, and *Space Touch* described according to the sate transition models used in the two experiments. The figure also shows the strategies (*On*, *Off*, *2D*, *3D*, *In*, and *In-Out*) as they grouped according to their characteristics (see Section 2.3). The *In* strategies (on the left) are duplicated (center column) to indicate that they are functional possibilities within the *In-Out* strategies to which they correspond and with which they constitute a group (2D *On* or *Off* or 3D *On*). The figure shows only the simplest representation of each route and does not include possible repeated steps. Im many routes the initial and/or middle steps may be repeated any number of times before selection is affected, e.g., in the *Space On* strategy the figure shows $d \to g \to f$, but this could be represented as $d \leftrightarrow g \to f$ (e.g., $d \to g \to d \to g \to f$) because the repeated step does not affect the selection of the target though it may affect the highlighting function.

—*Slide Touch* strategy is an extension of the *Direct On* strategy. Here also the target is selected when the pen touches it for the first time, but in this case the pen initially lands outside the target area before moving into it. Here, I = $\{a\}$, F = $\{c\}$, M = $\{b\}$, R = $\{a \to c, a \to b \to c\}$.

—*Direct Off* strategy: the target is highlighted only while the pen is touching it. The selection is made at the moment the pen is taken off the target. Here, I = $\{a\}$, F = $\{a\}$, M = $\{b, c\}$, and R = $\{a \to c \to a, a \to b \leftrightarrow c \to a\}$.

Table I. Initial States, Middle States, Final States, and Routes of the Six Strategies

Strategies	Initial States	Middle States	Final States	Routes	Numbers of Routes
Direct On	a	(no)	c	a → c	1
Slide Touch	a	b	c	a → c a → b → c	2
Direct Off	a	b, c	a	a → c → a a → b ↔ c → a	2
Slide Off	a	b, c	a	a → c → a a → b ↔ c → a a → c ↔ b → a a → b ↔ c ↔ b → a	4
Space On	d	g	f	d ↔ g → f	1
Space Touch	d	d, g	e, f	d ↔ g → f d ↔ g → d → e	2

—*Slide Off* strategy is an extension of the *Direct Off* strategy. The target is highlighted only while the pen is in contact with it; however, the selection is made when the pen is removed from any point on the screen either inside or outside the target area. Here, I = $\{a\}$, F = $\{a\}$, M = $\{b, c\}$, R = $\{a \rightarrow c \rightarrow a, a \rightarrow b \leftrightarrow c \rightarrow a, a \rightarrow c \leftrightarrow b \rightarrow a, a \rightarrow b \leftrightarrow c \leftrightarrow b \rightarrow a\}$.

—*Space On* strategy: the pen approaches from above. The target is highlighted while the pen is within the 1 cm high cylinder above the target. Selection is made at the moment the pen makes contact with the bottom of the target area (i.e., inside the bottom circle). Here, I = $\{d\}$, F = $\{f\}$, M = $\{g\}$, R = $\{d \leftrightarrow g \rightarrow f\}$ (see Figures 2 and 3).

—*Space Touch* strategy is an extension of the *Space On* strategy. The target is highlighted while the pen is within the 1 cm high cylinder above the target. After highlighting, the selection is made when the pen makes contact with any point on the screen either inside or outside the target area. Here, I = $\{d\}$, F = $\{e, f\}$, M = $\{d, g\}$, R = $\{d \leftrightarrow g \rightarrow f, d \leftrightarrow g \rightarrow d \rightarrow e\}$.

These strategies may be considered to be "strategy types" rather than fixed strategies. This means that the name of the strategy specifically indicates the point of actual selection and sometimes includes information about the route.

The *Direct On* and *Direct Off* strategies are already in common use. The *Slide Touch* strategy corresponds to the "first-contact" strategy [Potter et al. 1988]. The *Slide Off*, *Space On*, and *Space Touch* strategies were new strategies designed by Ren and Moriya [1997a].

2.3 Classification of the Six Strategies

Although there are a few studies on selection strategies, none have paid attention to particular strategy characteristics until now. We classified (grouped) the six strategies so that we could evaluate particular characteristics which pertain to selection strategies in general. Figure 3, therefore, shows the classifications of the six strategies according to their characteristics, as well as the six individual strategies. Notice that strategies may appear in more than one group depending on the various combinations of characteristics pertaining to them. The classifications were formulated after consideration of the six conditions created by the pen manipulations [Ren and Moriya 1995]. These conditions are: contact with the screen, removal from the screen, contact inside the target, contact outside the target, target highlighted, and target not highlighted.

—*2D and 3D* strategy groups: Targets exist both as planes (2D) and as solid bodies (3D). Here, the *2D* strategies are the *Direct On*, *Slide Touch*, *Direct Off*, and *Slide Off* strategies. The *3D* strategies are the *Space On* and *Space Touch* strategies.

—*On and Off* strategy groups: Contact and removal of the pen from the screen were considered as movements between the 2D plane and 3D space. Pen contact involves a movement from 3D space to the 2D plane, while removal involves a movement from the 2D plane to 3D space. These interactions were considered to be suitable conditions for the subject to recognize and confirm the moment of target selection. The strategies in which selection was made by contact with the screen (*Direct On*, *Slide Touch*, *Space On*, and *Space Touch* strategies) were named *On* strategies. The strategies in which selection was made by removal from the screen (*Direct Off* and *Slide Off* strategies) were named *Off* strategies. Where the target existed on the 2D plane, both the *On* and *Off* strategies were deployed. Where the target existed in 3D space, considering that the pen-tip is approaching the body of the 3D target from above in general when selecting a 3D target, we here only discuss the *On* strategies (*Space On* and *Space Touch* strategies).

—*In and In-Out* strategy groups: We considered the movement of the pen into and out of the target from the perspective of the user's eyes. When the pen moved into or out of the target, users could confirm whether or not the target was highlighted. Those strategies in which selection was made by contact within the target area were named *In* strategies (the *Direct On*, *Direct Off*, and *Space On* strategies). On the other hand, those strategies in which selection was made by contact either inside or outside the target were named *In-Out* strategies (*Slide Touch*, *Slide Off*, and *Space Touch*).

3. EXPERIMENT ONE

This section presents a comparison of the six strategies individually and the strategies grouped. We seek to determine the best individual strategy and the best strategy group. We also evaluate the effects variables have on the differences between the strategies. If the significance (or insignificance) of the differences between strategies is maintained when variables such as direction, distance, or target size are changed, we may consider that the particular variable has no significant influence on the efficiency of the strategies in general. Conversely if the significance (or insignificance) of the differences between strategies is not maintained when variables such as direction, distance, or target size are changed, we may consider that the particular variable has a significant influence on the efficiency of the strategies in general. For this to be conclusive it was obviously necessary to test the variables in a comprehensive and balanced way.

3.1 Method

3.1.1 *Participants.* Twenty-one volunteer participants (17 male, 4 female; all right-handed, university students) were tested for the experiment. Ten had had previous experience with pen-input systems, while the others had no experience.

3.1.2 *Apparatus.* The experiment was run on an NEC 9801DA PC and a Wacom tablet-cum-display with a stylus pen. The liquid crystal display resolution was 640 × 400 pixels. One pixel was about 0.36 mm. The pen/screen contact area was 1.40 mm in diameter.

3.1.3 *Procedure.* First the experiment was explained to each subject. Each subject had 20 practice trials immediately before the experiment started. The message *"Select a target as quickly and accurately as possible using the strategy"* was displayed on the screen of the experimental tool when the experiment started.

The steps for selecting a target were as follows (Figure 4):

(a) The initial position was displayed at the center of the screen. The initial position was the place where the pen was pointed immediately before beginning the selection procedure. The subject had been told which strategy to use and how many trials were to be done.

(b) The subject touched the initial position with the pen.

(c) A target was displayed with size and position changed at random by the computer. Targets of a particular size were never displayed in the same position twice. The distances between the initial position and the target were 39, 131, or 160 pixels, randomly selected by the computer.

(d) The subject attempted to select the target and then received a message on the screen to indicate whether or not he or she had made a successful selection.

(e) The subject then repeated (a) to (d) above.

(f) A message indicating the end of the test was displayed when the subject had completed the task.

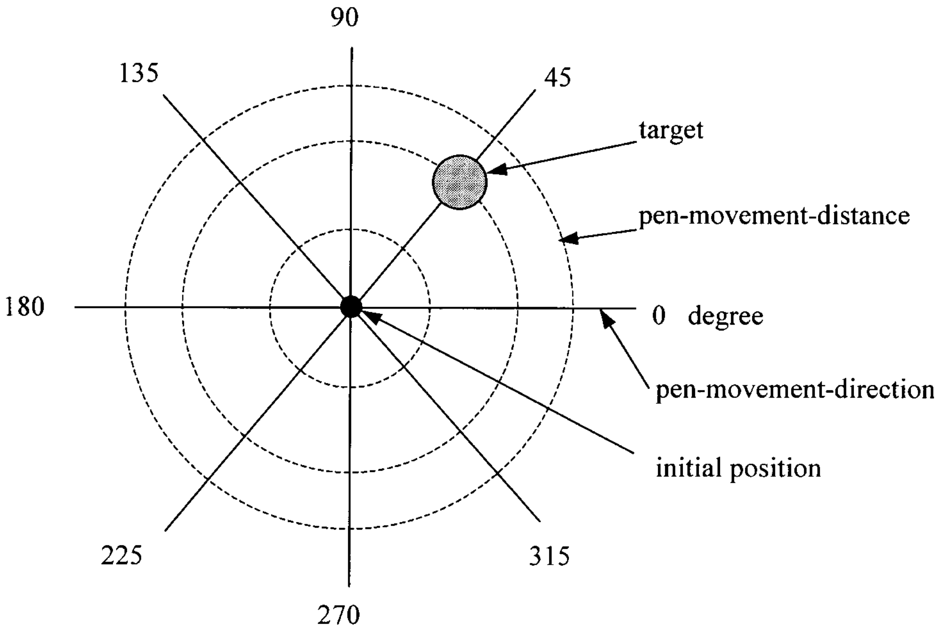

Fig. 4. The display of a target. The small, centered dot is the initial position. The large circle shows one of the 24 possible positions for the display of a target. The circular dotted lines show the three pen-movement-distances from the initial position to the target. The solid lines indicate the eight pen-movement-directions to the target from the initial position.

After they finished testing each strategy, the subjects were asked to fill in a questionnaire. The first question was: “For the strategy tested just now, when selecting T, how do you rate Q? Please answer on a 1-to-5 scale (1 2 3 4 5).” Here, 1 = lowest preference, and 5 = highest preference. “T” means large or small targets as tested in the particular trial. “Q” consisted of the six subquestions regarding selection accuracy, selection speed, selection ease, learning ease, satisfaction, and desire to use. The second question was: “Which positions (i.e., direction and distances) were most comfortable for selecting the targets in the strategy?” The subject marked his/her preferences on Figure 4.

The strategies were not mixed. In a given trial each subject used only one strategy. The data for each strategy were recorded automatically as follows:

(1) Presence or absence of error when a target was selected. One selection was a continuous operation from the moment the pen touched the initial position until removal of the pen from the screen surface. Feedback to the subject indicated whether the selection was successful or not. In either case, the subject could not cancel the selection.

(2) Position and size of the target displayed.

(3) The time lapsed between display of the target and the moment when the pen contacted the screen.

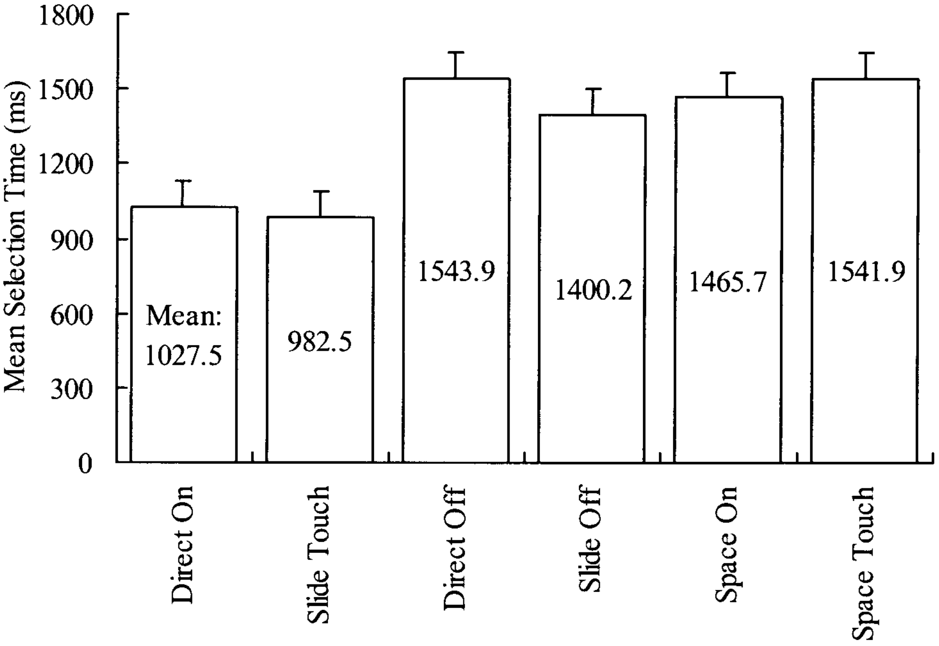

Fig. 5. Mean selection times (with standard error bars) for each individual strategy in Experiment One.

(4) The time lapsed between contact with the target and removal from the screen.

(5) The time lapsed between contact with the screen and contact with the target.

These times were measured to an accuracy of 10 ms. Data as defined in item (3) were recorded for the *Direct On*, *Space On*, and *Space Touch* strategies. Data as defined in item (5) were recorded for the *Slide Touch* strategy. Data as defined in item (4) were recorded for the *Direct Off* and *Slide Off* strategies.

3.1.4 *Design.* The experiment used a mixed factorial design.

—*Size of the target*: To examine the relationship between target size and strategy, three target sizes of 3, 5, and 9 pixels (1.1 mm, 1.8 mm, and 3.2 mm diameter circles) were used in all trials. All the targets for the experiment were circular. Circular targets were used so that the distance between the initial position and the edge of all targets on each radius remained constant in all directions.

—*Pen-movement-distance:* The distance to the target was the radius of a circle in which the center point was the initial position (Figure 4). To examine the relationship between distance and strategy efficiency, the distances of 39, 131, and 160 pixels (14.0, 47.2, and 57.6 mm) were determined by a preliminary experiment. (Distances of 39 pixels and 131 pixels were the average values used by 10 subjects in a preliminary experiment. When the wrist was in a fixed condition, 39 pixels was the radius of the arc which could be drawn by the subjects; 131 pixels was the radius of the circular arc which was the maximum finger-movement-distance. The outside circle radius of 160 pixels was determined according to the size limitations (height) of the screen. It was also a distance by which the wrist could be moved.).

—*Pen-movement-direction:* Eight directions were used. They were at 0, 45, 90, 135, 180, 225, 270, and 315 degrees from the initial position (Figure 4).

Each subject had a total of 92 trials for each strategy. These consisted of 20 practice trials and 72 test trials (= 3 target sizes × 3 distances × 8 directions). A break was taken at the end of each strategy trial. Whenever the subject felt tired he or she was allowed to take a rest. Each subject completed 432 test trials (= 6 strategies × 72). In each strategy 1512 test trials (= 21 subjects × 72) were completed. The order for the six strategies was different for each of the 21 subjects.

3.2 Results

An ANOVA (analysis of variance) with repeated measures was used to analyze performances in terms of selection times, error rates, and subjective preferences. Post hoc analysis was performed with Tukey's honestly significant difference (HSD) test.

3.2.1 *Comparison of Selection Times for the Individual Strategies.* There was a significant interaction between the six individual strategies in selection time, $F(5,120) = 10.8$, $p < 0.0001$. From this we could conclude that the selection time was influenced by the particular strategy, i.e., the selection times changed according to the strategy being applied. Figure 5 shows the average selection times for each of the six strategies. The *Slide Touch* strategy was the fastest among the six strategies (mean = 0.98s). The post hoc Tukey HSD test showed that the *Slide Touch* strategy was faster than the *Direct Off*, *Slide Off*, *Space On*, *Space Touch* strategies ($p < 0.05$). There was no significant difference in selection time between the *Slide Touch* and *Direct On* strategies. Analyses also showed that the *Direct On* strategy was faster than the *Direct Off*, *Slide Off*, *Space On*, and *Space Touch* strategies ($p < 0.05$). There were no other significant differences across the strategies (Table II).

3.2.2 *Comparison of Error Rates for the Individual Strategies.* There was a significant difference between the six strategies in error rate, $F(5,120) = 17.8$, $p < 0.0001$. This means that changes in the strategy affected the error rates. Figure 6 shows the mean error rates for each of the

Table II. Comparison of Selection Times for the Individual Strategies Based on the Post Hoc Tukey HSD test. Each strategy (y-axis) compared with each of the other strategies (x-axis) according to Tukey's test results. "=" means there was no significant difference in (selection time or error rate); ">" means the (y-axis) strategy was significantly greater than the other strategy (x-axis); "<" means the (y-axis) strategy was significantly less than the other strategy (x-axis), e.g., there is no significant difference (=) in time between *Direct On* and *Slide Touch*, but *Direct On* had a higher (>) error rate than *Slide Touch*. We have maintained the duplication of the results in the table to make it easier to read.

		Direct On	Slide Touch	Direct Off	Slide Off	Space On	Space Touch
Direct On	Time		=	<	<	<	<
	Error		>	>	>	=	>
Slide Touch	Time	=		<	<	<	<
	Error	<		<	=	<	=
Direct Off	Time	>	>		=	=	=
	Error	<	>		>	=	>
Slide Off	Time	>	>	=		=	=
	Error	<	=	<		<	=
Space On	Time	>	>	=	=		=
	Error	=	>	=	>		>
Space Touch	Time	>	>	=	=	=	
	Error	<	=	<	=	<	

six strategies. The *Slide Touch*, *Slide Off*, and *Space Touch* strategies had lower error rates (16.6%, 17.4%, and 15.5%) than the other three *(Direct On, Direct Off,*, and *Space On*). The post hoc Tukey HSD test showed that the *Slide Touch* had a lower error rate than the *Direct On, Direct Off*, and *Space On* strategies ($p < 0.05$). There was no significant difference in error rate between the *Slide Touch* and the *Slide Off*, or between the *Slide Touch* and the *Space Touch* strategies. Analyses also showed that the *Direct On* had a higher error rate than the *Direct Off*, *Slide Off*, and *Space Touch* strategies; the *Direct Off* had a higher error rate than the *Slide Off* and *Space Touch* strategies; the *Slide Off* had a lower error rate than the *Space On* strategy; the *Space On* had a higher error rate than the *Space Touch* strategy (all $p < 0.05$). There were no other significant differences across the strategies (Table II).

3.2.3 *Comparison of Selection Times for the Strategy Groups*. Figure 7 shows the selection times for the six strategy groups. There was a significant difference between the strategy groups in selection time, $F(5,120) = 2.63$, $p < 0.05$. The *In-Out* strategy group was faster (mean = 1.39s) than each of the other groups. The post hoc Tukey HSD test showed that there were no significant differences across the strategy groups (Table III).

3.2.4 *Comparison of Error Rates for the Strategy Groups*. Figure 8 shows the error rates for the six strategy groups. There was a significant

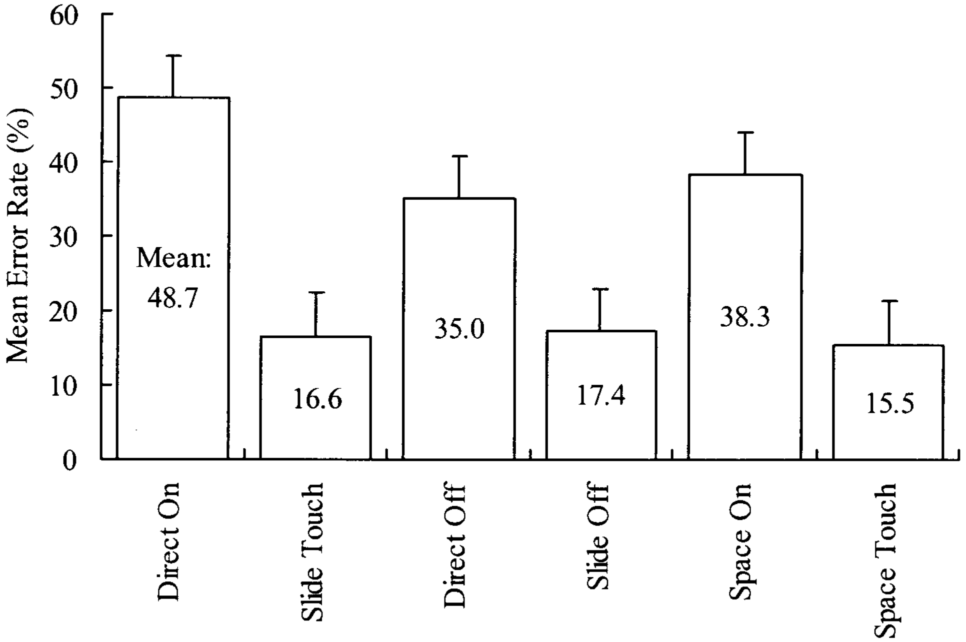

Fig. 6. Mean error rates for each individual strategy in Experiment One.

Table III. Comparison of Selection Times for the Strategy Groups Based on Tukey's Post Hoc HSD Test

		In	In-Out	On	Off	2D	3D
In	Time		=	=	=	=	=
	Error		>	=	>	=	>
In-Out	Time	=		=	=	=	=
	Error	<		=	=	=	=
On	Time	=	=		=	=	=
	Error	=	=		=	=	=
Off	Time	=	=	=		=	=
	Error	<	=	=		=	=
2D	Time	=	=	=	=		=
	Error	=	=	=	=		=
3D	Time	=	=	=	=	=	
	Error	<	=	=	=	=	

difference among the strategy groups in error rate, $F(5,120) = 6.91$, $p < 0.001$. The *In-Out* strategy group had the lowest error rate (16.5%), and the *In* strategy group had the highest error rate (40.7%). The post hoc Tukey HSD test showed that the *In-Out*, *Off*, and *3D* strategy groups had lower error rates than the *In* strategy group ($p < 0.05$). There were no other significant differences across the strategy groups (Table III).

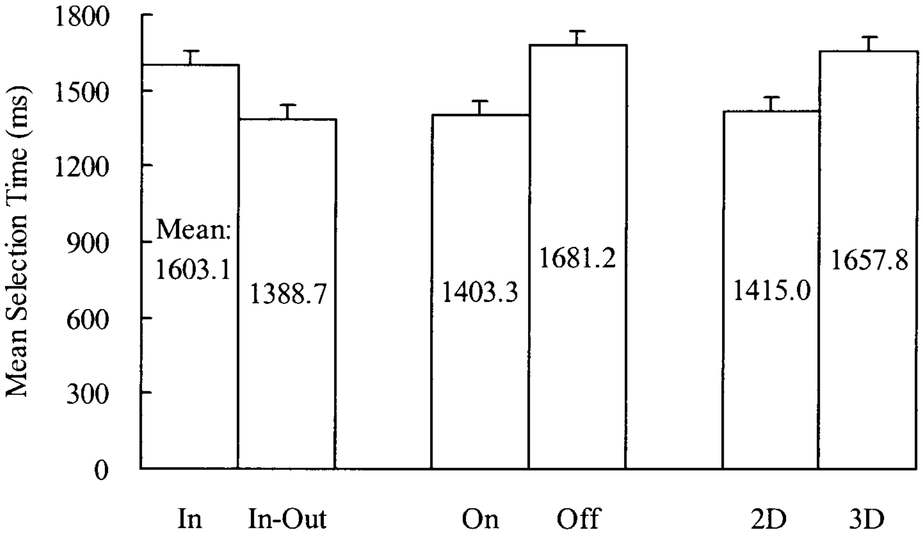

Fig. 7. Mean selection times for each strategy group in Experiment One. The *In* strategy group = *Direct On, Direct Off & Space On*; *In-Out* = *Slide Touch, Slide Off & Space Touch*; *On* = *Direct On, Slide Touch, Space On & Space Touch*; *Off* = *Direct Off & Slide Off*; *2D* = *Direct On, Slide Touch, Direct Off & Slide Off*; *3D* = *Space On & Space Touch.*

3.2.5 *The Influences of Three Variables on the Difference Between the Strategies.* Analyses were conducted to observe the significant difference in selection time and error rate between the six strategies and changes in the difference with reference to target size, pen-movement-distance, and pen-movement-direction. This analysis was aimed at identifying and quantifying the effect of target size, pen-movement-distance, and pen-movement-direction on the differences in selection time and error rate between the six individual strategies.

—*Target size:* A significant difference in selection time was observed between the six strategies for each target size, 3, 5, and 9 pixels, F(5,120) = 9.75, 6.85, and 5.22, $p < 0.001$. This means that significant differences in selection time remained when the target size was varied. There was a significant difference between the strategies in error rate for each of the target sizes of 3 and 5 pixels, F(5,120) = 24.7, 9.99, $p < 0.0001$. On the other hand, there was no significant difference in error rate for the target size 9 pixels, F(5,120) = 0.65. This means that the difference in error rate was significantly affected when the target size was varied.

—*Pen-movement-distance:* A significant difference in selection time was observed between the six strategies for each distance, 39, 131, and 160 pixels, F(5,120) = 7.33, 10.3, and 10.1, $p < 0.0001$. This means that significant differences in selection time remained even though

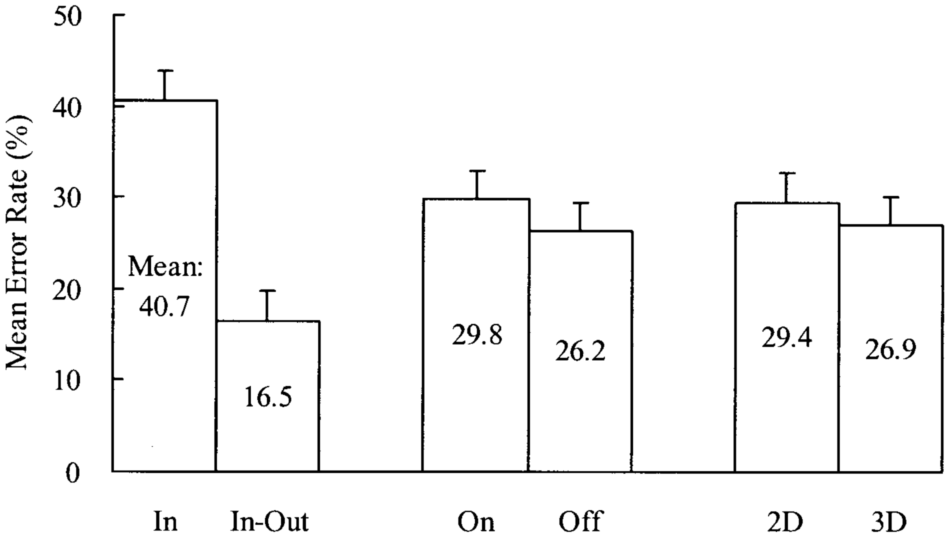

Fig. 8. Means error rates for each strategy group in Experiment One. The *In* strategy group = *Direct On*, *Direct Off & Space On*; *In-Out* = *Slide Touch*, *Slide Off & Space Touch*; *On* = *Direct On*, *Slide Touch*, *Space On & Space Touch*; *Off* = *Direct Off & Slide Off*; *2D* = *Direct On*, *Slide Touch*, *Direct Off & Slide Off*; *3D* = *Space On & Space Touch*.

pen-movement-distance was varied. There was a significant difference in error rate between the six strategies for each distance, 39, 131, and 160 pixels, F(5,120) = 15.2, 16.3, and 16.5, $p < 0.0001$. This means that significant differences in error rate remained even though pen-movement-distance was varied.

—*Pen-movement-direction:* A significant difference in selection time was observed between the six strategies in each direction, 0, 45, 90, 135, 180, 225, 270, and 315 degrees ($p < 0.0001$, in case of 180 degrees, $p < 0.001$). This means that significant differences in selection time remained even though pen-movement-direction was varied. There was a significant difference in error rate between the six strategies for each of the eight directions, all at the $p < 0.0001$ level. This means that significant differences in error rate remained even though pen-movement-direction was varied.

Analyses were also conducted between the strategy groups in pairs according to their particular characteristics (i.e., *On* & *Off*, *2D* & *3D*; *In* & *In-Out*). We looked at the significant difference in selection time and error rate and changes in these differences with reference to target size, pen-movement-distance, and pen-movement-direction. Significant differences in selection time were not found between the *On* and *Off* strategy groups, F(1, 40) = 6.01, $p < 0.01$, between the *2D* and *3D* strategy groups, F(1, 40) = 3.66, $p < 0.05$, or between the *In* and *In-Out* strategy groups, F(1, 40) = 3.37, $p < 0.01$. Significant differences in error rate were not observed between the *On* and *Off* strategy groups, F(1, 40) = 0.7, or between the *2D* and *3D* strategy groups, F(1, 40) = 0.4. However, a significant difference in error rate was found between the *In* and *In-Out* strategy groups, F(1, 40) = 34.2, $p < 0.0001$. To investigate which variables affected the difference in error rate between *In* and *In-Out* strategy groups, analyses were conducted to determine the significant difference in error rate between the *In* and *In-Out* strategy groups in terms of target size, pen-movement-distance, and pen-movement-direction.

—*Target size:* A significant difference was found between the *In* and *In-Out* strategy groups for each of the target sizes of 3 and 5 pixels in error rate, F(1, 40) = 52.3, 18.0, all $p < 0.01$. On the other hand, there was no significant difference in error rate for the target size 9 pixels, F(1, 40) = 1.2, $p < 0.01$. This means that the significant difference in error rate between the *In* and *In-Out* strategy groups was changed when the target size was varied.

—*Pen-movement-distance:* There was a significant difference in error rate between the *In* and *In-Out* strategy groups for each distance, 39, 131, and 160 pixels, F(1, 40) = 30.2, 34.7, and 33.3, all $p < 0.01$. This means that significant differences in error rate between the *In* and *In-Out* strategy groups remained even though pen-movement-distance was varied.

—*Pen-movement-direction:* There was a significant difference in error rate between the *In* and *In-Out* strategy groups for each of the eight directions, all $p < 0.01$. This means that significant differences in error rate between the *In* and *In-Out* strategy groups remained even though pen-movement-direction was varied.

3.2.6 *Subject Preferences*.

Target Size. Figure 9 shows the subjective ratings for the six strategies according to target size in Experiment One. These ratings were based on the average value of the answers given by the subjects to 12 questions. Significant main effects were seen between the six individual strategies with regard to target size (large targets, F(5, 30) = 14.8, $p < 0.0001$, and small targets, F(5, 30) = 58.1, $p < 0.0001$). The *Slide Touch* and *Slide Off* strategies were rated highly for both large targets and small targets. When selecting a small target, the *Slide Touch* strategy was the most preferred (mean = 3.08). Significant differences between the strategy groups were also found (large targets, F(5, 30) = 7.01, $p < 0.001$, and small targets, F(5, 30) = 45.3, $p < 0.0001$). The *In-Out* strategy group was rated highly for both large targets (mean = 4.68) and small targets (mean = 2.81).

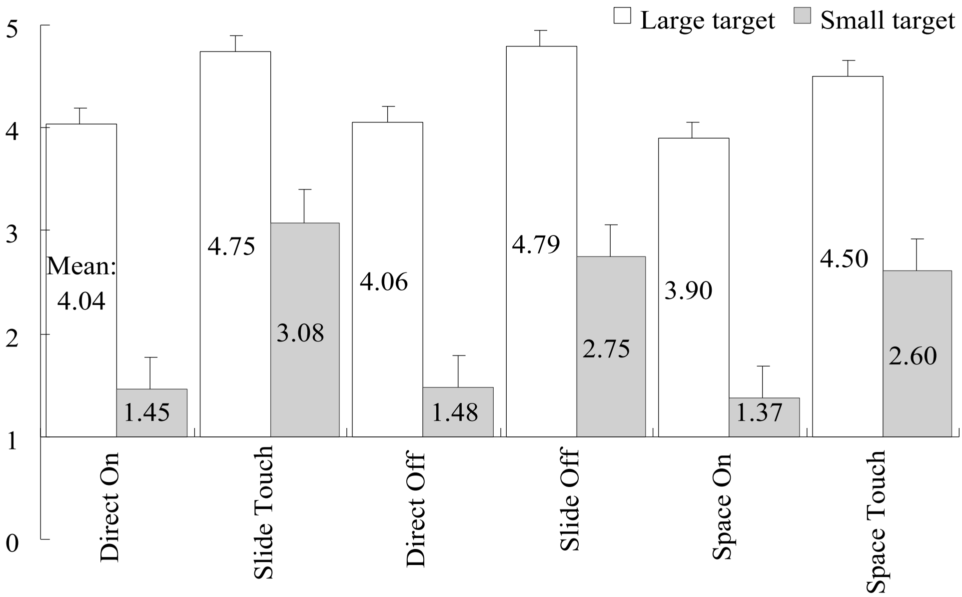

Fig. 9. Subjective evaluation for the six strategies according to target size in Experiment One (1 = lowest preference, 5 = highest preference).

Distance and Direction. From the marks left in Figure 4 by all subjects, we determined that the smallest radius (39 pixels) and the medium radius (131 pixels) were the most favored pen-movement-distances. These radii options were determined by a preliminary experiment. Though they were radii in which the movements of the hand were not large, nevertheless significant differences in the six strategies were observed. There was also a significant difference between the six strategies at the maximum outside radius of 160 pixels. Furthermore, the subjects indicated that 135, 180, and 225 degrees of pen-movement-direction could be comfortably accommodated.

3.3 Discussion

3.3.1 *Best Selection Strategies.* The results showed that the *Slide Touch* strategy was the best of the six, in terms of selection time (Figure 5), error rate (Figure 6), and subject preference (Figure 9). The analyses showed that the *Slide Touch* strategy had a lower error rate, and was faster than the *Direct Off* and *Space On* strategies. There was no significant difference in selection time between the *Slide Touch* strategy and the *Direct On* strategy, but the *Slide Touch* strategy had a lower error rate than the *Direct On* strategy. No significant differences were found in error rate between the *Slide Touch* and either the *Slide Off* or *Space Touch* strategies, but the *Slide Touch* strategy was faster than both of them (see Table II). Thus, the *Slide Touch* strategy was significantly better overall than the other individual strategies. An analysis of subject preferences also showed that the *Slide Touch* strategy was the most preferred (large targets, mean = 4.75, small targets, mean = 3.08).

Regarding strategy groups, the *In-Out, Off,* and *3D* strategy groups were better than the other three strategy groups, based on analyses of the post hoc Tukey HSD test. The analyses showed that there were no significant differences in either selection time or error rate between the *In-Out, On, Off, 2D*, and *3D* strategy groups when compared with each other; however, *In-Out*, *Off*, and *3D* had lower error rates than the *In* group, and there were no significant differences between the *In* and either *On* or *2D* strategy groups (Table III). We concluded therefore that overall, the *In-Out*, *Off,* and *3D* strategy groups are better than the other three. The subjects highly preferred the *In-Out* strategy group for both large targets (mean = 4.68) and small targets (mean = 2.81) rather than the *Off* (large targets, mean = 4.42, small targets, mean = 2.11), or the *3D* (large targets, mean = 4.2, small targets, mean = 1.99) strategy groups.

The *In-Out* strategy group (*Slide Touch, Slide Off,* and *Space Touch*) was more efficient than the other groups particularly in situations where other targets do not exist near the target, or in situations where targets are not too close together, or where other targets do not exist near one side of the target (e.g., the upper part). Sears and Shneiderman [1991] also cite this point with reference to touch-screen situations. For example, in the *Slide Touch* strategy, contact with the target may be affected after landing on the screen outside the target area. Selection is affected on contact with the target area. Since the first target contacted will be selected, prior visual confirmation is important but may be difficult to achieve. In this situation, the *Slide Off* strategy can be used because selection does not depend on the point of removal from the screen, and the last target highlighted will be selected. Therefore, the pen may pass through the target which will not be selected until the pen is removed from any point on the screen.

On the other hand, *In-Out* selection strategies would not be efficient in dense displays. In dense displays the *Direct On* and *Direct Off* strategies (*In* strategy group) can be used. For instance, the *Direct Off* strategy (which is in the *Off* strategy group) is the same as the familiar mouse technique. Here selection is affected after the pen has contacted the screen, moved into the target area, and been taken off the target area following visual confirmation. However, hand/eye coordination is essential when using the *Direct On* and *Direct Off* strategies. For the *Direct Off* strategy the pen must be within the target (i.e., "catching" the target) at the moment the pen is removed from the screen. In the *Direct On* strategy the pen approaches the screen and target area, and it is in the target area only momentarily.

When using an electromagnetic tablet, a target on the screen can be designed as a 3D target. Thus the *Space On* and *Space Touch* strategies (*3D* strategy group) may be used in the same situation. In the *Space On* and *Space Touch* strategies the pen can affect the target before it makes contact with the screen. This may be useful for highlighting without selection or prior to selection (or rejection) of the target.

3.3.2 *Relationships Between Interaction States, Routes, and Strategy Efficiency*. We compared the pairs of individual strategies which have a similar operation according to the state transition models and which belong to the same group (2D *On,* 2D *Off*, and 3D *On* respectively). We wanted to identify principles which make one strategy more efficient than another similar strategy. Therefore, we compared the two *On* strategies in the 2D plane (*Direct On* and *Slide Touch*), the two *Off* strategies in the 2D plane (*Direct Off* and *Slide Off*), and the two *On* strategies in the space (*Space On and Space Touch*).

We noted that with regard to these pairs (i) the *Slide Touch* strategy has the same initial and final states as the *Direct On* strategy; the *Slide Touch* also has more routes than the *Direct On*; (ii) the *Slide Off* strategy has the same initial, middle, and final states as the *Direct Off* strategy, but the *Slide Off* strategy has more routes than the *Direct Off*; (iii) the *Space On* and *Space Touch* strategies have the same initial state and the same final state although the *Space Touch* has one more possible final state and more routes than the *Space On* strategy (see Table I).

We had found that the *In-Out* strategy group (*Slide Touch, Slide Off, Space Touch*) was more efficient than the *In* strategy group (*Direct On, Direct Off, Space On*). Now we have noted that each individual strategy which belongs to the *In-Out* strategy group has more routes than its pair in the *In* strategy group.

If we were to find that the *Slide Touch* strategy is more efficient than the *Direct On* strategy (or *Slide Off* vs. *Direct Off*), we might suggest (H1) that when the initial and the final states are the same, then the selection strategy which has more possible routes is the more efficient of the two. If we were to find that the *Space Touch* strategy is more efficient than the *Space On* strategy, we might suggest (H2) that when the initial and final states of any two strategies are the same but one of the strategies has more possible final states, then the selection strategy which has more final states is more efficient.

To confirm these hypotheses we compared the experimental data pertaining to these strategy pairs (*Slide Touch* & *Direct On; Slide Off* & *Direct Off;* and *Space Touch* & *Space On*).

Slide Touch and Direct On. There was no significant difference in selection time between the *Slide Touch* and *Direct On* strategies, $F(1, 40) = 0.53$. However, the *Slide Touch* strategy had a lower error rate than the *Direct On* strategy, $F(1, 40) = 58.1$, $p < 0.0001$, and it had higher subjective ratings than the *Direct On* strategy for both large targets ($F(1, 10) = 22.9$, $p < 0.001$) and small targets ($F(1, 10) = 112.4$, $p < 0.0001$) (see Figure 9). Overall, the *Slide Touch* strategy was more efficient than the *Direct On* strategy. This was consistent with the first hypothesis (H1).

Slide Off and Direct Off. No significant difference was found in selection time between the *Slide Off* and *Direct Off* strategies, F(1, 40) = 1.52, $p < 0.05$. However, the *Slide Off* strategy had a lower error rate than the *Direct Off* strategy, F(1, 40) = 15.1, $p < 0.001$. The *Slide Off* strategy had higher subjective ratings than the *Direct Off* strategy for both large targets (F(1, 10) = 26.0, $p < 0.001$) and small targets (F(1, 10) = 67.2, $p < 0.0001$) (see Figure 9). Overall the *Slide Off* strategy was more efficient than the *Direct Off* strategy. This was also consistent with the first hypothesis (H1).

Space On and Space Touch. There was no significant difference between the *Space On* and the *Space Touch* strategies in selection time, F(1, 40) = 0.31, but a significant difference was found in error rate, F(1, 40) = 18.7, $p < 0.0001$. *Space Touch* had a lower error rate than *Space On*, and it had higher subjective ratings than *Space On* for both large targets (F(1, 10) = 19.1, $p < 0.01$) and small targets (F(1, 10) = 110.7, $p < 0.0001$). Based on these analyses, the *Space Touch* strategy was more efficient than the *Space On* strategy. This was consistent with the second hypothesis (H2).

These observations may be expanded in future to further define the relationships between interaction states, routes, and the efficiency of strategies. Such information would help to identify guidelines useful in the design of selection strategies in general.

3.3.3 *Factors Influencing the Differences Between the Selection Strategies.* Regarding target size, there were significant differences between the 6 strategies in terms of both selection time and error rate for target sizes of 3 pixels and 5 pixels. On the other hand, in the case of the target size of 9 pixels, no significant difference in error rate between the 6 strategies was observed. The analyses between the *In* and *In-Out* strategy groups show the same results. The significant differences between selection strategies were changed by changing the target size. In other words, the error rates were influenced by the selection strategies when the targets were small. Conversely, error rates were not influenced by selection strategies when target sizes were increased beyond a certain size. These results are important factors in the design of strategies for selecting small targets in pen-based systems. In the case of the target size of 9 pixels no significant difference in error rate between the 6 strategies was observed. However, as the amount of information displayed on the screen is increasing, users have to select smaller targets because the width and height of screens are limited. This tendency to display more information simultaneously is especially obvious in portable pen-based systems, particularly, personal digital assistants (PDAs), personal information managers (PIMs), and other pocket-sized pen-based applications. For example, target sizes under 5 pixels have a significant effect on the differences between strategies. Therefore a target size under 5 pixels is a significant factor in the design or choice of selection strategies. If the target size is limited to less than 5 pixels the choice of strategy must be particularly cognizant of the effects of target size. Above 5 pixels the target size has no significant bearing on the choice of selection strategy.

Regarding pen-movement-distance and pen-movement-direction, significant differences between the six strategies were found in both selection time and error rate for each of the pen-movement-distances and each of the pen-movement-directions. Significant differences in error rate between the *In* and *In-Out* strategy groups were also observed for each of the pen-movement-distances and each of the pen-movement-directions. This means that pen-movement distance and direction did not affect the significant differences between the six strategies or the significant differences between the strategy groups. In other words the significant differences between strategies and strategy groups remained when the distance and direction of pen movement were varied.

These observations will allow us to prioritize our focus in the design of hardware/software and particularly in design of better strategies. Furthermore, an evaluation of the significance of strategy variables allows us to build on current strategy conventions and to apply the information to various hardware/software environments.

4. EXPERIMENT TWO

Experiment One showed that when targets were 3 or 5 pixels in size, differences between the strategies were observed. On the other hand, when the target size was 9 pixels, the significant difference between selection strategies was not apparent. We, therefore, knew that the boundary value was between 5 and 9 pixels. We were interested to more accurately determine "the smallest maximum size," i.e., the boundary value for the target size below which there are significant differences, and above which there are no significant differences between the strategies. In this experiment we used five target sizes (1, 3, 5, 7, and 9 pixels).

4.1 Method

4.1.1 *Participants*. Nineteen volunteer subjects (14 male, 5 female, 18 right-handed, 1 left-handed), all university students, were tested for the experiment. Seven people had previous experience with pen-input systems, while the others had no such experience. These subjects and trials were completely independent of Experiment One.

4.1.2 *Apparatus*. The equipment was the same as for Experiment One (see Section 3.1.2).

4.1.3 *Procedure*. The procedure for Experiment Two was the same as for Experiment One with the following exceptions. In Experiment One there were 21 subjects, and the tablet was laid on a desktop for all subjects (i.e., on-desk conditions). In Experiment Two there were 19 subjects. Ten of the 19 subjects were asked to hold the tablet on their laps or in any position they found comfortable (i.e., off-desk conditions). These 10 were not allowed to put the tablet on the desk. In Experiment One three target sizes were used but in Experiment Two five target sizes were used.

The subjects were questioned about their preferences after they ended each trial: "For the strategy tested just now, how do you rate Q? Please answer on a scale of 1-to-9 (123456789)." Q consisted of six subquestions regarding selection accuracy, selection speed, selection ease, learning ease, satisfaction, and desire to use.

4.1.4 *Design.* The experiment used a mixed factorial design. The within-subject variables were target size (1-, 3-, 5-, 7-, and 9-pixel diameter circles), pen-movement-distance (131 pixels was the maximum radius of a circle from the initial position), and pen-movement-direction (0, 45, 90, 135, 180, 225, 270, and 315 degrees). The strategies were also within-subject variables.

Each subject performed a total of 60 trials for each strategy. These consisted of 20 practice trials and 40 test trials (= 5 target sizes × 8 directions).

A break was taken at the end of each strategy trial. Whenever the subject felt tired he or she was allowed to take a rest. Each subject completed 240 test trials (= 6 strategies × 40). In each strategy 760 test trials (= 19 subjects × 40) were completed. The order for the six strategies was different for each of the 19 subjects.

4.2 Results

4.2.1 *The Effect of Target Size on Selection Times.* Since we had shown in Experiment One that target size influences the differences between selection strategies, but that the pen-movement distance and direction do not influence the differences, we then considered how target size (not distance and direction) affected the differences between strategies. The results show that there was a significant difference between the six strategies in selection time for each target size (1 pixel, $p < 0.05$; 3, 5, 7, and 9 pixels, $p < 0.01$). This means that variations in target size do not influence the significant differences between the strategies with regard to selection time. In other words the difference between the strategies in selection time remains when the target size is varied.

4.2.2 *The Effect of Target Size on Error Rates.* Figure 10 shows error rates for each of the six strategies according to each of the target sizes, 1, 3, 5, 7, and 9 pixels. We looked at whether each target size affected the difference in error rate between the six strategies. The results show that there was a significant difference between the six strategies in error rate for each of the target sizes of 1, 3, and 5 pixels, $F(5,108) = 11.6, 15.6,$ and 6.35, all $p < 0.0001$; however, there was no significant difference between the 6 strategies in error rate for each target size of 7 or 9 pixels,

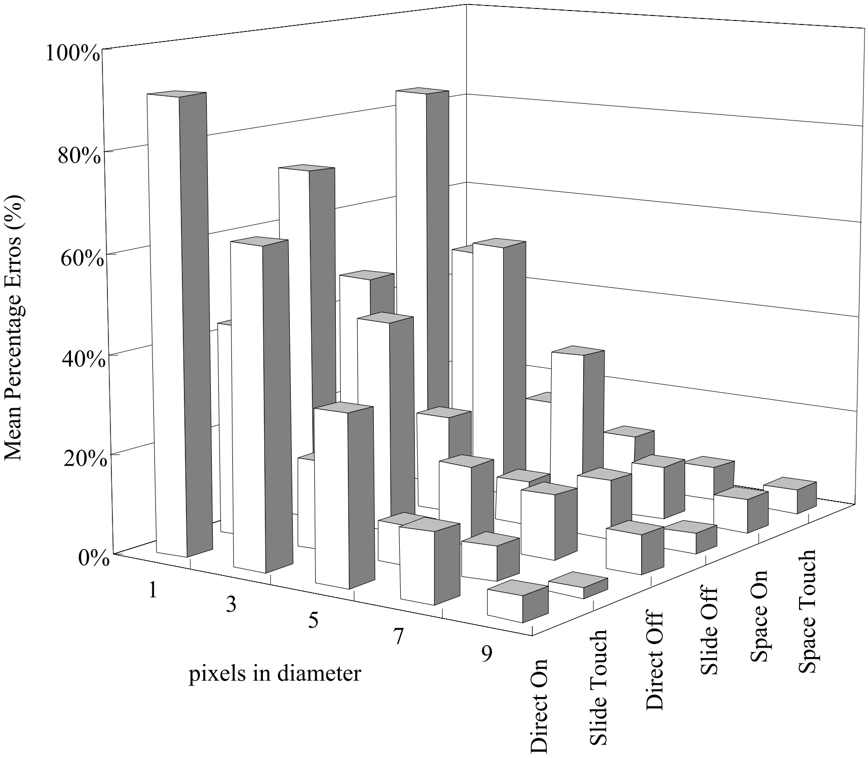

Fig. 10. Mean error rates per target size for the six strategies in Experiment Two.

F(5,108) = 0.52, 0.75. This means that target sizes of 5 pixels or less significantly affected the difference in error rate between the six strategies.

4.2.3 *On-Desk and Off-Desk Conditions.* No significant differences in error rate (F(1, 17) = 0.25) or selection time (F(1, 17) = 1.38, $p < 0.05$) due to the different conditions associated with on-desk and off-desk use were observed. Subjects using the tablet in off-desk conditions completed the 240 test trials with the tablet on their laps. All these subjects preferred the off-desk position. Other conditions (e.g., subjects standing) could be further researched and analyzed.

4.3 Best Individual Strategy and Best Strategy Group According to Experiment Two Data

4.3.1 *Comparisons of Selection Times and Error Rates for the Six Individual Strategies.*

Selection Times. There was a significant difference in selection time between the six strategies, F(5,108) = 3.17, $p < 0.05$, the *Direct On* strategy being the fastest. Figure 11 shows the selection times for the six strategies. The post hoc Tukey HSD test showed that the *Direct On*

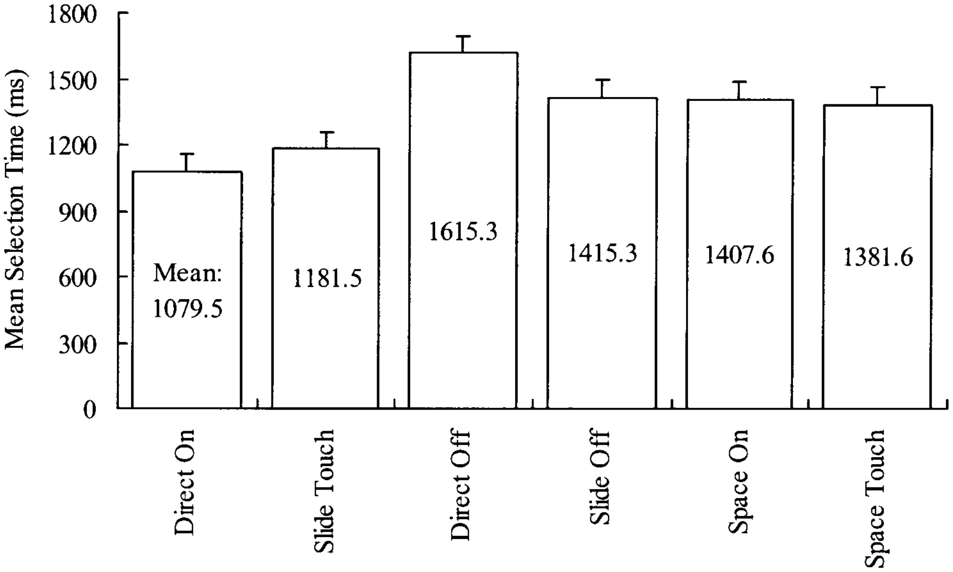

Fig. 11. Mean selection times for each strategy in Experiment Two.

strategy was faster than the *Direct Off* strategy ($p < 0.05$). There were no other significant differences across the strategies.

Error Rates. The error rates for each of the six strategies is shown in Figure 12. There was a significant difference for the six strategies in error rate, $F(5,108) = 9.76$, $p < 0.01$. The error rate for the *Slide Touch* strategy was the lowest of the six strategies (mean = 12.4%). The post hoc Tukey HSD test showed that the *Slide Touch* had a lower error rate than the *Direct On* and *Space On* strategies; the *Direct On* had a higher error rate than the *Slide Off* and *Space Touch* strategies; the *Slide Off* had a lower error rate than the *Space On* strategy; the *Space On* had a higher error rate than the *Space Touch* strategy (all $p < 0.05$). There were no other significant differences across the strategy groups.

Subject Preferences. The analysis of the questionnaire showed a significant difference in subject preferences for each of the six strategies, $F(5, 30) = 258.5$, $p < 0.0001$. Rated on a scale of 1 to 9 the *Slide Touch* strategy was the most preferred (mean = 8.03).

Since each of the *Slide Touch, Slide Off*, and *Space Touch* strategies had lower error rates than each of the *Direct On* and *Space On* strategies, and since the *Direct On* was faster than the *Direct Off* strategy, we concluded that the *Slide Touch, Slide Off*, and *Space Touch* are better than the other three strategies. However, according to Experiment One the *Slide Touch* is better than the other five strategies.

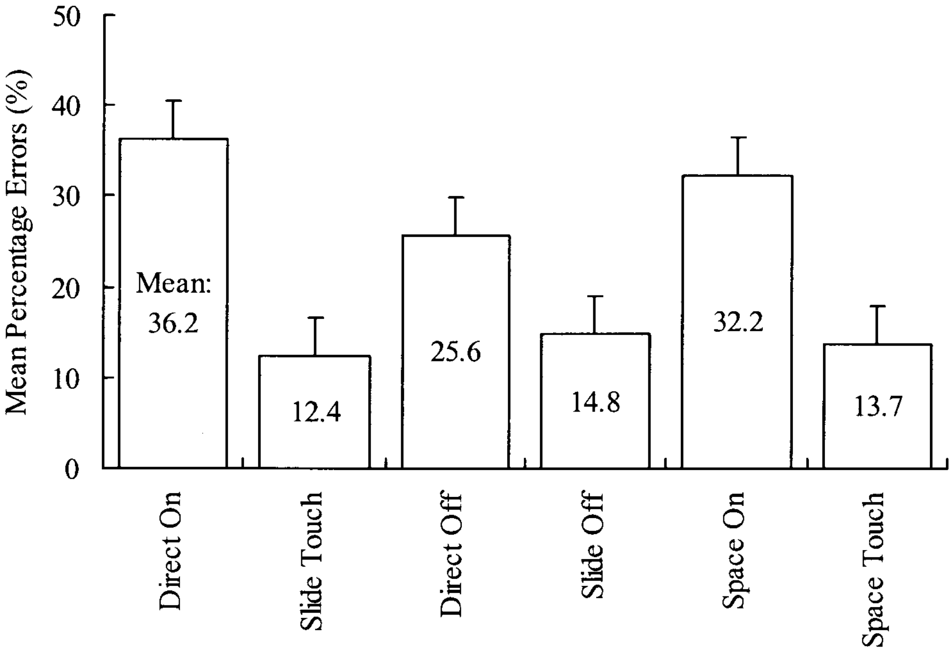

Fig. 12. Mean error rates for each strategy in Experiment Two.

4.3.2 *Comparisons of Selection Times and Error Rates for the Strategy Groups.*

Selection Times. Though the average selection time for the *On* strategy group was the fastest (mean = 1.26), there was no significant difference in selection time between the six strategy groups (*In, In-Out, On, Off, 2D,* and *3D*), F(5,108) = 1.09, $p < 0.05$. The post hoc Tukey HSD test showed that the *Off* strategy group was slower than the other five strategy groups ($p < 0.05$). There were no other significant differences across strategy groups.

Error Rates. However, there was a significant difference between the six strategy groups in error rate, F(5,108) = 3.79, $p < 0.01$. The *In-Out* strategy groups produced the lowest error rate (mean = 13.7%). The post hoc Tukey HSD test showed that the *In-Out* strategy group had a lower error rate than the *In* strategy group ($p < 0.05$). There were no other significant differences across strategy groups.

Subject Preference. The analysis of the questionnaire showed a significant main effect on subject preferences between the strategy groups, F(5, 30) = 232.2, $p < 0.0001$. The *In-Out* strategy group was the most preferred (mean = 7.84).

The *In-Out* strategy group was better than the *In* and *Off* strategy groups, since the *In-Out* strategy group had a lower error rate than the *In* strategy group and was faster than the *Off* strategy group. Considering that there were no differences in either selection time or error rate between the *In* and each of the *On, 2D*, and *3D* strategy groups, we conclude that the *In-Out* strategy group is better than the other five strategy groups. However, according to Experiment One the *Off and 3D* strategy groups are not significantly different to the *In-Out* strategy group.

4.4 Discussion

4.4.1 *The Smallest Maximum Size*. The difference in selection time between the strategies remained significant for each target size of 1, 3, 5, 7, and 9 pixels. However, while the difference in error rate between the strategies remained significant for each target size of 1, 3, and 5 pixels, they became insignificant for each target size of 7 and 9 pixels.

In general we can say that differences between strategies in error rate are affected by target size. Thus, it was important for us to identify the threshold target size above or below which target size has a significant bearing on error rates. We identified the threshold to be 5 pixels. In other words we determined 5 pixels (1.80 mm diameter circle) to be "the smallest maximum size," because for target sizes above this the differences in error rate between strategies are not significant. Thus, the comparative efficiency of strategies with regard to error rate is affected by target sizes of 5 pixels or less, and the choice of strategy with regard to target size becomes significant at 5 pixels or less. When a target is less than 5 pixels it is necessary to pay more particular attention to the choice of strategies in software design because the error rates of the strategies are affected differently. Conversely when selecting a target of more than 5 pixels, the error rate for all strategies is not significantly different, i.e., there are no significant differences between strategies in error rate for target sizes over 5 pixels.

Fitts' law [Fitts 1954], $MovementTime = m + nID$, $ID = \log_2(2A/W)$, states that the time taken to select a target is a function of the width of the target (W), the distance (or amplitude) to the target (A), m and n (empirically determined constants), and ID (*Index of Difficulty*). This law has been demonstrated in numerous studies, and there are many variations of this formula [MacKenzie 1992]. If A is a constant, when $W_1, W_2, \ldots > 5$ pixels (here, we assume $W_1, W_2, \ldots$ are widths of different target sizes, and that W can also express the diameter of a circular target as used in these experiments), then, as far as our results are concerned, there are no significant differences for $ID_1 = \log_2(2A/W_1)$, $ID_2 = \log_2(2A/W_2)$. In other words, when selecting a target size of more than 5 pixels, the difference in the ID (here, we consider error rates) will disappear. We note that some studies have suggested that Fitts' law is not an adequate model for all interactions (e.g., MacKenzie and Buxton [1992]). Our study may bear this out.

4.4.2 *The Best Individual Strategy and Best Strategy Group*. The *Slide Touch* strategy is the best of the individual strategies. When the results for Experiment One and Experiment Two were compared in simple pairs we found that the *Slide Touch* Strategy was the best strategy [Ren and Moriya 1997b; 1999]. The post hoc Tukey HSD test showed that, in Experiment One, the *Slide Touch* was indeed the best strategy. In Experiment Two, Tukey's test showed that the *Slide Touch*, *Slide Off*, and *Space Touch* strategies were all better with no significant difference, but considering the (Tukey) results of Experiment One and that in both Experiments the *Slide Touch* strategy had the highest subject preferences, we concluded that the *Slide Touch* strategy is the single best strategy.

The *In-Out* strategy group is the best of the strategy groups. When the results for Experiment One and Experiment Two were compared in simple pairs we found that the *In-Out* strategy group was the best group [Ren and Moriya 1997b; 1999]. Analysis based on the post hoc Tukey HSD test in both selection time and error rate showed, however, that in Experiment One, the *Off* and *3D* strategy groups were not significantly different in performance to the *In-Out* strategy group. However, analysis based on the post hoc Tukey HSD test when applied to Experiment Two showed that the *In-Out* strategy group was the best. When these results are combined and considering that the *In-Out* strategy group had the highest subject preferences in both Experiments, we concluded that the best group is the *In-Out* strategy group.

5. CONCLUSION AND FUTURE WORK

The article proposed two state transition models for selecting 2D and 3D targets with a pen. It also described the characteristics of selection strategies. We showed not only that the six strategies fit into the state transition models, but we also classified the strategies into strategy groups according to their characteristics and assessed the effects of various parameters on the strategies. Then, we described the methods and results of Experiment One and Experiment Two respectively.

Experiment One identified the best of the six individual strategies by comparing the strategies individually and by groups. These results, when combined with Experiment Two data, showed that the best strategy was the *Slide Touch* strategy when the strategies were evaluated individually, and the best strategy group was the *In-Out* strategy group when evaluated in groups. Furthermore, differences between strategies are influenced by variations in target size; however, they are not affected by pen-movement-distance and pen-movement-direction.

Experiment Two sought to find "the smallest maximum size," a boundary value for the size of targets, by observing the effects of five different target sizes (1, 3, 5, 7, and 9 pixels). We found that 5 pixels was the smallest maximum size, which was the size at and below which significant differences in error rate appear. Differences between on-desk and off-desk conditions were not found; however all subjects preferred off-desk conditions.

While we have isolated the best of the six strategies tested, we believe we have gone beyond that and provided information which suggests that there are many more options (albeit as yet undeveloped) than the six strategies. The state transition models and the development of hypotheses for design guidelines may provide tools for more efficient strategy design. Although the six strategies may be considered to be only examples of strategies in general we considered these six strategies to be inclusive of the essential elements of selection strategies. They allowed us to comprehensively test and to quantify the effects of variables on the differences between strategies in general. These results contribute to the body of information about how changes in variables can affect the quality of a selection strategy. An understanding of human limitations, the variables of selection strategies, and the integration of human motor skills with computer devices is vital to the progress of human-computer interaction research. We believe that these results will help designers to identify and quantify important factors, for user efficiency on pen-based systems. We also believe that this work defines values by which not only pen-based devices but also other devices may be researched.

This article provides the basis for the development of new and better selection strategies, for more far-reaching research on strategy and software characteristics, and for the design of pen-based computers. Many challenges remain in the field.

Expanding the State Transition Models. The state transition models (see Figures 1 and 2) provide new vocabulary in evaluating selection strategies with pen-based devices. However, they require further development, e.g., they do not deal with parameters such as time (that the pen stays in a certain statem, etc.), the state of the switch on the side of the pen (side switch), pen-tip sensitivity (pressure of pen-tip), pen rotation, highlighting, and audio output. Further research is required to expand these models.

Fitts' Law and Selection Strategies. Numerous studies have shown Fitts' law to hold for a variety of movements produced under different conditions; however the law only applies for one kind of selection strategy. It is not clear that Fitts' law, in its original form, applies to all selection strategies with all kinds of targets. No studies have considered whether the law holds for different strategies. The relationships between selection strategies and Fitts' law should be studied, e.g., plotting the selection time against the *Index of Difficulty* with different strategies, or new tasks paradigms presented by Accot and Zhai [1997; 1999] could be used to model the *Slide Touch*, *Direct Off*, and *Slide Off* strategies.

Target Shapes and the Smallest Maximum Size. We used circular targets to keep the distance which the pen reaches to the edge of a target constant in all directions. It has been reported elsewhere that differences in target shapes influence the selection time [Sheikh and Hoffmann 1994]. Thus various target shapes could be compared. It is also necessary to investigate the relationships between strategies and target shapes, and to find strategies which are suitable for specific shapes. It would be interesting to pay attention to whether or not small targets of different shapes would change the smallest maximum size.

Isolated Targets, Dense Targets, and Virtual Targets. In the experiments we used a single target. Consideration must be given to small isolated targets and to small targets in dense displays. Furthermore, the strategies in the *In-Out* strategy group all allow users to stray a little from the target, and thus the user need not be so accurate. Thus, for small targets, the strategies in the *In-Out* strategy group reduce selection times and error rates, as confirmed by our results. Future experiments will investigate how far from the target users touch down (in the *Slide Touch* strategy) and how far from the target they slide off (in the *Slide Off* strategy). This may reveal an effectively larger virtual target.

The Slide Touch Strategy and Other Selection Techniques. Comparisons between the *Slide Touch* strategy and other interaction (selecting/pointing) techniques proposed by other studies may be conducted to improve the performance of small target acquisition tasks (e.g., see Kabbash and Buxton [1995] and Worden et al. [1997]). Combinations of selection strategies and sound feedbacks, etc., after selection (e.g., see Brewster et al. [1995], Brewster and Crease [1997], and Brewster [1998]) should also be investigated to see how the combination enhances the performance of selection tasks. Further consideration could also be given to various selection techniques on the 2D plane and in 3D space, e.g., circle a 2D target, check-mark a target, double tap a target, slide through a 3D target, poke at a 3D target without contacting the screen surface, and so on.

ACKNOWLEDGMENTS

We would like to thank the subjects for their cooperation and John Cahill for the valuable comments. We wish to thank the anonymous reviewers of INTERACT'97 [Ren and Moriya 1997b], HCI'98 [Ren and Moriya 1998], and EHCI'98 [Ren and Moriya 1999] for their constructive comments on our earlier reports of this work. We also wish to thank the special issue editors and the three anonymous reviewers for thoughtful comments, which motivated much of the reanalysis, discussion, and presentation in this article. Their helpful reviews led to many improvements.

REFERENCES

ACCOT, J. AND ZHAI, S. 1997. Beyond Fitts' law: models for trajectory-based HCI tasks. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '97, Atlanta, GA, Mar. 22–27), S. Pemberton, Ed. ACM Press, New York, NY, 295–302.

ACCOT, J. AND ZHAI, S. 1999. Performance evaluation of input devices in trajectory-based tasks: An application of the steering law. In *Proceedings of the ACM Conference on Human*

Factors in Computing Systems (CHI '99, Pittsburgh, PA, May). ACM Press, New York, NY, 466–472.

BREWSTER, S. A. 1998. Using earcons to improve the usability of a graphics package. In *Proceedings of the primary European Annual Conference on Human Computer Interaction* (HCI'98, Sheffield Hallam University, Bristol, UK, Sept. 1-4). Springer-Verlag, Vienna, Austria, 287–302.

BREWSTER, S. A. AND CREASE, M. G. 1997. Making menus musical: The sonic enhancement of graphical buttons. In *Proceedings of the IFIP TC13 International Conference on Human-Computer Interaction* (INTERACT'97), S. Howard, J. Hammond, and G. Lindegaard, Eds. Chapman and Hall, Ltd., London, UK, 389–396.

BREWSTER, S. A., WRIGHT, P. C., DIX, A. J., AND EDWARDS, A. D. N. 1995. The sonic enhancement of graphical buttons. In *Proceedings of the 3rd IFIP Conference on Human-Computer Interaction* (INTERACT '95, Lillehammer, Norway, June 27–29), K. Nordby, P. H. Helmersen, D. J. Gilmore, and S. A. Arnesen, Eds. Chapman and Hall, Ltd., London, UK, 43–48.

BUXTON, W. 1990. A three state model of graphical input. In *Proceedings of the IFIP 1990 Conference on Human-Computer Interaction* (INTERACT '90). IFIP, Laxenburg, Austria, 449–456.

CHEN, M. 1993. A framework for describing interactions with graphical widgets. In *INTERACT '93 and CHI '93 conference companion on Human factors in computing systems* (CHI '93, Amsterdam, The Netherlands, Apr. 24—29), S. Ashlund, K. Mullet, A. Henderson, E. Hollnagel, and T. White, Eds. ACM Press, New York, NY, 131–132.

FITTS, P. M. 1954. The information capacity of the human motor system in controlling amplitude of movement. *J. Exp. Psychol. 47*, 6, 381–391.

GOLDBERG, D. AND RICHARDSON, C. 1993. Touch-typing with a stylus. In *Proceedings of the ACM Conference on Human Factors in Computing* (INTERCHI '93, Amsterdam, The Netherlands, Apr. 24–29), S. Ashlund, A. Henderson, E. Hollnagel, K. Mullet, and T. White, Eds. ACM Press, New York, NY, 80–87.

KABBASH, P. AND BUXTON, W. A. S. 1995. The "prince" technique: Fitts' law and selection using area cursors. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '95, Denver, CO, May 7–11), I. R. Katz, R. Mack, L. Marks, M. B. Rosson, and J. Nielsen, Eds. ACM Press/Addison-Wesley Publ. Co., New York, NY, 273–279.

MACKENZIE, I. S. 1992. Fitts' law as a research and design tool in human-computer interaction. *Human-Comput. Interact. 7*, 91–139.

MACKENZIE, I. S. AND BUXTON, W. 1992. Extending Fitts' law to two-dimensional tasks. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '92, Monterey, CA, May 3–7), P. Bauersfeld, J. Bennett, and G. Lynch, Eds. ACM Press, New York, NY, 219–226.

MACKENZIE, I. S. AND ZHANG, S. X. 1999. The design and evaluation of a high-performance soft keyboard. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '99, Pittsburgh, PA, May). ACM Press, New York, NY, 25–31.

MACKENZIE, I. S., NONNECKE, B., RIDDERSMA, S., MCQUEEN, C., AND MELTZ, M. 1994. Alphanumeric entry on pen-based computers. *Int. J. Hum.-Comput. Stud. 41*, 5 (Nov.), 775–792.

MACKENZIE, I. S., SELLEN, A., AND BUXTON, W. A. S. 1991. A comparison of input devices in elemental pointing and dragging tasks. In *Proceedings of the Conference on Human Factors in Computing Systems: Reaching through Technology* (CHI '91, New Orleans, LA, Apr. 27–May 2), S. P. Robertson, G. M. Olson, and J. S. Olson, Eds. ACM Press, New York, NY, 161–166.

POTTER, R. L., WELDON, L. J., AND SHNEIDERMAN, B. 1988. Improving the accuracy of touch screens: an experimental evaluation of three strategies. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '88, Washington, DC, May 15–19), J. J. O'Hare, Ed. ACM Press, New York, NY, 27–32.

REN, X. AND MORIYA, S. 1995. The concept of various pointing strategies on pen-based computers and their experimental evaluation. In *Proceedings of the Eleventh Symposium on Human Interface* (Kyoto, Japan). 565–574.

REN, X. AND MORIYA, S. 1997a. The strategy for selecting a minute target and the minute maximum value on a pen-based computer. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '97, Atlanta, GA, Mar. 22–27), S. Pemberton, Ed. ACM Press, New York, NY, 369–370.

REN, X. AND MORIYA, S. 1997b. The best among six strategies for selecting a minute target and the determination of the minute maximum size of the targets on a pen-based computer. In *Proceedings of the IFIP TC13 International Conference on Human-Computer Interaction* (INTERACT'97), S. Howard, J. Hammond, and G. Lindegaard, Eds. Chapman and Hall, Ltd., London, UK, 85–92.

REN, X. AND MORIYA, S. 1998. The influence of target size, distance and direction on the design of selection strategies. In *Proceedings of the primary European Annual Conference on Human Computer Interaction* (HCI'98, Sheffield Hallam University, Bristol, UK, Sept. 1-4). Springer-Verlag, Vienna, Austria, 67–82.

REN, X. AND MORIYA, S. 1999. Efficient strategies for selecting small targets on pen-based systems: an evaluation experiment for selection strategies and strategy classifications. In *Engineering for Human-Computer Interaction*, S. Chatty and P. Dewan, Eds. IFIP Transactions. Kluwer Academic Publishers, Hingham, MA, 19–37.

SEARS, A. AND SHNEIDERMAN, B. 1991. High precision touchscreens: design strategies and comparisons with a mouse. *Int. J. Man-Mach. Stud. 34*, 4 (Apr.), 593–613.

SEARS, A., PLAISANT, C., AND SHNEIDERMAN, B. 1992. A new era for high precision touchscreens. In *Advances in human-computer interaction (vol. 3)*, H. R. Hartson and D. Hix, Eds. Ablex Publishing Corp., Norwood, NJ, 1–33.

SHEIKH, I. AND HOFFMANN, E. 1994. Effect of target shape on movement time in a Fitts task. *Ergonomics 37*, 9, 1533–1547.

VENOLIA, D. AND NEIBERG, F. 1994. T-Cube: a fast, self-disclosing pen-based alphabet. In *Proceedings of the ACM Conference on Human Factors in Computing Systems: "Celebrating Interdependence"* (CHI '94, Boston, MA, Apr. 24–28). ACM Press, New York, NY, 265–270.

WORDEN, A., WALKER, N., BHARAT, K., AND HUDSON, S. 1997. Making computers easier for older adults to use: area cursors and sticky icons. In *Proceedings of the ACM Conference on Human Factors in Computing Systems* (CHI '97, Atlanta, GA, Mar. 22–27), S. Pemberton, Ed. ACM Press, New York, NY, 266–271.

ZHAI, S., BUXTON, W., AND MILGRAM, P. 1994. The "Silk Cursor": investigating transparency for 3D target acquisition. In *Proceedings of the ACM Conference on Human Factors in Computing Systems: "Celebrating Interdependence"* (CHI '94, Boston, MA, Apr. 24–28). ACM Press, New York, NY, 459–464.

ZHAI, S., BUXTON, W., AND MILGRAM, P. 1996. The partial-occlusion effect: Utilizing semitransparency in 3D human-computer interaction. *ACM Trans. Comput. Hum. Interact. 3*, 3, 254–284.