Memory & Cognition
2010, 38 (4), 474-484
doi:10.3758/MC.38.4.474

Do you know where your fingers have been? Explicit knowledge of the spatial layout of the keyboard in skilled typists

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Two experiments evaluated skilled typists' ability to report knowledge about the layout of keys on a standard keyboard. In Experiment 1, subjects judged the relative direction of letters on the computer keyboard. One group of subjects was asked to imagine the keyboard, one group was allowed to look at the keyboard, and one group was asked to type the letter pair before judging relative direction. The imagine group had larger angular error and longer response time than both the look and touch groups. In Experiment 2, subjects placed one key relative to another. Again, the imagine group had larger angular error, larger distance error, and longer response time than the other groups. The two experiments suggest that skilled typists have poor explicit knowledge of key locations. The results are interpreted in terms of a model with two hierarchical parts in the system controlling typewriting.

There is a paradox in skilled performance. Experts spend years acquiring knowledge about their skill, which they use very effectively to support their performance, but they have little explicit access to that knowledge. In the case of typewriting, skilled typists have little explicit knowledge of what their fingers are doing (Logan & Crump, 2009). Often, the paradox of skill is resolved by proposing two different kinds of knowledge: procedural knowledge, which is implicit and supports skilled performance directly, and declarative knowledge, which is explicit and does not support skilled performance directly (Anderson, 1976; Beilock & Carr, 2001; Cohen & Squire, 1980). From this perspective, years of practice are necessary to build up the requisite procedural knowledge, but that knowledge will not be explicitly available. In typewriting, the paradox of skill is resolved by proposing a hierarchical control system with two nested feedback loops: an *inner loop* that translates words into keystrokes and controls the movements of the fingers and hands, and an *outer loop* that connects to language generation and comprehension processes and provides the inner loop with a string of words to type (Crump & Logan, in press–a; Logan & Crump, 2009; Shaffer, 1975; see also John, 1996; Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008). Logan and Crump (2009) suggested that the inner and outer loops are informationally encapsulated, so that the outer loop has no explicit knowledge of what the inner loop is doing. The outer loop knows the inner loop is typing the words it provides, but the outer loop does not know how the inner loop assigns letters to keystrokes and keystrokes to spatial positions on the keyboard.

The purpose of this article is to further investigate the paradox of skill in typewriting by measuring the accuracy of explicit knowledge of the spatial layout of the keyboard. Skilled typists clearly have implicit knowledge of the spatial layout of the keyboard, because they choose the correct key location 5–6 times/sec when they are typing. Moreover, presenting letters and words to be typed in a spatial location incompatible with the keyboard location of the corresponding characters produces Simon-like interference effects (Logan, 2003; see also Rieger, 2004). Our question was whether this knowledge of the spatial layout of the keyboard is also explicit. Can typists access it consciously without seeing or touching the keyboard? Our hypothesis was that they cannot. Typists' explicit knowledge of the spatial layout of the keyboard is coarse and inaccurate.

Our hypothesis is based partly on intuition and partly on data. Our intuition as skilled typists ourselves is that we do not know much about which keys are where. We find it hard to type in the air or on a table top and find it hard to say which finger types which letter (see Crump & Logan, in press–b). The data come from experiments in which we asked skilled typists to type words and paragraphs while omitting the letters typed with the left or right hand (Logan & Crump, 2009). This instruction disrupted typing substantially, slowing typing speed by half, and doubling or tripling error rate. To comply with our instructions, subjects had to slow down their typing and see which hands typed which letters. We concluded that typists do not have explicit knowledge of the assignment of hands to keystrokes or keystrokes to keyboard locations. However, it

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is possible that typists had this knowledge explicitly but could not use it to alter the familiar flow of procedural knowledge as they typed, so a more direct assessment of explicit knowledge is necessary.

We assessed explicit knowledge of the spatial layout of the keyboard by adapting relative direction judgment tasks from the literature on spatial memory. In Experiment 1, we asked subjects to imagine standing on a reference letter on the keyboard (e.g., F) facing a particular direction (e.g., the computer screen, the numeric keypad, the space bar, the caps lock key), and then to point to the location of the target letter (e.g., X). In Experiment 2, we asked them to position the target letter with respect to the reference letter (e.g., placing the X in the keyboard position it occupies relative to F). The direction-pointing task has been used extensively to test explicit knowledge of large-scale environments such as countries or cities (McNamara, Rump, & Werner, 2003; Sholl, 1987; Stevens & Coupe, 1978; Werner & Schmidt, 1999), small-scale environments such as rooms (Mou & McNamara, 2002; Rieser, 1989; Shelton & McNamara, 1997, 2001), and representations of environments, such as maps and diagrams (McNamara, 1986; Tversky, 1981). One goal of our research was to see whether the pointing task could be applied to the "microscale" environment of a computer keyboard to reveal similar effects.

A key idea in the literature on spatial memory is that the layout of objects is represented with respect to a reference frame, which is often a salient axis in the display (e.g., an axis of symmetry, an axis provided by the room in which the objects appear, a geographic axis such as north–south or east–west). The locations of individual objects are represented with respect to the reference frame, and the reference frame is used to access object locations (McNamara et al., 2003; Mou & McNamara, 2002; Shelton & McNamara, 1997, 2001). Many studies have shown that it is easier to judge relative directions of objects aligned with the reference frame than relative directions of objects not so aligned (McNamara et al., 2003; Mou & McNamara, 2002; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shelton & McNamara, 1997, 2001). In typewriting, the rows and columns of the keyboard most likely form the reference frame in which the spatial layout of the keys is encoded, with the up–down axis of the keyboard aligned with the front–back axis of the typist. Thus, explicit knowledge of spatial layout should be easier to access when the keyboard is aligned with its typical orientation than when it is rotated. To assess reference-frame alignment effects, we varied the orientation of the letters to be judged with respect to the typical orientation of the keyboard (0º, 90º, 180º, and 270º). The spatial layout of the keyboard should be represented explicitly with respect to the typical orientation of the keyboard, so relative direction judgments should be more accurate when the letters are aligned with the typical orientation (i.e., 0º) than when they are not (i.e., 90º, 180º, and 270º). This benchmark prediction would establish a connection between typists' explicit representations of the spatial layout of the keyboard and people's explicit representations of the spatial layout of larger-scale environments. An alignment effect would show that typists had an explicit representation of the spatial layout of the keyboard and allow us to ask whether the explicit representation was as accurate as the implicit representation that guides typewriting.

The main dependent variable in both experiments was the error in spatial judgments. Both experiments measured *angular error*, which is the absolute value of the difference between the actual angle and the response angle produced by the subject (the actual angle is the angle between the reference letter and the target letter; the response angle is the direction in which the subject points). In addition, Experiment 2 measured *distance error*, which is the absolute value of the distance between the objective and subject-generated positions of the target letter. Our hypothesis that typists have poor explicit knowledge of the spatial layout of the keyboard predicts that both absolute error and distance error will be large. An important question is "large with respect to what?" To address this question, we compared performance in the experimental group (called the *imagine group* because they could only imagine the keyboard) with two control groups: the *look group* and the *touch group*. All groups included only skilled typists (see the Subjects sections, below).

Subjects in the look group were allowed to view a standard keyboard while making their judgments. Their performance provides a baseline on which errors are due only to visual perception and the process of transforming visual judgments into pointing responses. Philbeck, Sargent, Arthur, and Dopkins (2008) found substantial pointing errors in visual perceptual judgments, so we cannot assume that visual judgments of keyboard locations will be perfect. If explicit knowledge is as good as vision, subjects in the imagine group should perform as well as subjects in the look group; if explicit knowledge is less accurate than vision, as we hypothesize, the imagine group should perform worse than the look group.

Subjects in the touch group were allowed to touch the keyboard, but were prevented from seeing the keyboard, since their hands were placed inside a box covering the keyboard. In the touch condition, subjects were asked to type both the reference letter and the target letter prior to making their relative direction judgments. Typing the letters provides haptic and proprioceptive information available in normal typewriting and can be used to infer the locations of the keys on the keyboard. The inference may be based on judgments of perceptual information or on retrieval of locations associated with similar perceptual information in past episodes of typing. If explicit knowledge is as good as haptics and proprioception, subjects in the imagine group should perform as well as subjects in the touch group; if explicit knowledge is less accurate than haptics and proprioception, as we hypothesize, the imagine group should perform worse than the touch group.

We predict larger absolute errors and distance errors in the imagine group than in either the look group or the touch group, but we have no a priori predictions about the difference between the look group and the touch group. We could imagine arguments for one alternative or the other, but we have no strong reasons for choosing between them.

We measured a second dependent variable, response time (RT), which is the time that elapses between the onset of the letters to be judged and subjects' response (clicking the mouse on the circle; see the Procedure sections below). In the spatial memory literature, RT and absolute error often show the same trends (McNamara et al., 2003; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; Shelton & McNamara, 1997, 2001), so we expect similar effects of orientation and similar differences between the imagine group and the look group. For the touch group, RT is harder to interpret. They were allowed a preview of the letters and they had to type them before the RT interval began, and this may have sped their responses on the subsequent spatial judgment tasks. Absolute and distance errors can be interpreted more readily and consequently will form the basis of most of our conclusions.

EXPERIMENT 1

The first experiment tested explicit knowledge of key locations with a relative direction judgment task. On each trial, subjects were shown a *reference* letter in the center of a circle and a *target* letter below the circle (see Figure 1). They were asked to imagine standing at the reference letter in the center of the circle (the letter *F* in Figure 1), facing the orientation of the reference letter, and then point to the direction of the target letter from their current position. Pointing was indicated by a mouse click on the circumference of the circle. If subjects have poor explicit knowledge of keyboard locations, the imagine group should judge relative direction less accurately than the look group. If explicit knowledge is less accurate than haptics and proprioception, the imagine group should perform worse than the touch group.

We manipulated the rotation of the reference letter across four blocks as a within-subjects factor. There were four rotation conditions: 0º, 90º, 180º, and 270º. In the 0º condition, the reference letter was presented in a normal upright fashion. In the remaining conditions, the reference letter was rotated 90º, 180º, or 270º clockwise. In each rotation condition, subjects made their key position judgments relative to the orientation of the reference letter: They were asked to imagine that the keyboard had been rotated in line with the orientation of the reference letter. We expected that subjects' performance would be better when the reference letter was aligned with the key-

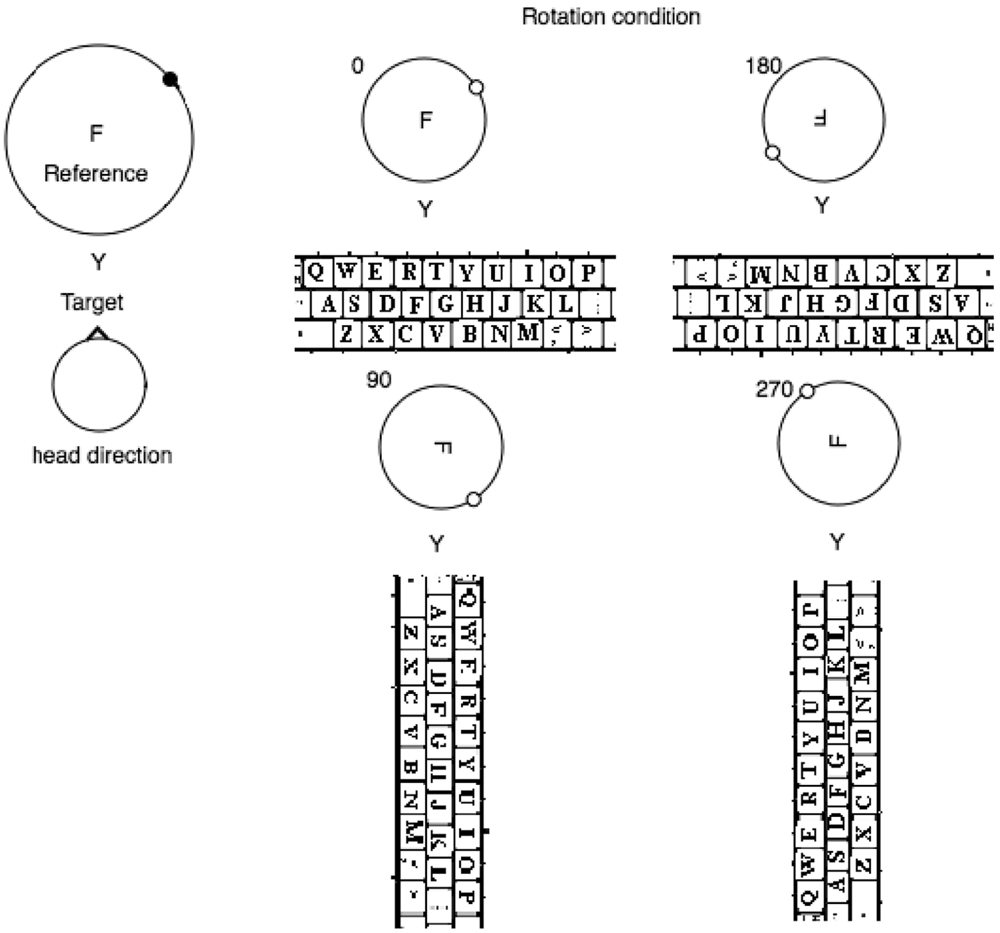

Figure 1. The left side depicts the display presented to subjects in the test trials in Experiment 1. The right side depicts examples of the test trials in each rotation condition. The point on each circle indicates the correct response.

board (0º) than when it was misaligned (90º, 180º, 270º). This alignment effect would be consistent with previous results in the spatial memory literature (McNamara et al., 2003; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; Shelton & McNamara, 1997, 2001).

Method

Subjects. The subjects were 60 typists sampled from the Vanderbilt University subject pool, 20 in each of the three groups (imagine, look, and touch). Subjects were recruited for their self-reported ability to type 40 words per minute (wpm) or better. Their skill was measured using a typing test from Logan and Zbrodoff (1998), which involved typing short paragraphs about the merits of border collies. The mean scores were 68 wpm (range: 38–102) for the imagine group, 62 wpm (range: 30–100) for the look group, and 62 wpm (range: 44–101) for the touch group. A one-way ANOVA showed that there were no significant differences in typing speed between the three groups [$F(2,57) = 0.62, p > .05$]. All subjects were compensated with course credit or $12 for 1 h of participation.

Apparatus and Stimuli. The experiment was controlled by METACARD on a PC with a 15-in. SVGA monitor. On each trial a circle (diameter 9.6 cm) was displayed in the center of the screen. The reference letter was displayed in the middle of the circle, rotated 0º, 90º, 180º, or 270º, depending on the rotation condition for that block of trials. The target letter was displayed below the circle in its normal upright orientation. The distance from the edge of the circle to the top of the target letter was 1.4 cm. Both of the letters were about 1 cm × 1 cm. After subjects clicked the mouse on the circle, a 3.5 cm × 1.5 cm submit button was displayed 2 cm below the target letter.

Reference and target letter pairs were chosen in a quasirandom fashion to provide a representative sample of all possible letter pairs. The keyboard was divided into five regions spanning all of the letters on the keyboard (e.g., 1, QWERT; 2, YUIOP; 3, ASDFG; 4, HJKL; 5, ZXCVBNM). For each trial, letter pairs were created by randomly sampling a reference letter and a target letter from separate regions on the keyboard. Letter pairs were sampled from all of the following 20 combinations of the five different regions: 1–2, 1–3, 1–4, 1–5, 2–1, 2–3, 2–4, 2–5, 3–1, 3–2, 3–4, 3–5, 4–1, 4–2, 4–3, 4–5, 5–1, 5–2, 5–3, and 5–4. This sampling strategy omitted letter pairs chosen from within the same keyboard region. Each block consisted of 40 trials, and the 40 letter pairs were chosen by exhaustively drawing 2 letter pairs from the 20 combinations of keyboard regions.

Design and Procedure. Two independent variables were manipulated: keyboard group (imagine, look, touch) and rotation condition (0º, 90º, 180º, 270º). Keyboard group was manipulated between subjects, and rotation condition was manipulated within subjects. The procedure for the imagine and look groups is illustrated in Figure 1. The procedure for the touch group is illustrated in Figure 2. There were 40 trials in each rotation condition, for a total of 160 trials. Rotation condition was blocked. Letter pairs were sampled randomly for each block, and the order of blocks was randomly determined for each subject. Dependent variables were absolute angular error and RT. Absolute angular error was defined as the absolute value of the difference (in degrees) between the actual angle and the response angle given by the subject for each trial. The actual angle was the angle between the reference letter and the target letter on the keyboard. RT was defined as the time between the onset of the target and reference letters in the direction judgment phase of each trial and the mouse click that indicated the angle on the circle. Thus, RT was defined in the same way for all three groups. Note that the prior presentation of the letters to be typed in the touch group was not included in the RT interval.

Subjects were instructed to judge the direction of the target letter relative to the reference letter. For each rotation condition, subjects were asked to imagine that the keyboard was rotated in correspondence with the reference letter. As a result, their direction judgments should also be rotated to reflect key location on the rotated keyboard. Responses were made by clicking a mouse on the point on the circle that corresponded to the direction from the reference to the target letter on the computer keyboard. The starting position of the mouse cursor was centered 2.0 cm below the bottom of the target letter. After clicking the mouse on the circle, subjects were shown a "submit" button on the bottom of the screen. Then, subjects moved the mouse cursor to the "submit" button and clicked on it, in order to proceed to the next trial. If subjects were uncertain about their response, they could click the circle again at a new location before clicking the "submit" button. Trials that included a second click were excluded in the later data analysis. The intertrial interval (ITI) was 1,000 msec. These trial parameters were the same for the imagine and look groups, and were modified slightly for the touch group.

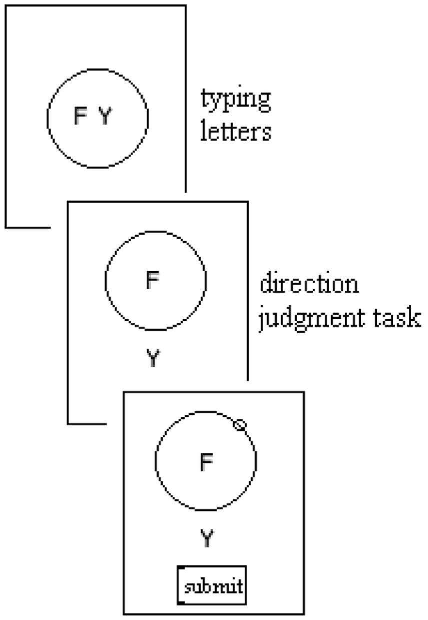

Figure 2. An example of a trial for the touch group in Experiment 1. Subjects first see letters to be typed, then the stimulus for the direction judgment, and then they make their direction judgments.

Subjects in the imagine group were not allowed to view the keyboard during the experiment, and were instructed to make their key direction judgments only from memory (i.e., to imagine key locations on the keyboard). To ensure this, we removed the keyboard from the testing room. The look group was given a standard QWERTY keyboard, which they could view but were told not to touch when making their responses.

The touch group was also provided with a standard QWERTY keyboard, which they could feel but not see. The keyboard was covered with the top from a box of printer paper. One of the side flaps from the box was cut away to allow subjects to place their hands inside the box and access the keyboard. Prior to each trial, subjects were presented with the reference letter and the target letter (each 1 cm × 1 cm) in the center of the circle (see Figure 2) in their normal upright position, regardless of the rotation condition for the following direction judgment. The letter on the left was always the reference letter, and the letter on the right was always the target letter used in the subsequent direction judgment task for that trial. Subjects were instructed to place their hands on the keyboard in the box, type the two letters, and then press the space bar. Subjects were not given feedback during typing of the letter pairs; 500 msec after the space bar press, subjects were given the direction judgment task. After the direction judgment task (1,000-msec ITI), subjects put their hands in the box and placed their fingers on the keyboard for the beginning of the next trial.

Results and Discussion

Before data analysis, trials were excluded if the angular error or RT was more than ±3 standard deviations (*SDs*) from the mean of the group. Trials were not included in the analysis if subjects clicked the circle a second time. Approximately 5% of trials were excluded. Mean accuracy for correctly typing both letters in the prime letter pair across all rotation conditions was 86% (range: 62%–100%). Mean absolute angular error for each subject in the touch condition included both trials in which the subject correctly and incorrectly typed the preceding letter pairs. A separate analysis was conducted that filtered out direction judgments for incorrect letter typing trials, which yielded the same pattern of significant effects. Mean angular errors and mean RTs for each group are plotted as a function of rotation in Figure 3.

Mean angular error and RTs were analyzed using a 4 (rotation: 0º, 90º, 180º, 270º) × 3 (group: imagine, look, touch) mixed model ANOVA. There were two major findings. First, angular error was larger and RT was longer for the imagine group than for the look and touch groups regardless of rotation. Second, all groups' angular errors were smaller and RTs were shorter in the 0º rotation condition than in other rotation conditions.

Both of these conclusions were supported by statistical analyses. For angular error, the main effect of group was significant [$F(2,57) = 9.17$, $MS_e = 371.58$, $p < .001$]. Mean angular errors in the imagine, look, and touch groups were 47.41º, 27.63º, and 22.78º, respectively. Planned comparisons revealed that angular error was significantly larger in the imagine group than in the look group and the touch group [$ts(57) \geq 3.25$, $p < .01$], but the touch group was not significantly different from the look group [$t(57) = 0.80$, $p > .05$]. The main effect of rotation was significant [$F(3,171) = 5.76$, $MS_e = 248.42$, $p < .001$]. Mean angular errors in the 0º, 90º, 180º, and 270º rotations were 25.38º, 33.92º, 35.24º, and 35.88º, respectively. Planned comparisons showed that angular error in the 0º condition was significantly smaller than that at the 90º, 180º, and 270º conditions [$ts(171) \geq 3.65$, $p < .001$], but there were no significant differences between 90º and 180º, 180º and 270º, or 90º and 270º [$ts(171) \leq 0.68$, $p > .05$]. The interaction between group and rotation condition was not significant [$F(6,171) = 1.63$, $p > .05$].

We performed several analyses to determine whether angular error was affected by the value of the objective angles, the row of the keyboard, and so on. We found no systematic results in measure of (absolute) angular error or in measures of signed angular error.

Mean RT for each group is plotted in Figure 3B. The main effect of group was significant [$F(2,57) = 5.68$, $MS_e = 7.43$, $p < .01$]. Mean RTs in the imagine, look, and touch groups were 7.08, 5.31, and 4.20 sec, respectively. Planned comparisons revealed that RTs were significantly longer in the imagine group than in the look and touch groups [$ts(57) \geq 2.05$, $p < .05$], and RTs were not significantly different in the look group and the touch group [$t(57) = 1.29$, $p > .05$]. The main effect of rotation was significant [$F(2,57) = 21.76$, $MS_e = 4.53$, $p < .001$], consistent with a mental rotation effect. Mean RTs in the 0º, 90º, 180º, and 270º conditions were 4.11, 5.35, 7.22, and 5.43 sec, respectively. RTs in the 0º condition were significantly shorter than in the 90º, 180º, and 270º conditions [$ts(171) \geq 3.19$, $p < .01$]. RTs in the 90º and 270º conditions were significantly shorter than in the 180º condition [$ts(171) \geq 4.61$, $p < .001$], but not significantly different from each other [$t(171) = 0.21$, $p > .05$]. The interaction between group and rotation condition was not significant [$F(6,171) = 0.29$, $p > .05$].

We calculated correlations between task performance measures and typing speed in wpm within each group. For angular error, the correlations were −.30, −.23, and −.35 for imagine, look, and touch subjects, respectively. None of these correlations were significant. For RT, the correlations were −.18, −.52, and −.01 for imagine, look, and touch subjects, respectively. The correlation in the look group was significant at $p < .05$.

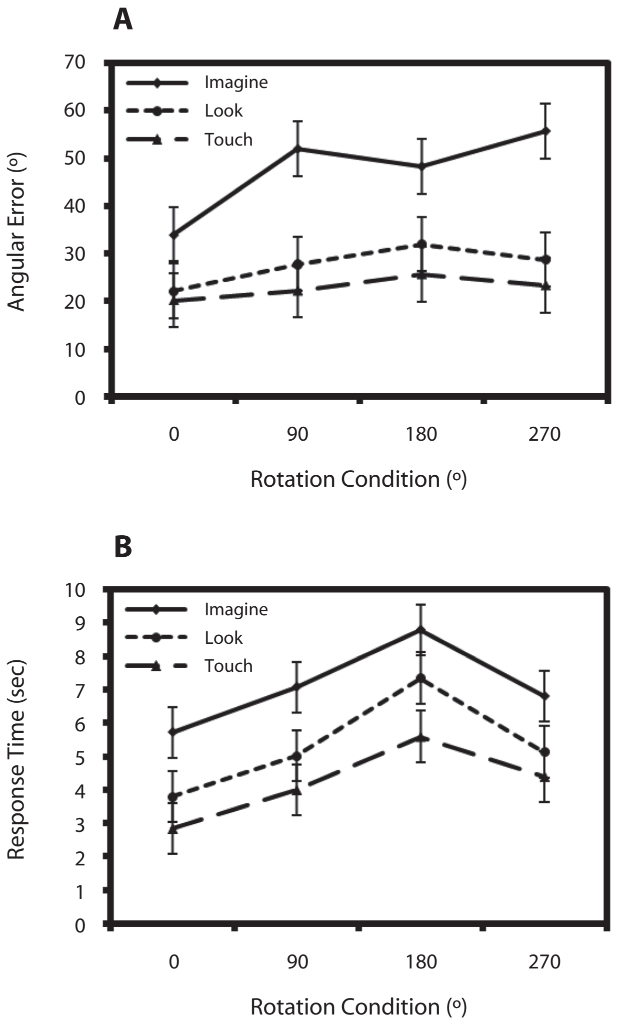

Figure 3. (A) Angular error as a function of rotation condition and group in Experiment 1 (error bars are confidence intervals corresponding to Fisher's least significant difference, as estimated from the ANOVA). (B) Response time as a function of rotation condition and group in Experiment 1.

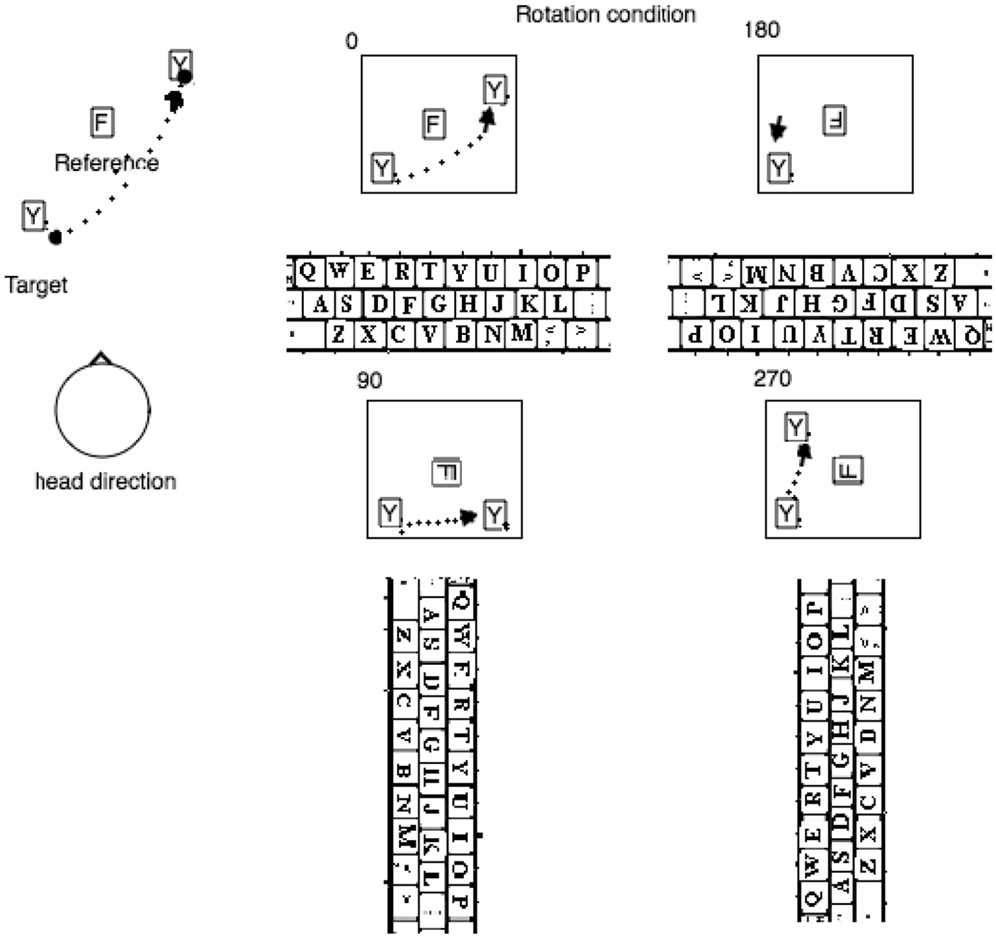

Figure 4. The left side depicts the display presented to subjects in the test trials in Experiment 2. The right side depicts examples of the test trials in each rotation condition. The dashed line with an arrow indicates the target letter Y being adjusted from its original position (the bottom left corner) to the right position by clicking the mouse at the proper location.

The results of Experiment 1 demonstrate larger angular error and longer RTs for the imagine group than for the look or touch group, which suggests that the explicit spatial layout knowledge of the computer keyboard is not as good as vision or kinesthesis and haptics. These results showed that skilled typists had poor explicit knowledge about key location on the computer keyboard, despite their ability to type quickly and accurately without looking at the keyboard. The results from the touch group showed that skilled typists' fingers know key location precisely, so the haptic and proprioceptive information from normal typewriting can be used to infer or retrieve the locations of the keys on the keyboard. More broadly, the data are consistent with a hierarchical model in which the inner loop has the precise knowledge of key location but the outer loop does not (Crump & Logan, in press–a; Logan & Crump, 2009).

EXPERIMENT 2

In Experiment 1, mean angular error was more than 20º even in the look group, suggesting that subjects were generally poor at making direction judgments. Moreover, Experiment 1 did not provide an estimate of explicit knowledge about the distance between keys. To assess the generality of our findings across judgment tasks and to document explicit knowledge of distances, we conducted Experiment 2.

In Experiment 2, we measured explicit knowledge of key location by allowing subjects to place a moveable key in its correct position relative to a reference letter. This new method allowed a measure of both angular error and distance error in key placement. Subjects were shown a reference key in the center of the screen, and a target key was placed at the bottom left of the screen (see Figure 4). The target key could be moved to any location on the screen by clicking that location with the mouse. Subjects were asked to place the target letter in its correct position relative to the reference letter. All other aspects of Experiment 2 were the same as in Experiment 1. In particular, we manipulated rotation (0º, 90º, 180º, and 270º) within subjects and availability of information about the keyboard (imagine, look, and touch) between subjects.

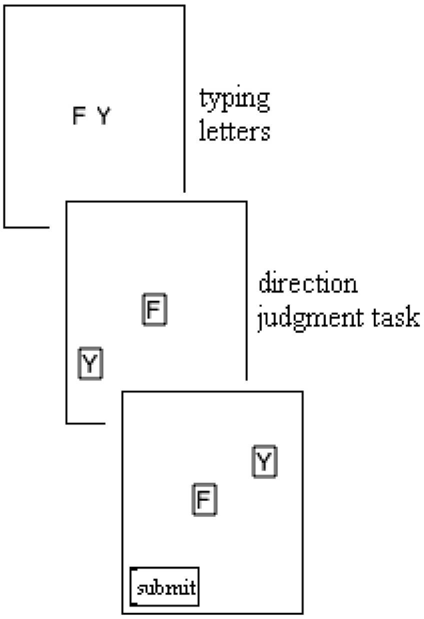

Figure 5. An example of a trial for the touch group in Experiment 2. Subjects first see letters to be typed, then the stimulus for the direction judgment, and then they make their direction judgments.

Method

Subjects. The subjects were 60 typists sampled from the Vanderbilt University subject pool, 20 in each of the three groups (imagine, look, and touch). Subjects were recruited for their self-reported ability to type 40 wpm or better. The mean typing speeds on the typing test were 60 wpm (range: 27–90) for the imagine group, 63 wpm (range: 31–96) for the look group, and 65 wpm (range: 30–113) for the touch group. A one-way ANOVA conducted on typing speed found no significant differences among the groups [$F(2,57) = 0.15$, $p > .05$]. All subjects were compensated with course credit, or \$12 for 1 h of participation.

Materials, Design, and Procedure. The design and procedure in Experiment 2 were essentially the same as in Experiment 1, except for the following changes: The reference letter and target letters appeared inside square boxes that were 2.0 × 2.0 cm. As illustrated in Figures 4 and 5, the reference letter always appeared in the center of the screen, and the target letter appeared in the bottom left corner. Subjects adjusted the location of the target letter by clicking the mouse to any point on the computer screen, at which time the target letter box would appear in the new location. After the target letter was moved to its judged position, a 3.5 cm × 1.5 cm "submit" button was displayed 2 cm below the bottom of the starting position of the target letter. Subjects clicked the mouse cursor on the "submit" button to go to the next trial. Dependent variables were absolute angular error, absolute distance error, and RT. Absolute distance error was the absolute value of the difference between the correct Euclidean distance between the reference and target letters and the judged distance. RT was defined as the difference between the onset of the reference and target letter display in the location judgment phase of the task, and the mouse click moving the square to its final position. For the touch group, the time required to type the letters before the location judgment phase of the task was not included in the RT measure.

Results and Discussion

Before-data analysis trials were excluded if the angular error, RT, or distance error was more than ±3 *SD*s of the group mean and if subjects clicked the mouse more than once (i.e., changed their mind about the target location). Approximately 4% of trials were excluded by this criterion. Mean accuracy for correctly typing both letters in the prime letter pair across all rotation conditions was 89% (range: 57%–99%). Mean absolute angular error for each subject in the touch condition included both trials in which the subject typed the letter pairs correctly and incorrectly. We conducted a separate analysis that filtered out the incorrect letter typing trials in the touch condition, which showed the same pattern of significant effects.

Mean angular error, distance error, and RT were analyzed with 4 (rotation: 0º, 90º, 180º, 270º) × 3 (group: imagine, look, touch) mixed ANOVAs. The means across subjects in each group are displayed in Figure 6. There were two major findings. First, angular and distance errors were larger, and RTs were longer, in the imagine group than in the look and touch groups, regardless of rotation. Second, all groups' angular and distance errors were smaller and RTs were shorter in the 0º condition than in other rotation conditions.

These conclusions were supported by statistical analysis. For angular error, the main effect of group was significant [$F(2,57) = 5.08$, $MS_e = 265.30$, $p < .01$]. Mean angular errors in the imagine, look, and touch groups were 29.49º, 16.61º, and 14.25º, respectively. Planned comparisons revealed that angular error was larger in the imagine group than in the look and touch groups [$ts(57) \geq 2.50$, $p < .05$] but not different between the look and touch groups [$t(57) = 0.46$, $p > .05$]. The main effect of rotation was significant [$F(3,171) = 6.81$, $MS_e = 122.83$, $p < .001$]. Mean angular errors in the 0º, 90º, 180º, and 270º conditions were 15.18º, 20.16º, 24.22º, and 20.90º, respectively. Angular error at 0º was significantly smaller than at 90º, 180º, and 270º [$ts(171) \geq 2.46$, $p < .05$]. Angular error was smaller at 90º than at 180º [$t(171) = 2.01$, $p < .05$], but 90º was not significantly different from 270º [$t(171) = 0.37$, $p > .05$]. The difference between 180º and 270º was not significant [$t(171) = 1.64$, $p > .05$]. The interaction between group and rotation was not significant [$F(6,171) = 2.06$, $p > .05$]; however, the effect of rotation appeared to be confined to the look and touch groups. There was no effect in the imagine group.

For RT, the main effect of group was significant [$F(2,57) = 5.95$, $MS_e = 3.75$, $p < .01$]. Mean RTs in the imagine, look, and touch groups were 5.91, 5.42, and 3.89 sec, respectively. RTs in the imagine group were significantly longer than in the touch group [$t(57) = 3.30$, $p < .01$], but not significantly longer than in the look group [$t(57) = 0.81$, $p > .05$]. RTs in the touch group were significantly shorter than in the look group [$t(57) = 2.50$, $p < .05$]. The main effect of rotation was significant [$F(3,171) = 37.69$, $MS_e = 2.03$, $p < .001$], consistent with a mental rotation effect. Mean RTs in the 0º, 90º, 180º, and 270º conditions were 4.17, 4.69, 6.72, and 4.72 sec, respectively. RTs in the 0º condition were significantly shorter than the 90º, 180º, and 270º conditions [$ts(171) \geq 2.00$, $p < .05$]. RTs in the 90º and 270º conditions were significantly shorter than in the 180º condition [$ts(171) \geq$

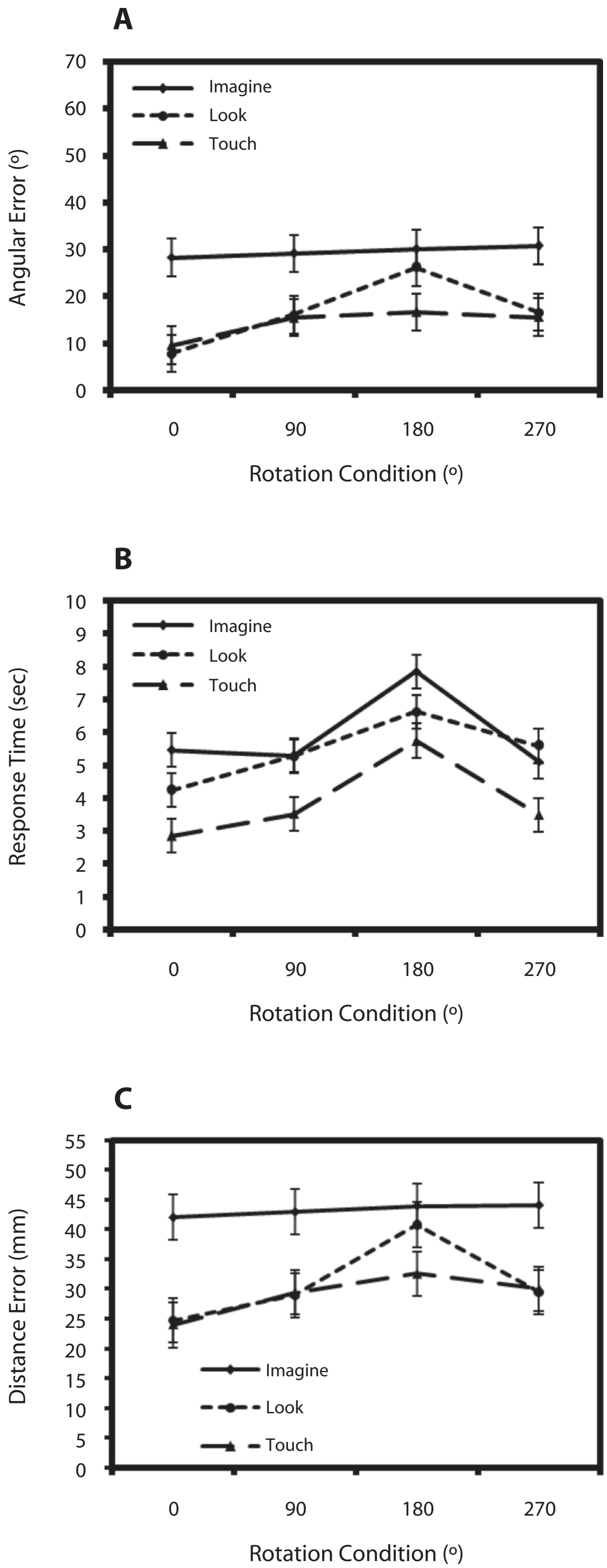

Figure 6. (A) Angular error as a function of rotation condition and group in Experiment 2. (B) Response time as a function of rotation condition and group in Experiment 2. (C) Distance error as a function of rotation condition and group in Experiment 2.

7.72, $p < .001$], but not significantly different from each other [$t(171) = 0.12$, $p > .05$]. The interaction between group type and rotation condition was not significant [$F(6,171) = 1.97$, $p > .05$].

For absolute distance error, the main effect of group was significant [$F(2,57) = 4.11$, $MS_e = 290.81$, $p < .05$]. Mean distance errors in the imagine, look, and touch groups were 43.25, 30.96, and 28.98 mm, respectively. Planned comparisons revealed that distance error was significantly greater in the imagine group than in the look group and touch group [$ts(57) \geq 2.28$, $p < .05$]. There was no significant difference between the look group and touch group [$t(57) = 0.37$, $p > .05$]. The main effect of rotation was significant [$F(3,171) = 7.28$, $MS_e = 108.92$, $p < .001$]. Mean distance errors in the 0º, 90º, 180º, and 270º conditions were 30.23, 33.76, 39.07, and 34.51 mm, respectively. Distance error in the 0º condition was significantly smaller than in the 180º and 270º conditions [$ts(171) \geq 2.25$, $p < .05$], but not significantly smaller than that in the 90º condition [$t(171) = 1.85$, $p > .05$]. Distance errors in the 90º and 270º conditions were significantly smaller than in the 180º condition [$ts(171) \geq 2.39$, $p < .05$], but distance error in the 90º condition was not significantly smaller than in the 270º condition [$t(171) = 0.39$, $p > .05$]. The interaction between group and rotation condition was not significant [$F(6,171) = 1.98$, $p > .05$], but again, rotation effects were apparent in the look and touch groups but not in the imagine group.

Again, we looked for systematic effects of variation in the angle between target and reference letters, row of the keyboard, and so on, in measures of absolute error, RT, and absolute distance error, and found none.

In addition to these measures of explicit knowledge of key distances, a measure of implicit knowledge of key distances can be estimated from accuracy on the paragraph typing tests conducted at the end of each session. We assume that key location is represented by a bivariate normal distribution centered on the key, and typing accuracy reflects the proportion of the distribution that falls on top of the key. Errors occur when subjects sample from the tails of the distribution that fall off the key. Note that this analysis interprets all errors as misdirected movements, and analyses of error corpora suggest that is not the case (Grudin, 1983; Lessenberry, 1928; F. A. Logan, 1999). Thus, the analysis will overestimate the variability in implicit knowledge of key locations; nevertheless, it provides an interesting point of comparison. We use the observed accuracy scores on the typing test to estimate the *SD* of this distribution, calculating a *z* score for the radius of the bivariate normal distribution by taking the square root of the quantile of a chi-square distribution with 2º of freedom that corresponds to typing accuracy. Typists in the imagine condition had a mean accuracy of 93% when performing the typing test. The 93rd quantile for $X^2(2)$ is 5.20. The square root of this value yields the radius as a *z* score (2.28), which can be converted to an *SD* of 4.2 mm for the bivariate normal distribution of implicit key locations. By contrast, the *SD* of the mean signed error in distance judgments for the 0º rotation in the imagine condition, which measures the accuracy of explicit knowledge, was 53 mm. Thus, explicit knowledge is 12.6 times less precise than implicit knowledge. Again, this analysis assumes all errors are misdirected movements (Grudin, 1983; Lessenberry, 1928; F. A. Logan, 1999), and so underestimates the accuracy of implicit knowledge.

We calculated correlations between task performance measures and typing speed in wpm in each group. For absolute error, the correlations were $-.36$, $-.10$, and $-.38$ for the imagine, look, and touch groups, respectively. None of these correlations were significant. For RT, the correlations were $-.11$, $-.46$, and $-.21$ for the imagine, look, and touch groups, respectively. The correlation in the look group was significant at $p < .05$. For distance error, the correlations were $-.35$, $-.12$, and $-.38$ for the imagine, look, and touch groups, respectively. None of the correlations were significant.

The results of Experiment 2 indicated that the imagine group had larger angular and distance error, and longer RT than the look group and touch group. Consistent with the findings from Experiment 1, this suggests that skilled typists have poor explicit knowledge about key location, although their implicit knowledge is quite good.

GENERAL DISCUSSION

We investigated the quality of skilled typists' explicit knowledge for the spatial layout of keys on a regular QWERTY keyboard, and found that skilled typists have poor explicit knowledge of the spatial layout, despite their ability to make rapid keystrokes to specific key locations 5–6 times/sec. In Experiment 1, we adopted a traditional task from the spatial memory literature to test our hypothesis, assessing the quality of explicit knowledge by comparing relative direction judgments about key location in imagine, look, and touch conditions. We found larger angular error and longer RTs for the imagine group than for the look and touch groups, indicating poor relative direction judgments when subjects were asked to explicitly recollect the spatial layout of keys on a keyboard, rather than utilize perceptual information from visual, haptic, or proprioceptive sources. The touch group's angular error was not different from that of the look group, suggesting that judgments relying on perceptual information did not depend on the particular modality in which information was received. Procedural differences in timing between look and touch conditions prevent us from drawing strong conclusions about the similarity of angular errors. In Experiment 2, we measured both angular error and distance error in key placement. Again, the imagine group had larger angular and distance error and longer RT than the look group and touch group. These findings replicated the basic pattern of results from Experiment 1, and demonstrate that deficits in explicit knowledge did not depend on particular task requirements.

Our finding that skilled typists have poor explicit knowledge of the spatial layout of the keyboard can be explained within the context of our inner/outer loop theory typing (Crump & Logan, in press; Logan & Crump, 2009), and has implications for the role of explicit knowledge in mediating routine action in general. The inner/outer loop theory of typing proposes that typing is controlled hierarchically by nested feedback loops, each processing separate aspects of the knowledge that mediates typing skill (Crump & Logan, in press–a; Logan & Crump, 2009; Shaffer, 1975). The *inner loop* translates words into keystrokes, controls serial order, and controls the movements of the fingers and hands; the *outer loop* connects to language generation and comprehension processes and provides the inner loop with a string of words to type (John, 1996; Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008). The novel contribution of our research is to hypothesize that knowledge in the inner loop is encapsulated, therefore not directly accessible to the outer loop. Logan and Crump (2009) found evidence for this hypothesis by demonstrating that typing performance is disrupted when skilled typists are asked to monitor their hand movements. The present experiments provide converging evidence for the encapsulation hypothesis by demonstrating that skilled typists have poor explicit knowledge of the spatial locations of keys on the keyboard. Given that skilled typists can type rapidly in normal circumstances, we assume that accurate knowledge of the spatial layout of the keyboard is represented within the inner loop and is not available for explicit report. Explicit knowledge of spatial layout in the outer loop is much less accurate.

An important question is whether explicit knowledge of spatial layout could be improved by testing it in other ways. For example, subjects could be shown a keyboard with stickers over the letters and asked to say which letter went with which key. Or they could be asked whether one letter was above or below another or right or left of another. Indeed, we found that absolute error could be reduced by having subjects place one key in its position relative to another key (Experiment 2) instead of having them point to it (Experiment 1). Explicit judgments may become more accurate as the testing situation approximates the normal typing situation more closely, reinstating the cues with which explicit spatial knowledge is normally associated. However, close approximations to typing invite the use of implicit knowledge, and it is possible that explicit judgments may improve because typists use implicit knowledge to simulate typing and base their explicit judgments on visual, proprioceptive, or kinesthetic feedback from simulating typing. Indeed, accuracy was substantially better in the touch conditions in both experiments, which allowed typists to base their explicit judgments on tactile and kinesthetic feedback from having typed the probed letters. We suspect that explicit knowledge may be better under some testing conditions than others, but it will always be worse than the implicit knowledge that guides actual typing.

We emphasize that typists have a lot of explicit knowledge about typewriting that is not about spatial layout. Although we have not tested this formally, we are sure they know that there are keys representing each letter of the alphabet; that there are three rows of keys with a space bar on the bottom, shift keys on the side, a return key on the right, and numeric keys on the top; and the approximate size of the keyboard (also see Beilock & Carr, 2001). However, this knowledge does not support their typing performance. In order to type skillfully, they need to know where the keys are on the keyboard, and we show that their explicit knowledge of key locations is very poor.

It is worth speculating on why some details of typing remain available for explicit report, yet features like spatial layout, which are critical to the task at hand, are not readily available for explicit report. We suggest that poor explicit knowledge of the keyboard may develop from the demands that typewriting places on spatial information processing at the level of words and the level of keystrokes (Crump & Logan, in press–a). The spatial layout of words in text and letters within words is largely incompatible with the spatial layout of the keystrokes that express the words on the keyboard; for example, the letters appear in different left-to-right order in text and on the keyboard. Somehow, typists must resolve the incompatibility between these spatial representations to prevent interference (Logan, 2003). We suggest that hierarchical control with outer and inner loops may develop as a way of resolving this interference, separating the spatial information in text from that in the keyboard by encapsulating it in different feedback loops.

Our demonstration of poor explicit knowledge of the spatial layout of the keyboard in skilled typists has implications beyond the domain of typing and informs both the literature on spatial memory and the larger skill-learning literature. Our present tasks were created by adapting relative direction judgment tasks from the literature on spatial memory. Several basic patterns of our results conformed to expectations for performance based on similar tasks from the spatial memory literature.

In Experiment 1, we found poor judgment of relative direction, even when typists were allowed to look at the keyboard. This finding is consistent with previous studies of spatial memory with a similar direction-judgment task, which found mean angular errors of 20º or more (McNamara et al., 2003; Mou & McNamara, 2002; Shelton & McNamara, 1997, 2001) and fits with previous research documenting poor pointing abilities when subjects are asked to adopt nonegocentric reference frames (Philbeck et al., 2008). Additionally, we manipulated the orientation of the letters in both experiments to investigate well-documented alignment effects in spatial memory (McNamara et al., 2003; Mou & McNamara, 2002; Roskos-Ewoldsen et al., 1998; Shelton & McNamara, 1997, 2001). Our results demonstrated poorer directional and distance judgments when the reference frame was rotated away from upright. These aspects to our findings conceptually replicate standard findings in the spatial memory literature, and demonstrate that judgment tasks from the spatial memory literature, which are normally applied to large-scale environments, can be successfully applied to the "microscale" environment of a computer keyboard.

Turning our attention to skill learning, we suggest that skills that demand speed, like playing piano or guitar, should be controlled hierarchically like typing. The feedback loops in the inner loop are shorter and may allow faster performance than feedback loops that engage both the outer loop and the inner loop (Lashley, 1951). More generally, we might expect hierarchical control in skills that are rich in information. The inner loop can deal with the details and leave the outer loop free to consider higher level goals (Crump & Logan, in press–a). Encapsulation of inner-loop knowledge may be an important step in acquiring high levels of skill (LaBerge & Samuels, 1974). Poor explicit knowledge, as demonstrated in our experiments, and disrupted performance when attending to details (Beilock, Carr, MacMahon, & Starkes, 2002; Beilock, Wierenga, & Carr, 2002; Logan & Crump, 2009), may be important diagnostics for encapsulated inner-loop knowledge in particular and hierarchical control in general (Botvinick & Plaut, 2004; Cooper & Shallice, 2000). Future research will test the validity of these speculations and compare theories of hierarchical control with plausible alternatives.

AUTHOR NOTE

This research was supported by National Institute of Mental Health Grant R01-MH073878-01 and National Science Foundation Grant BCS 0646588. We are grateful to Trisha Van Zandt and Andy Tomarken for statistical advice and to Martina Rieger for helpful comments on the manuscript. Correspondence may be addressed to G. D. Logan, Department of Psychology, Vanderbilt University, Nashville, TN 37203 (e-mail: gordon.logan@vanderbilt.edu).

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(Manuscript received April 5, 2009;
revision accepted for publication November 3, 2009.)