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Speed–Accuracy Trade-Off in Skilled Typewriting: Decomposing the Contributions of Hierarchical Control Loops

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Typing performance involves hierarchically structured control systems: At the higher level, an outer loop generates a word or a series of words to be typed; at the lower level, an inner loop activates the keystrokes comprising the word in parallel and executes them in the correct order. The present experiments examined contributions of the outer- and inner-loop processes to the control of speed and accuracy in typewriting. Experiments 1 and 2 involved discontinuous typing of single words, and Experiments 3 and 4 involved continuous typing of paragraphs. Across experiments, typists were able to trade speed for accuracy but were unable to type at rates faster than 100 ms/keystroke, implying limits to the flexibility of the underlying processes. The analyses of the component latencies and errors indicated that the majority of the trade-offs were due to inner-loop processing. The contribution of outer-loop processing to the trade-offs was small, but it resulted in large costs in error rate. Implications for strategic control of automatic processes are discussed.

Keywords: motor control, hierarchical processing, speed–accuracy trade-off, skilled performance, action sequence

A major issue in studies of cognitive skill concerns the ways in which skilled performance can be controlled strategically. Skill is acquired through training, and the extensive training required to attain high levels of skill makes component processes highly automatic (Anderson, 1982; Fitts, 1964; Logan, 1988; Schneider & Shiffrin, 1977); practice makes them specialized, stereotyped, and inflexible. Paradoxically, expert skills are often robust and flexible, so they can be utilized in various task contexts (MacKay, 1982). The present study addresses this paradox, asking whether automatic processes can be controlled strategically. To this end, we investigated a basic form of strategic control in cognitive performance—the trade-off between speed and accuracy. We focused on typewriting, which is one of the most prevalent skills among college students in modern society (Logan & Crump, 2011).

Hierarchical Control in Skilled Typing

Typewriting is an ideal subject for investigation of skilled performance. College students typically have a semester of formal training in middle school and 10 to 11 years of experience in which they type every day (Logan & Crump, 2011). Typing is a complex skill: It involves selecting specific keys that correspond to the letters in a to-be-typed word, moving appropriate fingers to precise key locations, and executing keystrokes in the correct order. Skilled typists implement these processes rapidly without watching the fingers that they control (i.e., touch typing).

Typewriting is an expression of language, and language has hierarchically nested structures: Texts contain sentences, sentences contain words, and words contain letters. Skilled typewriting involves hierarchically organized cognitive processes that address these levels of representation (Fendrick, 1937; Lashley, 1951; Logan & Crump, 2011; Shaffer, 1975; Sternberg, Knoll, & Turock, 1990). Logan and Crump (2011) proposed a two-loop theory of skilled typewriting, whereby typing is controlled by two nested feedback loops: *outer* and *inner loops*. The outer loop begins with a text to be typed and ends with a series of words; the inner loop begins with a word to be typed and ends with a series of keystrokes (see Figure 1a). In terms of cognitive processes (see Figure 1b), the outer loop is a central process that constructs and organizes the intention or *plan* to perform typing (Miller, Galanter, & Pribram, 1960), comprehends or generates language, retrieves lexical representations, and passes them to the inner loop. The inner loop controls individual keystrokes, activating the keystrokes in each word in parallel (Crump & Logan, 2010a; Logan, Miller, & Strayer, 2011), imposing a serial order on the activated keystrokes, and navigating the correct fingers to the target key locations in the correct order (Logan & Crump, 2009).

Each part in the hierarchy consists of a feedback loop that monitors a distinct source of information: The outer loop monitors

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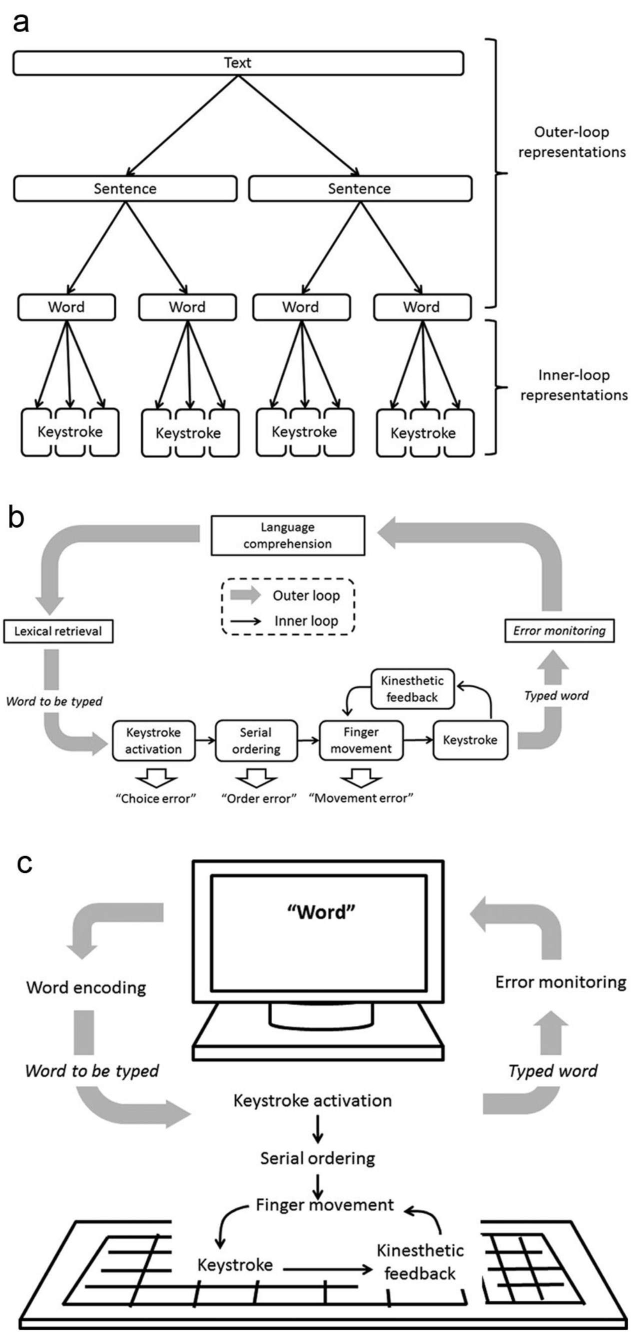

Figure 1. The two-loop theory: (a) linguistic representations used in the outer and inner loops, (b) cognitive processes constituting the outer and inner loops, and (c) hypothetical processes involved in the present experiments.

words typed on the computer monitor, and the inner loop monitors sensory and haptic feedback from each keystroke (Crump & Logan, 2010b; Logan & Crump, 2010). The inner loop is informationally encapsulated (Fodor, 1983), so the outer loop does not know how individual keystrokes are implemented by the inner loop (Logan & Crump, 2009; Liu, Crump, & Logan, 2010; Tapp & Logan, 2011). This suggests that the two loops operate autonomously, communicating only through words that are passed from the outer loop to the inner loop.

Speed–Accuracy Trade-Off Strategies in Typewriting

A basic form of control over performance is the trade-off between speed and accuracy: Subjects can choose to perform tasks accurately by reducing the speed of performance or they can choose to perform tasks quickly at a cost of making more errors. This *speed–accuracy trade-off* has been a major interest to cognitive psychologists for the last few decades, focusing primarily on choice reaction time (RT) tasks (e.g., Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Meyer, Irwin, Osman, & Kounios, 1988; Ollman, 1966; Pachella, 1974; Ratcliff, 2006; Rinkenauer, Osman, Ulrich, Müller-Gethmann, & Mattes, 2004; Strayer & Kramer, 1994; Wickelgren, 1977). As with performance in choice RT tasks, skilled typists are capable of controlling their typing speed across a reasonable range (e.g., Gentner, 1983, 1987), but how they do so is still not well understood.

Speed–accuracy trade-offs in choice RT tasks have been explained in two ways. First, they may reflect changes in the proportion of guessing responses (e.g., Dutilh, Wagenmakers, Visser, & van der Maas, 2011; Ollman, 1966; Yellott, 1971). Fast guesses may be based on purely random choices or on partial information (e.g., Meyer et al., 1988; Ruthruff, 1996). Subjects can trade accuracy for speed by increasing the proportion of fast guesses, and they can trade speed for accuracy by decreasing the proportion of fast guesses. In typing, fast guessing would imply that typing errors are random; however, typing errors are structured (e.g., transpositions, doubling, omissions, and substitutions) and the structure cannot be readily explained by a random choice among 26 alternatives.

Second, speed–accuracy trade-offs may reflect adjustments of response thresholds (e.g., Forstmann et al., 2008; Ratcliff, 1978, 2006; Swensson, 1972). This account is more common in the literature. It assumes a sequential-sampling process for response selection in which evidence for alternative responses accumulates to threshold over time during a trial (e.g., Ratcliff & Smith, 2004). When threshold is set high, it takes more time to accrue evidence, but the outcome will be more accurate. When threshold is set low, it takes less time to accrue evidence, but the outcome is error-prone.

Sequential-sampling models are designed to account for RT data in tasks where the main cognitive process is perceptual encoding or memory retrieval. In some cases, typing starts with encoding of words (i.e., transcription); in other cases, it starts with memory retrieval (i.e., composition). Thus, the sequential-sampling process may be relevant to speed–accuracy strategies in typewriting, especially in the outer loop where the to-be-typed word is encoded or retrieved. However, it is less clear that the same notion would apply to the inner loop where individual keystrokes are implemented (but see Heath & Willcox, 1990; Viviani & Laissard, 1996).

Tasks that have been modeled within the sequential-sampling model framework typically require a single discrete response on each trial. By contrast, typewriting consists of a continuous sequence of actions, although each action is a discrete keystroke. Thus, an alternative view that is better tailored to continuous sequences of actions may be required to account for the speed–accuracy trade-off in skilled typing. For instance, in Rumelhart and Norman's (1982) typing model, finger and hand movements are proportional to the activation levels of the corresponding keystroke representations. Thus, every bit of activation is translated into a movement toward the corresponding key location. The model reflects the continuous, parallel nature of action sequences and allows successive keystrokes to temporally overlap, which is a key feature of skilled typing (Flanders & Soechting, 1992). In this model, the notion of threshold adjustment may not be applied so readily because keystroke execution may begin when activation starts to accumulate, even before a threshold is reached.

Control of Speed and Accuracy in Action Sequences

In the motor-control literature, the most well-known relationship between speed and accuracy is *Fitts's law* (Fitts, 1954). Fitts's law states that the time to make an aimed movement is a function of the ratio of the movement amplitude (the distance between the starting point and the target position) to the target width (see also Keele, 1968; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Fitts's law expresses a speed–accuracy trade-off: Increasing the speed of movement reduces the precision of movement, whereas decreasing the speed of movement improves the precision of movement. The landing point of a movement is randomly distributed, so the precision of the movement is reflected in the variability of the landing position. Fitts's law says that movement errors (i.e., variability) increase as movement speed increases (Schmidt et al., 1979). Fitts's law is relevant to the operations of the inner loop because the fingers must be moved precisely to the key locations on the keyboard.

In the sequence production literature, several researchers have argued that changes in the speed of action sequences reflect modulations in a rate parameter (e.g., McGill, 1962; Shapiro, Zernicke, Gregor, & Diestel, 1981; Tuller, Kelso, & Harris, 1982, 1983; Wing & Kristofferson, 1973). The idea is closely associated with the *generalized motor program* concept (Keele, 1968; Schmidt, 1975), which suggests that acquisition of skilled performance reflects development of invariant motor patterns stored in memory, or *motor schemata*. The schema for a given skilled action does not change across variable conditions, but parameters of the schema (force, timing, extension, angle, etc.) are modulated to adapt the motor patterns to the context.

Changes in the speed of typing have been explained as adjustments of a rate parameter (e.g., Terzuolo & Viviani, 1980), but Gentner (1982, 1987) challenged this explanation. He argued that changing a rate parameter should produce a constant ratio of the duration of a component process (e.g., interkeystroke interval [IKSI]) to the total duration of the action sequence across different speed conditions. Based on his reviews of relevant studies, Gentner (1987) concluded that this proportional duration model did not hold in most motor tasks, including typewriting (but see Heuer, 1988). Subsequently, he simulated characteristic patterns of IKSI across different typing speeds with Rumelhart and Norman's (1982) model of skilled typing, which does not assume a central processor that controls the rate of typing. Instead, the model assumes that all keystrokes are activated simultaneously, and each keystroke inhibits all subsequent keystrokes to maintain the correct order of keystrokes. Gentner (1987) found that changing the level of inhibition between keystrokes was sufficient to account for the data. A high level of inhibition resulted in faster (and presumably less accurate) typing performance, whereas a low level of inhibition resulted in slower (and presumably more accurate) typing performance. However, the Rumelhart and Norman (1982) model failed to fit to the IKSI data when typists typed at a slow rate.

These results imply that control of speed and accuracy in skilled typing involves both central and peripheral mechanisms, consistent with the two-loop model of skilled typing. A drawback of Gentner's (1987) demonstration is that the Rumelhart and Norman (1982) model does not specify how the level of inhibition is actually modulated. In the simulations, it was Gentner himself who changed the level of inhibition according to typing rate, not the model. A model of the speed–accuracy trade-off in typing must specify the computations that modulate the level of inhibition, which could involve a central system to decide parameter values (Logan & Gordon, 2001).

The Present Study

The main purpose of the present study was to decompose the contributions of the outer and inner loops (Logan & Crump, 2011) in controlling speed and accuracy in skilled typewriting. Previous studies examined changes in typing speed that occurred naturally during text transcriptions (e.g., Gentner, 1982, 1983; Terzuolo & Viviani, 1980; but see Gentner, 1987). In our first two experiments, we used a discontinuous typing task in which typists typed a single word on each trial and imposed a deadline to restrict the time available to type a single word. In the second two experiments, we used a continuous typing task in which typists typed a short paragraph. We first tested three procedures for providing feedback about typing speed and then examined a wide range of speed constraints with a procedure in which typists were most accurate in controlling their typing speed.

In Experiment 1, the word was presented at the beginning of each trial and typists were instructed to finish typing it before the deadline expired. This procedure is similar to typical deadline procedures in speed–accuracy trade-off studies of choice RT (e.g., Link, 1971; Pachella & Pew, 1968; Ratcliff, 2006; Rinkenauer et al., 2004; Yellott, 1971). Hypothetical task processes are illustrated schematically in Figure 1c. In the task, typists first have to encode a word to start typing it, so both outer-loop and inner-loop processes are included in the deadline. Typists could trade speed for accuracy in either process, or both, to meet the deadline. In Experiment 2, we preexposed the word before the trial began so typists had time to encode it. Then a "go" signal was presented and typists were instructed to complete typing the word before the deadline expired. The preexposure was intended to allow typists to complete outer-loop processing before the go signal occurred, so they could only adjust speed and accuracy in the inner loop to meet the deadline. Hence, the outer- and inner-loop contributions to speed–accuracy trade-offs can be examined by looking at changes in RT and IKSI across deadlines in the two experiments.

Experiments 3 and 4 examined speed–accuracy strategies in continuous typing in which typists copied a paragraph at various typing rates. In Experiment 3, we tested three different feedback procedures that provided typists with an external cue to match their typing speed to a desired rate. These procedures included *metronome* (presenting tones at a specific rate), *speedometer* (presenting two numbers on the screen that indicate a desired typing rate and the actual typing rate of the typist), and *color* (changing the color of letters in the to-be-typed paragraph at a desired rate). Color was the most effective procedure, so we used it in Experiment 4 to examine speed–accuracy trade-offs across a wide range of typing rates (from 10% slower to 90% faster than normal typing rate, in 10% increments).

Continuous typing tasks emphasize the contribution of the inner loop. Skilled typing (50 to 100 words per minute [WPM]; Logan & Crump, 2011) is much slower than language generation (i.e., speaking rate is about 200 WPM; Rayner & Clifton, 2009) and language comprehension (i.e., reading rate is about 300 WPM; Rayner & Clifton, 2009), so the inner loop is more likely to limit typing speed than the outer loop. Variations in the time required for different outer-loop processes may be absorbed into the slack produced by waiting for the inner loop to finish typing the current word (Pashler, 1994). However, outer-loop processing may affect the nature of errors. Consequently, we analyzed IKSI to assess the contribution of inner-loop processes and we analyzed the nature of errors to assess the combined contribution of inner- and outer-loop processes.

Experiment 1

In Experiment 1, each trial began with a fixation point followed by a target word. Typists started typing as soon as the word appeared. Typing speed was manipulated by instructing them to complete typing before a time deadline that varied across blocks. In the first block, typists were asked to type displayed words at their normal typing rate without making errors. The mean typing duration (defined by the interval from onset of a word to the last keystroke) was computed for each typist and taken as that individual's normal typing speed. In the subsequent blocks, typists had to type each word 10%, 20%, or 30% faster than their normal typing speed. The deadlines were created by subtracting the respective percentages of the typists' normal typing duration. Each word was exposed until the deadline expired, and typists were instructed to finish typing the word before it disappeared from the screen.

The goal of Experiment 1 was to investigate separate contributions of the outer and inner loops in controlling speed and accuracy. The three main measures of performance, RT, IKSI, and errors each relate to outer- and inner-loop processing (Logan & Crump, 2011). RT is defined as the time between the onset of the word and the first keystroke, and it measures both word encoding time in the outer loop and keystroke execution time in the inner loop. IKSI is the time between successive keystrokes and measures inner-loop keystroke execution time. Errors in this task are at the keystroke level and measure failures at different inner-loop processing stages: letter choice, letter order, and finger movement (see Figure 1b). We expect the deadline procedure to produce speed–accuracy trade-offs that can be analyzed in terms of outer- and inner-loop processes. If speed increases are driven by faster word encoding in the outer loop, then we expect reductions in RT. If speed increases are achieved by faster keystroke execution in the inner loop, then we expect reductions in IKSI. Sacrificing accuracy for speed may also systematically change proportions of choice, order, and movement errors, further isolating inner-loop contributions to the trade-off.

Moreover, we examined whether speed stress alters the nature of error monitoring in paragraph typing. We examined IKSI for keystrokes that immediately followed error keystrokes. Posterror IKSIs tend to be longer than IKSIs that follow correct keystrokes or precede errors (e.g., Salthouse, 1984; Shaffer, 1973, 1975). Posterror slowing occurs whether or not typists are aware of their errors (Logan & Crump, 2010), suggesting that posterror slowing results from inner-loop operations. We examined whether speed stress modulates the extent to which the inner loop monitors the accuracy of keystrokes by looking at posterror slowing as a function of speed stress.

Method

Subjects. Sixteen volunteers were recruited from the Vanderbilt University community who were capable of touch typing. They were paid $12 for a 1-hr experimental session. All reported to have normal or corrected-to-normal visual acuity and no motor impairment. Their typing skill was assessed with a typing test in which subjects typed a short paragraph as quickly and as accurately as they could (details of the test are described by Logan & Zbrodoff, 1998). Their mean typing speed was 76.79 WPM (SE = 4.41; range, 42.0 to 106.38); their mean typing accuracy was 91.19% (SE = 1.03; range, 80.61% to 97.37%).

Apparatus and stimuli. The apparatus consisted of a 19-in VGA monitor and a personal computer. Responses were registered on a QWERTY keyboard. Stimuli were five-letter words displayed in the Courier New font with the font size of 18 point, centered on the screen. These words were sampled from a list of 792 words generated from the MRC Psycholinguistic Database (Wilson, 1987). The Corpus of Contemporary American English (Davies, 2008) was used to obtain the word frequency of these words per million. Word frequency ranged from 0.1 to 2,913.9 occurrences per million, and the mean and standard deviation of word frequency were 82.4 and 262.8 occurrences per million, respectively.

Procedure. Typists were tested individually in a cubicle under normal fluorescent lighting. Typists sat in front of the computer screen at an unrestricted viewing distance of approximately 55 cm. They read on-screen instructions and performed a block of 10 practice trials for which they were asked to type a five-letter word on the screen as accurately as they could at their normal typing speed. Upon completion, typists performed eight test blocks. Each block consisted of 95 trials; 760 unique words (95 words $\times$ 8 blocks) were randomly selected from the word list for these trials. Each word appeared only once in a session.

The first and eighth test blocks were the *normal-rate conditions* in which typists were asked to type words at their normal typing speed without a typing deadline. The remaining six blocks were the *deadline conditions* for which typists were instructed to complete typing each word within a specific deadline. The deadlines for the subsequent deadline condition blocks were determined uniquely for each typist based on their normal typing rate that was measured in the first test block. The experimenter did not inform typists about the deadline procedure or the relationship between their average typing duration and the deadlines in the subsequent blocks prior to the first test block, so it is unlikely that typists took advantage of the present procedure (e.g., intentionally slowing typing speed to increase the available time window in the subsequent blocks). In addition, typists were instructed to satisfy two conditions in the first test block: (a) average typing duration per word should be less than 1,500 ms, and (b) the overall accuracy should be better than 90%. These criteria were imposed to encourage typists not to type too fast or too slow but at their normal typing rate. Before the block started, typists were told that these criteria were easy to satisfy if they typed at their normal typing rate without making many errors. One typist failed to satisfy the speed criterion and was replaced with a new typist. The mean typing duration (i.e., the interval between onset of a word and the last keystroke) for correct trials in this block was computed for each typist (M = 1,168 ms, SE = 43.99, range = 916 to 1,477 ms) and taken as that individual's normal typing speed. This value was used to determine the typing deadlines for the subsequent blocks.

In the next six blocks, typists were instructed to complete typing each word within a specific deadline. Typists were given 20 practice trials with a deadline before they went on to the test blocks. The deadline for the practice trials was set at their normal typing speed. The next six blocks consisted of two cycles of three test blocks for which the deadline was 10%, 20%, or 30% shorter than the respective typists' normal typing speed. These deadlines varied across blocks, and the order was counterbalanced across typists. Finally, the eighth test block was identical to the first block, with a new set of five-letter words.

Each trial started with a fixation cross at the screen center for 500 ms, which was immediately replaced with a five-letter word. In the normal-rate block, the word remained on the screen until the trial ended. Each keystroke was echoed on the screen in lower case below the to-be-typed word. When five keystrokes were produced, the screen was replaced by the fixation display, signaling the beginning of the next trial. If five keystrokes had not been made within 30 s, the trial was terminated and the message "Faster!" appeared on the display for 1,000 ms. In the deadline blocks, the word stimulus was replaced by a black rectangle when the deadline was reached. Typists were instructed to complete typing before the rectangle erased the word; they were asked to continue typing if they failed to finish typing before the deadline. When five keystrokes were produced before the deadline, the rectangle was replaced by the fixation cross for the next trial. When fewer than five keystrokes were produced before the deadline, the message "Faster!" replaced the rectangle, which was printed in red and stayed on the screen for 1000 ms, followed by the fixation cross for the next trial. A keystroke was considered an error if the key did not correspond to the letter at the current letter position of the word (e.g., for the word "*MARCH*," the first keystroke was correct if, and only if, the "*m*" key was pressed).

Each test block ended with a feedback display, which showed the mean typing duration per word, the proportion of correct trials (i.e., trials for which no error keystroke was made), the proportion of correct trials for which all letters were typed before the deadline, and the proportion of correct keystrokes made before the deadline. An experimental session lasted less than an hour.

Results and Discussion

The following analyses included only keystrokes that were made before the deadline because typists often stopped typing or typed random letters to move to the next trial (as each trial ended after five keystrokes were registered) when the deadline expired.[1] To ensure that the effects we report here are not artifacts of truncating normal typing at the deadline, we computed the proportions of trials for which the respective keystrokes occurred after the deadline and compared them with the proportions of these trials that would be expected if typists typed at their normal typing rate (see Appendix), which indicated that typists did increase their typing rate as the deadline decreased. Our analysis here focuses on RT, IKSI, and percentage error (PE). The data were subjected to repeated measures ANOVAs with Condition (normal rate, 10%, 20%, 30%) as a within-subject factor. The degrees of freedom were corrected with the Greenhouse–Geisser adjustment wherever the sphericity assumption of ANOVA was violated.

Meeting speed requirement. Typists were able to control the speed of typing in response to the deadlines (see Appendix), but they did not meet the deadlines as well as they were supposed to. Mean RTs for the 10%, 20% and 30% deadlines were 9%, 11%, and 13% shorter than mean RT in the normal-rate condition (i.e., 56, 69, and 82 ms faster). Mean IKSIs were 15%, 18%, and 22% shorter than mean IKSI in the normal-rate condition (i.e., 20, 25, and 30 ms/keystroke faster). We calculated the proportion of trials for which typists failed to complete each of the five keystrokes before the deadline (see Figure 2). If typists met the deadlines, the proportions should be low and the same for each deadline. However, the proportions increased as the deadline decreased, suggesting that typists could not control their typing well enough to meet the deadlines. Thus, the present data suggest there are some limits to the flexibility of skilled typing performance.

Speed–accuracy trade-offs. Although not meeting the speed criteria consistently, typists exhibited speed–accuracy trade-offs (see Table 1). Mean RT for each deadline condition is plotted against percentage of correct responses for the first keystroke (on which RT depended) in Figure 3 (top panel). The pattern shows a typical speed–accuracy trade-off. Mean RT decreased as deadline decreased, $F(1.27, 19.10) = 48.77$, $MSE = 987.95$, $p < .001$, $\eta_p^2 = .765$, and percentage of errors for the first keystroke (PE_1) increased, $F(1.20, 18.05) = 14.98$, $MSE = 88.31$, $p < .001$, $\eta_p^2 = .500$. The effects remained significant when the normal-rate condition was excluded from the comparisons; $F(1.74, 26.17) = 18.55$, $MSE = 160.80$, $p < .001$, $\eta_p^2 = .553$, for RT and, $F(1.30, 19.45) = 10.34$, $MSE = 39.05$, $p < .003$, $\eta_p^2 = .408$, for PE_1. We cannot tell which loop is responsible for the speed–accuracy trade-offs because RT includes the durations of both outer-loop and inner-loop processes.

Next, we examined speed–accuracy trade-offs in IKSI. Mean IKSI for each deadline is plotted against percentage of correct responses for the second keystroke through the fifth keystroke in Figure 3 (middle panel), showing a typical speed–accuracy trade-off as well. Mean IKSI decreased with the deadline, $F(1.54, 23.00) = 53.50$, $MSE = 99.90$, $p < .001$, $\eta_p^2 = .781$, and percentage of errors for the second to fifth keystrokes (PE_{2-5}) increased, $F(1.19, 17.84) = 16.42$, $MSE = 197.51$, $p < .001$, $\eta_p^2 = .523$. These effects remained significant after the normal-rate condition was excluded from the comparisons; for IKSI, $F(1.47, 21.99) = 13.61$, $MSE = 40.68$, $p < .001$, $\eta_p^2 = .476$, and for PE_{2-5}, $F(1.23, 18.50) = 10.90$, $MSE = 94.92$, $p < .002$, $\eta_p^2 = .421$. These speed–accuracy trade-offs can be attributed to the inner loop because IKSI only includes the duration of inner-loop processes.

[1] We also analyzed the data including only trials for which the entire word was typed before the deadline expired. However, we thought that it was problematic to analyze the current data in this way because more than 80% of trials would be excluded for the 30% faster condition (see Figure 3). In either case, nevertheless, the results were similar to the ones reported in the main text.

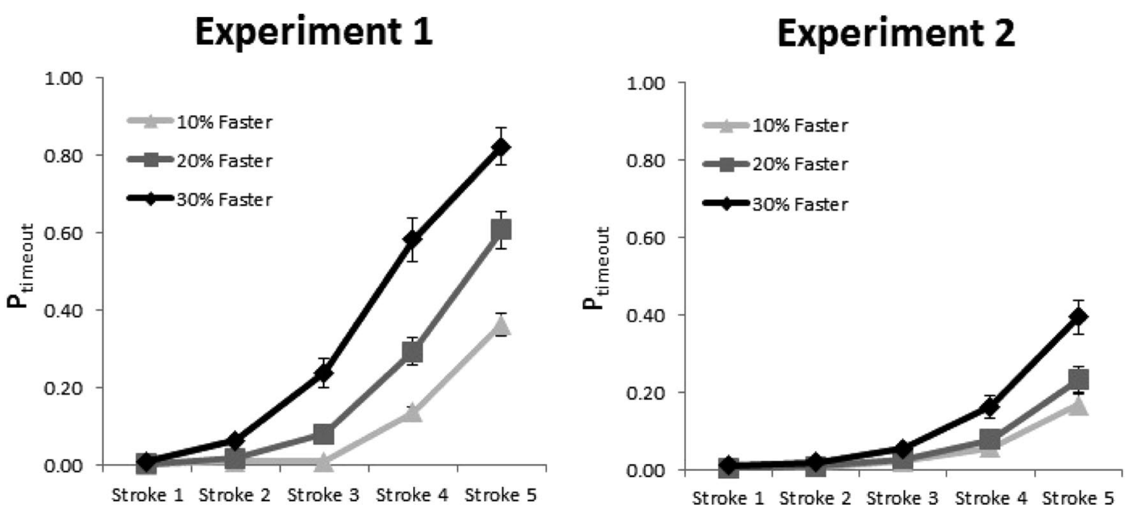

Figure 2. Proportions of trials in which the respective keystrokes did not occur before the deadline ($P_{timeout}$) for the three deadline conditions in Experiments 1 and 2 (error bars represent standard error of means).

We also plotted the latency of individual keystrokes against percentage of correct responses for the respective keystrokes in Figure 3 (bottom panel). Speed–accuracy trade-offs are apparent in each keystroke. PE tended to increase for later keystrokes because errors disrupt subsequent keystrokes.

Analysis of error types. Analysis of error types provides some insight into the processes typists controlled to trade accuracy for speed in the inner loop (see Figure 1b). We assumed that the inner loop starts with parallel activation of the keystrokes in the word (e.g., Crump & Logan, 2010a; Logan, 2003; Logan et al., 2011). At this stage in the inner loop, *choice errors* may occur if incorrect keystrokes are activated more than correct keystrokes (substitutions; e.g., typing "*POB*ER" for "*POWER*") or as much as correct keystrokes (insertions; e.g., typing "*POBWER*" for "*POWER*"), or if the activation of correct keystrokes is insufficient (omissions; e.g., typing "*POER*" for "*POWER*"). After the keystrokes are activated, they must be ordered serially (Rumelhart & Norman, 1982). *Order errors* occur when this process fails. Order errors include transpositions (e.g., typing "*LF*OOR" for "*FLOOR*") and doubling errors (e.g., "*FLL*OR" for "*FLOOR*"; see Rumelhart & Norman, 1982). Finally, keystrokes must be executed by moving the fingers and striking the keys. Finger movements are governed by Fitts's law and errors occur when typists trade speed for accuracy. *Movement errors* involve pressing keys that are adjacent to the correct letter (e.g., typing "*UACHT*" for "*YACHT*").[2] We calculated the frequencies of movement, order, and choice errors, collapsing over subcategories.[3] The results appear in Figure 4.

First, we computed the frequencies of the three error types for each subject and submitted them to a 4 (Typing Rate: normal rate, 10%, 20%, and 30% faster) × 3 (Error Type: movement, order, and choice) ANOVA. The frequencies of the three error types were similar, $F(2, 30) < 1$, $MSE = 303$, $\eta_p^2 = .041$, and the frequencies of all error types increased as the deadline decreased, $F(1.23, 18.39) = 18.51$, $MSE = 363$, $p < .001$, $\eta_p^2 = .552$, although the frequency of order errors was somewhat smaller in the 30% condition than in the other deadline conditions, as reflected in the Typing Rate × Error Type interaction, $F(2.07, 31.02) = 3.96$, $MSE = 186$, $p = .028$, $\eta_p^2 = .209$.

Furthermore, to assess whether typists traded specific error types for speed, we calculated the proportions of the three error types relative to the total number of errors in the respective conditions (see Figure 4, right panel) and ran separate ANOVAs as a function of Typing Rate (normal rate, 10%, 20%, and 30% faster). The proportions of movement and choice errors were

Table 1
Mean Response Times (RTs), Interkeystroke Intervals (IKSIs), Percentage Errors for the First Keystroke (PE_1), and Percentage Errors for the Second to Fifth Keystrokes ($PE_{2–5}$)

Condition	RT	IKSI	PE_1	$PE_{2–5}$
Experiment 1				
Normal rate	610 (20.61)	137 (6.43)	1.41 (0.08)	4.72 (0.63)
10% faster	554 (16.71)	117 (5.81)	7.67 (0.37)	14.10 (2.05)
20% faster	541 (16.45)	112 (5.86)	9.49 (0.55)	18.70 (3.51)
30% faster	528 (17.22)	107 (5.78)	15.40 (0.90)	27.44 (5.51)
Experiment 2				
Normal rate	324 (18.29)	132 (5.80)	1.99 (0.47)	5.72 (1.20)
10% faster	241 (20.88)	110 (5.68)	3.37 (0.48)	11.29 (1.24)
20% faster	230 (19.77)	103 (5.17)	4.48 (0.80)	13.16 (1.33)
30% faster	221 (18.35)	99 (5.38)	6.13 (0.76)	18.12 (1.65)

Note. Values in the parentheses are standard errors of means.

[2] Movement errors included all errors in which a key adjacent to the target key was pressed. It is possible that some of the movement errors were actually choice errors that happened to occur at a key adjacent to the target.

[3] There are ambiguities in these error categories. For instance, it is impossible to distinguish substitution and insertion when errors occur in the fifth position. In addition, it is difficult to distinguish subcategories of errors when more than two errors occur in a word (e.g., transposition plus substitution cannot be distinguished from two substitutions). Thus, whenever ambiguity arose, errors were classified as choice errors because at least one choice error was involved in ambiguous cases.

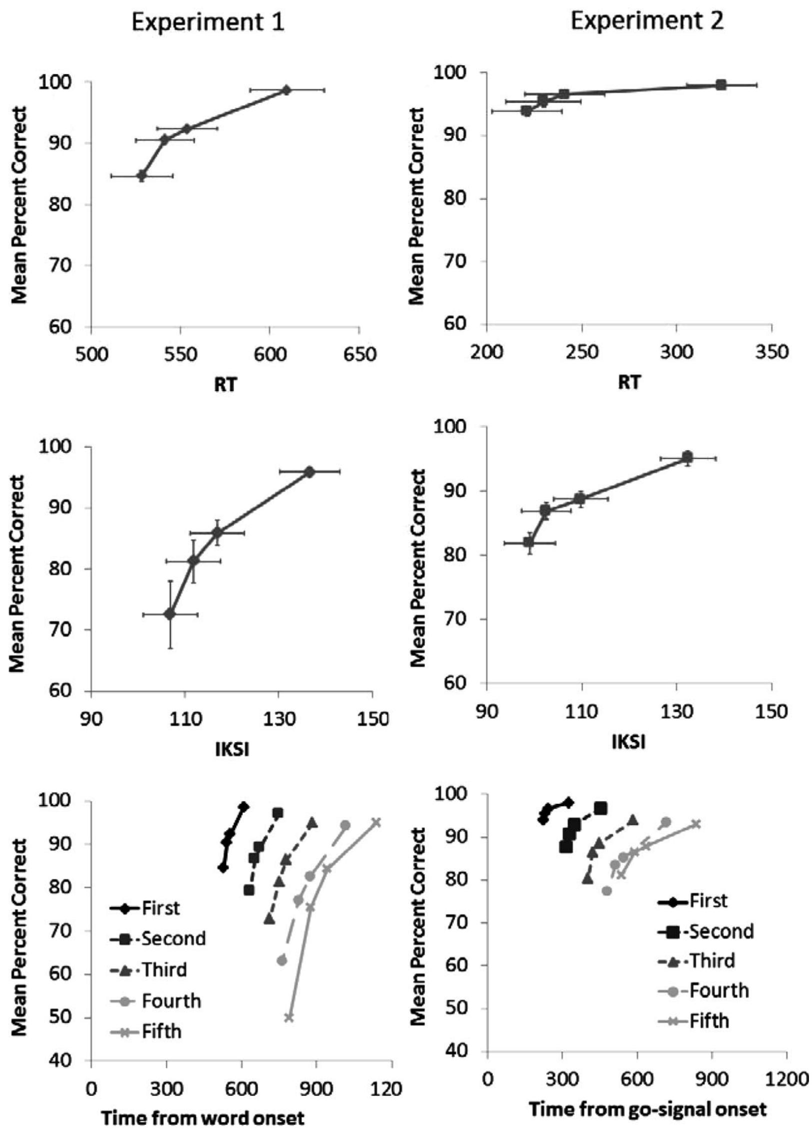

Figure 3. Speed–accuracy functions for response times (RT; top panels), interkeystroke intervals (IKSI; middle panels), and the latencies for individual keystrokes (bottom panels) in Experiments 1 and 2. The data points include the normal-rate, 10%, 20%, 30% faster conditions (error bars represent one standard error of means).

relatively constant across conditions, with $F(3, 45) < 1$, $MSE = .009$, $\eta_p^2 = .047$, for movement errors, and $F(3, 45) = 2.50$, $MSE = .010$, $p = .072$, $\eta_p^2 = .143$, for choice errors, although the proportion of order errors was larger in the normal-rate condition and somewhat smaller in the 30% faster condition, $F(3, 45) = 7.15$, $MSE = .007$, $p < .001$, $\eta_p^2 = .323$. These outcomes suggest that the speed–accuracy trade-offs in the present experiment were not due to trading specific error types for speed. The rate of all of the inner-loop processes (activating letters, ordering keystrokes, executing keystrokes) seems to have been adjusted in response to the deadline.

Estimation of fitts error. Following Fitts's law, we measured the accuracy of finger movements by estimating the variability of finger movements from movement errors (Schmidt et al., 1979). We did not record the actual finger movements during the experiment, but we hypothesized that the landing point of the finger movement is normally distributed around the center of the target key (see Liu et al., 2010). Then, we used the proportion of movement errors in the respective conditions to estimate the corresponding standard deviations of the bivariate normal distribution for each typist, that is, *Fitts error*. Averaged across typists, the movement error rates were 0.013, 0.044, 0.061, and 0.085, for the normal-rate, 10%, 20%, and 30% faster conditions, respectively. With the radius of the target surface area of 0.8 cm, these rates corresponded to Fitts error of 0.300, 0.391, 0.420, and 0.457 cm, for the four conditions. The increase of Fitts error was significant, $F(1.31, 19.7) = 16.97$, $MSE = .010$, $p < .001$, $\eta_p^2 = .531$.

Posterror slowing. IKSI are plotted as a function of the keystroke positions relative to the error in Figure 5. In the normal-rate condition, IKSI for the keystroke that immediately followed an

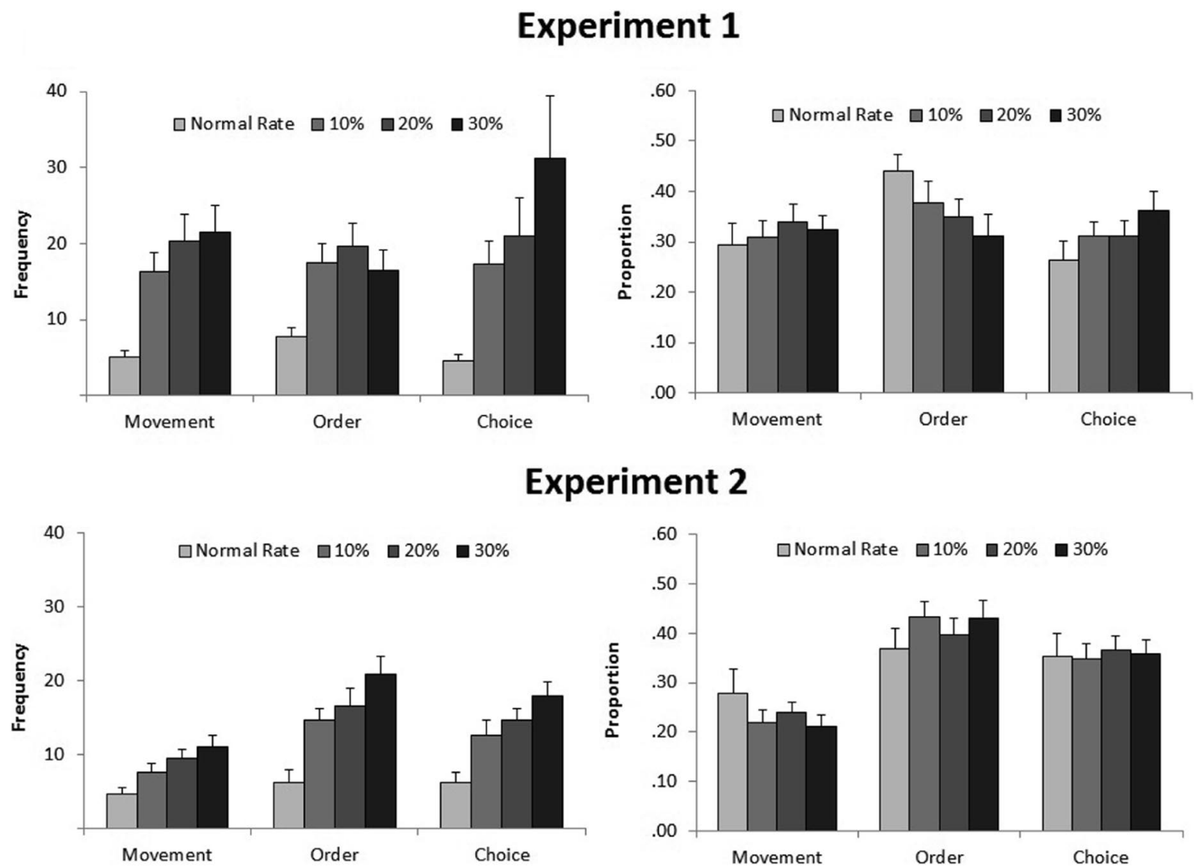

Figure 4. Mean frequencies and proportions of movement, order and choice errors in Experiments 1 and 2 (error bars represent one standard error of means).

error keystroke (i.e., E + 1) tended to be longer than the keystroke that immediately preceded an error keystroke (i.e., E − 1), yielding posterror slowing. However, posterror slowing was not apparent in the three deadline conditions. To support this observation statistically, we computed the differences between E + 1 and E − 1 for each subject and submitted this to an ANOVA as a function of Typing Rate (Normal rate, 10%, 20%, 30% faster), which revealed a significant effect, $F(1.15, 17.32) = 52.82$, $MSE = 6{,}836$, $p < .001$, $\eta_p^2 = .779$. The result implies that qualitative change took place in typing process in the deadline conditions.

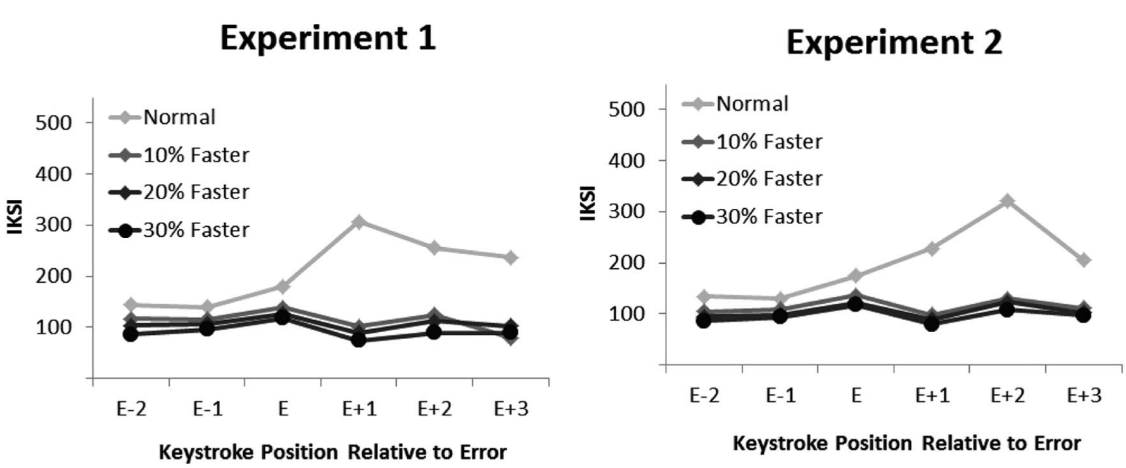

Figure 5. Mean interkeystroke interval (IKSI) as a function of keystroke position relative to error for the normal-rate and the three deadline conditions in Experiments 1 and 2.

Summary

The present results suggest that typists were able to control typing speed according to the time deadline imposed in a given block, but they were not able to meet the required criterion precisely (i.e., 10%, 20%, or 30% faster than normal speed). It is not clear whether typists were unable or unwilling to speed up further and sacrifice accuracy. RT and IKSI decreased, and PE and Fitts errors increased with speed stress, suggesting speed–accuracy trade-offs. Posterror slowing became very small in the deadline conditions. This finding suggests that the inner loop became more of an open-loop-like process as speed stress increased. There was no specific type of error that was traded off with speed, which implies that the speed–accuracy trade-offs could not be attributed to a specific processing component in the inner loop.

The reduction of RT from the 10% to 30% conditions was about 25 ms. RT reflects outer- and inner-loop processing, so the 25-ms reduction represents the sum of the outer- and inner-loop contributions (Logan & Crump, 2011). The reduction in IKSI from the 10% to 30% conditions was about 10 ms. Thus, the inner-loop contribution to RT was no less than 10 ms. It is tempting to interpret the results as suggesting that the outer-loop contribution was 25 − 10 = 15 ms. However, this subtraction logic might not work in the present case: The processes underlying successive keystrokes overlap temporally (Flanders & Soechting, 1992), so IKSI reflects the difference in the finishing times of successive keystrokes, not the difference in the processing durations. Consequently, some of the inner-loop contribution might have been absorbed in the temporal overlap of successive keystrokes, as in dual-tasking situations (Pashler, 1994). Thus, it is logically possible that typists increased the speed of the inner-loop processing by 25 ms/keystroke without changing outer-loop processing. To distinguish the contributions of the outer- and inner-loop operations to the control of speed and accuracy in typewriting, we attempted to exclude outer-loop processing in Experiment 2.

Experiment 2

In Experiment 1, typists started typing words as soon as they appeared on the display. Thus, RT involved the latency of word-encoding time in the outer-loop processing as well as the latency of the inner-loop processing of the first keystroke (Logan & Crump, 2011). In Experiment 2, we sought to exclude the contribution of outer-loop processing by providing typists sufficient time to encode the word and prepare subsequent keystrokes before cuing them to begin typing the word. Therefore, we presented typists with a to-be-typed word at the beginning of each trial and instructed them to withhold typing until a go signal appeared 1,500 ms later (following Balota & Chumbley, 1985). Thus, only inner-loop processing should occur after the go signal (see Figure 1c).

Method

Subjects. A new group of 16 typists was recruited from the same subject pool as in Experiment 1, with the same criteria for subject selection. These typists had mean typing rate of 75.24 WPM (*SE* = 4.43; range, 47.82 to 104.21) and mean typing accuracy of 92.75% (*SE* = 1.03; range, 81.55% to 99.07%). Thus, the typists' typing skills in the present experiment were comparable with those of Experiment 1.

Apparatus, stimuli, and procedure. The apparatus and stimuli were the same as those in Experiment 1. For Experiment 2, each block consisted of 85 trials; 680 unique words were randomly selected from the word list for each typist.

The procedure was essentially identical with Experiment 1, except for the following differences. Each trial started with a fixation cross, which was presented for 500 ms and was replaced with a word. The word was exposed for 1,000 ms, and a yellow rectangle replaced the word. After 500 ms, the rectangle changed its color to green, which served as a go signal. Typists were instructed to start typing the word as soon as the color changed to green. The computer did not accept keystrokes made before the onset of the go signal. In the deadline blocks, a black rectangle replaced the green rectangle when the deadline was reached. RT was the interval between the onset of the go signal and a depression of the first key. IKSI was defined as in Experiment 1. Experiment 2 closely followed Experiment 1 in other respects. The mean normal typing duration (i.e., the interval between onset of the go signal and the last keystroke) was 932 ms (*SE* = 39.35; range, 738 ms to 1,328 ms). No typists were replaced.

Results and Discussion

The results were analyzed in the same manner as in Experiment 1 and are summarized in Table 1. The appendix also reports the analysis that examined the proportions of trials for which the respective keystrokes occurred after the deadline and compared them with the proportions that were expected if typists typed at their normal typing rate in each deadline condition, which indicated that they did increase their typing rate according to the deadline.

Meeting speed requirement. Typists came much closer to meeting the deadlines in this experiment than they did in Experiment 1. RT was 26%, 29%, and 32% shorter than RT in the normal-rate condition for the 10%, 20%, and 30% conditions, respectively (i.e., RT was 83, 94, and 103 ms faster). IKSI was 17%, 22%, and 25% shorter than IKSI in the normal-rate condition for the 10%, 20%, and 30% conditions, respectively (i.e., IKSI was 22, 29, and 33 ms/keystroke faster). The proportions of trials for which individual keystrokes missed the deadline increased for shorter deadlines and increased for later letters in the word (see Figure 2).

Speed–accuracy trade-offs. We observed speed–accuracy trade-offs in RT and IKSI (see Figure 3). RT decreased, $F(2.30, 34.48) = 81.91$, $MSE = 570.89$, $p < .001$, $\eta_p^2 = .845$, and PE for the first keystroke (PE_1) increased, $F(2.07, 31.07) = 17.24$, $MSE = 4.11$, $p < .001$, $\eta_p^2 = .535$, as deadline decreased. Both effects were significant after the normal-rate condition was excluded: for RT, $F(1.63, 24.51) = 4.91$, $MSE = 391.26$, $p < .021$, $\eta_p^2 = .247$, and for PE_1, $F(1.62, 24.29) = 11.34$, $MSE = 3.35$, $p < .001$, $\eta_p^2 = .430$.

IKSI also decreased, $F(1.93, 29.00) = 152.99$, $MSE = 36.36$, $p < .001$, $\eta_p^2 = .911$, and PE for the second to fifth keystrokes ($PE_{2–5}$) increased, $F(1.74, 26.11) = 33.36$, $MSE = 20.23$, $p < .001$, $\eta_p^2 = .690$, as the deadline decreased. Again, both effects were significant when the normal-rate condition was excluded: for IKSI, $F(1.73, 25.94) = 39.47$, $MSE = 14.10$, $p < .001$, $\eta_p^2 = .725$, and for $PE_{2–5}$, $F(1.44, 21.66) = 27.16$, $MSE = 10.38$, $p < .001$, $\eta_p^2 = .644$.

Analysis of error types. The frequencies of movement, order, and choice errors are shown in Figure 4. Movement errors were less frequent than order or choice errors. The frequencies of all error types increased as the deadline shortened, but the frequencies of order and choice errors increased more than the frequency of movement errors. These observations were confirmed by a 4 (Typing Rate: normal rate, 10%, 20%, and 30% faster) × 3 (Error Type: movement, order, and choice) ANOVA, which revealed main effects of error type, $F(2, 30) = 9.10$, $MSE = 76.52$, $p < .001$, $\eta_p^2 = .378$, and typing rate, $F(1.60, 23.97) = 34.16$, $MSE = 55.78$, $p < .001$, $\eta_p^2 = .695$, and the interaction of these variables, $F(6, 90) = 2.83$, $MSE = 17.55$, $p < .014$, $\eta_p^2 = .159$.

The proportions of the three error types out of all error trials were similar across conditions, Fs < 1.5, $\eta_p^2 < .1$, indicating that there was no tendency to trade specific error types for typing speed (see Figure 4). These results appear consistent with the idea that typing speed is controlled by modulating the rate of all inner-loop processes.

The preexposure procedure in the present experiment was intended to exclude the outer-loop operations. To assess the influences of the procedure, we computed the frequencies of the three error types for the first keystroke separately from those for the subsequent keystrokes (see Figure 6). The most salient finding is that there were more errors in Experiment 1 ($M = 5.36$) than in Experiment 2 ($M = 2.12$) for the first keystroke, $F(1, 30) = 7.40$, $MSE = 136.63$, $p < .011$, $\eta_p^2 = .198$, whereas there was little difference between the two experiments (11.18% vs. 9.78%) for the subsequent keystrokes, $F(1, 30) < 1$, $MSE = 288$, $\eta_p^2 = .021$.

These results suggest that the preexposure procedure allowed the outer loop to operate accurately, even under time pressure, but provided little benefit to the inner-loop operations guiding subsequent keystrokes. Nevertheless, the profiles of the three error types were still similar for both the first keystroke and the subsequent ones.

Estimation of fitts error. As in Experiment 1, we estimated Fitts errors by using the movement error rate. In the present experiment, the movement error rates were 0.015, 0.025, 0.031,

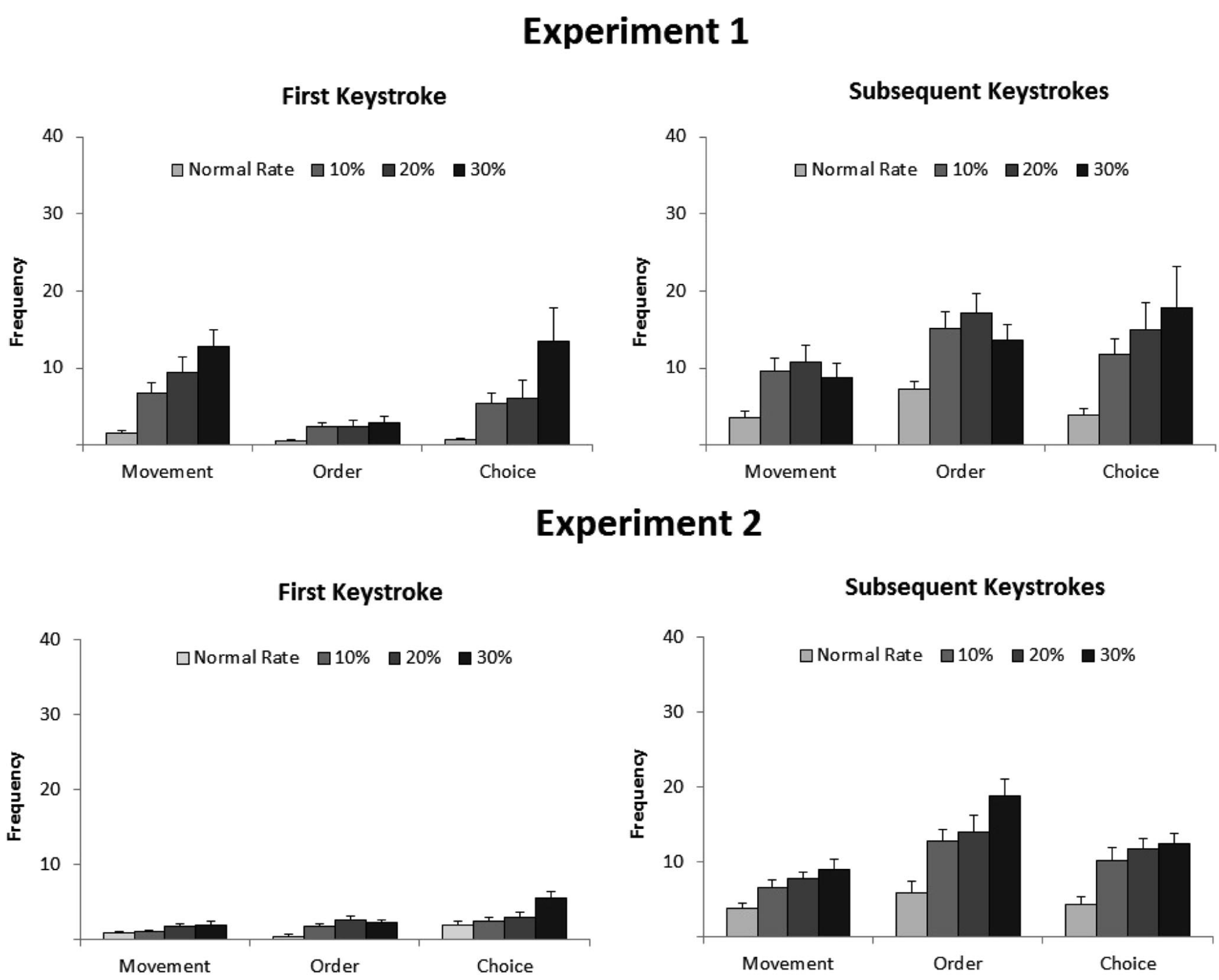

Figure 6. Mean frequencies of movement, order, and choice errors for the first keystroke and for the subsequent keystrokes in Experiments 1 and 2 (error bars represent one standard error of means).

and 0.040, for the normal-rate, 10%, 20%, and 30% faster conditions, respectively, and the corresponding Fitts errors were 0.289, 0.351, 0.367, and 0.383 cm. The results indicated a significant increase of Fitts errors as deadline decreased, $F(1.18, 17.69) = 7.30$, $MSE = .009$, $p < .012$, $\eta_p^2 = .327$, thus suggesting decreased accuracy of finger movements for shorter deadlines.

Posterror slowing. As in Experiment 1, IKSI are plotted as a function of the keystroke positions relative to error in Figure 5. As in Experiment 1, the posterror slowing was apparent for the normal-rate condition but not in the three deadline conditions. An ANOVA on the differences between E + 1 and E − 1 as a function of Typing Rate (normal rate, 10%, 20%, 30% faster) supported the observation, $F(1.19, 17.86) = 22.14$, $MSE = 2{,}180$, $p < .001$, $\eta_p^2 = .596$. An interesting outcome of the present analysis is that the magnitude of slowing peaked at E + 2 rather than at E + 1.

Summary

The present results are consistent with those of Experiment 1. RT and IKSI decreased and PE increased as deadline decreased. IKSI was similar to that observed in Experiment 1, and the reduction of IKSI across deadlines (11 ms) was similar to that in Experiment 1 (10 ms). These results suggest that the speed of inner-loop processing may be at a maximum in these experiments. However, the error rate was quite low: Errors occurred on fewer than 20% of trials in the 30% deadline condition. Thus, it is not clear whether typists were unable to speed up beyond this level or were just unwilling to do so; this issue will be addressed in Experiment 4.

The main difference between Experiments 1 and 2 was the preexposure of the word to be typed to exclude outer-loop processing in Experiment 2. If outer-loop processing was responsible for the reduction in RT with deadline in Experiment 1, there should have been small or no reduction in RT in Experiment 2, in which the outer loop was excluded. However, the RT reduction from the 10% condition to 30% condition was 26 ms in Experiment 1 and 20 ms in Experiment 2, suggesting that most of the RT reduction in Experiment 1 was due to inner-loop processing. Thus, the control of inner-loop processing may be more flexible than the control of outer-loop processing. Indeed, the increases in PE for the first keystroke were much larger in Experiment 1 than in Experiment 2 (see Table 1). Therefore, Experiments 1 and 2 revealed that the outer loop contributed to the RT reduction very little, whereas it contributed to the increase of errors at the first keystroke, implying that a small benefit and a large cost of changing the speed of the outer-loop processing.

Experiment 3

Experiments 1 and 2 indicated that speed–accuracy strategies in discontinuous single-word typing are attributable mainly to inner-loop operations. In the following two experiments, we examined speed–accuracy strategies in continuous typing, whereby typists were asked to type a paragraph. Typing speed is much slower than reading or speaking rates (Logan & Crump, 2011; Rayner & Clifton, 2009), so the inner loop constitutes a limiting factor in controlling typing speed in continuous typing. Thus, any variability in outer-loop latency may be absorbed into cognitive slack, and thus we expect that changes in typing rate are attributable mainly to the inner loop. And yet the contribution of the outer loop could still appear in errors. Hence, we assessed typing speed to examine the contribution of the inner loop, and we assessed typing errors to examine the joint contributions of the inner loop and the outer loop.

In Experiment 3, we explored three methods of manipulating speed–accuracy strategies: metronome, speedometer, and color change. A session was divided into four phases. In the first phase, normal typing rate was established by having typists copy the same paragraph twice. Subsequently, three experimental phases followed. The speedometer phase presented two numbers, the target typing rate and the current typing rate, which was continuously measured and updated while typing a paragraph; typists were instructed to match their current typing rate as closely as possible to the target rate. The metronome phase presented an auditory click over speakers indicating the target tempo for individual keystrokes; typists were instructed to type in time with the metronome as closely as possible. The color phase gradually changed the color of letters in the to-be-typed paragraph according to the target typing rate; typists were instructed to type at a rate consistent with the advancing color cues on the letters. In each phase, subjects were asked to type the same paragraph at different speeds: 20% slower than normal, normal, and 20% faster than normal.

We first examined how well typists were able to match their typing speed to the required rate with the three procedures. Then, we assessed speed–accuracy trade-offs, analyzed the nature of typing errors, and observed whether posterror slowing would be altered as speed stress increased, in the same manner as in Experiments 1 and 2. Based on these analyses, we determined which of the three feedback procedures would be the most effective means to induce speed–accuracy trade-offs in continuous typing and used the procedure to examine speed–accuracy control of continuous typing more extensively in Experiment 4, testing a wider range of typing rates.

Method

Subjects. A new group of 16 touch typists were recruited from the Vanderbilt University community. All typists were paid $12 for a 1-hr experimental session. Their mean typing speed was 70.46 WPM ($SE = 3.61$; range, 51.03 to 102.18); their mean typing accuracy was 92.37% ($SE = 1.16$; range, 80.95% to 99.54%).

Apparatus, stimuli, and procedure. The apparatus was identical with that used in Experiments 1 and 2. The typing materials were four short paragraphs, consisting of 110 to 117 words, also used for the typing test administered at the beginning of each session in Experiments 1 and 2 (see Logan & Zbrodoff, 1998). On each trial, a paragraph was presented in the upper portion of the display, and typed letters were echoed in a text box below the paragraph. Both texts were presented in a 12-point font size. Typists were informed that the backspace key functioning was disabled during the experiment, so they were not allowed correcting typing errors.

The experiment involved four phases. At the beginning of the session, each participant was randomly assigned one of the four short paragraphs, and the same paragraph was used for all phases. In the first phase, a paragraph was typed twice, and the average WPM was taken as a measure of normal typing rate for each participant. The remaining three phases include the speedometer, metronome, and color phases and were presented in a randomized order. Each phase involved typing the paragraph three separate times, at three different rates: 20% slower than normal, normal, or 20% faster than normal. Within each phase, each rate was presented in a random order.

The speedometer phase presented participants with two numbers centered above the to-be-typed paragraph: a target WPM and a continuously updated number representing their current WPM. Current WPM was calculated by a tracking algorithm averaging WPM over the 10 most recent keystrokes. The target and current WPM values were presented in 24-point font. Typists were instructed to monitor and adjust their own typing rate in accordance with the target WPM. The *metronome* phase presented an auditory click resembling a metronome sound over speakers, indicating the timing for individual keystrokes. The sound was 60 ms in duration and presented at a volume level deemed comfortable by each subject. Typists were instructed to type individual keystrokes in time with the metronome. The *color* phase presented color cues overlaid on the to-be-typed paragraph. When typists initiated typing, individual letters in the to-be-typed paragraphs incrementally changed color from black to blue. Typists were instructed to adjust their typing rate to match the rate with which letters changed color. In all phases, typists were encouraged to match their rate as closely as possible to the target rate, while making as few errors as possible.

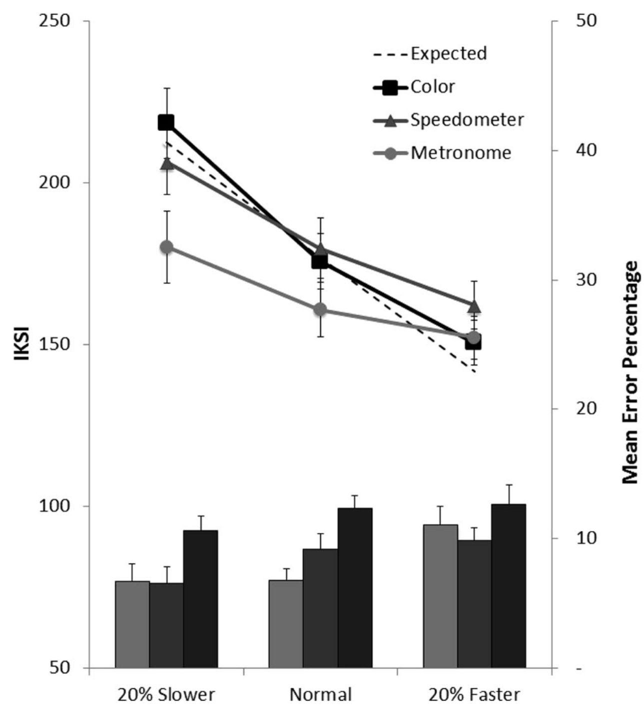

Figure 7. Mean interkeystroke interval (IKSI) and percentage errors as a function of speed stress in the color, speedometer, and metronome procedures, and expected IKSI in Experiment 3 (error bars represent one standard error of means).

Results and Discussion

The data were analyzed in terms of IKSI and PE (see Figure 7). PE was computed as percentage of incorrectly typed words to the total number of words in a paragraph.

Meeting speed requirement. To examine how well typists met speed requirements with the respective feedback procedure, expected IKSI was computed by adding or subtracting 20% of IKSI in the normal-rate condition in the first phase for each typist (see Figure 7). On average, the expected IKSIs for the 20% slower, normal-rate, and 20% faster conditions were 212, 177, and 142 ms/keystroke, respectively. IKSI in the color phase most closely matched the expected IKSI across the three speed conditions. For the color procedure, observed IKSIs were 218, 176, and 151 ms/keystroke for the 20% slower, normal-rate, and 20% faster conditions, respectively; these values correspond to −23%, 1%, and 26% faster than the normal typing rate. For the speedometer procedure, observed IKSIs were 206, 180, and 162 ms/keystroke for the 20% slower, normal-rate, and 20% faster conditions, respectively; these values correspond to −17%, −2%, and 8% faster than the normal typing rate. For the metronome procedure, observed IKSIs were 180, 161, and 152 ms/keystroke for the 20% slower, normal-rate, and 20% faster conditions; these values correspond to −2%, 9%, and 14% faster than the normal typing rate. Therefore, typists were able to match their typing speed to the target rate with the color procedure.

Speed–accuracy trade-offs. IKSI for the three speed conditions were plotted against percentages of correct words separately for the three feedback procedures in Figure 8. Overall, IKSI decreased as speed stress increased, but IKSI decreased more for the color procedure than for the speedometer procedure or the metronome procedure (also see Figure 7). This observation was supported by a 3 (Feedback: color, speedometer, metronome) × 3 (Typing Rate: 20% slower, normal rate, 20% faster) ANOVA, which showed a significant interaction between Feedback and Typing Rate, $F(2.20, 33.01) = 6.92$, $MSE = 236$, $p < .002$, $\eta_p^2 = .316$. In addition, PE increased as typing rate increased mainly due to the color procedure, and PE was overall largest with the metronome procedure ($M = 11.21\%$), intermediate with the speedometer procedure ($M = 9.45\%$), and smallest with the color procedure ($M = 7.97\%$). According to 3 (Feedback: color, speedometer, metronome) × 3 (Typing Rate: 20% slower, normal rate, 20% faster) ANOVAs carried out on PE for the three procedures separately, PE increased significantly with Typing Rate for the color procedure (*M*s = 6.76%, 6.81%, and 11.07%, for the slow, normal, and fast conditions, respectively), $F(2, 30) = 17.86$, $MSE = 5.49$, $p < .001$, $\eta_p^2 = .544$, and for the speedometer procedure (6.56%, 9.19%, 9.87%), $F(2, 30) = 6.84$, $MSE = 7.19$, $p < .004$, $\eta_p^2 = .313$, but not for the metronome procedure (10.60%, 12.35%, 12.68%), $F(1.37, 20.57) = 2.04$, $MSE = 14.40$, $\eta_p^2 = .120$. Taken together, these outcomes suggest that speed–accuracy trade-offs were most pronounced with the color procedure.

Analysis of error types. Errors were analyzed in a similar manner as in Experiments 1 and 2, using the same three categories; choice, order, and movement. The frequencies, as well as the proportions to all errors, were computed for the respective error types for each feedback condition. Mean frequencies and proportions are shown in Figure 9.

In all three feedback conditions, choice errors were more frequent than order and movement errors. Furthermore, choice errors appear more frequent in the 20% faster condition, especially with

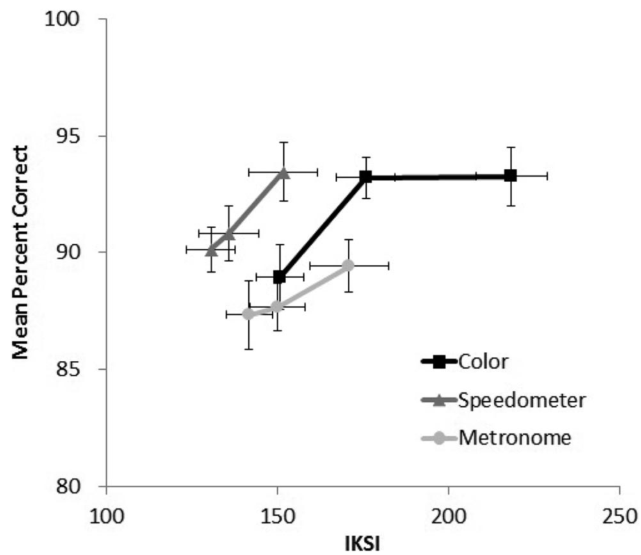

Figure 8. Speed–accuracy functions for interkeystroke interval (IKSI) in Experiment 3. The data points include the 20% slower, normal, and 20% faster conditions for each function (error bars represent one standard error of means).

the color procedure; movement and order errors did not change as much across typing rates. These observations are supported by the following ANOVA results: separate 3 (Typing Rate: 20% slower, normal rate, 20% faster) × 3 (Error Type: movement, order, choice) ANOVAs on error frequency revealed a main effect of error type in all three feedback conditions, *F*s > 31, *p*s < .001, which reflected larger frequency of choice errors than order and movement errors. Yet the color procedure alone yielded a main effect of error type, $F(2, 30) = 20.15$, $MSE = 2.84$, $p < .001$, $\eta_p^2 = .573$, and its interaction with typing rate, $F(2.64, 39.58) = 11.24$, $MSE = 6.23$, $p < .001$, $\eta_p^2 = .428$, indicating that error frequency increased reliably only for the color procedure and that the increase depended mainly on choice errors.

These outcomes reflected in the analysis on error proportions as well: Error proportion was higher for choice errors than for order and movement errors. The proportions of the three error types did not differ reliably across speed conditions (see Figure 9): Separate 3 (Typing Rate: 20% slower, normal, 20% faster) × 3 (Error Type: movement, order, choice) ANOVAs on error proportion revealed main effects of error type in all procedures, *F*s > 36, *p*s < .001, but the interaction between typing rate and error type was marginal for the color procedure, $F(4, 60) = 2.42$, $MSE = .063$, $p < 058$, $\eta_p^2 = .139$, and was far from significant for the other procedures, *F*s < 1.

The predominance of choice errors indicates that errors occurred mostly at keystroke activation rather than at serial ordering or keystroke execution. These outcomes differed from the results of Experiments 1 and 2, where the frequencies of the three error types did not differ significantly. However, the proportions of the three error types did not change as typing rate increased, which is consistent with Experiments 1 and 2.

Estimation of fitts error. As in Experiments 1 and 2, movement error rates were converted into Fitts errors, assuming that the variability in finger movement follows a bivariate normal distribution. With the color procedure, Fitts errors were 0.194, 0.270, and 0.263 cm for the 20% slower, normal-rate, and 20% faster conditions, respectively; with the speedometer procedure, Fitts

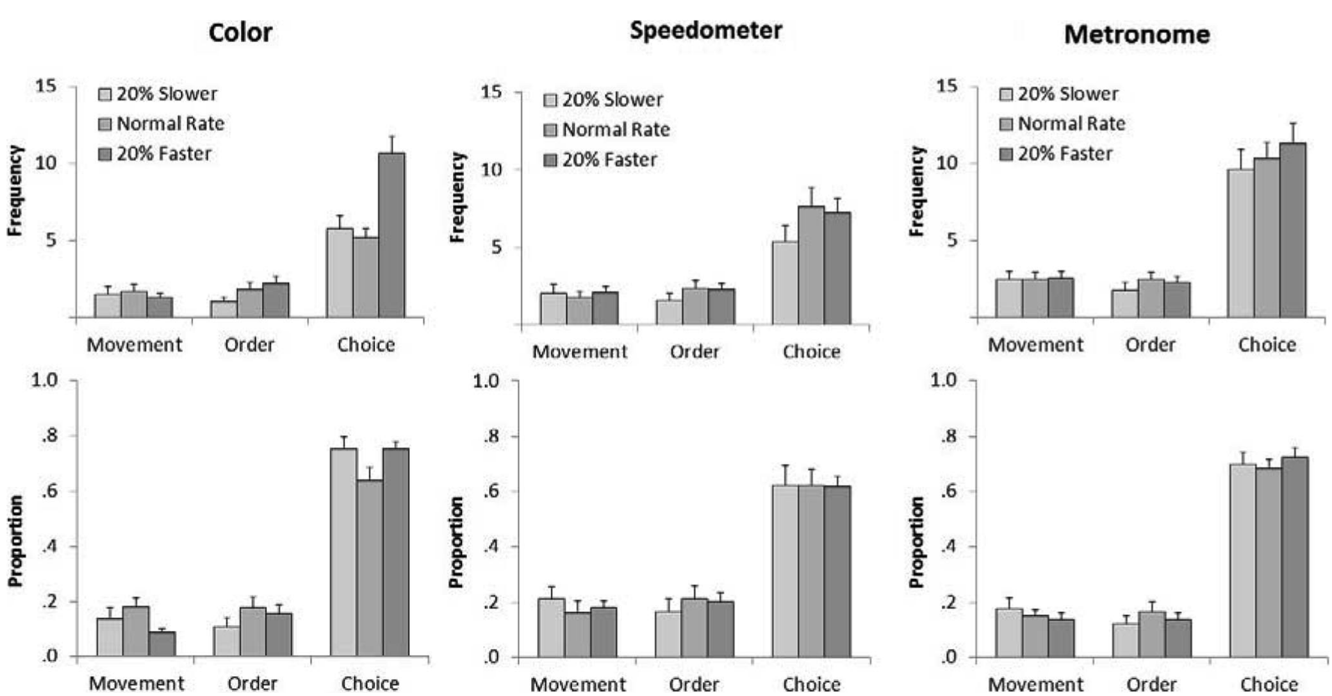

Figure 9. Mean frequencies and proportions of movement, order and choice errors with the color, speedometer, and metronome feedback procedures in Experiment 3 (error bars represent one standard error of means).

errors were 0.306, 0.306, and 0.309 cm, respectively; and with the metronome procedure, they were 0.260, 0.255, and 0.299 cm. We submitted Fitts errors to a 3 (Feedback: color, speedometer, and metronome) $\times$ 3 (Typing Rate: 20% slow, normal, 20% fast) ANOVA, which revealed no significant effects, $Fs < 2.4$, $ps > .1$. Thus, Fitts errors did not increase as speed stress increased nearly as much as they did for single-word typing of Experiments 1 and 2.

Posterror slowing. Figure 10 displays IKSI for keystrokes in the neighborhood of error keystrokes for the three feedback procedures. IKSI was longer at E + 1 than at other positions, which indicates posterror slowing. Posterror slowing quickly dissipated for the subsequent keystrokes. Speed stress reduced posterror slowing with the color procedure but not in the speedometer or metronome procedure. With the color procedure, the differences between E + 1 and E − 1 IKSIs were 300, 252, and 131 ms for the 20% slower, normal-rate, and 20% faster conditions, respectively. With the speedometer procedure, the differences were 228, 304, and 235 ms; and with the metronome procedure, the differences were 209, 175, and 236 ms. The lack of reduction in posterror slowing for the speedometer and metronome procedures suggests that typists may have more difficulty controlling typing speed with those procedures than with the color procedure.

Summary

Experiment 3 demonstrated speed–accuracy trade-offs in continuous paragraph typing. As in single-word typing, posterror slowing diminished as speed stress increased with the color procedure. Thus, speed stress appeared to influence error monitoring in continuous typing similarly to the way it did in single-word typing. Nevertheless, the nature of errors in Experiment 3 differed from those of single-word typing in that choice errors were predominant in the present experiment, whereas the three error types occurred equally frequently in Experiments 1 and 2. In addition, speed stress influenced Fitts errors to a smaller extent in the present experiment than in Experiments 1 and 2. Based on our interpretations of the three error types (see Figure 1b), these results suggest that speed stress had the strongest influence on keystroke activation in continuous paragraph typing.

In addition, Experiment 3 explored the three feedback procedures for inducing speed–accuracy trade-offs (color, metronome, and speedometer) in continuous paragraph typing. The color feedback provided the best means for controlling typing speed. Typists were less able to match their typing rate to the target rate with the metronome procedure, possibly because monitoring auditory signals is more difficult than monitoring visual signals when copying visually presented texts. Typists were not much better at matching their typing rate to the target rate with the speedometer feedback, which required directing attention away from to-be-typed letters to compare the current typing rate with the target rate. The color feedback may have worked best because typists could trace the target rate without moving attention away from to-be-typed letters. Consequently, in Experiment 4, we adopted the color feedback procedure for more thorough examinations of speed–accuracy trade-offs in continuous paragraph typing.

Experiment 4

Experiment 4 used the color feedback procedure from Experiment 3 to examine speed–accuracy trade-offs across a wide range of typing rates, from 10% slower than their normal rate to 90% faster in steps of 10%. We assessed how well typists were able to match their typing speed to the target rate by fitting a power function of the form, $IKSI = \alpha + \beta \cdot S^{-\gamma}$ to the IKSI data, where S represents the speed condition. If typists were able to meet speed requirements, IKSI should decrease linearly as speed stress increases, and the rate parameter of the power function (γ) should be equal to -1. If there is a limit to the control of typing speed, the asymptote of the power function (α) should be greater than 0, reflecting the limiting value of IKSI.

Method

Subjects. A new group of 16 touch typists were recruited from the same subject pool as in Experiment 3. Their mean typing speed was 65.98 WPM (SE = 2.63; range, 50.49 to 88.84) and mean accuracy was 93.93% (SE = 0.80; range, 85.98 to 99.10). All typists received $12 for a 1-hr session.

Apparatus, stimuli, and procedure. The apparatus and stimuli were the same as those of Experiment 3. The color feedback procedure described in Experiment 3 was employed for all conditions, with the following changes. The first phase established normal typing rate, by having typists copy the same paragraph twice. The experimental phase involved 11 separate attempts at copying the same paragraph from the first phase at different rates,

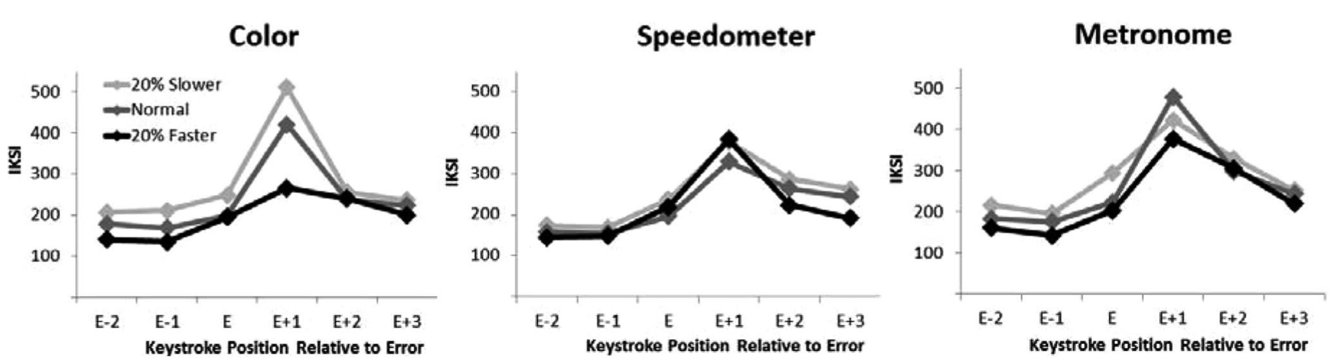

Figure 10. Mean interkeystroke interval (IKSI) as a function of keystroke position relative to error for the color, speedometer, and metronome conditions in Experiment 3.

from 10% slower than normal to 90% faster than normal, with 10% increments. At the beginning of each paragraph, typists were shown the to-be-typed paragraph presented above a blank text field. Typists used a computer mouse to click a "begin" button presented at the bottom on the display. The computer started a timer when the first key was pressed after the mouse click. As typists typed the entire paragraph, they again used the mouse to click an end button, positioned on the right of the start button, and went on to the next paragraph.

In all phases, typists were encouraged to match their typing speed as closely as possible to the target rate that was indicated by the color changes on the paragraph. Typists were also instructed to weigh more on speed than on accuracy. They were warned that the target rate would be very fast in the latter portion of the experiment and that they should sacrifice accuracy in attempt to match their typing speed to the timing of the color cue. Typists were allowed to finish typing the paragraph even when the to-be-typed paragraph had fully changed color, indicating that they had failed to match the target typing rate.

Results and Discussion

A unique aspect of the present results is that typists omitted substantial numbers of words, and they omitted more words as speed stress increased, especially as the target rate became faster than 30% of their normal typing speed (see Table 2), as indicated by a repeated-measures ANOVA on the proportions of omitted words in the last seven typing rates (30% faster, . . ., 90% faster), $F(1.38, 20.69) = 4.20$, $MSE = 155.39$, $p < .001$, $\eta_p^2 = .219$. We suggest the omissions occurred because typists tried to catch up with the target rate when they lagged behind, a strategy not permitted in single-word typing of Experiments 1 and 2.

Meeting criteria for typing speed. The observed and expected IKSIs are plotted in Figure 11. As in Experiment 3, the expected IKSI was computed for each condition for each typist by adding or subtracting a given percentage of the normal IKSI. The observed IKSI was very similar to the expected IKSI from the 10% slower condition up to the 40% faster condition, but the observed IKSI deviated from the expected IKSI after the 50% faster condition. To confirm this observation, we carried out a 2 (Statistics: observed vs. expected) × 11 (Typing Rate: 10% slower, normal rate, 10% faster, . . ., 90% faster) ANOVA, which revealed a significant interaction between the two factors, $F(1.26, 18.87) = 11.89$, $MSE = 163$, $p < .002$, $\eta_p^2 = .442$. We used the error term for this interaction to compute Fisher's least significant difference to compare the observed and expected IKSIs in each speed-stress condition (error bars in Figure 11). This analysis indicated that the observed IKSI became significantly larger than the expected IKSI at the 60% faster block. The outcomes are in contrast to the single-word typing task of Experiments 1 and 2, in which typists were unable to meet the speed requirements in the 30% faster conditions. Typists appear capable of adjusting their typing speed better in paragraph typing than in single-word typing.

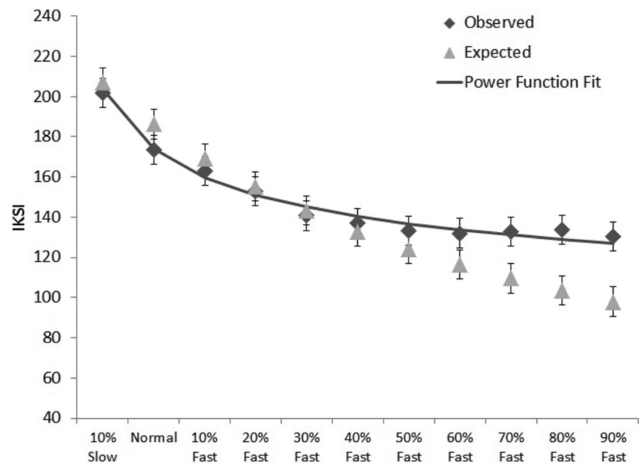

Figure 11. Observed and expected interkeystroke interval (IKSI) as a function of speed stress in Experiment 4 (error bars represent Fisher's least significant difference between observed and expected IKSI), and predicted IKSI based on the power function fit.

To determine the lower limit of typing speed, a power function of the form, $IKSI = \alpha + \beta \cdot S^{-\gamma}$, was fitted to the observed IKSI for each typist, where S represents typing rate by integers 1 to 11 (i.e., $S = 1$ for 10% slower, $S = 2$ for normal rate, and so on). The parameter γ represented the rate of the decrease with speed stress. If typists speeded up as instructed, IKSI should decrease linearly and γ should be equal to -1. If typists are limited in their ability to speed up their typing, then α should be greater than zero. β represents the amount of decrease in IKSI from the initial level to asymptote. The power function fit the observed IKSIs very well (see Figure 11). The correlation between observed and predicted values was $R = .990$ and the root mean squared deviation was 9.90 ms. The parameters of the function (averaged across typists) were $\alpha = 61$, $\beta = 143$, and $\gamma = 0.4$. Thus, IKSI did not decrease linearly with typing rate, implying that typists were unable to meet speed requirements. In addition, on average, the 61-ms asymptote indicates a lower limit of IKSI. When looked at individually, the asymptote for six typists equaled zero. If these typists were excluded, the mean asymptote was 97 ms.

Speed–accuracy trade-offs. IKSI and PE are also summarized in Table 2. IKSI decreased and PE increased as typing rate increased, indicating speed–accuracy trade-offs (see Figure 12). IKSI and PE for the 11 typing rates (10% slower, normal rate, 10% faster, . . ., 90% faster) were submitted to separate one-way ANOVAs, which supported this impression; for IKSI, $F(1.39,$

Table 2
Interkeystroke Interval (IKSI), Percentage Errors (PE), and Proportions of Words Omitted (P_{Omit}) in Experiment 4

Condition	IKSI	PE	P_{omit}
10% slower	197 (8.09)	5.33 (0.92)	.11 (0.30)
Normal rate	168 (8.06)	8.36 (1.51)	2.01 (7.44)
10% faster	160 (6.14)	7.46 (1.32)	.27 (0.60)
20% faster	150 (5.99)	9.67 (1.73)	.98 (2.21)
30% faster	137 (5.63)	10.93 (1.07)	.55 (1.75)
40% faster	133 (5.97)	13.13 (1.71)	1.47 (3.36)
50% faster	130 (6.28)	18.71 (2.13)	3.20 (6.65)
60% faster	127 (7.97)	20.33 (2.75)	5.71 (10.80)
70% faster	126 (9.85)	19.61 (2.44)	5.82 (11.83)
80% faster	126 (10.78)	21.27 (2.62)	7.41 (14.45)
90% faster	122 (11.38)	23.79 (3.24)	8.79 (15.60)

Note. Values in the parentheses are standard errors of means.

20.86) = 28.76, MSE = 289, $p < .001$, $\eta_p^2 = .657$, and for PE, $F(2.19, 32.83) = 14.24$, MSE = 215, $p < .001$, $\eta_p^2 = .487$.

Analysis of error types. Errors were analyzed in terms of the same categories as in Experiments 1 and 2 (i.e., movement, order, and choice errors). The frequencies, as well as the proportions to all errors, were computed for the respective error types separately for each target rate and typist.

Mean error frequencies are shown in the upper panel of Figure 13. As in Experiment 3, choice errors occurred more frequently than movement and order errors and the frequency of choice errors increased with more speed stress than the frequency of movement and order errors did. Separate one-way ANOVAs evaluating speed stress for the three error types indicated that the frequencies of choice and order errors changed with speed stress (Fs > 6.12, ps < .001), but the frequency of movement errors did not change significantly, $F = 1.81$, $p > .1$.

Proportions of the error types are shown in the lower panel in Figure 13. Error proportion was higher for choice errors (M = 0.64) than order errors (M = 0.22) and movement errors (M = 0.13). A 3 (Error Type: movement, order, and choice) × 11 (Typing Rate: 10% slower, normal rate, 10% faster, . . ., 90% faster) ANOVA revealed that the proportions of choice, order, and movement errors changed across conditions, as indicated by a significant interaction between Error Type and Typing Rate, $F(6.55, 98.25) = 2.59$, MSE = .092, $p < .019$, $\eta_p^2 = .147$. The proportion of choice errors tended to increase with speed stress, and the proportion of order and movement errors decreased somewhat with speed stress, reflecting predominance of choice errors.

As in Experiment 3, the larger proportions of choice errors in the present experiment suggest that errors are more likely to occur during keystroke activation. The increase in the proportion of choice errors with speed stress also suggests that speed stress affected keystroke activation in continuous typing. These results differ from the single-word typing results in Experiments 1 and 2.

Estimation of fitts error. We estimated Fitts errors for each speed-stress condition in the same manner as in Experiments 1 through 3. From the 10% slower to 90% faster conditions, Fitts errors were 0.204, 0.251, 0.278, 0.215, 0.210, 0.248, 0.248, 0.302, 0.283, 0.311, 0.333, and 0.253 cm. A linear trend test from a one-way ANOVA on the 11 speed conditions revealed a significant increase in Fitts errors with speed stress, $F(1, 15) = 5.83$, MSE = .119, $p < .029$, $\eta_p^2 = .280$. Fitts's errors were generally smaller than those obtained in single-word typing in Experiments 1 and 2 but still increased as speed stress increased.

Posterror slowing. Figure 14 displays IKSI for keystrokes in the neighborhood of error keystrokes. One subject made no errors in the normal-rate condition. All data from this subject were excluded from the posterror slowing analysis.

IKSI was longer for keystrokes that immediately followed an error, indicating posterror slowing, and the slowing quickly dissipated for the subsequent keystrokes (see Figure 14). The magnitude of posterror slowing decreased as speed stress increased; the differences between E + 1 and E − 1 were 208, 165, 191, 92, 70, 79, 34, 50, 91, 53, and 48 ms from the 10% slower to the 90% faster conditions. An ANOVA on the posterror slowing in these 11 speed conditions revealed a significant effect, $F(10, 140) = 3.84$, MSE = 42,056, $p < .012$, $\eta_p^2 = .215$. The decrease leveled off after the 30% to 50% speed conditions where the observed IKSI began to deviate from the expected typing rate (see Figure 12).

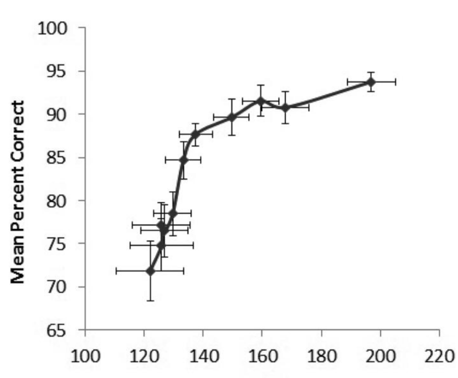

Figure 12. Speed–accuracy functions interkeystroke interval (IKSI) in Experiment 4. The data points include the 11 speed conditions (10% slower, normal rate, 10% faster up to 90% faster; error bars represent one standard error of means).

Summary

The present experiment assessed speed–accuracy control in continuous paragraph typing using a wide range of typing rates. The comparison of the observed and expected typing rates indicated that typists successfully matched their typing speed to the target rate until the 50% faster block but were unable to keep up with the target rate after that block. This indicates that there is a limit to how fast the inner loop can operate. The power function asymptote suggests this limit is 61 ms/keystroke, averaged across typists. Posterror slowing decreased with speed stress and reached an asymptotic value in the 50% fast block as well. In the 50% faster block, typing rate may have become too fast to intervene. Alternatively, typists may have chosen not to slow down after error keystrokes because doing so would prevent them from meeting the target typing rate. Further investigation is required to dissociate these possibilities.

Consistent with Experiment 3, the present experiment also showed a pattern of errors that differed from the pattern in the discontinuous typing tasks in Experiments 1 and 2. Whereas the three error types (choice, order, and movement) occurred equally frequently in discontinuous typing, choice errors dominated in continuous typing. Future investigations might explore the reasons for this difference.

General Discussion

The present study examined strategic control of speed and accuracy in skilled typewriting. We asked how each level of the hierarchically organized cognitive processes that underlie skilled typewriting contributes to strategic control of speed and accuracy, examining speed–accuracy trade-offs in discontinuous and continuous typing. The results have important implications for the nature of control in skilled performance.

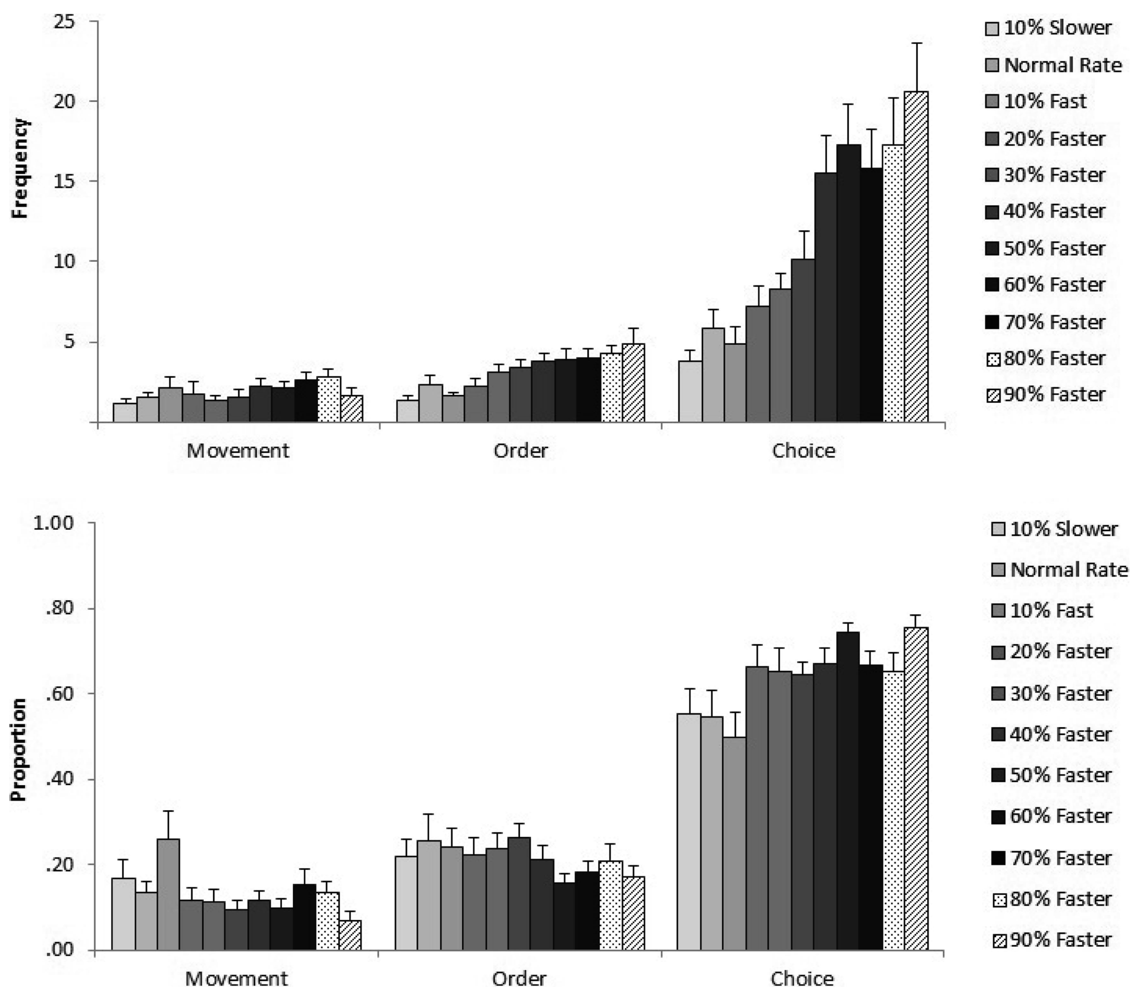

Figure 13. Mean frequencies and proportions of movement, order and choice errors in Experiment 4 (error bars represent one standard error of means).

Speed–Accuracy Trade-Offs in the Inner and Outer Loops

According to the two-loop theory of skilled typewriting (Logan & Crump, 2011), the outer loop encodes words and passes them to the inner loop, and the inner loop activates and implements keystroke schemata for the letters comprising the word. To examine the contributions of the outer and inner loops, Experiments 1 and 2 adopted a discontinuous typing task in which typists typed a single word on each trial. In Experiment 1, RT reflected outer-loop processing (e.g., word encoding) as well as inner-loop processing (e.g., execution of the first keystroke), whereas IKSI reflected inner-loop processing alone. Speed–accuracy trade-offs were observed in both RT and IKSI. To exclude the outer-loop processing in RT, we preexposed words in Experiment 2. RT was much shorter than in Experiment 1, but it decreased just as much with speed stress. The reduction in IKSI with speed stress was similar in the two experiments. Thus, the results suggest that the speed–accuracy trade-offs were mainly driven by the inner loop.

Experiments 3 and 4 adopted a continuous typing task in which typists typed short paragraphs consisting of 111 to 117 words to emphasize the contribution of the inner loop. Speed–accuracy trade-offs were observed in the continuous typing task as well. Experiment 3 compared three feedback methods for controlling typing speed and found that typists controlled their typing speed more effectively when the target rate was indicated color changes than by a speedometer or a metronome. Experiment 4 used the color procedure with a wider range of typing rates, from 10% slower than normal to 90% faster. Typists were able to match their typing speed to target rates up to 50% of their normal typing rate, but they started lagging behind when the target rate became faster. A power function fit to IKSI suggested that typists could not type faster than 61 ms/keystroke. This asymptote is about 200 WPM, which is still slower than typical reading rates (300 WPM; Rayner & Clifton, 2009). These results are consistent with the assumption that typing rate is limited by how fast the inner loop can operate.

Posterror slowing decreased as typing rate increased in all experiments. Experiment 4 suggested that posterror slowing reached an asymptotic level at the 50% faster rate. Posterror slowing may diminish with stronger speed stress because typists choose to ignore errors in order to keep up with the speed require-

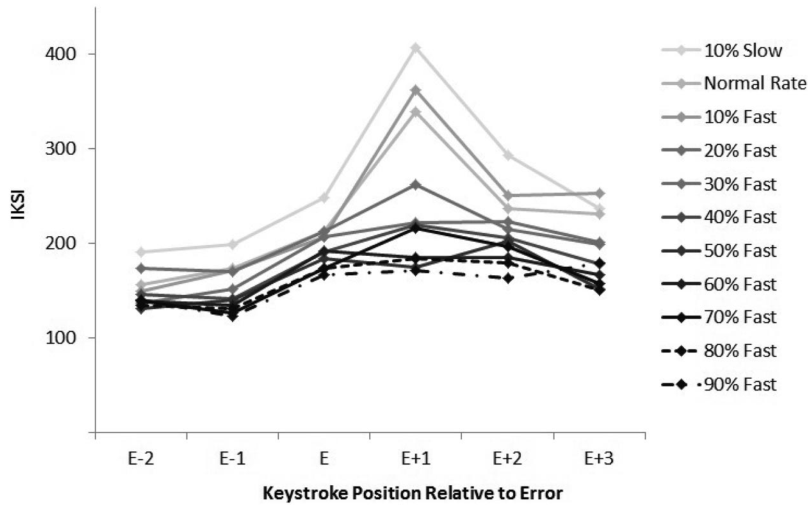

Figure 14. Mean interkeystroke interval (IKSI) as a function of keystroke position relative to error for the respective speed conditions.

ments. Alternatively, speed stress may not allow typists time to adjust speed–accuracy criteria following errors (e.g., Rabbitt, 1969).

Locus of Speed–Accuracy Control in Skilled Typing

To determine the locus of the speed–accuracy trade-off in the inner loop, we categorized errors as choice, order, and movement errors, corresponding to three component processes in the inner loop: activation of keystroke schemata, serial ordering of the keystrokes, and execution of the keystrokes, respectively (see Figure 1b). In Experiments 1 and 2, the frequencies of choice, order, and movement errors were about the same and increased in a similar fashion as the deadline decreased. Similar results were also obtained when errors in the first keystroke (reflecting outer- and inner-loop processing) and errors in the subsequent keystrokes (reflecting inner-loop processing) were analyzed separately. Therefore, in discontinuous single-word typing, speed–accuracy trade-offs were attributable all components of the inner loop.

In Experiments 3 and 4, two aspects of typing errors differed from those in discontinuous typing. First, typists omitted words as they lagged behind the target typing rate, and the proportion of omitted words increased as speed stress increased. We suggest the outer loop controls the decision to omit words. Second, choice errors occurred more frequently than order or movement errors in continuous typing, and in Experiment 4, the proportion of choice errors increased more with speed stress than the proportion of order and movement errors. This suggests that keystroke activation is an important locus of the speed–accuracy trade-off in continuous typing.

Overall, the four experiments suggest that changes in typing speed are mainly due to the inner loop. The speed of outer-loop processing may be increased by using fast guessing (e.g., Ollman, 1966) or by lowering threshold (e.g., Ratcliff, 1978). Fast guessing would work for tasks for which there are only few alternative responses, but guessing would almost surely result in errors in the present task because numbers of possible words (>50,000) and letters (26) that could be typed are very large. Lowering threshold would result in misidentification of words. Typists in the present study rarely typed wrong words; most errors were made by pressing wrong keys. These outcomes corroborate the conclusion that the speed–accuracy trade-offs are due to inner-loop operations.

The small outer-loop contribution to the speed–accuracy trade-off speaks to the division of labor between the inner and outer loops in skilled typing. The outer loop controls word-level processing, so outer-loop errors would result in typing the wrong words. Thus, decreasing outer-loop accuracy would increase word-level errors but not letter-level errors. The inner loop controls letter-level processing, so inner-loop errors would result in pressing the wrong keys. Thus, decreasing the accuracy of the inner loop only affects individual keystrokes. The small outer-loop contribution may reflect the relative speeds of outer- and inner-loop processing. The outer loop reads the word, and reading occurs at rates of 250 to 350 WPM (Rayner & Clifton, 2009). Typing is much slower than reading, occurring at rates of 50 to 100 WPM (Logan & Crump, 2011). The outer loop is fast and the inner loop is slow, so speeding up the outer loop would not benefit overall typing speed very much.

The typing task in the present experiments required copying visually presented texts, whereas everyday typing mostly involves composing text (Logan & Crump, 2011). Composition typing under time pressure is a common experience; for example, standardized tests (e.g., SAT, GRE, and TOEFL) often include composing essays within an allocated time. In such conditions, typists may become more prone to committing outer-loop errors as speed stress increases, resulting in poor sentence composition and grammatical errors. It would be interesting to see whether this is indeed the case and whether these outer-loop errors are also structured as inner-loop errors at the keystroke level are.

Automaticity and Control in Skilled Typing

The results of the present study provide insight into the nature of control and automaticity in skilled performance (Anderson, 1982;

Fitts, 1964; Logan, 1988; MacKay, 1982; Schneider & Shiffrin, 1977). When people become highly skilled, they are able to shift attention to higher-order processing and let lower-order processing run automatically (Vallacher & Wegner, 1987). Skilled typists can construct sentences while typing an e-mail without thinking about how their fingers type the intended words. Prior work has provided multiple lines of evidence for this division of labor. When typists are required to monitor which hand is used to type letters, fluent performance is disrupted (Logan & Crump, 2009; Tapp & Logan, 2011). Thus, attending to the details of automatized routines can disrupt performance. Typists locate key positions quickly and accurately during normal typing, but they are poor at making explicit judgments of key location (Liu et al., 2010). Here, automatic processes in the inner loop provide precise representations of keyboard layout that are not available to the outer loop. It is tempting to relate the distinction between inner and outer loops to the distinction between automatic and controlled processing, with the automatic inner loop operating independently of, and without control from, the outer loop. However, there are good reasons to resist that temptation (see also Logan & Crump, 2011).

The present conclusion that speed–accuracy trade-offs are mainly due to changes in inner-loop processing contradicts the notion that automatic processes lack control. In our view, automaticity is not opposite to control in skills like typing. Automatization occurs through training, and this training affords more precise control over performance, and not independence from control. Instead, automatization can be viewed as a change in the way skills are controlled (Logan, 1988). In skilled typing, this reflects a form of control over motor movements driven by a well-rehearsed plan or goal-based intention (Logan, 1982; Logan & Crump, 2011). Our previous findings show that the inner loop can operate autonomously, but our current findings emphasize that some aspects of inner-loop processes remain under control.

Finally, it is also important to consider two loci of control: One is its *site*, where control is enacted, and the other is its *source*, where control originates. In the present study, we focused primarily on the site of control, which led us to the conclusion that inner-loop processing is the primary site of speed–accuracy trade-offs in typing. However, this conclusion does not eliminate the outer loop as a possible source of the speed–accuracy trade-offs. The rate of inner-loop processing may be determined by a higher-order timing process that acts like a metronome to control the rate at which keystrokes are executed (e.g., Heuer, 1988; MacKay, 1982; Wing & Kristofferson, 1973), although typists could not synchronize their typing to an external metronome very well (Experiment 3). It is also possible that the rate of typing is determined indirectly by adjusting some parameter of the inner-loop processes (e.g., response threshold; Heath & Willcox, 1990; Viviani & Laissard, 1996). The outer loop could be the source of this adjustment. Typing rate could also be controlled by the interaction between inner-loop processes (e.g., by modulating the inhibitory strength among keystroke nodes; Gentner, 1987; Rumelhart & Norman, 1982), so the inner loop is both the source and the site of the control. The present data do not distinguish these alternative mechanisms of the control of speed and accuracy in typewriting. Future studies will be required to distinguish the source and the site of control in skilled typewriting.

Conclusions

We showed that skilled typists could control the speed–accuracy trade-off in response to deadlines (Experiments 1 and 2) and external cues that paced their typing (Experiments 3 and 4). The control was not perfect, in that typists were not always able to match the required typing rates. Experiment 4 suggested they had difficulty typing at rates faster than 100 ms/keystroke. We interpreted our results in terms of a hierarchical model of typewriting. All four experiments suggested that the speed–accuracy trade-off is controlled mostly by adjusting the speed of inner-loop processing. The outer loop may have been the source of control, but the inner loop was more likely to have been the site at which control was exercised.

References

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89,* 369–406. doi:10.1037/0033-295X.89.4.369

Balota, D. A., & Chumbley, J. (1985). The locus of word-frequency effects in the pronunciation task: Lexical access and/or production? *Journal of Memory and Language, 24,* 89–106. doi:10.1016/0749-596X(85)90017-8

Bogacz, R., Wagenmakers, E.-J., Forstmann, B. U., & Nieuwenhuis, S. (2010). The neural basis of the speed–accuracy tradeoff. *Trends in Neurosciences, 33,* 10–16. doi:10.1016/j.tins.2009.09.002

Crump, M. J. C., & Logan, G. D. (2010a). Hierarchical control and skilled typing: Evidence for word-level control over the execution of individual keystrokes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36,* 1369–1380. doi:10.1037/a0020696

Crump, M. J. C., & Logan, G. D. (2010b). Warning: This keyboard will deconstruct—The role of the keyboard in skilled typewriting. *Psychonomic Bulletin & Review, 17,* 394–399. doi:10.3758/PBR.17.3.394

Davies, M. (2008). *The corpus of contemporary American English (COCA): 410+ million words, 1990-present*. Retrieved from http://www.americancorpus.org

Dutilh, G., Wagenmakers, E.-J., Visser, I., & van der Maas, H. L. J. (2011). A phase transition model for the speed–accuracy trade-off in response time experiments. *Cognitive Science, 35,* 211–250. doi:10.1111/j.1551-6709.2010.01147.x

Fendrick, P. (1937). Hierarchical skills in typewriting. *Journal of Educational Psychology, 28,* 609–620. doi:10.1037/h0054049

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381–391. doi:10.1037/h0055392

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243–285). New York, NY: Academic Press.

Flanders, M., & Soechting, J. F. (1992). Kinematics of typing: Parallel control of the two hands. *Journal of Neurophysiology, 67,* 1264–1274.

Fodor, J. A. (1983). *The modularity of mind*. Cambridge, MA: MIT Press.

Forstmann, B. U., Dutilh, G., Brown, S., Neumann, J., von Cramen, D. Y., Ridderinkhof, K. R., & Wagenmakers, E.-J. (2008). Striatum and pre-SMA facilitate decision making under time pressure. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 105,* 17538–17542. doi:10.1073/pnas.0805903105

Gentner, D. R. (1982). Evidence against a central control model of timing in typing. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 793–810. doi:10.1037/0096-1523.8.6.793

Gentner, D. R. (1983). The acquisition of typewriting skill. *Acta Psychologica, 54,* 233–248. doi:10.1016/0001-6918(83)90037-9

Gentner, D. R. (1987). Timing of skilled motor performance: Tests of the proportional duration model. *Psychological Review, 94,* 255–276. doi:10.1037/0033-295X.94.2.255

Heath, R. A., & Willcox, C. H. (1990). A stochastic model for inter-keypress times in a typing task. *Acta Psychologica, 75,* 13–39. doi:10.1016/0001-6918(90)90064-M

Heuer, H. (1988). Testing the invariance of relative timing: Comment on Gentner (1987). *Psychological Review, 95,* 552–558. doi:10.1037/0033-295X.95.4.552

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70,* 387–403. doi:10.1037/h0026739

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York, NY: Wiley.

Link, S. W. (1971). Applying RT deadlines to discrimination reaction time. *Psychonomic Science, 25,* 355–358.

Liu, X., Crump, M. J. C., & Logan, G. D. (2010). Do you know where your fingers have been? Explicit knowledge of the spatial layout of the keyboard in skilled typists. *Memory & Cognition, 38,* 474–484. doi:10.3758/MC.38.4.474

Logan, G. D. (1982). On the ability to inhibit complex movements: A stop-signal study of typewriting. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 778–792. doi:10.1037/0096-1523.8.6.778

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95,* 492–527. doi:10.1037/0033-295X.95.4.492

Logan, G. D. (2003). Simon-type effects: Chronometric evidence for keypress schemata in typewriting. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 741–757. doi:10.1037/0096-1523.29.4.741

Logan, G. D., & Crump, M. J. C. (2009). The left hand doesn't know what the right hand is doing. *Psychological Science, 20,* 1296–1300. doi:10.1111/j.1467-9280.2009.02442.x

Logan, G. D., & Crump, M. J. C. (2010). Cognitive illusions of authorship reveal hierarchical error detection in skilled typists. *Science, 330,* 683–686. doi:10.1126/science.1190483

Logan, G. D., & Crump, M. J. C. (2011). Hierarchical control of cognitive processes: The case for skilled typewriting. In B. Ross (Ed.), *The psychology of learning and motivation* (Vol. 54, pp. 1–27). Burlington, MA: Academic Press.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108,* 393–434. doi:10.1037/0033-295X.108.2.393

Logan, G. D., Miller, A. E., & Strayer, D. L. (2011). Electrophysiological evidence for parallel response selection in skilled typists. *Psychological Science, 22,* 54–56. doi:10.1177/0956797610390382

Logan, G. D., & Zbrodoff, N. J. (1998). Stroop-type interference: Congruity effects in color naming with typewritten responses. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 978–992. doi:10.1037/0096-1523.24.3.978

MacKay, D. G. (1982). The problem of flexibility, fluency, and speed–accuracy tradeoff in skilled behavior. *Psychological Review, 89,* 483–506. doi:10.1037/0033-295X.89.5.483

McGill, W. J. (1962). Random fluctuations of response rate. *Psychometrika, 27,* 3–17. doi:10.1007/BF02289660

Meyer, D. E., Irwin, D. E., Osman, A. M., & Kounios, J. (1988). The dynamics of cognition and action: Mental processes inferred from speed–accuracy decomposition. *Psychological Review, 95,* 183–237. doi:10.1037/0033-295X.95.2.183

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the structure of behavior*. New York, NY: Adams-Bannister-Cox. doi:10.1037/10039-000

Ollman, R. T. (1966). Fast guess in choice reaction time. *Psychonomic Science, 6,* 155–156.

Pachella, R. G. (1974). The interpretation of reaction time in information-processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 41–82). Hillsdale, NJ: Lawrence Erlbaum.

Pachella, R. G., & Pew, R. W. (1968). Speed–accuracy tradeoff in reaction time: Effect of discrete criterion time. *Journal of Experimental Psychology, 76,* 19–24. doi:10.1037/h0021275

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220–244. doi:10.1037/0033-2909.116.2.220

Rabbitt, P. M. (1969). Psychological refractory delay and response-stimulus interval duration in serial, choice-response tasks. *Acta Psychologica, Amsterdam, 30,* 195–219. doi:10.1016/0001-6918(69)90051-1

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review, 85,* 59–108. doi:10.1037/0033-295X.85.2.59

Ratcliff, R. (2006). Modeling response signal and response time data. *Cognitive Psychology, 53,* 195–237. doi:10.1016/j.cogpsych.2005.10.002

Ratcliff, R., & Smith, P. L. (2004). A comparison of sequential sampling models for two-choice reaction time. *Psychological Review, 111,* 333–367. doi:10.1037/0033-295X.111.2.333

Rayner, K., & Clifton, C. (2009). Language processing in reading and speech perception is fast and incremental: Implications for event-related potential research. *Biological Psychology, 80,* 4–9. doi:10.1016/j.biopsycho.2008.05.002

Rinkenauer, G., Osman, A., Ulrich, R., Müller-Gethmann, H., & Mattes, S. (2004). On the locus of speed-accuracy trade-off in reaction time: Inference from the lateralized readiness potential. *Journal of Experimental Psychology: General, 133,* 261–282.

Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive-motor performance. *Cognitive Science, 6,* 1–36. doi:10.1207/s15516709cog0601_1

Ruthruff, E. (1996). A test of the deadline model for speed–accuracy tradeoffs. *Perception & Psychophysics, 58,* 56–64. doi:10.3758/BF03205475

Salthouse, T. A. (1984). The effects of age and skill in typing. *Journal of Experimental Psychology: General, 113,* 345–371. doi:10.1037/0096-3445.113.3.345

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225–260. doi:10.1037/h0076770

Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn, J. T., Jr. (1979). Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychological Review, 47,* 415–451. doi:10.1037/0033-295X.86.5.415

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84,* 1–66. doi:10.1037/0033-295X.84.1.1

Shaffer, L. H. (1973). Latency mechanisms in transcription. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 435–448). New York, NY: Academic Press.

Shaffer, L. H. (1975). Control processes in typing. *The Quarterly Journal of Experimental Psychology, 27,* 419–432. doi:10.1080/14640747508400502

Shapiro, D. C., Zernicke, R. F., Gregor, R. J., & Diestel, J. D. (1981). Evidence for generalized motor programs using gait pattern analysis. *Journal of Motor Behavior, 13,* 33–47.

Sternberg, S., Knoll, R. L., & Turock, D. L. (1990). Hierarchical control in the execution of action sequences: Tests of two invariance properties. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 3–55). Hillsdale, NJ: Lawrence Erlbaum.

Strayer, D. L., & Kramer, A. F. (1994). Strategies and automaticity: I. Basic findings and conceptual framework. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20,* 318–341.

Swensson, R. G. (1972). The elusive tradeoff: Speed vs. accuracy in visual discrimination tasks. *Perception & Psychophysics, 12,* 16–32. doi:10.3758/BF03212837

Tapp, K. M., & Logan, G. D. (2011). Attention to the hands disrupts skilled typewriting: The role of vision in producing the disruption. *Attention, Perception, & Psychophysics, 73,* 2379–2383. doi:10.3758/s13414-011-0208-5

Terzuolo, C. A., & Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. *Neuroscience, 5,* 1085–1103. doi:10.1016/0306-4522(80)90188-8

Tuller, B., Kelso, J. A. S., & Harris, K. S. (1982). Interarticulator phasing as an index of temporal regularity in speech. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 460–472. doi:10.1037/0096-1523.8.3.460

Tuller, B., Kelso, J. A. S., & Harris, K. S. (1983). Converging evidence for the role of relative timing in speech. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 829–833. doi:10.1037/0096-1523.9.5.829

Vallacher, R. R., & Wegner, D. M. (1987). What do people think they're doing? Action identification and human behavior. *Psychological Review, 94,* 3–15. doi:10.1037/0033-295X.94.1.3

Viviani, P., & Laissard, G. (1996). Motor templates in typing. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 417–445. doi:10.1037/0096-1523.22.2.417

Wickelgren, W. A. (1977). Speed–accuracy tradeoff and information processing dynamics. *Acta Psychologica, 41,* 67–85. doi:10.1016/0001-6918(77)90012-9

Wilson, M. (1987). *MRC Psycholinguistic Database: Machine usable dictionary (Version 2.00).* Retrieved from http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm

Wing, A. M., & Kristofferson, A. B. (1973). The timing of interresponse intervals. *Perception & Psychophysics, 13,* 455–460. doi:10.3758/BF03205802

Yellott, J. I. (1971). Correction for guessing and the speed–accuracy tradeoff in choice reaction time. *Journal of Mathematical Psychology, 8,* 159–199. doi:10.1016/0022-2496(71)90011-3

(*Appendix follows*)

Appendix

The Validity of the Deadline Procedure in Manipulating Speed-Accuracy Strategies

The results of Experiments 1 and 2 indicate that typists increased typing speed according to the deadline. However, it is possible that RT and IKSI decreased as the deadline decreased because the analysis excluded keystrokes that were made after the deadline. This would produce shorter RTs and IKSIs for shorter deadlines, even if typists did not change typing speed across conditions. If this were the case, mean keystroke latencies in a given deadline condition would be equal to mean of IKSIs in the normal-rate condition whose latency was shorter than the deadline. To address this concern, we estimated the probability that a keystroke is made after a given deadline (i.e., probability of timeout from the proportion of trials in the normal-rate condition for which the latency of the keystroke was shorter than the deadline. We computed the expected keystroke latencies and the probability of timeout for each deadline condition and compared with the observed values for each typist. The results are averaged across typists and summarized in the Appendix Table, which indicate that the predicted latency was consistently longer, and the predicted proportions of timeout are larger, than the observed values. These results indicate that typists indeed produced keystrokes considerably faster than the normal typing rate according to the given deadline. Furthermore, as shown in Table 1, the accuracy of keystrokes that were made before the deadline increased as the deadline decreased. Taken together, these results indicate that the present deadline procedure successfully induced speed–accuracy trade-offs in skilled typing.

Observed and Predicted Latency and Probability of Timeout for Individual Keystrokes for the Three Deadline Conditions

	10% Faster		20% Faster		30% Faster	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
Experiment 1: Keystroke latency						
Stroke 1	554	616	541	613	528	605
Stroke 2	675	752	655	739	632	710
Stroke 3	781	861	751	825	710	767
Stroke 4	876	947	830	880	757	843
Stroke 5	944	991	875	924	782	877
Experiment 1: Probability of timeout						
Stroke 1	0.00	0.01	0.00	0.01	0.01	0.05
Stroke 2	0.01	0.03	0.02	0.08	0.06	0.26
Stroke 3	0.01	0.13	0.08	0.34	0.24	0.71
Stroke 4	0.14	0.41	0.29	0.76	0.58	0.98
Stroke 5	0.36	0.77	0.61	0.97	0.82	1.00
Experiment 2: Keystroke latency						
Stroke 1	241	375	230	367	221	361
Stroke 2	347	496	327	487	317	471
Stroke 3	447	611	420	584	401	545
Stroke 4	549	696	512	648	479	586
Stroke 5	637	744	589	683	535	624
Experiment 2: Probability of timeout						
Stroke 1	0.00	0.02	0.00	0.04	0.01	0.05
Stroke 2	0.01	0.05	0.01	0.08	0.02	0.14
Stroke 3	0.02	0.11	0.03	0.23	0.06	0.43
Stroke 4	0.06	0.33	0.08	0.56	0.16	0.81
Stroke 5	0.17	0.66	0.23	0.85	0.39	0.96

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