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Different (Key)Strokes for Different Folks: How Standard and Nonstandard Typists Balance Fitts' Law and Hick's Law

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Fine motor skills like typing involve a mapping problem that trades Fitts' law against Hick's law. Eight fingers have to be mapped onto 26 keys. Movement time increases with distance, so Fitts' law is optimized by recruiting more fingers. Choice difficulty increases with the number of alternatives, so Hick's law is optimized by recruiting fewer fingers. The effect of the number of alternatives decreases with consistent practice, so skilled typists achieve a balance between Fitts' law and Hick's law through learning. We tested this hypothesis by comparing standard typists who use the standard QWERTY mapping consistently with nonstandard typists who use fewer fingers less consistently. Typing speed and accuracy were lower for nonstandard typists, especially when visual guidance was reduced by removing the letters from the keys or covering the keyboard. Regression analyses showed that accommodation to Fitts' law (number of fingers) and Hick's law (consistency) predicted typing speed and accuracy. We measured the automaticity of typing in both groups, testing for hierarchical control in 3 tasks: word priming, which measures parallel activation of keystrokes, keyboard recall, which measures explicit knowledge of letter locations, and hand cuing, which measures explicit knowledge of which hand types which letter. Standard and nonstandard typists showed similar degrees of hierarchical control in all 3 tasks, suggesting that nonstandard typists type as automatically as standard typists, but their suboptimal balance between Fitts' law and Hick's law limits their ability to type quickly and accurately.

Keywords: skill, automaticity, hierarchical control

We watch with amazement as the guitarist shreds the fretboard, the pianist tickles the ivories, and our fingers dance over the computer keyboard. The dazzling speed and effortless grace disguises the difficulty of the underlying choice process, which has to map one of 10 fingers onto each of 120–124 positions on the guitar neck, 88 keys on the piano, and 60–100 keys on the computer keyboard. We suggest the choice is constrained by a tradeoff between two fundamental laws of psychology: One is *Fitts' law*, which says that movement time increases linearly with the logarithm of distance (for targets of equal size; Fitts, 1954). Fitts' law may be optimized by recruiting all 10 fingers, which minimizes the distance between the nearest finger and the target. The other is *Hick's law*, which says that response time (RT) increases linearly with the logarithm of the number of choices (for equiprobable choices; Hick, 1952; Hyman, 1953). Hick's law may be optimized by reducing the number of fingers to choose from to one.

To achieve the high levels of skill seen in guitarists, pianists, and typists, something has to give. Fitts' law is immutable: No amount of practice can change the distance between the keys. Hick's law bends with practice, reducing the effect of number of choices (Logan, 1979). As it bends, more fingers can be recruited with less cost in RT. As more fingers are recruited, movement distance decreases, which decreases the cost in movement time. Performance becomes fast and fluent. Skill acquisition is further constrained by the principle of *consistent mapping* (Shiffrin & Schneider, 1977): Hick's law only bends if the mapping between fingers and targets is consistent throughout practice; departures from consistency impair the acquisition and expression of skill (Logan, 1979).

This perspective leads us to predict that the expression of fine motor skills will depend on how effectively skilled practitioners balance the tradeoff between Fitts' law and Hick's law. Practitioners who use more fingers and use them more consistently should reach higher levels of performance than practitioners who use fewer fingers less consistently. The purpose of this article is to test this prediction in skilled typewriting, comparing *standard typists*, who use the standard QWERTY mapping consistently, to *nonstandard typists* who depart from it by using fewer fingers or using fingers inconsistently. Standard typists should type faster and more accurately than nonstandard typists. We also asked whether standard typists rely less on visual guidance (Snyder, Logan, & Yamaguchi, 2015) and type more automatically and hierarchically (Crump & Logan, 2010b; Logan & Crump, 2009) than nonstandard typists.

We focused on typewriting because it has become a nearly universal skill since the dawn of the information age (Logan & Crump, 2011). In a 2014 census, the United Nations found that 96% of people worldwide had cell phones and 43% of households

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worldwide had computers (79% in developed countries; http://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx). Teachers and students invest substantial amounts of time learning to type, and our research has implications for how the time should be invested. While formal training is common in American middle schools, many typists acquire some skill earlier, hunting and pecking on the keyboard of their family computer. Self-taught skills may depart significantly from the standard mapping and may compete with or dominate the standard mapping. Our research measures the costs and benefits of nonstandard mapping, which should inform policy decisions about investments in formal training and remediation.

Visual Guidance

We suggest that nonstandard typists rely more on visual guidance than standard typists because of the nature of their skill and the way they acquire it. Everyone is a nonstandard typist to begin with: Everyone starts with a hunt and peck strategy, searching the keyboard for each key and choosing a finger to strike it, possibly choosing the nearest to optimize Fitts' law. At first, search and finger choice are based on visual information gained from looking at the keyboard. With practice, typists develop spatial representations of the keyboard and their hands that they can access through kinesthesis and proprioception (Klatzky & Lederman, 2003; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001) and choose the nearest finger without vision (Crump & Logan, 2010c; Snyder et al., 2015). We suggest that nonstandard typists never abandon visual information entirely. It is compatible with kinesthesis and proprioception and provides converging evidence about key and finger locations. Looking at the keyboard is compatible with their typing habits: Modern typists spend much more time composing text than copying it (Logan & Crump, 2011), so there is nothing to draw their eyes away from the keyboard. The downside is that the closest finger is not always the one with the standard mapping. Practice with visual guidance may lead to suboptimal habits.

By contrast, training with standard mapping is intended to teach people to "touch type" without looking at the keyboard, so standard typists should not rely on visual information. We assume that standard typists remember the locations of the keys and the fingers used to strike them, retrieving keystrokes (Rosenbaum et al., 2001) without comparing locations of fingers and keys and choosing the nearest. The memory representations are implicit and accessible primarily through kinesthesis and proprioception (Crump & Logan, 2010c).

Standard mapping optimizes Fitts' law, recruiting all eight fingers, and Hick's law, mapping fingers to keys consistently. Each key is associated with just one finger. This consistency reduces interference from competing fingers, which speeds retrieval and increases accuracy (Logan, 1988; Shiffrin & Schneider, 1977). However, the retrieved finger may not always be the nearest, so looking at the keyboard may create competition and interference. Standard typists may be better off not looking at the keyboard.

We tested reliance on vision by having typists type paragraphs while we manipulated visibility in three conditions: In the *visible* condition, typists typed on a normal keyboard with the letters and their hands visible. In the *blank* condition, typists typed on a keyboard with blank stickers attached to the keys, so their hands were visible but the letters were not. In the *covered* condition, a box was placed over typists' hands and the keyboard, so neither hands nor letters were visible (Snyder et al., 2015; Tapp & Logan, 2011). We expect standard typists to be unaffected by this manipulation. Nonstandard typists should get progressively worse across conditions, as more visual information is withheld.

Automaticity and Hierarchical Control

We asked whether nonstandard typing was less automatic than standard typing. The balance between Fitts' law and Hick's law limits the quality of performance, and that may limit the degree of automaticity typists may attain. Nonstandard typists with suboptimal balances may type less automatically than standard typists with optimal balances. However, optimal performance is only one criterion for automaticity (Logan, 1988; Moors & de Houwer, 2006). Nonstandard typists may type as effortlessly and autonomously as standard typists even if their performance is suboptimal. In real-world typing, autonomy and effort may be more important than optimal speed. Typists want to type without thinking about it so they can focus on writing.

In typing, automaticity is expressed as hierarchical control. Unlike many of the cognitive tasks studied in the automaticity literature (Logan, 1988; Palmeri, 1997; Rickard, 1997; Shiffrin & Schneider, 1977; Siegler, 1987), the multiple steps in novice typing cannot be reduced to a single step by practice. Skilled typists still have to serially order the letters in the word, find the keys to strike, and choose the fingers to strike them with, just like novices. The difference is that novices execute these steps in working memory under top–down control while experts execute them in the motor system under hierarchical control (see Figure 1;

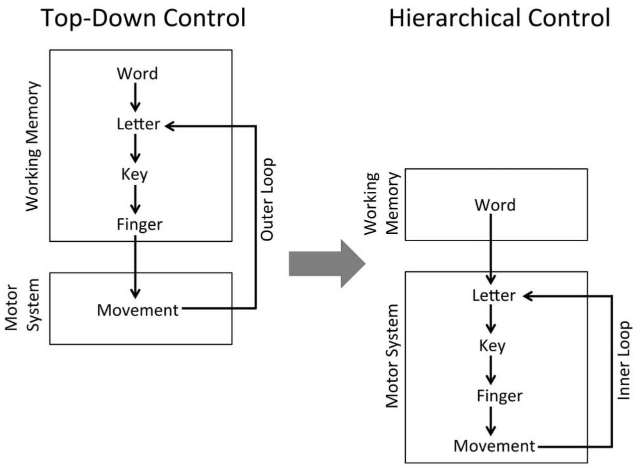

Figure 1. Computational analysis of typing under top–down and hierarchical control, including the representations held in working memory and the motor system and the information flow between the processes that operate on them. A word activates its constituent letters, a serial order process selects a letter to be typed, selects the key associated with the letter, selects a finger to strike it with, and executes a movement. Under top–down control, all of these processes except the movement are done in working memory. Under hierarchical control, all of these processes are done in the motor system. Under top–down control, working memory represents words, letters, keys, and fingers. Under hierarchical control, working memory only represents words.

also see Logan & Crump, 2011; Shaffer, 1976; Sternberg, Knoll, & Turock, 1990).

We assume hierarchical control emerges with practice. Hunt-and-peck typing under top–down control creates associations between words, letters, keys, and movements in the motor system, which strengthen with practice (Rosenbaum et al., 2001). Eventually, the associations become strong enough that the motor system can retrieve the sequence of keystrokes on its own, given only the word to be typed. At some point, typists trust motor memory enough to abandon top–down control and let the motor system control typing. At this point, typing is hierarchical. Typists do not have to think about their typing precisely because top–down processes do not have to select and sequence keys, fingers, and movements. This frees up working memory to think other thoughts (see Figure 1).

We assume that hierarchical control emerges with practice in much the same way other skills and habits emerge with practice: There is a period in which control is exclusively top down, followed by a period in which control is a mixture of top–down and hierarchical, depending on relative strengths and strategic choices, and ending with a period in which control is primarily hierarchical (Anderson, 1987; William & Harter, 1899; Fitts & Posner, 1967; Keller, 1958; Logan, 1988; Rickard, 1997). The details of the transitions are important topics for future research. We also assume that the choice between top–down and hierarchical control is voluntary, so skilled typists may switch between them at will. They can bring top–down processes online to stop (Logan, 1982), interrupt (Yamaguchi, Logan, & Li, 2013), or correct typing (Crump & Logan, 2013), to deal with unfamiliar materials (Yamaguchi & Logan, 2014b), changes in key positions (Yamaguchi & Logan, 2014a) or unfamiliar keyboards (Crump & Logan, 2010c; Yamaguchi & Logan, 2014b).

Abundant evidence suggests that skilled typists achieve hierarchical control (Logan & Crump, 2011; Shaffer, 1976; Sternberg et al., 1990). We asked whether standard and nonstandard typists achieve the same degree of hierarchical control by comparing them on three tasks that test critical properties of hierarchical control: word priming, keyboard recall, and hand cuing. The *word-priming task* tests a hallmark feature of hierarchical control, which is ability of one higher-level unit in working memory to activate several lower-level units in the motor system (Crump & Logan, 2010b; also see Logan, 2003; Logan, Miller, & Strayer, 2011). Word priming measures whether words activate their constituent letters in parallel. Typists are given a word to type and are probed with a single letter from the first, middle, or last position in the word or from another word. Skilled typists respond faster to probes from the primed word than probes from another word, indicating that the prime activates its constituent letters in parallel. The priming effect decreases across position in the word, reflecting a gradient of activation. We ask whether standard and nonstandard typists show the same within-word priming effect and the same gradient of activation.

The *keyboard recall task* tests the encapsulation of knowledge about the locations of letters on the keyboard in lower-level motor processes, which is another hallmark of hierarchical control (Liu, Crump, & Logan, 2010; Snyder, Ashitaka, Shimada, Ulrich, & Logan, 2014). Typists are given a blank keyboard and are asked to fill in the letters. Their accuracy reflects their explicit knowledge of the keyboard. Skilled typists do poorly on this task despite being able to type quickly and accurately, suggesting that their knowledge of letter locations is encapsulated in the motor system (Snyder et al., 2014). We ask whether standard and nonstandard typists show the same poor explicit knowledge of the keyboard.

The *hand-cuing task* tests the encapsulation of knowledge about the mapping of letters to fingers in the motor system, asking whether typists have explicit knowledge of which hand types which letter (Logan & Crump, 2009; Snyder & Logan, 2013; Tapp & Logan, 2011). Typists type single words preceded by a *whole cue*, which tells them to type the whole word, or a *hand cue*, which tells them to type only the letters assigned to one hand (e.g., if the cue is *Left* and the word is *dock*, type *d* and *c*). Skilled typists find typing with hand cues very difficult. It slows their RT and typing rate dramatically, suggesting that their higher-level processes do not know which hand types which letter. We ask whether standard and nonstandard typists show the same disruption from hand cues.

Method

Subjects

We chose a sample size of 48 typists (24 standard, 24 nonstandard) based on power estimates: A previous sample of 800 typists typing similar paragraphs yielded a mean of 68 and a *SD* of 18 words per minute (WPM; Crump & Logan, 2013). A sample size of 48 gives a power of 0.47 to detect a 5 WPM difference and a power of 0.96 to detect a 10 WPM difference. We recruited typists from the general university population through a computerized subject pool. The recruitment advertisements described the standard mapping. One asked for typists who used the standard mapping. The other asked for typists who used nonconventional mappings. The advertisements appear in the Appendix. We classified typists as standard or nonstandard when they arrived at the laboratory by showing them the standard mapping in a picture of a keyboard with the keys assigned to each finger in a different color (see Figure A1), and asking them whether or not they used those fingers for those keys. They were to report “standard” if they typed every letter with standard mapping and “nonstandard” if they typed one or more letters with a different mapping. Based on this report, we assigned 24 typists to the standard group and 24 to the nonstandard group. Typists received course credit or pay for participating in one 90 min session (standard: 12 credit, 12 paid; nonstandard: 13 credit, 11 paid). Their mean age, sex, and typing experience are presented in Table 1.

Apparatus and Stimuli

The words and letters to be typed and echoes of typists’ responses were displayed on a flat screen computer monitor (BenQ XL2411Z) controlled by a personal computer (ASUS M32BF). Responses were collected on two standard computer keyboards (ASUS model KB73211). The keyboards and keys were black. We covered the keys on one keyboard with blank stickers (all black). We covered the keys on the other keyboard with stickers depicting the letters (white letters on a black background) so the blank, visible, and covered keyboards would feel the same. We covered the hands and keyboard with the top of a box of printer paper with one side cut out, measuring 10.8 × 27.9 × 44.5 cm. All procedures were programmed in LIVECODE (http://livecode.com). The material to be typed and the response echoes appeared as black characters in a 24.1 × 19.7 cm light gray window centered on a black screen. Instructions for all computerized tasks were presented in Helvetica font. Instructions were in 18 point font for the sentence and paragraph tasks, 20 point font for the priming task, and 22 point font for the hand cuing task. The stimuli in the full-alphabet sentence task and the paragraphs in the speed tests were presented in 18 point font. The stimuli in the word priming and hand cuing tasks were presented in 40 point font.

The full-alphabet sentence task used 10 sentences, which appear in the Appendix. Each sentence contained each letter of the alphabet at least once. The average length was 12.50 (SD = 2.46) words and 67.70 (SD = 9.55) characters, including spaces and punctuation. Many letters appeared more than once. Hand and finger movements were recorded at 60 frames/sec on a video camera (Canon VIXIA HF R500), which was mounted on a tripod (Ravelli APLT2) behind the flat screen display aimed at the keyboard and fingers. The keyboard and fingers filled 50.4% of the image. We recorded performance on all tasks but only analyzed video for the full-alphabet sentence task.

The paragraph typing task used three paragraphs expressing the many merits of border collies (see Appendix) and are similar to other paragraphs we have used in our research expressing other merits of border collies (see Crump & Logan, 2013). Paragraphs 1–3 were 106, 113, and 107 words in length (471, 517, and 490 characters), and included 5, 6, and 5 sentences.

The word-priming task used 280 five-letter words, presented in the Appendix. All of the letters within each word were unique. Mean Kuèera–Francis word frequency was 63.43 (SD = 241.35) per million (MRC Psycholinguistic Database; Coltheart, 1981; http://www.psych.rl.ac.uk/).

The hand-cuing task used three prime words (*Left*, *Right*, and *Both*) and 48 four-letter target words, which are presented in the Appendix. For the cues, the first letter was uppercase and the rest were lowercase. For the target words, all letters were uppercase. There were six examples of eight kinds of target words: two kinds of *unimanual* words, in which all the letters were typed in one hand or the other (RRRR, LLLL) and six kinds of *bimanual* words, in which two letters were typed with one hand and two letters were typed with the other (LLRR, RRLL, LRLR, RLRL, LRRL, RLLR). The mean Kuèera–Francis word frequency was 90.35 (SD = 172.35).

Procedure

The 90 min experimental session included the following events. First, typists gave informed consent in writing and filled out a typing survey asking them about their age, sex, and experience (10 min). Then they performed the keyboard recall task (2 min). After keyboard recall, we verbally confirmed their typing style, and took them to a smaller room for computer testing. There, they did the full-alphabet sentence task (5 min), typed paragraphs with the keyboard visible, blank, and covered (10 min), and then performed word priming, hand cuing, and word/nonword tasks (10–15 min for each task). Finally, they returned to the reception room, had their hands traced for size measurements, were debriefed, compensated, and thanked for their participation (5 min). Throughout the session, instructions and breaks took 10–15 min.

Full-alphabet sentence. The 10 sentences were presented one at a time in random order, centered in the top half of the viewing window. Typists' responses were echoed below. On each trial, typists clicked on a "Begin Typing" box with a mouse, typed the sentence, and then clicked on an "End Typing" box. Video was recorded continuously throughout the 10 sentences. The mouse movements provided visual markers of the beginning and end of each sentence.

Keyboard recall. In the keyboard recall task, typists were presented with a blank keyboard on a 21.6 × 14 cm piece of paper (see Figure A2) and were asked to fill in the keys with the appropriate letters in 80 s. They changed pens every 20 s to provide coarse timing data, beginning with an orange pen, then changed to pink, green, and red pens. We counted the number of letters recalled in correct positions and the number of letters recalled in incorrect positions in each 20 s epoch.

Paragraph typing. Typists typed three paragraphs under three visual conditions (visible, blank, and covered). The order of visual conditions and paragraphs were counterbalanced separately across the 48 subjects, with eight subjects receiving each of the six possible orders of conditions or paragraphs. We planned to counterbalance standard and nonstandard groups, but after realizing that many typists who reported using standard mapping actually used nonstandard mappings, we focused on counterbalancing over the whole group. Counterbalancing was not perfect within standard and nonstandard groups, but departures from perfect counterbalancing were not large.

The paragraphs to be typed were presented one at a time in the top half of the viewing window. Responses were echoed below. The experimenter set up the visibility condition, changing keyboards and placing the box to cover the keyboard and hands as necessary, and then left the typist to complete the paragraph. When typists finished, they clicked "Next" with a mouse and opened the door to let the experimenter in to set up the next condition.

Word priming. The word priming, hand cuing, and word/nonword tasks were run in counterbalanced order. Over the 48 typists, eight had each of the six possible orders of conditions. Within standard and nonstandard groups, counterbalancing was not perfect but it was close.

The word-priming task involved 280 trials in which each word was presented once on a go trial or a probe trial. Each trial began with a 500 ms fixation cross in the center of the viewing window. It was replaced by the prime word, which was displayed for 250 ms and then extinguished. On go trials (140 total), the screen remained blank for 1,000 ms, whereupon a go signal appeared (a row of asterisks) instructing the typist to type the prime word as quickly and accurately as possible and type the space bar to end the trial. On probe trials (140 of total), the screen remained blank for 500 ms, whereupon a single capital letter appeared. Typists were instructed to type the single letter as quickly and accurately as possible and type the space bar to end the trial. The words or letters they typed were echoed on the screen below the probe. There were four probe types, three probing the first, middle, and last letter of the prime word and one probing a letter from another word. Each probe type occurred equally often. Words were assigned to go and probe trials randomly, with the same random assignment for all typists. The order of go and probe trials was randomized separately for each typist.

Hand cuing. The hand-cuing task involved 144 trials, in which 48 unique words were presented three times, once with the "whole" cue (*Both*) and once with each of the "hand" cues (*Left* and *Right*). The order was randomized for each typist. Each trial began with a cue presented above the center of the viewing window, which remained on the screen throughout the trial. One second after cue onset, a fixation cross appeared below the cue for 500 ms, which was replaced by the word to be typed. Typists were told to type the letters of the word appropriate to the cue and end their response by typing the space bar. The letters they typed were echoed on the screen below the word to be typed. For unilateral words typed all in the forbidden hand, typists simply typed the space bar.

Word/nonword. We included a 300-trial word/nonword task in which typists typed equal numbers of four- and five-letter words, pronounceable nonwords, and unpronounceable nonwords. We forgot to include RT measurement in the program, and accuracy was near ceiling, so we lost the most informative data and will not discuss the task further.

Results

Standard Versus Nonstandard Typists

The mean responses to the typing questionnaire for each group are presented in Table 1. The groups were equivalent in age and hours spent typing each day. All typists grew up with access to computers in their homes, all had formal training in typing, and all but one (a standard typist) currently owned a computer. We measured hand size in 16 standard and 19 nonstandard typists, and found no difference (though the 16 men had larger hands than the 19 women; 8.7 vs. 7.8 cm, $t(33) = 4.89$, $p = .00003$, $MSE = 0.176$, JZS Bayes factor = 687.196(A)). The main difference between groups was that nonstandard typists began typing a year and a half earlier and consequently had typed for more years. Thus, nonstandard typists may be more likely to have ingrained self-taught habits before formal instruction. Interestingly, standard and nonstandard typists gave very similar estimates of their typing speed and accuracy, suggesting that nonstandard typists are not aware that their style of typing may limit their performance.

We assessed the number of fingers typists used and the consistency with which they assigned fingers to keys by analyzing videos of the typists typing the 10 full-alphabet sentences. Forty-four typists completed all 10 sentences. Four completed only nine because of technical problems. We played the videos in slow motion or frame by frame to determine which finger struck which key for each of the (551 letter keystrokes × 48 typists ≈) 26,448 keystrokes. The second author scored all of the keystrokes and her results are reported in this article. We had a second person score 5,432 keystrokes from five standard and five nonstandard typists. She agreed with the second author on 5,403 keystrokes (99.5%).

The videos showed that standard and nonstandard typists balanced the tradeoff between Fitts' law and Hick's law differently. We assessed typists' adaptation to Fitts' law by counting the number of fingers each typist used across the sentences, including a finger in the count if it was used at least once. The frequency distribution for numbers of fingers used across all 48 typists is presented in Figure 2 (top panel). As expected, standard typists accommodated better, typing with significantly more fingers than nonstandard typists (7.67 vs. 5.92; see Table 1). Figure 3 plots the number of standard and nonstandard typists using each of the eight fingers. Nonstandard typists focus on the index and middle fingers near the center of the keyboard. Standard typists also recruit ring and little fingers.

We assessed adaptation to Hick's law by calculating the consistency with which typists mapped fingers onto keys. We measured consistency by counting the number of fingers each typist used to type each letter across repetitions and sentences. The number of repetitions of letters across sentences ranged from 10 (*q*, *x*) to 70 (*e*) and averaged 21. We defined consistent typing as using the same single finger to type a letter on each repetition. Using another finger even once counted as inconsistent. The frequency distribution for number of keys struck consistently across all 48

Table 1

Mean (SD in Brackets) Measures of Experience, Self Estimates of Typing Speed and Accuracy, Middle Finger Length, Number of Fingers Used, and Number of Keys Struck Consistently for Reported Standard and Reported Nonstandard Typists

Measure	Reported standard	Reported nonstandard	$t(46)$	JZS Bayes factor
Years of age	20.08 (2.89)	20.92 (3.65)	.878	2.542 (N)
Females	16/24	12/24[a]		
Years spent typing	10.48 (3.09)	12.42 (3.23)	2.125*	1.736 (A)
Age learned	9.67 (2.47)	8.15 (2.31)	2.207*	1.993 (A)
Weeks of formal training	27.46 (39.32)	22.58 (21.21)	.535	3.096 (N)
Hours of typing per day	3.98 (1.61)	5.25 (3.35)	1.677	1.121 (N)
Self estimated words per minute	68.60 (15.56)	70.23 (18.95)	.325	3.333 (N)
Self estimated accuracy	88.13 (7.08)	85.82 (9.11)	.982	2.350 (N)
Middle finger length in cm[b]	8.19 (.55)	8.28 (.79)	.376[c]	2.903 (N)
Number of fingers used	7.67 (.56)	5.92 (1.64)	4.944*	1562.319 (A)
Number of keys struck consistently	22.71 (5.08)	13.13 (4.84)	6.693*	358898.9 (A)

Note. For JZS Bayes factors, N = favors null hypothesis; A = favors alternative hypothesis.
[a] One typist identified as "nonbinary." [b] Length measures were obtained for 16 standard typists and 19 nonstandard typists. [c] Degrees of freedom = 33.
$^*p < .05$.

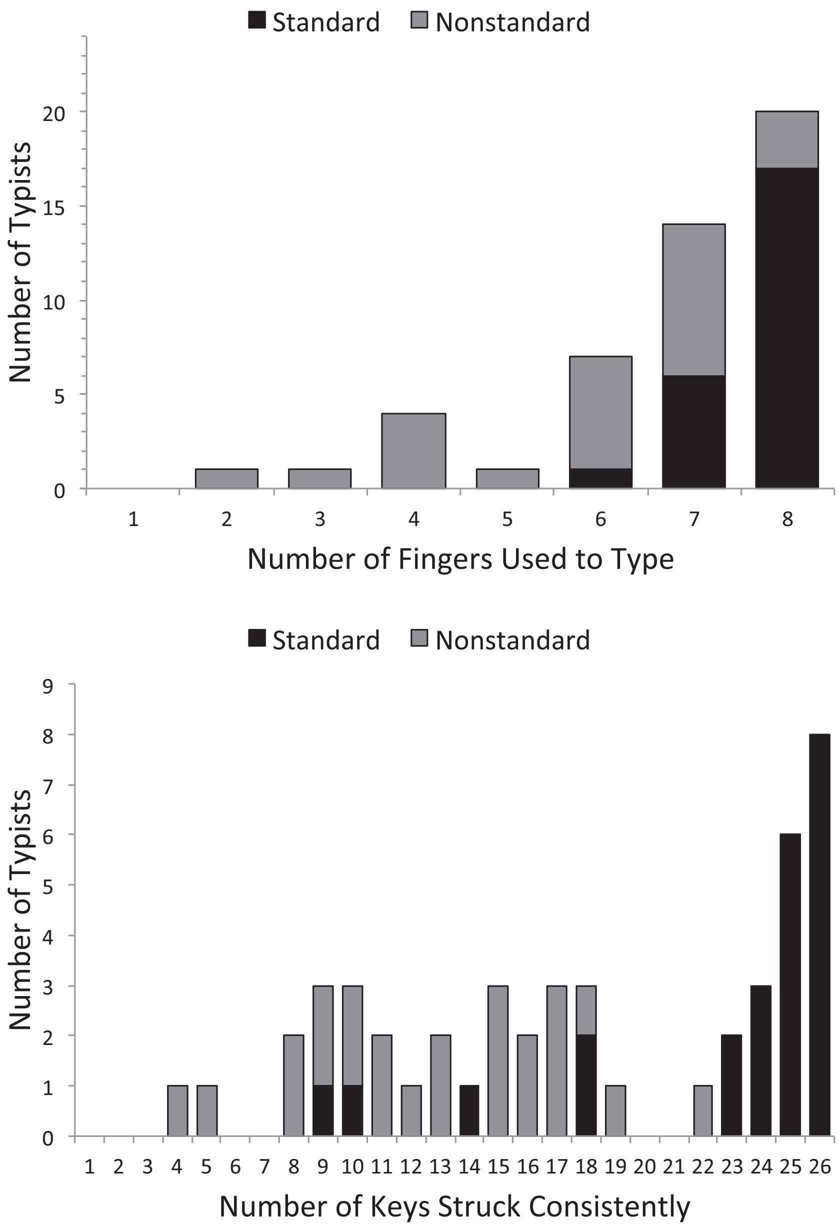

Figure 2. Full-alphabet sentence typing: Frequency distributions of number of fingers used to type (top) and number of keys struck consistently (bottom) across all 48 typists. Black bars represent standard typists. Gray bars represent nonstandard typists.

typists is plotted in Figure 2 (bottom panel). We also counted the number of fingers used to type each key, plotting the mean distributions for standard and nonstandard typists in Figure 4. We calculated the entropy in fingers assigned to each key (entropy = $\Sigma\text{-}p\cdot\log_2(p)$). Across typists, the number of keys struck consistently correlated −.689 with the mean number of fingers per key and −.982 with entropy, so we focused our analysis on the number of keys struck consistently.

As expected, standard typists accommodated better to Hick's law, striking significantly more keys consistently than nonstandard typists (22.71 vs. 12.92; see Table 1). We counted the number of standard and nonstandard typists typing each letter consistently. The numbers for each group are plotted on different images of the keyboard in Figure 5. The top panels represent the number of typists typing each key typed consistently with any finger, using standard or nonstandard mapping. Most standard typists typed most keys consistently with some deviations at the edges of the keyboard. Nonstandard typists typed less consistently with somewhat greater consistency at the edges. The bottom panels represent the number of typists typing each key consistently using nonstandard fingers. Few standard typists typed consistently with nonstandard fingers. The few who did tended to type letters at the edge of the keyboard consistently, using their ring fingers instead of their little fingers. Many nonstandard typists typed consistently with

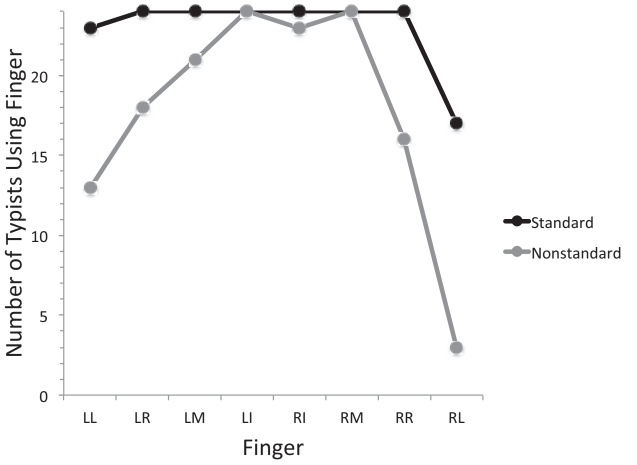

Figure 3. Full-alphabet sentence typing: Number of standard and nonstandard typists using each finger at least once in typing 10 full-alphabet sentences.

nonstandard fingers, especially near the edges of the keyboard, where letters would be typed with ring and middle fingers.

We confirmed typists' self reports of their typing style with the video analysis, counting typists as standard if they used all eight fingers consistently and nonstandard if they used fewer fingers or struck keys less consistently. By this criterion, all 24 typists who claimed to use a nonstandard mapping actually used one. Surprisingly, only 10 of the 24 typists who claimed to use the standard mapping actually used it. The 14 "nonstandard standard" typists fell between actual standard and reported nonstandard typists in number of fingers used (8.00, 7.43, and 5.92 for actual standard, "nonstandard standard," and reported nonstandard typists, respectively) and the number of keys struck consistently (25.70, 20.57, and 12.92, respectively). The data for actual nonstandard, nonstandard standard, and reported nonstandard typists are presented separately for paragraph typing, word priming, keyboard recall, and hand cuing in Figure A3.

Because of the surprisingly small number of actual standard typists, we analyzed the data in two ways. First, we did the group analyses we planned initially, comparing typists who reported using standard mapping with typists who reported using nonstandard mappings using analysis of variance (ANOVA) and *t* tests. Second, we did dimensional analyses, correlating the number of fingers used and the number of keys struck consistently with speed and accuracy, using regression. The two analyses generally led to the same conclusions.

Keyboard Visibility and Typing Speed and Accuracy

Group analysis. We assessed typing speed and accuracy by having typists type paragraphs with the keyboard visible, blank, or covered. We calculated WPM by dividing the number of keystrokes in the paragraph by the time between the first and last keystrokes in minutes to get keystrokes per minute, and dividing by 5 to get WPM. The mean WPM and percentage of words typed correctly for each group are plotted as a function of condition in Figure 6. No data were excluded. The data were analyzed in 2 (mapping group: standard vs. nonstandard) × 3 (keyboard visibility: visible, blank, and covered) mixed ANOVAs with mapping between subjects factor and keyboard visibility within subjects.

Over conditions, standard typists were faster (79.99 vs. 65.63 WPM), $F(1,46) = 7.79$, $p = .008$, $MSE = 952.24$, $\eta_p^2 = 0.15$, and more accurate (93.57 vs. 83.22%), $F(1,46) = 14.51$, $p = .0004$, $MSE = 272.60$, $\eta_p^2 = 0.24$, than nonstandard typists. Over groups, reducing keyboard visibility reduced speed, $F(2,92) = 7.87$, $p = .0007$, $MSE = 54.83$, $\eta_p^2 = 0.15$, and accuracy, $F(2,92) = 14.26$, $p = .000004$, $MSE = 128.96$, $\eta_p^2 = 0.24$. However, these main effects were modulated by strong interactions between group and visibility: for WPM, $F(2,92) = 5.34$, $p = .006$, $MSE = 54.83$, $\eta_p^2 = 0.10$; for percent correct, $F(2,92) = 11.00$, $p = .00005$, $MSE = 128.96$, $\eta_p^2 = 0.19$. Keyboard visibility mattered only for nonstandard typists. Standard typists were unaffected but nonstandard typists got progressively worse as keyboard visibility was reduced, consistent with the hypothesis that nonstandard typists rely on visual guidance more than standard typists.

Standard typists were faster and more accurate than nonstandard typists in all visibility conditions, but the differences were significant only for the blank (WPM: $t(46) = 3.25$, $p < .01$, $MSE = 5.42$, JZS Bayes factor [BF; Rouder, Speckman, Sun, Morey, & Iverson, 2009] = 16.72(A); Accuracy: $t(46) = 3.41$, $p = .001$, $MSE = 2.22$, JZS BF = 24.57(A)) and covered conditions (WPM: $t(46) = 2.68$, $p = .010$, $MSE = 6.24$, JZS BF = 7.92(A); Accuracy: $t(46) = 3.61$, $p = .0008$, $MSE = 6.18$, JZS BF = 24.57(A)). The differences in the visible conditions were neither significant nor clearly null (WPM: $t(46) = 1.93$, $p = .059$, $MSE = 4.50$, JZS BF = 1.28(A); Accuracy: $t(46) = 1.08$, $p = .2858$, $MSE = 1.05$, JZS BF = 2.16(*N*)). However, the 10 typists who actually used the standard mapping were faster than the 24 nonstandard subjects in the visible condition (84.96 vs. 71.72 WPM), $t(33) = 1.08$, $p = .044$, $MSE = 1.05$, JZS BF = 1.71(A).

Dimensional analysis. We complemented the group analysis with a dimensional analysis that focused on the measures that defined group membership: the number of fingers used to type, which reflects typists' accommodation to Fitts' law, and the number of keys struck consistently, which reflects typists' accommodation to Hick's law. Figure 7 plots typing speed and accuracy

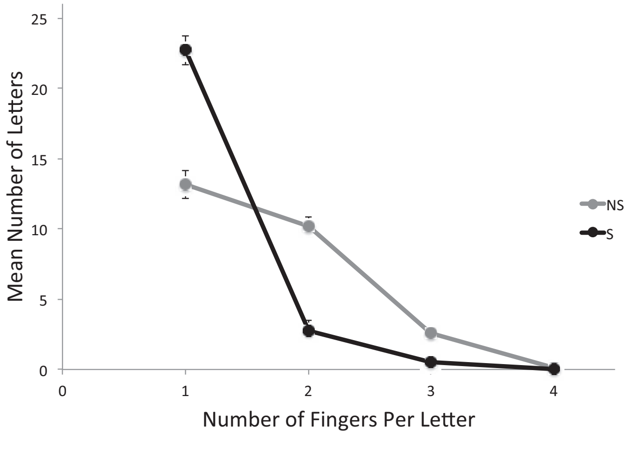

Figure 4. Number of letters typed using 1–4 fingers for standard and nonstandard typists. Fewer fingers indicate greater consistency. Error bars are *SEM*s.

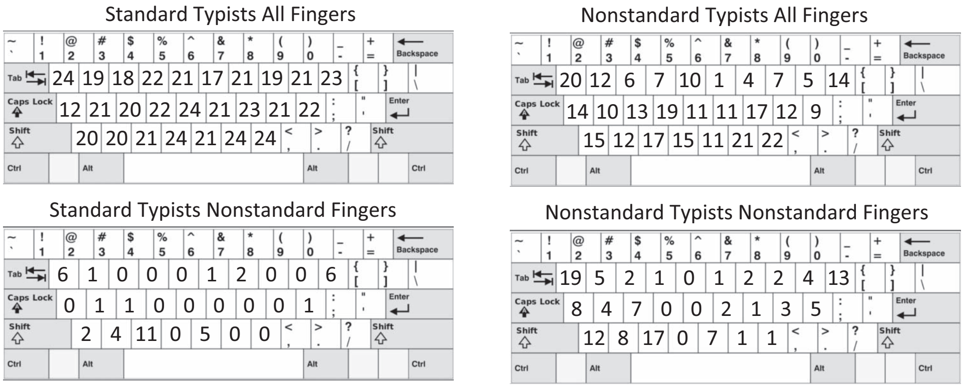

Figure 5. Full-alphabet sentence typing: Number of standard (left panel) and nonstandard (right panel) typists striking each key consistently. Top panels include all keys struck consistently with any finger. Bottom panels show keys struck consistently with "nonstandard" fingers that do not correspond to the standard mapping.

against these measures, with separate points for each typist in each visibility condition (visible, blank, and covered). Data points in the rightmost column in each panel (8 fingers, 26 letters) represent typists who actually type with standard mapping. All the other points reflect nonstandard typists. The data show considerable variability among nonstandard typists. Each panel shows positive trends, suggesting that better adaptation to Fitts' law (fingers) and Hick's law (consistency) produces better performance.

Table 2 presents correlations between fingers and consistency and speed and accuracy in each visibility condition. All of the correlations were significant except for fingers in the visible condition. The correlations were much larger when the keyboard was covered, reflecting lower accuracy. Accuracy was especially bad in typists who used fewer than eight fingers or struck fewer than 20 keys consistently.

We dissected the ANOVA interactions between group and visibility in mixed maximum-likelihood regression analyses with fingers and consistency as between-subjects predictors and keyboard visibility (visible, blank, and covered) as within-subjects predictors. One analysis predicted speed; the other predicted accuracy. Summary tables for both analyses are presented in Table 3. Number of fingers—the Fitts's law adaptation—affected both speed and accuracy. Number of fingers interacted significantly with visibility for both speed and accuracy, suggesting that visual guidance is especially important for typists who type with fewer fingers. Number of keys struck consistently—the Hick's law adaptation—affected both speed and accuracy. Consistency interacted with visibility in speed but not in accuracy. Using few fingers inconsistently produces slower typing, especially when visibility is limited.

Word Priming

Group analysis. The word-priming task is the first of three to compare the extent of hierarchical processing in standard and nonstandard typists, assessing parallel activation of the keystrokes in a word. We excluded trials with errors (9.13% of the data). Mean RTs for correct responses to probes are plotted as a function of probe position (first, middle, or last letter) for each group in the top panel of Figure 8. RTs to control probes from other words are plotted as horizontal lines for comparison.

Parallel activation of keystrokes is evident in two effects: One is a gradient of activation across the word, producing an increase in RT across probe position. The other is greater activation for letters within the word, producing longer RTs to probes that are not part of the word (Crump & Logan, 2010b; also see Logan, 2003; Logan et al., 2011). We assessed these effects with planned orthogonal contrasts based on a 2 (mapping group: standard, nonstandard) × 4 (probe position: first, middle, last, and other) mixed ANOVA on the probe RTs and accuracies and found evidence supporting parallel activation. The ANOVA showed significant main effects of mapping group, $F(1, 46) = 13.09$, $p = .0007$, $MSE = 27548.88$, $\eta_p^2 = 0.22$, and probe position, $F(3, 138) = 148.46$, $p = .05 \times 10^{-14}$, $MSE = 1439.77$, $\eta_p^2 = 0.76$. The interaction between them was not significant, $F(3, 138) = 2.33$, $p = .077$, $MSE = 1439.77$, $\eta_p^2 = 0.05$, but we proceeded with the planned comparisons anyway.

We assessed the gradient of activation with a contrast that compared the linear trend in RTs to within word probes across position in the word, ultimately comparing the first position with

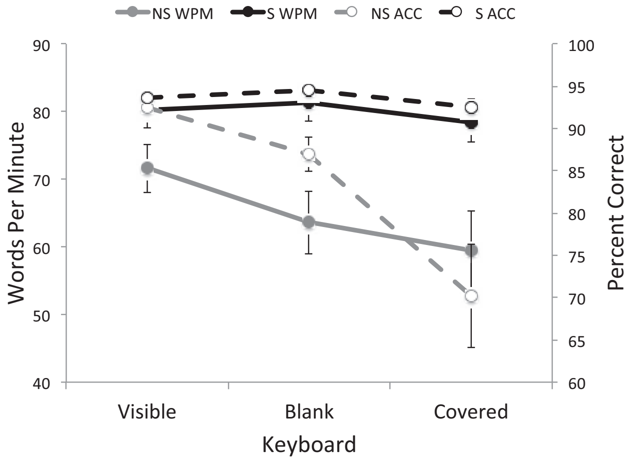

Figure 6. Typing speed (words per minute) and accuracy (percent correct) for standard (S) and nonstandard (NS) typists as a function of keyboard visibility. Error bars are *SEM*s.

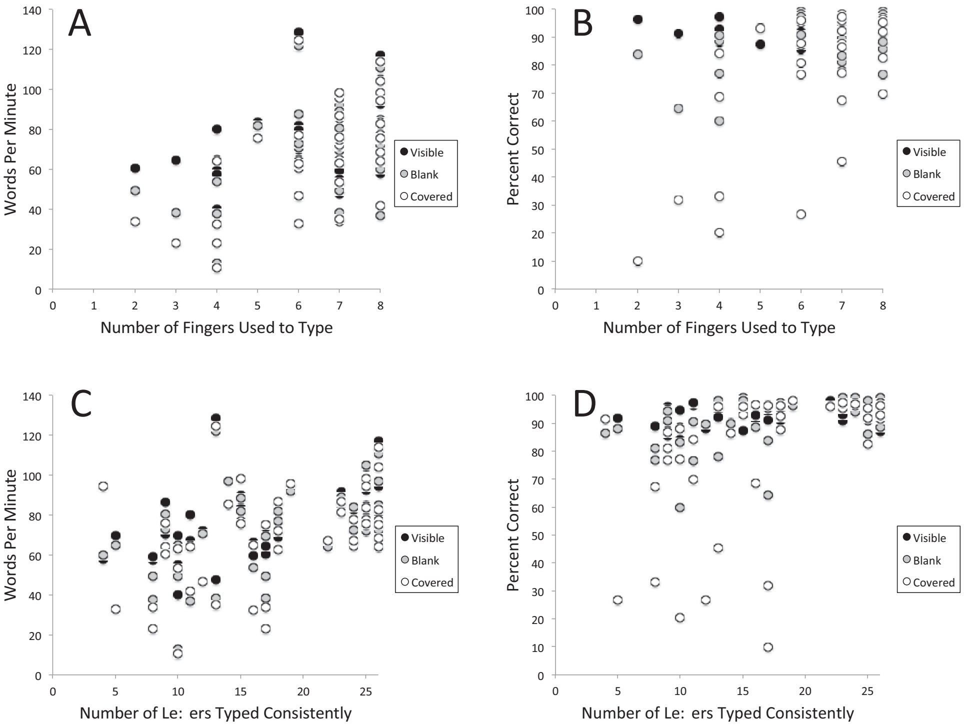

Figure 7. Dimensional analysis of typing speed and accuracy: The top panels show adaptation to Fitts' law: words per minute (Panel A) and accuracy (Panel B) as a function of the number of fingers used to Type 10 full-alphabet sentences. The bottom panels show adaptation to Hick's law: words per minute (Panel C) and accuracy (Panel D) as a function of the number of letters typed consistently.

the last. The contrast was significant overall, $F(1, 138) = 340.31$, $p < .1 \times 10^{-20}$, and significant for both standard, $F(1, 138) = 267.03$, and nonstandard typists, $F(1, 138) = 422.47$, all $ps < .1 \times 10^{-20}$, all *MSEs* = 1439.77. A contrast that compared the gradient in standard and nonstandard typists was significant, $F(1, 138) = 8.87$, $p = .003$, *MSE* = 1439.77, suggesting a steeper gradient in nonstandard typists.

We assessed the amount of priming with a contrast that compared the average RT for the three within-word probes with RT for other-word probes. The contrast was significant overall, $F(1, 138) = 70.92$, and significant for both standard, $F(1, 138) = 99.43$, and nonstandard typists, $F(1, 138) = 47.23$, all $ps < .1 \times 10^{-9}$, all *MSEs* = 1439.77. A contrast that compared priming in standard and nonstandard typists was significant, $F(1, 138) = 4.80$, $p = .003$, *MSE* = 1439.77, suggesting less priming in nonstandard typists.

The bottom panel of Figure 8 shows the results expressed as priming scores. Consistent with the contrast analysis, both groups show priming and gradients of priming, but the gradient is somewhat steeper for nonstandard typists. Priming is the same for the two groups for the first letter but becomes smaller for subsequent letters for nonstandard typists. The interpretation of these differ-

Table 2
Correlations of Typing Speed (Words Per Minute) and Accuracy (Percent Correct) With Number of Fingers Used to Type and With Consistency of Finger Use in the Paragraph Typing Task

		Keyboard		
Predictor	Measure	Visible	Blank	Covered
Number of fingers	Words per minute	.283	.460*	.514*
	Percent correct	.189	.542*	.709*
Consistency	Words per minute	.343*	.469*	.437*
	Percent correct	.335*	.503*	.504*

* $p < .05$.

Table 3
Regression Analysis of Typing Speed (Words Per Minute) and Accuracy (Percent Correct) With Number of Fingers Used to Type (Fingers), Number of Keys Struck Consistently (Consistency), and Keyboard Visibility (Visibility) as Predictors Error Degrees of Freedom = 44

	Words per minute			Percent correct		
Effect	*df*	*F*	Cohen *f*	*df*	*F*	Cohen *f*
Visibility (V)	2	4.08*	0.36	2	4.18*	.36
Fingers (F)	1	3.82*	0.24	1	13.15*	.50
Consistency (C)	1	5.01*	0.29	1	7.36*	.36
F × C	1	0.11	0.00	1	2.27	.16
V × F	2	5.10*	0.41	2	8.48*	.56
V × C	2	3.40*	0.32	2	1.60	.16
V × F × C	2	3.18	0.30	2	1.19	.09

Note. Error degrees of freedom (*df*) = 44.
* $p < .05$.

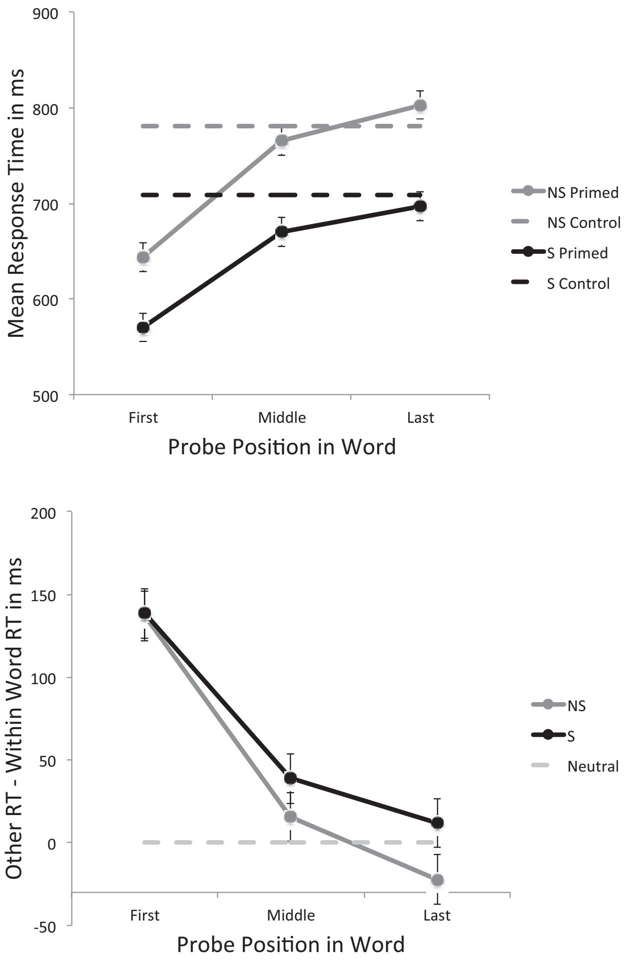

Figure 8. Word priming: Top panel: Mean response time (RT) to single letter probes as a function of their position in the prime word for standard (S) and nonstandard (NS) typists. Control trials represent letter probes from other words. Bottom panel: Priming scores (control RT—within word RT) as a function of their position in the word for standard and nonstandard typists. Error bars are Fisher's Least Significant Difference for $p < .05$ calculated from the highest order interaction.

ences between groups must be tempered by the lack of a significant interaction between groups and probe position, on which these contrasts are based.

A 2 (mapping group: standard, nonstandard) × 4 (probe position: first, middle, last, and other) mixed ANOVA on accuracy showed no significant differences. Accuracy was high for all probe positions in both groups (standard = 95.8, 95.0, 93.7, and 96.2% for first, middle, last, and other, respectively; nonstandard = 94.8, 95.1, 94.3, and 95.0%, respectively).

On go trials, in which typists typed the whole word, standard typists had shorter RTs than nonstandard typists (487 vs. 585 ms), $t(46) = 2.84$, $p = .007$, $MSE = 10.42$, JSZ BF = 6.678(A), consistent with the difference in probe RTs, perhaps because nonstandard typists used fewer fingers and so had to move greater distances. Standard typists had shorter interkeystroke intervals (IKSIs: 134 vs. 149 ms) and higher accuracy (87.38 vs. 86.13%) than nonstandard typists, but neither difference was significant. For IKSI, $t(46) = 1.76$, $p = .085$, $MSE = 15.42$, JSZ BF = 1.004(*N*); for accuracy, $t(46) = 0.71$, $p = .484$, $MSE = 5.42$, JSZ BF = 2.841(*N*).

Dimensional analysis. We performed a maximum-likelihood regression analysis, predicting probe RT with probe position, fingers, and consistency as predictors. The summary table for the analysis appears in Table 4. The only significant effects were position, reflecting priming, and fingers, reflecting Fitts' law: Typists who use fewer fingers have longer distances to move to type the probe letter.

Keyboard Recall

Group analysis. The keyboard recall task assesses encapsulation of knowledge about the locations of letters on the keyboard in lower-level processes (Snyder et al., 2014). We counted the number of letters recalled in correct and incorrect (error) positions in each 20 s epoch (identified by ink color). When typists wrote a letter twice (57 of 1,248 total responses), we counted the first response. The first response was clear when the two responses occurred in different epochs. When the two responses occurred in the same epoch, we counted them as a single error if they were both incorrect placements, and we counted them as .5 correct and .5 error if one was correct and the other was an error. We tried other scoring procedures, always counting correct and error placements in the same epoch as correct, always counting them as incorrect, or counting them as both correct and incorrect. The results were very similar and the pattern of significant effects was the same. The mean number of letters recalled correctly and incorrectly (error), counting correct and error responses in the same epoch as .5, is plotted for 20 s epoch in the recall period for each group in Figure 9. Correct and error data were analyzed in separate 2 (mapping group: standard, nonstandard) × 4 (recall epoch: 1–4) mixed ANOVAs. No data were excluded from analysis.

Both standard and nonstandard typists showed incomplete and inaccurate explicit knowledge of the keyboard. Standard typists recalled 17.1 letters correctly, placed 4.4 in the wrong location, and omitted 4.5. Nonstandard typists correctly recalled 14.6, incorrectly placed 6.6, and omitted 4.8. Correct recall was highest in the first 20 s and declined after that, $F(3, 138) = 93.95$, $p = .4 \times 10^{-32}$, $MSE = 8.75$, $\eta_p^2 = 0.67$, suggesting that typists ran out of knowledge, not time. Standard typists placed more letters in correct positions than nonstandard typists, but the difference was not

Table 4
Summary Table for Regression Analysis of Word Priming Effects

Effect	*df*	*F*	Cohen $\hat{f}$
Position (P)	3	88.02*	2.33
Fingers (F)	1	8.02*	.38
Consistency (C)	1	1.47	.10
F × C	1	.03	.00
P × F	3	1.73	.21
P × C	3	1.15	.10
P × F × C	3	2.5	.31

Note. Error degree of freedom (*df*) = 44 for each effect.
$^{*} p < .05$.

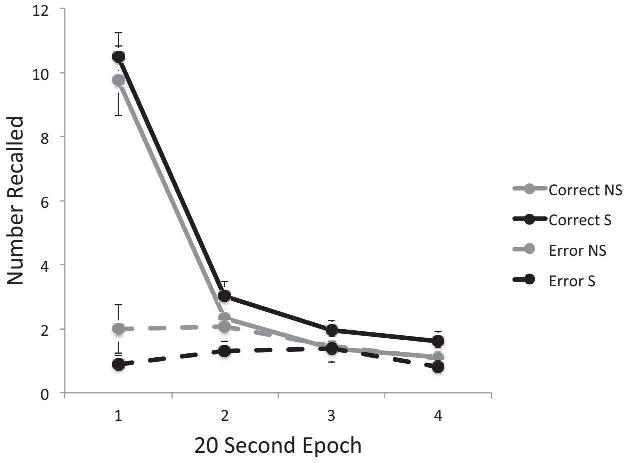

Figure 9. Keyboard recall: Mean number of letters recalled in correct (correct) and incorrect (error) positions by standard (S) and nonstandard (NS) typists as a function of epoch in the 80 second recall period. Error bars are *SEM*s.

significant, $F(1, 46) = 3.72$, $p = .060$, $MSE = 5.22$, $\eta_p^2 = 0.08$. Error recall did not vary across epochs, $F(3, 138) = 1.40$, $p = .246$, $MSE = 3.198$, $\eta_p^2 = 0.03$. Standard typists placed significantly fewer letters in incorrect positions than nonstandard typists, $F(1, 46) = 4.84$, $p = .033$, $MSE = 3.26$, $\eta_p^2 = 0.09$). The poorer performance for nonstandard typists was surprising given the evidence that they rely more on visual guidance. Apparently, looking at the keys does not guarantee memory for their locations.

For both groups, the low accuracy and high error and omission rates in keyboard recall contrast sharply with their high accuracy typing the same letters on the sentence typing task, which taps both implicit and explicit knowledge. Standard and nonstandard typists typed 91.8 and 89.9% of the words correctly. If the letters are typed independently, then the probability of typing the whole word correctly is the product of the probabilities of typing each letter correctly. If the probabilities are equal, then the probability of typing an N-letter word correctly is the probability of typing a letter correctly raised to the Nth power: $P(\text{word correct}) = P(\text{letter correct})^{N}$. Thus, the probability of typing letters correctly can be estimated as the Nth root of the probability of typing words correctly: $P(\text{letter correct}) = P(\text{word correct})^{1/N}$. The words in the sentences averaged 4.51 letters in length, so accuracy per letter is the 4.51th root of accuracy per word. For standard and nonstandard typists, accuracy per letter was 98.1 and 97.7%, respectively. Both values are much higher than keyboard recall accuracy (65.8 and 56.2%, respectively), suggesting that both groups rely on implicit knowledge to support accurate typing. Explicit knowledge of the keyboard is not sufficient in either group.

Dimensional analysis. We performed least-squares regression analyses predicting correct and error recall (separately) summed over recall epoch from fingers and consistency. No effect was significant in either analysis.

Hand Cuing

Group analysis. The hand-cuing task assesses encapsulation of knowledge about the hands and fingers used to type specific letters (Logan & Crump, 2009; Snyder & Logan, 2013; Tapp & Logan, 2011). Two typists in the nonstandard group were excluded for not following instructions (responding appropriately to the hand cue). We excluded data from trials with errors (see Table 4). Mean RTs to the first keystroke and IKSIs for subsequent keystrokes are plotted in Figure 10 as a function of cuing condition. Accuracy data are presented in Table 5.

Both standard and nonstandard typists showed evidence of encapsulation: Hand cue trials, which required explicit monitoring of the hands and fingers, produced longer RTs and IKSIs than whole cues, which did not require monitoring. For RT, the differences were 446 and 440 ms for standard and nonstandard typists, respectively. For IKSI, the differences were 130 and 124 ms, respectively. These are large disruptions compared to baseline RT and IKSI, suggesting that knowledge of key to finger mapping is not directly available to conscious awareness (Logan & Crump, 2009; Snyder & Logan, 2013; Tapp & Logan, 2011).

These conclusions were supported by a 2 (mapping group: standard vs. nonstandard) × 2 (cue type: hand vs. whole) × 2

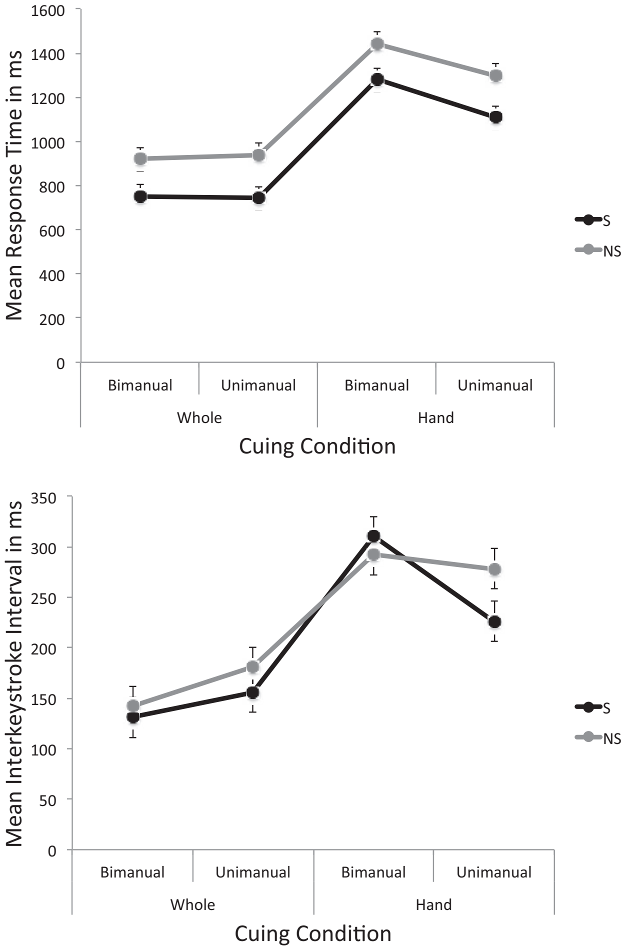

Figure 10. Hand cuing: Mean response time (top) and interkeystroke interval (bottom) for standard (S) and nonstandard (NS) typists as a function of cue type (whole, hand) and word type (unimanual, bimanual). Error bars are Fisher's Least Significant Difference for $p < .05$ calculated from the highest order interaction.

Table 5
Mean Accuracy (Percent Correct) for the Hand-Cuing Task as a Function of Group, Cue Type, and Word Type

	Whole cue		Hand cue	
Typing style	Bimanual	Unimanual	Bimanual	Unimanual
Standard	89.93	90.97	84.90	88.19
Nonstandard	92.55	89.39	85.92	82.95

(word type: unimanual vs. bimanual) mixed ANOVAs on the RTs. The RT ANOVA showed significant main effects of cue type, $F(1, 44) = 217.13$, $p = .01 \times 10^{-16}$, $MSE = 41598.81$, $\eta_p^2 = 0.83$, and word type, $F(1, 44) = 17.58$, $p = .0001$, $MSE = 15992.03$, $\eta_p^2 = 0.29$, and a significant interaction between them, $F(1, 44) = 18.23$, $p = .0001$, $MSE = 17509.32$, $\eta_p^2 = 0.29$. Neither the main effect of group nor any of its interactions were significant: Fs(1,44) = 0.09, 0.04, 1.74, and 3.18 for the main effect, Group × Cue type, Group × Word type, and Group × Cue type × Word type, respectively, *MSEs* = 26783.53, 41598.81, 15992.03, and 17509.32, respectively, *ps* = .77, .84, .19, and .08, respectively, η_p^2s = 0.00, 0.00, 0.04, and 0.07, respectively.

An ANOVA with the same structure on IKSIs showed a significant main effect of cue type, $F(1, 44) = 96.75$, $p = .01 \times 10^{-11}$, $MSE = 462.45$, $\eta_p^2 = 0.69$, and significant interactions between cue type and word type, $F(1, 44) = 36.42$, $p = .0000002$, $MSE = 2348.53$, $\eta_p^2 = 0.45$, word type and group, $F(1, 44) = 4.20$, $p = .046$, $MSE = 3737.93$, $\eta_p^2 = 0.09$, and cue type, word type, and group, $F(1, 44) = 5.36$, $p = .025$, $MSE = 2348.53$, $\eta_p^2 = 0.11$. The interactions reflect the relative difficulty of typing unimanual words and the relative ease of monitoring them. Unimanual words require hand repetitions, which are difficult, while bimanual words allow hand alternations, which are easy (Salthouse, 1986), so unimanual words are slower than bimanual words on trials with whole cues. By contrast, hand repetitions may make monitoring easier, so unimanual words are monitored more quickly than bimanual ones on trials with hand cues. The interactions with group may result from differences in consistency of mapping fingers onto keys between groups. Nonstandard typists may type some unimanual words with two hands, making monitoring more difficult.

An ANOVA with the same structure on accuracy showed a significant main effect of cue type, $F(1, 44) = 24.16$, $p = .00001$, $MSE = 51.79$, $\eta_p^2 = 0.35$, and a significant interaction between mapping group and word type, $F(1, 44) = 7.84$, $p = .0076$, $MSE = 40.09$, $\eta_p^2 = 0.15$. Standard typists did better on unimanual words than bimanual words; nonstandard subjects did the opposite. No other effects were significant.

Dimensional analysis. We performed separate maximum-likelihood regression analyses on RT, IKSI, and accuracy using hand cue, word type, fingers, and consistency as predictors. Summary tables for the analyses appear in Table 6. The effect of hand cue was significant in all three analyses and the interaction between hand cue and word type were significant in the RT and IKSI analyses, reflecting encapsulation of knowledge in lower level processes. The interaction between fingers and consistency was significant in the RT and accuracy analyses, reflecting the cost of a poorer balance between Fitts' law and Hick's law. The remaining significant interactions involving fingers and consistency were significant in only one of the analyses.

Postscript

While this article was under review, Feit, Weir, and Oulasvirta (2016) published an article in the proceedings of a computer science conference (CHI '16) that also compared standard and nonstandard typists. They used motion capture software to analyze movements while typists typed visually displayed sentences on visible keyboards with the letters marked on the keys. Their study was conducted in Finland and sampled both Finnish and English speakers, testing them in the language in which they preferred to type. Their sample size was smaller ($N = 30$ vs. 48) and their typists were slower on average (58.5 vs. 76.0 WPM), but their results are very similar to ours (or rather, ours are similar to theirs).

Table 6
Summary Tables for Regression Analyses on Hand Cuing Data

		Response time		Interkeystroke interval		Percent correct	
Effect	Error *df*	*F*	Cohen $\hat{f}$	*F*	Cohen $\hat{f}$	*F*	Cohen $\hat{f}$
Hand cue (H)	45	70.03*	1.23	61.15*	1.14	6.23*	.34
Word (W)	45	2.69	.19	.00	.00	.11	.00
Finger (F)	42	.83	.00	1.23	.07	1.10	.05
Consistency (C)	42	1.91	.14	.23	.00	3.06	.21
H × W	45	4.46*	.27	26.23*	.74	1.64	.12
F × C	42	12.06*	.49	1.47	.10	8.01*	.39
H × F	126	.09	.00	2.81	.20	.43	.00
W × C	126	1.13	.05	8.95*	.42	5.45*	.31
H × C	126	.05	.00	4.86*	.29	.85	.00
W × F	126	.07	.00	.23	.00	.38	.00
H × F × C	126	.00	.00	3.19	.22	1.17	.06
W × F × C	126	2.88	.20	1.11	.05	.73	.00
H × W × F	126	.42	.00	.49	.00	1.05	.03
H × W × C	126	2.22	.16	16.57*	.58	.35	.00
H × W × F × C	126	11.50*	.48	1.93	.14	1.55	.11

Note. Each effect has 1 degree of freedom (*df*).
$^*p < .05$.

Like us, Feit et al. (2016) found no difference in typing speed between their 13 standard typists and their 17 nonstandard typists (57.8 vs. 58.9 WPM, respectively), while typing on a visible keyboard, $t(28) = 0.221$, $p = .827$, $MSE = 4.978$, JZS BF $= 2.832(N)$. Their sample size limited their power (power to detect a 10 WPM difference was only .56) but the Bayes Factor favors the null hypothesis.

Motion capture analysis showed that standard typists used more fingers than nonstandard typists and used them more consistently, but only 3 of the 13 standard typists used the standard mapping perfectly consistently. Regression analyses showed that typing speed was predicted by the consistency of mapping fingers onto keys, measured as entropy, suggesting that fast typing depends on adaptation to Hick's law. Typing speed was also predicted by measures of movement distance, consistent with Fitts' law. Feit et al. did not find significant correlations with number of fingers used for typing, testing typists with the keyboard visible. We found no significant correlation between fingers and typing speed when the keyboard was visible, though our correlations were significant in the blank and covered keyboard conditions (see Table 2).

Interestingly, Feit et al. measured typists' gaze direction while typing and found that nonstandard typists spent much more time looking at the keyboard than standard typists (41 vs. 20%, respectively). This corroborates our finding that restricting keyboard visibility selectively impairs nonstandard typists. Overall, the results agree quite closely, demonstrating that the basic effects survive independent replication.

Discussion

Balancing Fitts' Law and Hick's Law

We began with the hypothesis that fine motor skills involve balancing a tradeoff between Fitts' law and Hick's law. Recruiting more fingers reduces movement time but complicates the choice between fingers. Choice time can be reduced by consistent practice. Thus, we predicted higher levels of speed and accuracy in typists who use more fingers more consistently. The standard mapping of fingers to keys minimizes distance and maximizes consistency, so we predicted better performance in typists who used the standard mapping than in typists who used nonstandard mappings. The results confirmed both predictions. Standard typists used more fingers more consistently and typed faster and more accurately than nonstandard typists, especially when visibility of the keyboard was degraded. Typing speed and accuracy correlated with the number of fingers used and the number of keys struck consistently. Thus, skilled performance depends on the balance between Fitts' law and Hick's law. We suggest the balance determines the highest level of performance a typist can attain. Suboptimal balances lead to lower performance at asymptote.

Automaticity and Hierarchical Control

We asked whether the better performance of standard typists was accompanied by a higher degree of automaticity, expressed as greater hierarchical control. We tested hierarchical control in three tasks and found the same qualitative and quantitative effects for standard and nonstandard typists in each task. They showed similar gradients of activation across position in the word-priming task, suggesting parallel activation of keystrokes in both groups (Crump & Logan, 2010b). The gradient was somewhat steeper in nonstandard typists, suggesting a narrower range of parallel activation. Neither group had enough explicit knowledge of the keyboard to support their demonstrated ability to type accurately, suggesting that their knowledge of letter to key mapping is mostly implicit in the motor system (Snyder et al., 2014). Standard and nonstandard typists both slowed dramatically when typing with hand cues, suggesting their knowledge of the mapping of keys to movements was also implicit in the motor system (Logan & Crump, 2009; Snyder & Logan, 2013; Tapp & Logan, 2011). Thus, nonstandard typists seem to have the same degree of hierarchical control as standard typists (Logan & Crump, 2011; Shaffer, 1976; Sternberg et al., 1990). Both seem able to type without thinking about letters, keys, and movements, having handed that off to the motor system.

It is interesting that nonstandard typists achieved the same degree of hierarchical control as standard typists with suboptimal adaptations to Fitts' law and Hick's law. It runs counter to the common intuition that higher degrees of automaticity are associated with better performance (Cohen, Dunbar, & McClelland, 1990; Logan, 1988; MacLeod & Dunbar, 1988; Rickard, 1997; Shiffrin & Schneider, 1977; Siegler, 1987). Typists may value hierarchical control because it reduces the load on working memory (compare the left and right panels of Figure 1), and that may motivate a shift from top–down to hierarchical control before performance is optimal. We assume that typists adopt hierarchical control when the memories in the motor system are reliable enough to support typing without top–down control. Memories strengthen with practice, and may become reliable before they are optimal (Crump & Logan, 2010a). Memories for nonstandard mappings also improve with practice (Yamaguchi & Logan, 2014a). They may become reliable even if they are suboptimal. We suspect our nonstandard typists performed worse because of suboptimal mapping, not lack of practice. They started typing a year and a half before the standard typists and spent the same time on computers each day (see Table 1).

Typing performance is difficult to optimize because it requires achieving a balance between Fitts' law and Hick's law. Different balances impose different constraints on performance, and typists must adapt to the balance they choose. Balances that recruit more fingers consistently will lead to better performance, but every balance can be improved with practice, headed toward its own local maximum. Many paths to local maxima may produce motor memories that are reliable enough to support typing without top–down control (Rosenbaum et al., 2001).

Visual Guidance

Our results show that the cost of nonstandard typing is increased reliance on vision (also see Feit et al., 2016). We suspect that nonstandard typists retain vestiges of the hunt and peck strategy, sometimes choosing the finger closest to the target key. Visual or spatial guidance may be helpful in resolving interference. When retrieval suggests two candidates, proximity to the target may break the tie, allowing a faster choice than retrieval by itself. However, the nearest finger is not always the one assigned in standard mapping, so using vision to resolve present interference may strengthen memories that cause more interference in the future. Visual guidance may subvert adaptation to Hick's law.

Increased reliance on visual guidance may have other costs. The eyes cannot be on the keyboard and the screen at the same time. Thus, nonstandard typists would derive fewer benefits from information on the screen as they type. For example, typists monitor the screen for explicit error detection (Logan & Crump, 2010; Snyder et al., 2015). Nonstandard typists might miss more errors. When people write compositions, they often read the text as they type it to check for errors of grammar, meaning, and style. Attention to the keyboard would disrupt reading and impair error detection. Attention to the keyboard might produce more specific interference when writing about space or spatial relations (Logan, 1994). However, these effects might be small. All but two of our typists typed on laptops, where the screen is close to the keyboard, making switching between them easier and potentially reducing the costs. Whether such costs exist is an important question for future research.

Remedial Training for Nonstandard Typists?

Should nonstandard typists invest in remedial training to learn the standard mapping? Feit et al. (2016) found no difference in typing speed between standard and nonstandard typists (58 vs. 59 WPM, respectively). In the present study, with faster typists, the differences between standard and nonstandard typists were clearer, but they were relatively small. When the keyboard was visible, nonstandard typists averaged 72 WPM and our one two-finger typist managed 60 WPM. That is fast enough to qualify as a professional typist. It may be fast enough for many typing situations, where top speed is not so critical. An unpublished study in our laboratory found that skilled typists who typed at 78 WPM on a speed test slowed to 45 WPM when composing texts. Modern typists spend much of their time composing (Logan & Crump, 2011), so the suboptimal top speed of nonstandard typists may not matter much. From this perspective, remedial training on the standard mapping may not be worth the investment. Typists may care more about typing hierarchically than typing quickly. Hierarchical control lets them type without thinking so they can think about higher level goals.

Should schools invest in teaching typing earlier? Our nonstandard typists started typing at an earlier age than our standard typists, so their habits may have been more strongly ingrained before they began formal training. In debriefing, we asked our nonstandard typists why they persisted with nonstandard mapping despite having formal training on the standard mapping. Of the 22 who responded, 10 said their own style was faster or easier and 12 said it was more comfortable or convenient. Thus, they had little incentive to acquire high levels of skill with standard mapping. Earlier training on standard mapping may prevent the development of suboptimal habits, but suboptimal habits may be good enough. The benefits of earlier training may not be large enough outweigh the costs the typist and the educational system would have to pay.

These speculations rest on how representative our standard and nonstandard typists were of the general population. Our nonstandard typists may have been especially good. They were recruited from a competitive university environment and may have responded to our advertisement to show off their high level of skill. Feit et al. (2016) found similar results in a sample from a broader population. It would be interesting to know the levels of skill in the general population. We were surprised to find that only 10 of 24 typists who reported using the standard mapping actually used it. Altogether, 79% of typists in our sample were nonstandard. Feit et al. (2016) found 90% were nonstandard. It would be interesting to know how these numbers compare to the general population. Perhaps standard typists are a rare breed.

Beyond Typing

Typing is one example of a broad range of fine motor skills that pit Fitts' law against Hick's law. Playing musical instruments, operating equipment, and interfacing with machines all require mapping fingers onto positions. The range of distances and the nature of the patterns vary from one skill to another, but Fitts' law and Hick's law hold nevertheless. The mapping is more complicated with musical instruments than with typing. Different fingers may play the same note in different contexts (chords, melodies), but the same finger often plays the same note in a given context. The content may vary between skills, but learning and performance are governed by the same principles: consistency within context facilitates encoding and retrieval (Logan, 1988; Logan & Etherton, 1994; Shiffrin & Schneider, 1977). Thus, our results with typing should generalize to a broad range of fine motor skills: People who balance Fitts' law and Hick's law better will perform better.

Fine motor skills may be limited by other laws besides Fitts' and Hick's. Music must be played in rhythm, and that adds temporal constraints to the retrieval process (Palmer & Pfordresher, 2003; Pfordresher, Palmer, & Jungers, 2007). Hands must be coordinated (Heijink & Meulenbroek, 2002). Emotion must be conveyed (Juslin, 2000). Improvising requires choosing the notes to play as well as choosing the fingers to play them with (Johnson-Laird, 2002). Playing in a group requires coordinating pitch and rhythm with others (Zamm, Pfordresher, & Palmer, 2015). Each skill involves its own constraints and its own tradeoffs between fundamental psychological laws. Much can be learned from identifying the laws that apply, learning how they trade off against each other, and learning how skilled practitioners balance the tradeoff. We hope we have shown this approach is productive in skilled typing.

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Appendix

Subject Recruitment Advertisements on SONA System

Standard Typing Study

**********PLEASE ONLY SIGN UP FOR THIS STUDY IF YOU MEET THE TYPING STYLE REQUIREMENTS. IF YOU DO NOT MEET THE TYPING STYLE REQUIREMENTS BELOW, SIGN UP FOR "Paid Study - Nonstandard Typing Style" (A SEPARATE STUDY). If you have any questions about the requirements, please email the researcher.********** You will perform a series of typing tasks in which you are to type a word or letter as quickly and as accurately as you can. This study requires subjects to be capable of touch-typing using 10 fingers at the conventional finger placement on the keyboard. The finger assignments in the conventional finger placement are as follows: left pinky: QAZ, left ring: WSX, left middle: EDC, left index: RFVTGB, right index: YHNUJM, right middle: IK, right ring: OL, right pinky: P

Figure A1. Display of standard mapping used to confirm whether typists use the standard mapping (depicted) or a nonstandard mapping. See the online article for the color version of this figure.

(*Appendix continues*)

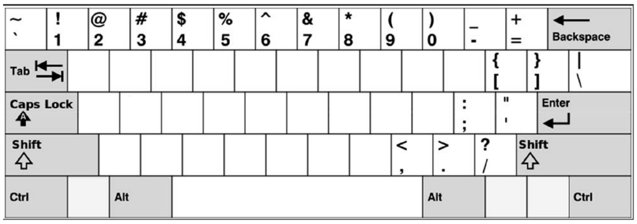

Figure A2. Blank keyboard used for the keyboard recall task.

Nonstandard Typing Study

**********PLEASE ONLY SIGN UP FOR THIS STUDY IF YOU MEET THE TYPING STYLE REQUIREMENTS. IF YOU DO NOT MEET THE TYPING STYLE REQUIREMENTS BELOW, SIGN UP FOR "Paid Study - Standard Typing Style" (A SEPARATE STUDY). If you have any questions about the requirements, please email the researcher.********** You will perform a series of typing tasks in which you are to type a word or letter as quickly and as accurately as you can. This study requires subjects that type using a NONCONVENTIONAL finger placement on the keyboard. The finger assignments in the CONVENTIONAL finger placement are as follows: left pinky: QAZ, left ring: WSX, left middle: EDC, left index: RFVTGB, right index: YHNUJM, right middle: IK, right ring: OL, right pinky: P ****We are looking for participants that do not type using the finger to key mapping listed above****

Full-Alphabet Sentences

The quick brown fox jumps over the lazy dog.

Six javelins thrown by the quick savages whizzed 40 paces beyond the mark.

The public was amazed to view the quickness and dexterity of the juggler.

We quickly seized the black axle and just saved it from going past him.

A mad boxer shot a quick, gloved jab to the jaw of his dizzy opponent.

Whenever the black fox jumped the squirrel gazed suspiciously.

The job requires extra pluck and zeal from every young wage earner.

While making deep excavations we found some quaint bronze jewelry.

Six big juicy steaks sizzled in a pan as five workmen left the quarry.

The July sun caused a fragment of black pine wax to ooze on the velvet quilt.

Paragraphs for Typing Speed and Accuracy Tests

1. It is difficult to know how man ever managed large flocks of sheep on the rough and hilly terrain of these areas without the help of these wonderful dogs. The strains that proved most adept at the specialized type of work required were highly prized and selectively bred from. This produced the sort of collie we know today. From looking at very old photographs, it is remarkable how little they have changed in the last hundred years or so. It proves that the early flockmasters knew well the type of dog that was built on the correct lines for the job it was intended to do.

2. One other sphere where border collies are most successful is in search and rescue. Dog handlers are required to go out and look for missing climbers and walkers. A lot of these people get lost in areas where sheep are grazed. Border collies have to range well ahead of the handlers to cover the maximum amount of ground, so they must be tested for their trustworthiness with sheep before training starts. It does show what an adaptable breed the border collie is, in that it can be taught to ignore an animal that it has been specifically bred to herd. Border collies are becoming more and more popular for this purpose.

3. A border collie from the correct source can be a charming pet. However, dogs bred from a strong working line can become very frustrated and destructive if they find themselves in an environment where there is nothing for them to do. The job is the border collie's main reason for living. The desperate need to work is slightly diluted in certain lines of border collies that are bred for the show ring. It is important to remember that, although a border collie is usually quite happy to be a loving pet, he will need plenty of exercise, and preferably some occupation for his very able brain.

(*Appendix continues*)

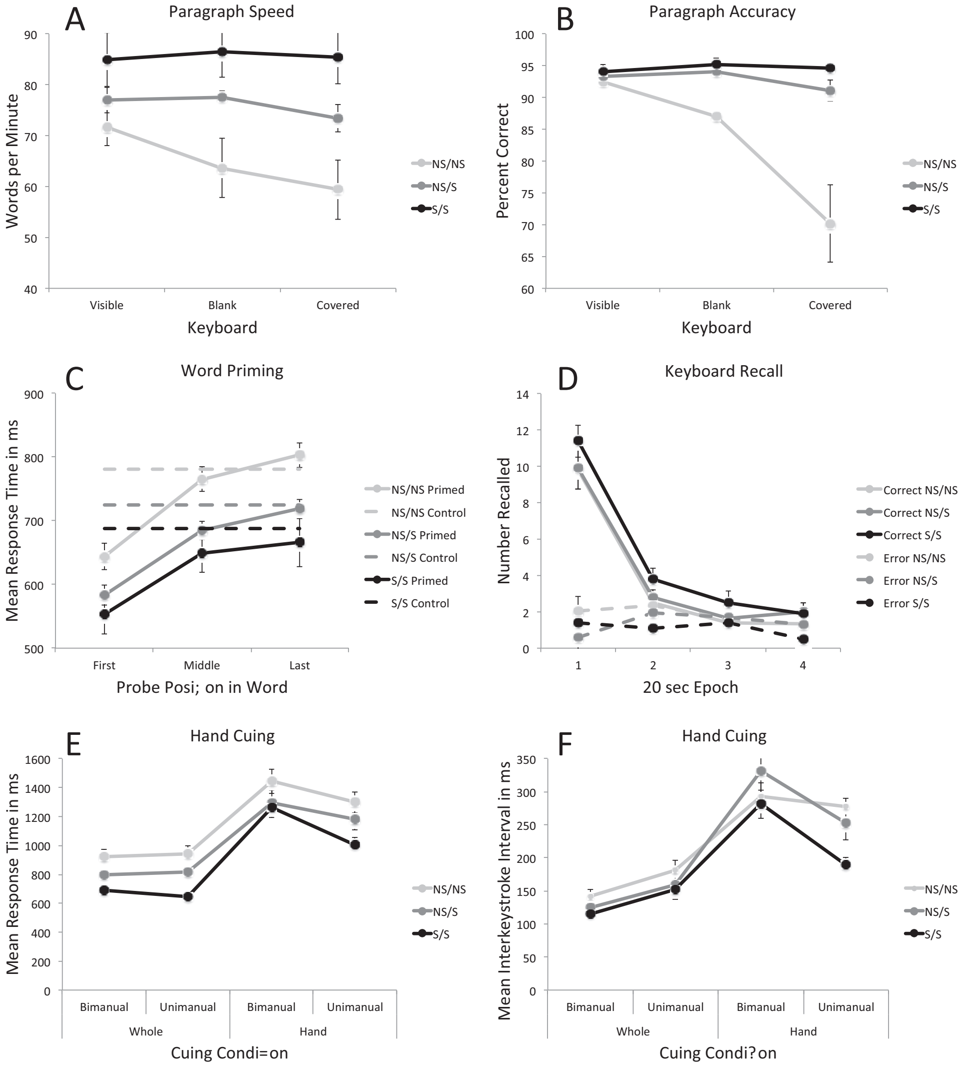

Figure A3. Mean performance by actual standard (S/S; $N = 10$), nonstandard standard (NS/S; $N = 14$), and actual nonstandard (NS/NS; $N = 24$) typists on paragraph typing (Panels A, B), word priming (Panel C), keyboard recall (Panel D), and hand cuing (Panels E, F). The NS data in previous figures are NS/NS data here. The S data were a mixture of the NS/S and S/S data here. Error bars are *SEM*s.

Words for Word Priming Task

Abide, about adobe, adore, agent agile, agony, alter, amber, amour, amuse, angel, anvil, arise, arose, aside aspen awful, baron, baton, beach, beard, begin, begun, blame blank, block, blush, bonus, brave, brawl, bread, bride, brush, brute, budge, built, bulge, bunch, buxom, cadet, cameo, canoe, caper, chafe, chalk, cheat, chief, chunk, churn, cigar, claim, clean, cobra, comet, comic, corps, crash, crate, crawl, crazy, crush, daunt, deity, delta, devil, dimly, ditch, douse, drape, dream, dwarf, empty, envoy, extra, exult, fairy, field, fiend, filth, first, flame, flesh, float, flung, flush, flyer, foamy, forge, forty, frail, frame, fudge, ghost, gipsy, gland, glare, glide, glint, gloat, glove, graft, grape, grasp, grate, groan, guide, harsh, hasty, haunt, heady, heart, hinge, hotel, house, hyena, ideal, image, inert, irony, jerky, joint, juicy, jumpy, knelt, knife, laden, laugh, learn, light, liken, liner, liver, lodge, lofty, logic, lover, lower lucid, lucky lymph, lynch, magic, maple, maybe, midst, milky, mirth, molar, money, month, munch, musty, north, noted, novel, nudge, orbit, other, paste, pasty, patch, pause, piano, pilot, pique, plant, plate, poker, polka, porch, prime, prize, pulse, punch, ranch, range, rangy, reach, react, relax, relic, rider, ridge,

(*Appendix continues*)

rifle, rival, roast, rough, rusty, sable, sandy, saucy, scald, scamp, serum, shack, shaft, shaky, shank, shave, shirt, shock, shone, snore, shown, since, sixth, sixty, slain, slink, smack, smear, smite, snare, sneak, snort, solar, space, spark, spent, spoil, spoke, spray, spurt, squat, stain, stake, stale, stalk, stamp, stand, stare, stern, stick, story, stung, surge, swarm, swine, swing, syrup, thick, thine, think, thong, threw, throb, thumb, thump, tough, trace, track, trade, train, twirl, unfit, untie, vague, value, vocal, vomit, waste, watch, waxen, weigh, whack, whisk, whole, width, wield, winch, windy, women, would, wreck, wrest, write, wrong, wrote, yearn.

Words for Hand Cuing Task

LLLL: brag, cage, date, fast, gear, star

LLRR: bail, crop, echo, grin, sail, walk

LRLR: both, clap dock, form, sick, wish

LRRL: find, glow, role, song, suit, tune

RLLR: harm, item, mash, navy, park, peak

RLRL: hair, idle, laid, land, melt, pant

RRLL: hide, just, live, mice node, poet

RRRR: holy, jump, link, milk, plum, pony

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