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Pushing Typists Back on the Learning Curve:

Revealing Chunking in Skilled Typewriting

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Abstract

Theories of skilled performance propose that highly trained skills involve hierarchically structured control processes. The present study examined and demonstrated hierarchical control at several levels of processing in skilled typewriting. In the first two experiments, we scrambled the order of letters in words to prevent skilled typists from chunking letters, and compared typing words and scrambled words. Experiment 1 manipulated stimulus quality to reveal chunking in perception, and Experiment 2 manipulated concurrent memory load to reveal chunking in short-term memory. Both experiments manipulated the number of letters in words and nonwords to reveal chunking in motor planning. In the next two experiments, we degraded typing skill by altering the usual haptic feedback by using a laser-projection keyboard, so that typists had to monitor keystrokes. Neither the number of motor chunks (Experiment 3) nor the number of short-term memory items (Experiment 4) was influenced by the manipulation. The results indicate that the utilization of hierarchical control depends on whether the input allows chunking but not on whether the output is generated automatically. We consider the role of automaticity in hierarchical control of skilled performance.

Keywords: Hierarchical control; working memory; motor chunk; automatic processes; unit of processing.

Complex skills consist of multiple cognitive and perceptual-motor components. Skilled performers are able to utilize these component processes in concert to optimize performance. To implement multiple components in a rapid succession, skilled performance requires hierarchically organized control processes (Lashley, 1951). Although the notion of hierarchical control has appeared in psychological literature many times (e.g., Abrahamse, Ruitenberg, de Kleine, & Verwey, 2013; Bryan & Harter, 1899; Cooper & Shallice, 2000; Leonard & Newell, 1964; MacKay, 1982; Miller, Galanter, & Pribram, 1960; Rhodes et al., 2004; Verwey, 2001), it remains controversial (e.g., Botvinick & Plaut, 2004; Cooper & Shallice, 2006; Elman, 1990). Studies of typewriting are particularly suited to address the hierarchical nature of skilled performance (Fendrick, 1937; Logan & Crump, 2011; Salthouse, 1986; Shaffer, 1975a; Yamaguchi, Crump, & Logan, 2013). Thus, the present study investigated hierarchical control in the context of typewriting.

Hierarchical control involves higher-level processes that determine the functioning of lower-level processes (Lashley, 1951; Logan & Crump, 2011; Miller et al., 1960). There are four defining properties of hierarchical control (Logan & Crump, 2011): First, different levels of hierarchical control are sensitive to different aspects of the environment (*selective influence*). Second, different levels of hierarchical control operate on different units of processing (*chunking*). Third, different levels of hierarchical control divide intellectual labor and operate autonomously (*encapsulation*). Finally, different levels of hierarchical control rely on different sources of feedback to their actions (*distinct feedback sources*). The present study focused on chunking in skilled typewriting. We provide evidence indicating chunking at several levels of processing and examine conditions under which hierarchical control is utilized in skilled typewriting.

Hierarchical Control of Skilled Performance

Lashley (1951) provided seminal analyses of skilled performance, in which he pointed out that the intervals between successive actions are too short for the sensory consequences of one action to trigger the next in a serial fashion (Keele & Posner, 1968). To achieve such rapid expression of skill, a set of elementary actions must be processed as a single unit, or a "chunk" (Miller, 1956). Chunking benefits performance by enabling parallel processing of component actions and reducing cognitive load in maintaining action plans, which allows skilled performers to concentrate on higher-level action goals (e.g., Newell & Rosenbloom, 1981; Vallacher & Wegner, 1987).

Typewriting provides a good example of hierarchical control. Typewriting involves controlling complex sequences of keystrokes while concentrating on copying or composing complex sentences. Yet, skilled typists type very quickly, compared to novices (Butsch, 1932; Fendrick, 1937; Salthouse, 1984). The differences between skilled typists and novices stem from the way typing is controlled (Bryan & Harter, 1899; Lashley, 1951; Logan & Crump, 2011; Shaffer, 1968). Novice typists control typing with a "hunt-and-peck" method, reading each letter, finding the corresponding key on the keyboard, moving a finger to the key, and pressing it. Hunt-and-peck typing imposes serial processing of letters and keystrokes. By contrast, skilled typists control typing with a "touch-typing" method, reading a word, activating its constituent keystrokes in parallel, and executing them serially but temporally overlapping (e.g., Rumelhart & Norman, 1982). In contrast to hunt-and-peck typing, touch-typing requires letters or keystrokes to be processed in parallel. This parallel processing depends on hierarchical control, in which several letters and keystrokes are processed as a single unit, or a chunk (Lashley, 1951; Logan & Crump, 2011).

Logan and Crump (2011) distinguished between two levels of hierarchical control in skilled typing, implemented as an *outer loop* and an *inner loop* (see Figure 1a). The *outer loop* is a higher-level control process that comprehends language, decomposes sentences into individual words, and submits the words to the inner loop one at a time. The *inner loop* is a lower-level control process that receives words from the outer loop, activates their keystrokes in parallel, and executes them in the correct order. The unit of processing in the outer loop is a single word, and the unit of processing in the inner loop is a single letter or keystroke (see Figure 1b). The two loops rely on different sources of feedback (Logan & Crump, 2010). The outer loop monitors visual feedback from the display, detecting errors in the words typed on the display; the inner loop monitors haptic feedback from the keys (e.g., the feel of the edges and depressions in the keys, and the resistance of the keys when they are pressed) and tracks finger positions on the keyboard (e.g., aligning the fingers with the keyboard and directing the fingers to the keys). This separation of feedback sources allows the two loops to operate autonomously. This *two-loop theory of skilled typewriting* is supported by several previous studies (Crump & Logan, 2010a, 2010b, 2010c; Liu, Crump, & Logan, 2010; Logan, 2003; Logan & Crump, 2009, 2010; Logan, Miller, & Strayer, 2011; Snyder & Logan, 2013), and it provides a framework for interpreting typing performance in terms of the underlying control processes (Yamaguchi, Crump, & Logan, 2013; Yamaguchi, Logan, & Li, 2013).

Pushing Typists Back on the Learning Curve

Hierarchical control is acquired through training (Bryan & Harter, 1899; Fitts & Posner, 1967; Leonard & Newman, 1964; MacKay, 1982; Pew, 1974; Rhodes et al., 2004; Verwey, 1996; Verwey, 1999). Thus, one strategy for studying hierarchical control in skilled typing is to compare novice and skilled typists. Fortunately, skilled typing is pervasive in modern society, but unfortunately, most people learn to type when they are children (Logan & Crump, 2011). Thus, comparisons between novice and skilled typists would be confounded by large differences in cognitive and neurological development that would be hard to disentangle. We adopted a different strategy: We manipulated the materials typists typed and the keyboard they typed on to disable the associations that support skilled typing. Our manipulations were intended to push skilled typists back on the learning curve[1], so that they can no longer utilize their skill. This allows us to examine skilled and unskilled typing in the same typists, avoiding the confounds involved in comparing true novices with skilled adults.

We suggest that typing skill relies on three kinds of association (see Figure 1b), and typists can be pushed back on the learning curve by disabling each kind of association. Typing relies on (1) associations between words and letters, which allows concurrent processing of letters (Crump & Logan, 2010b; Logan et al., 2011), (2) associations between letters and keys, which support implicit knowledge about key

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[1] Schmidt and Lee (2005) defined motor learning as a process of acquiring the capability for producing skilled actions that occurs as a direct result of training, which produces relatively permanent changes in that capacity (see Magill, 2007; Salmoni, Schmidt, & Walter, 1984). According to their view, a typical “learning curve”, a plot of performance level as a function of trials, may not be a pure measure of learning because it also involves transient changes in performance such as fatigue and motivational factors. In the present usage of the term “learning curve,” we assume that typists have acquired relatively permanent changes in the capacity for performing typing through prior experiences, and we intend to investigate the control processes underlying such changes by manipulating factors that would degrade the acquired skill.

locations (Liu, Crump, & Logan, 2010; Logan, 2003), and (3) associations between keys and finger movements, which enable the inner loop to direct the fingers to the corresponding keys (Crump & Logan, 2010a). The experiments we report in this article degraded typing skill by disabling two of these associations (word-letter and key-finger associations) and asked what levels of chunking were altered by doing so.

Associations between words and letters can be disabled by scrambling the order of letters in words (Fendrick, 1936; Shaffer, 1973; Shaffer & Hardwick, 1968; Thomas & Jones, 1970; West & Sabban, 1982). Scrambling letter order prevents chunking of letters into larger units. This pushes skilled typists back on the learning curve by requiring serial processing of individual letters, as in the hunt-and-peck typing style of novice typists. Scrambling letter order may affect several levels of processing in skilled typing. It affects perceptual chunking: familiar words are encoded as single, unitized entities rather than collections of distinct letters (e.g., Reicher, 1969; McClelland & Johnston, 1977; McClelland & Rumelhart, 1981). Scrambling letter order may affect chunking in short-term memory; familiar words are retained as single objects rather than sets of separate objects (e.g., Miller, 1956; Murdock, 1961). Scrambling letter order may affect chunking in motor planning; familiar words activate their constituent keystrokes in parallel rather than in series (Crump & Logan, 2010b; Logan, 2003; Logan et al., 2011). Scrambling letter order may affect chunking in execution of keystrokes; familiar words allow production of familiar sequences of keystrokes that are produced as a group (e.g., Gentner, Larochelle, & Grudin, 1988; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, 1996). We examined chunking at these levels of typing by having skilled typists type words and scrambled words (nonwords).

Associations between keys and finger movements can be disabled by altering the haptic feedback from the keyboard that supports finger movements (Crump & Logan, 2010c; Gordon & Soechting, 1995). We altered haptic feedback with a laser keyboard that projected an image of the QWERTY layout on a flat surface and registered keystrokes when typists touched the surface. The laser keyboard removes the feel of the keys and the resistance of the keys as typists type, making it harder for them to align their fingers and navigate on the keyboard. The laser keyboard slows skilled typing substantially (Crump & Logan, 2010a, 2010b). We assume that altering haptic feedback disables associations between keys and finger movements, and this pushes skilled typists back on the learning curve, requiring them to pay attention to individual keystrokes like hunt-and-peck typists. Altering haptic feedback may affect chunking in motor planning because it focuses attention on individual keystrokes and distracts it from familiar sequences. Altering haptic feedback may also affect chunking in short-term memory if it forces the outer loop to monitor individual keystrokes instead of familiar chunks. We examine these possibilities by using the laser keyboard (Crump & Logan, 2010a, 2010c).

The Present Study

The present study focused on hierarchical control of skilled typewriting. The main purpose was to examine an essential characteristic of hierarchical control (chunking) at three levels of processing (perception, short-term memory, and motor planning) by pushing skilled typists back on the learning curve. We used a discrete typing task to separate outer-loop processing from inner-loop processing (Logan & Crump, 2011). The discrete typing task requires typists to type one letter string (word or nonword) on each trial as quickly as they can. It provides two separate latency measures that allow us to distinguish hierarchical from non-hierarchical control (see Figure 2): the interval between the onset of the string and the first keystroke (*response time*, or *RT*) and the interval between successive keystrokes (*interkeystroke interval*, or *IKSI*). If typing is controlled hierarchically, then RT reflects the time for outer loop and inner loop processing and IKSI reflects the time for inner loop processing. If typing is controlled non-hierarchically, then both RT and IKSI reflect the time for outer loop and inner loop processing.

In the first two experiments, we examined chunking at three levels of processing; perception, memory, and motor planning. Both experiments involved typing words and nonwords that varied in length. In Experiment 1, we focused on chunking in perception. We manipulated stimulus quality by adding noise (superimposing white lines on letter strings printed in black; see Figure 3), and observed the effect on RT and IKSI. In Experiment 2, we focused on chunking in short-term memory. Skilled typists typed words and nonwords that varied in length (*string length*) while performing a concurrent memory load task, and we observed the effects on memory performance. In both Experiments 1 and 2, we examined chunking in motor planning. RT increases with the number of motor programs, or *motor chunks*, that need to be retrieved and loaded into a motor buffer (e.g., Henry & Rogers, 1960; Klapp et al., 1979).

Experiments 3 and 4 investigated the effect of altering haptic feedback on hierarchical control in motor planning and short-term memory. In Experiment 3, typists typed words and nonwords with a regular keyboard or a laser keyboard. We examined the number of motor chunks in typing with the two types of keyboard by looking at the string length effect on RT when typing words and nonwords. In Experiment 4, we used the concurrent memory load procedure of Experiment 2, requiring typists to type words with the regular and laser keyboards while retaining a concurrent memory load

Experiment 1

Experiment 1 manipulated associations between words and letters by having typists type words and nonwords in order to investigate chunking in perception and motor planning. To examine chunking in perception, typists typed words and nonwords with and without a noise mask overlaid on the stimuli (see Figure 3). Noise affects stimulus encoding (Sternberg, 1969), and so should increase the latency of the outer loop but not the latency of the inner loop. Thus, when typing words, which allow chunking of letters, noise should increase RT, but not IKSI. When typing nonwords, which do not allow chunking of letters, noise should increase both RT and IKSI.

To examine chunking in motor planning, we varied the number of letters (string length) in words and nonwords to manipulate the number of motor chunks. RT increases with the number of motor chunks (Henry & Rogers, 1960; Klapp et al., 1979; Rhodes et al., 2004; Sternberg, Monsell, Knoll, & Wright, 1978; van Mier & Hulstjin, 1993), so we expected longer RT with more motor chunks. If words are typed as single chunks, there should be no string length effect in RT to words. If nonwords are typed as several motor chunks, then there should be a large string length effect in RT to nonwords (Sternberg et al., 1978). RT also increases with the size of motor chunks (Klapp, 1995), so it is possible that RT to words might increase with string length. However, this increase may be smaller than the increase in RT to nonwords.

Method

Subjects

Twenty four undergraduate students at Vanderbilt University participated in the experiment. They received experimental credits toward their psychology courses for participation. All typists had English as their first language, and were touch-typists who were capable of typing with the conventional finger placements on the QWERTY keyboard. Typing rate was assessed at the beginning of each session with a typing test from Logan and Zbrodoff (1998) that involved copy typing 100-word paragraphs. Mean typing rate was 82.80 words per minute (*WPM*; *SE* = 3.05). The mean accuracy was 94.18% (*SE* = 0.60). The typists reported having 4.64 months (*SE* = 0.73) of formal training in typing on average and 10.33 years of typing experience (*SE* = 0.29). They also reported spending 4.33 hours (*SE* = 0.42) per day in front of computer.

Apparatus and Stimuli

The apparatus consisted of a 19-in. color VGA monitor and a personal computer. Stimuli were words and nonwords, presented in 24 point Courier New font, printed in black against a white background. The words were obtained from the MRC Psycholinguistic Database (Coltheart, 1981; http://www.psych.rl.ac.uk/), consisting of 200 samples of 3-, 4-, or 5-letter words each. Mean word frequency per million was roughly equivalent across the three string lengths; 140.72 (*SE* = 24.25), 148.08 (24.25), and 111.58 (18.80) for 3-, 4-, and 5-letter words, respectively, $F(2, 297) < 1$, MSE = 114.52. The nonword stimuli were constructed by scrambling the order of letters in the word stimuli randomly; when this procedure resulted in another word or a familiar acronym, one of the letters was arbitrarily chosen and replaced with another letter whose key was located adjacent to the key for the original letter (e.g., the letter ‘d’ could be replaced by ‘s’ or ‘f’; see Appendix for complete lists of words and nonwords used in the present experiment). The noise mask consisted of a string of seven “/” symbols arrayed horizontally to cover the entire word or nonword. The mask was printed in white (see Figure 3).

Procedure

The experiment was conducted individually for each typist in a cubicle under normal fluorescent lighting. Typists sat in front of the computer monitor at an unrestricted viewing distance of 55 cm and read on-screen instructions. Each typist performed two blocks of 12 practice trials, the first of which presented words and nonwords without the noise mask (*no noise* condition) and the second of which presented word and nonwords with the noise mask (*noise* condition). After these practice blocks, typists performed six blocks of 90 test trials, in which words and nonwords appeared equally frequently in a random order. The noise condition and the no noise condition were administered in separate blocks. The two conditions appeared in an alternating order. Half the typists performed the no noise block first, and the other half performed the noise block first. An experimental session took less than an hour.

Each trial started with a fixation cross at the center of screen, which lasted for 750 ms. The cross was replaced by a word or nonword that consisted of three, four, or five letters, appearing in upper case. They appeared in the upper portion of the screen (6.5 cm above the screen center). Typists were instructed to type the material as quickly and as accurately as they could. Typed letters were echoed in lowercase 6.5 cm below the center of the screen immediately after each key was pressed because typists are used to seeing their keystrokes echoed in most interactions with computers.

Skilled typists type at the same rate whether or not keystrokes are echoed (Diehl & Seibel, 1963; Snyder, Logan & Yamaguchi, 2013), but we decided to echo keystrokes to make the interaction with the experimental computer more familiar. When typing completed or after 5,000 ms if typing did not complete, a feedback message appeared at the screen center. The message was “Correct” for correct trials, “Wrong!” for error trials, and “Too Slow” for trials where typists did not complete typing all the letters in the string. Trials were considered correct only if all letters were typed correctly. The feedback lasted for 500 ms. The fixation cross replaced the feedback message to signal the next trial.

Results

Mean RT and IKSI for correct trials and percentage errors (PE) were computed for each typist and submitted to 2 (Stimulus Type; word vs. nonword) x 2 (Stimulus Quality; noise vs. no noise) x 3 (String Length; 3, 4, 5 letters) ANOVAs. All variables were within-subject factors. The ANOVA results are summarized in Table 1. RT, IKSI, and PE are plotted in Figure 4. The differences we discuss below are significant in the relevant ANOVA unless noted otherwise. We present means across typists and the standard errors of those means.

Chunking in Perception

Chunking in perception was assessed by examining the effect of stimulus noise on RT and IKSI for words and nonwords. We expected that noise would increase RT for words and nonwords, but increase only IKSI for nonwords. These predictions were confirmed, supporting chunking in perception.

RT was longer for nonwords (*M* = 774 ms; *SE* = 21) than for words (*M* = 636; *SE* = 14), and it increased with noise (*M*s = 683 vs. 727 ms for no noise and noise trials; *SE*s = 17 and 18, respecively). The effect of noise tended to be larger for nonwords (*M* = 51 ms; *SE* = 27) than for words (*M* = 37 ms; *SE* = 24), although the interaction did not reach significance. These results indicate that typing material and noise affected outer-loop, inner-loop processing, or both.

IKSI was longer for nonwords (*M* = 168 ms; *SE* = 6) than for words (*M* = 121 ms; *SE* = 3). IKSI also increased with noise, and the effect was larger for nonwords than for words; the interaction was significant. The noise effect for nonwords (*M* = 9 ms; *SE* = 2.) was significant, *F*(1, 23) = 15.16, *MSE* = 187, $p < .001$, $\eta_p^2 = .397$, but the effect for words (*M* = 4 ms; *SE* = 2) did not reach significance, *F*(1, 23) = 3.89, *MSE* = 118, $p = .061$, $\eta_p^2 = .145$. The effect of noise on IKSI also increased with string length for nonwords but not for words (see Figure 4); the interaction between Stimulus Length and Stimulus Quality was only significant for nonwords, *F*(2, 46) = 4.03, *MSE* = 95, $p = .024$, $\eta_p^2 = .149$, but not for words, *F*(2, 46) < 1, *MSE* = 44, $p = .480$, $\eta_p^2 = .031$. The lack of the noise effect in IKSI for words suggests that noise affected the outer loop, and the presence of the noise effect in IKSI for nonwords implies that outer loop processing occurs in the middle of typing nonwords. Hence, the unit of encoding is larger for words than for nonwords, implying chunking in perception.

PE was larger for nonwords (*M* = 9.30%; *SE* = 0.44) than for words (*M* = 5.67%; *SE* = 0.36). PE increased with noise for nonwords (*M*s = 8.11% and 10.49% without noise and with noise, respectively; *SE*s = 0.46 and 0.60) but not for words (*M*s = 5.59% and 5.76%; *SE*s = 0.45 and 0.45), which makes sense because encoding of words is supported from top-down process based on prior knowledge, but encoding of nonwords is not (McClelland & Rumelhart, 1981).

Chunking in Motor Planning

Chunking in motor planning was assessed by examining the effect of string length on RT. We expected that RT would increase with string length, but the increase would be larger for nonwords than for words. This prediction was confirmed, supporting chunking in motor planning.

RT increased with string length, and the string-length effect was larger for nonwords (*M* = 35 ms/letter; *SE* = 4) than for words (*M* = 15 ms/letter; *SE* = 2). The larger string length effect on RT for nonwords supports the idea that there are more motor chunks in nonwords than in words of equivalent length. IKSI increased with string length for nonwords (*M* = 17 ms/letter; *SE* = 2) but not for words (*M* = 1 ms/letter; *SE* = 1). These outcomes are consistent with the idea that keystrokes are activated in series for nonwords, but keystrokes are activated in parallel for words, implying chunking in motor planning. PE increased for longer strings (*M*s = 5.49%, 7.48%, and 9.50% for 3, 4, and 5 letters; *SEs* = 0.38, 0.43, and 0.51), but the effect did not interact with other variables.

Discussion

Experiment 1 demonstrated chunking in perception by having skilled typists type words and nonwords to disable associations between words and letters. When typing words, noise disrupted RT but not IKSI. Noise increases encoding time (Sternberg, 1969), so the results indicate that RT includes encoding time, but IKSI does not, consistent with the idea that words are unitized perceptually (Reicher, 1969) and encoded as a chunk. When typing nonwords, noise disrupted both RT and IKSI. Thus, both RT and IKSI include encoding time, consistent with the idea that nonwords are encoded as multiple chunks. The results with nonwords suggest that typists did not encode all letters before they initiated the first keystroke, and then implemented them in series. If they had, there would not have been any effect of noise on IKSI. Thus, the present results indicate that skilled typists encode letters separately when they cannot chunk typing materials.

Experiment 1 also demonstrated chunking in motor planning. RT increased with string length, and the effect was larger for nonwords than for words. The results imply that there were more motor chunks for nonwords than for words. The string length effect on RT was the same with and without noise, suggesting that motor chunks are distinct from perceptual chunks. Thus, the string length effect on RT cannot be attributed to increased encoding time for longer letter strings. Also, string length affected IKSI for nonwords but not for words, which is also consistent with the idea that nonwords require more motor chunks than words.

Experiment 2

Experiment 2 disabled associations between words and letters to examine chunking in short-term memory and its relation to chunking in motor planning. To examine chunking in short-term memory, typists typed words and nonwords varying in length while performing a concurrent memory load task. Typists first memorized a letter string (word or nonword) and then a digit string. After the digit string extinguished, a go signal appeared, and typists typed the letters. Then they recalled the digits. Short-term memory capacity is limited (Cowan, 2000; Miller, 1956), so the more chunks the typing task requires, the less capacity is available for retaining digits. We hypothesize that words are represented as single chunks regardless of their length, so there should be no string length effect on the accuracy of recalling digits when words are typed. We hypothesize that nonwords are represented as several chunks, so there should be a string length effect on the accuracy of recalling digits when nonwords are typed. Thus, the effect of string length on the accuracy of recalling digits can reveal chunking in the typing task.

We examined the relationship between chunking in short-term memory and chunking in motor planning by evaluating the effect of concurrent memory load on typing performance (i.e. RT and IKSI). If both types of chunking are done in the outer loop, the string length effect should be larger with high memory load than with low memory load. If short-term memory chunking is done in the outer loop and motor chunking is done in the inner loop, then the string length effect should be unaffected by memory load. The present experiment presented strings to be typed before the memory items, so the present procedure allowed typists sufficient time to encode words and nonwords before they started typing (Wright et al., 2004; Yamaguchi, Crump, & Logan, 2013). This excludes possible contributions of encoding to the string length effect in RT, and allows stronger claims about motor chunks than Experiment 1.

Method

Subjects

A new group of 24 undergraduate students at Vanderbilt University participated in the present experiment to fulfill experiment credits for their psychology courses. All reported having normal or corrected-to-normal visual acuity and normal color vision.

They had English as their native language and were capable of touch typing. Their mean typing speed was 83.32 WPM (*SE* = 3.12) and their mean accuracy was 93.21% (*SE* = 0.84). On average, they had 4.78 months of formal training in typing (*SE* = 0.64) and 11.25 years of typing experiences (*SE* = 0.55). They reported spending 3.73 hours per day (*SE* = 0.36) in front of computer.

Apparatus and Stimuli

The apparatus was identical with that used in Experiment 1. For the typing task, stimuli consisted of 3- and 5-letter words and nonwords that were used in Experiment 1. For the concurrent memory task, stimuli were strings of five digits that were randomly chosen on each trial. For the low-load condition, five digits were identical (e.g., *“22222*”), and for the high-load condition, five digits were unique (e.g., “*94032*”). The digits were presented in 18 pt. Courier New font, arrayed horizontally at the center of screen.

Procedure

The experiment was conducted individually in a cubicle. Each typist performed two blocks of 12 practice trials, for which the two lengths of words and nonwords occurred equally frequently in a random order. The first block was the low-load condition, and the second block was the high-load condition. These practice trials were not included in the analysis. The next eight blocks were composed of 60 test trials. Half the blocks were for the low-load condition, and the other half were for the high-load condition. The two conditions were administered in an alternating order, and the order was counterbalanced across typists.

On each trial, typists were presented with a word or nonword, which remained on the screen for 500 ms and was replaced by a 750-ms blank screen. Then, a string of five (identical or unique) digits appeared for 1,000 ms, which was followed by a 500-ms blank screen. The message “GO!” occurred as a go signal to prompt typists to type the word or nonword as quickly and as accurately as they could. The go message was accompanied by a tone (800-Hz pitch, 500-ms duration) presented binaurally through headphones. The go signal occurred at the upper portion of the screen (6.5 cm above the screen center) and was erased after 500 ms. Typed letters were echoed at the lower portion of the screen (6.5 cm below the screen center) in lower case.

As 3,000 ms elapsed after the onset of the go signal, typists were prompted to enter the string of digits by the message “Enter the digits!”, and typists used their right hand to enter digits on a number pad on the right side of the keyboard within a 5,000-ms time window. The entered digits were also echoed on the screen in the same manner as for the typing task. After the digit entry, feedback for the typing and memory tasks appeared at the upper and lower portions of the screen, respectively. For both tasks, the messages “Correct”, “Error!”, and “Too Slow”, appeared for the correct, incorrect, and no responses, respectively. No response occurred when typists failed to complete typing or enter digits in the given time windows. For the typing task, a trial was considered correct only if all letters were typed correctly in the correct order. For the memory task, a trial was considered correct only if all digits were correctly entered in the correct order.

Each of the eight test blocks ended with the accuracy scores for the two tasks, which displayed the percentages of correct responses in that block separately for the two tasks. An experimental session lasted less than an hour.

Results

Mean RT and IKSI for correct responses for the typing task, and percentage errors for typing (PE_{typing}) were computed for each typist. Percentage error for recall (PE_{recall}) was computed for trials in which a word or nonword was typed correctly. The results are summarized in Figure 5. These dependent variables were submitted to 2 (Stimulus Type: word vs. nonword) x 2 (String Length: 3 letter vs. 5 letter) x 2 (Memory Load: high vs. low) ANOVAs. As in Experiment 1, the differences described below are significant in the ANOVAs unless noted otherwise. The results are summarized in Table 2.

Chunking in short-term memory

Chunking in short-term memory was assessed by examining the effect of string length in the typing materials on PE_{recall}. We expected that PE_{recall} would be larger for longer strings than for shorter strings, but this influence of string length would be more pronounced for nonwords than for words. The results confirmed this prediction, supporting chunking in short-term memory.

PE_{recall} was larger for nonwords (*M* = 19.11%; *SE* = 1.64) than for words (*M* = 7.58%; *SE* = 0.94). It also depended on string length, and the string length effect was larger for nonwords (*M*s = 10.79% vs. 27.43% for 3 and 5 letters; *SE*s = 1.34 and 2.22) than for words (*M*s = 5.97% vs. 9.18% for 3 and 5 letters; *SE*s = 0.84 and 1.20). These patterns were more pronounced for the high memory load condition than for the low memory load condition (see Figure 5). These results indicate that the units of short-term memory representation are larger for typing words than for typing nonwords, implying chunking in short-term memory.

Dissociation between short-term memory and motor chunks

To assess whether chunking in short-term memory was the same as chunking in motor planning, we examined whether the string length effect on RT (the index of motor chunking) would depend on memory load (the index of short-term memory). We expected that the string length effect would be larger for the high memory load if chunking in short-term memory is the same as chunking in motor planning, but the string length effect would be the same for high and low memory loads if chunking in short-term memory is dissociable from chunking in motor planning. The results supported the dissociation between chunking in short-term memory and chunking in motor planning.

For RT, there was a string length effect for typing nonwords (*M* = 13 ms/letter; *SE* = 5.81) but not for typing words (*M* = -4 ms/letter; *SE* = 4.62), suggesting a greater number of motor chunks for nonwords than for words. These outcomes are consistent with Experiment 1. The string length effects were smaller here than in Experiment 1 because the pre-exposure of the strings allowed typists to partially complete motor planning before the go signal occurred (see Klapp, 1995; Wright et al., 2004; Yamaguchi, Crump, & Logan, 2013). A portion of the string length effect in Experiment 1 could have been due to longer encoding for longer strings, but pre-exposure of the strings excluded this possibility in the present experiment. Memory load increased RT, and the increase was larger for nonwords (*M*s = 476 ms vs. 629 ms for low and high loads; *SE*s = 22 and 22) than for words (*M*s = 453 ms vs. 553 ms for low and high loads; *SE*s = 31 and 25). However, the string length effect did not differ statistically between low and high memory conditions for words (*M*s = -6 ms/letter and -1 ms/letter for high and low memory loads, respectively) or for nonwords (*M*s = 8 ms/letter and 18 ms/letter), dissociating motor chunks from short-term memory.

For IKSI, the string length effect was also larger for nonwords (*M* = 15 ms/letter; *SE* = 2) than for words (*M* = 3 ms/letter; *SE* = 1). These results are consistent with Experiment 1. There was little effect of memory load on IKSI for words (*M*s = 147 ms vs. 149 ms; *SE*s = 7 and 6) or nonwords (*M*s = 181 ms vs. 190 ms for low and high loads; *SE*s = 9 and 8). The string length effect did not differ between low and high memory load conditions for words (*M*s = 4 ms/letter and 2 ms/letter for high and low memory loads, respectively) or for nonwords (*M*s = 17 ms/letter and 13 ms/letter). The results imply dissociation between motor chunks from short-term memory, which is consistent with previous studies that suggested a distinction between input and output buffers (e.g., FitzGerald, Tattersall, & Broadbent, 1988; Tattersal & Broadbent, 1991).

PE_{typing} depended on all of the three variables (see Figure 5): Most notably, high memory load increased PE_{typing} for nonwords (*M*s = 7.13% vs. 16.97% for low and high loads; *SE*s = 0.95 and 1.71), but not for words (*M*s = 4.19% vs. 4.11% for low and high loads; *SE*s = 0.57 and 0.49). Also, high memory load increased the string length effect for nonwords, but it did not affect the string length effect for words. Thus, short-term memory load increased with string length for nonwords but not for words, again suggesting units of short-term memory are larger for words than for nonwords.

Discussion

Experiment 2 demonstrated that the units of short-term memory representation are larger for words than for nonwords, implying chunking in short-term memory. This conclusion is supported by the higher recall error rate, and the larger effect of string length on recall errors, for nonwords than for words. There was an effect of string length on recall errors not only for nonwords but also for words. This suggests that the units of short-term memory representation for typing words may be smaller than words (e.g., syllables), or it may reflect differential decay of short-term memory (e.g., Barrouillet & Camos, 2012), given that it takes longer to type longer words than shorter ones (i.e., longer words may prevent rehearsal more than shorter words). In either case, the increase of recall error per letter was very small for words (1.07%), as compared to nonwords (5.55%), suggesting that the number of letters in words had only a minor impact on recall performance. Also, the present experiment dissociated the effect of short-term memory load from the effect of string length in both RT and IKSI. This finding implies that two types of chunking are involved at different levels of skilled typewriting (Smyth & Pendleton, 1989; Tattersall & Broadbent, 1991), presumably one in the outer loop and the other in the inner loop.

To summarize, Experiments 1 and 2 provided novel evidence revealing chunking in three levels of processing in skilled typing; perception, short-term memory, and motor planning. The results of the experiments imply that hierarchical control depends on associations between words and letters, which allow chunking of component processes recruited for typing familiar words. When typing unfamiliar nonwords, the same component processes may be recruited for the constituent letters, but they cannot operate in parallel. Thus, the utilization of hierarchical control depends on typing materials.

Experiment 3

Experiment 3 disabled associations between fingers and keys by having skilled typists type on a laser keyboard that projected an image of the keys on a tabletop and registered responses when typists' fingers struck the tabletop. The laser keyboard is similar to the keyboards on touch-screen devices (e.g., tablet PCs and smartphones), which many users find difficult to type on. Consistent with this common complaint, typing is much slower and less accurate with the laser keyboard (Crump & Logan, 2010c). Compared to a normal keyboard, typing on a laser keyboard increases RT by 50% and IKSI by 100%, and there is little change in the disruption after 400 trials of practice (Crump & Logan, 2010a, 2010c). We assume the disruption occurs, not simply because typists are unfamiliar with the laser keyboard, but because the laser keyboard alters the haptic feedback to the fingers that is usually present when typing on a normal keyboard, removing the feel of the keys and the resistance of the keys that are important in aligning the fingers with the keyboard and controlling finger movements (Crump & Logan, 2010a, 2010c; Gordon & Soechting, 1995). The goal of Experiment 3 was to determine whether the laser keyboard also disrupts hierarchical control of typing by disabling chunking in motor planning. We evaluated explanations of slower typing, one that assumes hierarchical control is disrupted and one that does not.

First, altering haptic feedback might force the outer loop to take control of typing away from the inner loop, controlling the execution of each keystroke. This would slow RT and IKSI, as observed. Outer-loop control of individual keystrokes would destroy motor chunking, decomposing chunks into strings of letters. Words should be typed like nonwords, whose hierarchical control is already compromised. Thus, with the laser keyboard, words should be typed as slowly as nonwords, and the effect of string length should be as large for words as for nonwords.

Second, altering haptic feedback might force the outer loop to monitor each keystroke, looking at the fingers to be sure that they struck the right key and looking at the screen to be sure that the keystroke was registered. This would also slow RT and IKSI, as observed (Logan & Crump, 2009; Snyder & Logan, 2013). The inner loop could still control the selection and execution of each keystroke, although at a slower rate. Thus, motor chunking would still be preserved. Words would be typed faster than nonwords, and the string length effect would be larger for nonwords than for words.

In addition, we also examined how altering haptic feedback influences post-error slowing (longer IKSI for keystroke that immediately follow an error keystroke; e.g., Shaffer, 1975a) with the laser keyboard to that with the regular keyboard. Previous research suggests that typewriting involves two error detection mechanisms, an outer-loop mechanism that monitors the letters echoed on the screen for errors, and an inner-loop mechanism that monitors finger movements (Logan & Crump, 2010; Snyder, Logan, & Yamaguchi, 2013). Post-error slowing is associated with the inner-loop mechanism. Thus, we expect post-error slowing for words and nonwords with regular and laser keyboards, because all these conditions involve the inner loop. The regular and laser keyboards may engage different motives for post-error slowing. The laser keyboard may engage a “prevention” motive (Crump & Logan, 2013), in which typing is slower for several keystrokes after an error to reduce the likelihood of further errors. Errors are more prevalent with the laser keyboard and can be prevented by slowing down. The regular keyboard may engage a “cure” motive (Crump & Logan, 2013), in which typing is slower immediately after an error when typists must inhibit their natural tendency to correct errors. Errors are less prevalent with the regular keyboard, and skilled typists may feel no need to adjust the speed-accuracy tradeoff (although they can if they are required to; Yamaguchi, Crump & Logan, 2013).

Method

Subjects

A new group of 24 touch typists were recruited from the Vanderbilt University community. All typed with the conventional finger placements on the QWERTY keyboard. Four typists received experimental credits toward their psychology courses, and the remaining typists were paid $12 for participation. The mean typing speed and accuracy in the typing test were 85.84 WPM (*SE* = 3.66) and 94.66% (*SE* = 0.77), respectively. These typists reported having 5.27 months (*SE* = 0.75) of formal training and 11.42 years (*SE* = 0.78) of typing experience, and spending 4.65 hours per day (*SE* = 0.48) in front of computer.

Apparatus, Stimuli, and Procedure

The apparatus was the same as those of the preceding experiments. Stimuli were the 3, 4, and 5-letter words and nonwords that were also used in Experiment 1. The task was also similar to that of Experiment 1 without the noise mask. Each typist performed two separate sets of trials, each consisting of one block of 12 practice trials and four blocks of 90 test trials, in which all combinations of string length and stimulus type were intermixed randomly. Typists initiated each block by pressing the space bar. In one of the two sets of trials, typists used the regular keyboard to perform the task; in the other, they used the laser-projection keyboard (Golan Technology, Brooklyn, NY), which was used in Crump and Logan's (2010a, 2010c) studies. Half the typists used the regular keyboard in the first block and the laser-projection keyboard in the second block; the order was reversed for the other half. The procedure closely followed that of Experiment 1 in other respects.

Results

Mean RT and IKSI for correct responses and PE were computed for each typist (see Figure 6) and submitted to 2 (Keyboard: regular vs. laser) x 2 (Stimulus Type: word vs. nonword) x 3 (String Length: 3, 4, and 5 letters) ANOVAs. The results are summarized in Table 3. Again, differences discussed below are significant in the ANOVAs unless noted otherwise.

Chunking in typing words and nonwords

To examine whether altering haptic feedback disabled hierarchical control, we first examined whether words were typed like nonwords with the laser keyboard. Typing was slower with the laser keyboard, but words were still typed faster than nonwords, suggesting that the laser keyboard did not disable hierarchical control.

RT increased nearly by 50% with the laser keyboard (*M* = 997 ms; *SE* = 18) as compared to the regular keyboard (*M* = 668 ms; *SE* = 17). Nevertheless, RT was shorter for words than for nonwords with the regular keyboard (*M*s = 611 vs. 725 ms for words and nonwords; *SE*s = 13 and 22) and with the laser keyboard (*M*s = 942 vs. 1052 ms for words and nonwords; *SE*s = 16 and 21), and the advantage for the words did not differ between the two keyboard types. Overall, RT was shorter for words (*M* = 611 ms; *SE* = 12) than for nonwords (*M* = 725 ms; *SE* = 18). These outcomes suggest that, even with the laser keyboard, units of typing are still larger for words than for nonwords.

IKSI increased by 145% with the laser keyboard (*M* = 384 ms; *SE* = 20) as compared to the regular keyboard (*M* = 157 ms; *SE* = 7). IKSI was still shorter for words than for nonwords with the laser keyboard. The difference between words and nonwords was smaller with the laser keyboard (*Ms* = 368 vs. 401 ms for words and nonwords; *SE*s = 21 and 20; difference = 33 ms), than with the regular keyboard (*M*s = 134 vs. 180 ms; *SE*s = 6. and 9; difference = 46 ms). We suggest that nonwords increased IKSI for the laser keyboard less than it did for the regular keyboard due to "cognitive slack" (Pashler, 1998; Yamaguchi, Logan, & Li, 2013)[2]. The IKSI results suggest that units of typing are still larger for words than for nonwords when typing with the laser keyboard.

PE increased with the laser keyboard (*M* = 5.37% and 16.41% for the regular and laser keyboards, respectively; *SE*s = 0.74 and 1.56). With the regular keyboard, PE was larger for nonwords (*M* = 6.73%; *SE* = 4.01) than for words (*M* = 4.01%; *SE* = 6.73), but the difference disappeared with the laser keyboard (*M*s = 16.59% and 16.23% for words and nonwords; *SE*s = 1.42 and 1.85). These results are consistent with the findings that typing errors depend primarily on the inner loop operations (Yamaguchi, Crump, & Logan, 2013).

Chunking in motor planning

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[2] With words, the outer loop is only engaged for the first keystroke, so it affects RT but not IKSI. IKSI depends only on inner-loop processing. With nonwords, the outer loop is engaged for all keystrokes, affecting IKSI as well as RT. The outer loop and inner loop can go on in parallel, so the outer loop can prepare keystroke N+1 while the inner loop executes keystroke N. We assume that outer loop processing takes longer than inner loop processing with the regular keyboard, so the inner loop has to wait for the outer loop to prepare the next keystroke. This waiting time is called "cognitive slack" (Pashler, 1998). We assume that the laser keyboard prolongs inner loop processing, increasing IKSI for words and nonwords. This increase in inner-loop processing time reduces cognitive slack for nonwords, reducing the amount of time the inner loop has to wait for the outer loop to finish before it can start to execute the next keystroke. Thus, the difference in IKSI for words and nonwords will be smaller for the laser keyboard than for the regular keyboard, as observed (see also Yamaguchi, Logan, & Li, 2013).

Chunking in motor planning was also assessed by examining the string length effect on RT for words and nonwords. If altering haptic feedback decomposed motor chunks, we expected that the string length effect would be as large for words as for nonwords. The string length effect was still larger for nonwords, corroborating the earlier conclusion that the laser keyboard did not affect hierarchical control in typing words.

RT increased with string length. However, for words, the string length effect did not differ between the regular keyboard (*M* = 13 ms/letter; *SE* = 3) and the laser keyboard (*M* = 13 ms/letter; *SE* = 4). Thus, the laser keyboard did not increase the number of motor chunks. For nonwords, the string length effect was smaller with the regular keyboard (*M* = 26 ms/letter; *SE* = 5) than with the laser keyboard (*M* = 55 ms/letter; *SE* = 9). This difference was mainly attributable to the longer RT for 5-letter nonwords. Possibly, typists may have encoded more letters before typing with the laser keyboard because they needed to shift their eyes from the screen to their hands to monitor their typing.

IKSI also increased with string length. For words, the string length effect was not larger for the laser keyboard (*M* = –4 ms/letter; *SE* = 4) than for the regular keyboard (*M* = 4 ms/letter; *SE* = 1), suggesting that the laser keyboard did not increase the number of motor chunks. For nonwords, the string length effect was larger for the laser keyboard (*M* = 27 ms/letter; *SE* = 4) than for the regular keyboard (*M* = 16 ms/letter; *SE* = 3), perhaps because the outer loop had to monitor keystrokes.

For PE, the effect of string length was larger with the laser keyboard (*M*s = 12.20%, 15.76%, and 21.27%, for 3, 4 and 5 letters; *SE*s = 1.37, 1.68, and 2.04) than with the regular keyboard (*M*s = 4.17%, 5.09%, and 6.85%; *SE*s = 0.80, 0.79, and 1.03), reflecting the increased probability of making error for each keystroke.

Post-error slowing

To examine the role of haptic feedback in detection of errors, we computed IKSI for error trials as a function of keystroke positions relative to error keystroke. Figure 7 shows mean IKSI collapsed across three string lengths and typists. To index the magnitude of post-error slowing, we subtracted the IKSI for keystrokes that immediately preceded the error keystroke (E-1) from the IKSI for keystrokes that immediately followed the error keystroke (E+1). Two typists were excluded from the analysis because they had an empty cell in one of the regular keyboard conditions (either for word or nonword trials). We submitted the post-error slowing scores for the remaining 22 typists to a 2 (Stimulus Type: word vs. nonword) x 2 (Keyboard Type: regular vs. laser) ANOVA, which only revealed a significant main effect of Keyboard Type, $F(1, 21) = 14.00$, $MSE = 26{,}796$, $p < .001$, $\eta_p^2 = .400$. Post-error slowing was larger with the regular keyboard ($M = 393$ ms; $SE = 33$) than with the laser keyboard ($M = 263$ ms; $SE = 32$), suggesting that post-error slowing occurred for different reasons for the two keyboards.

Next, we examined the persistence of post-error slowing by subtracting IKSI for E+2 from IKSI for E+1. We excluded two additional typists who also had an empty cell in one of the regular keyboard conditions, and submitted the remaining 20 typists' scores to a 2 (Stimulus Type: word vs. nonword) x 2 (Keyboard Type: regular vs. laser) ANOVA, and found a significant main effect of Keyboard Type, $F(1, 19) = 32.60$, $MSE = 28{,}659$, $p < .001$, $\eta_p^2 = .632$. E+2 keystroke was faster than E+1 keystroke by 249 ms

(*SE* = 44) for the regular keyboard, whereas it was faster only by 33 ms (*SE* = 32) for the laser keyboard, indicating greater persistence of post-error slowing for the laser keyboard. This suggests a prevention motive for post-error slowing with the regular keyboard and a cure motive for post-error slowing with the regular keyboard (Crump & Logan, 2013).

Discussion

Experiment 3 found that the laser keyboard disrupted skilled typing substantially, increasing both RT and IKSI, and it also affected the magnitude and persistence of post-error slowing, indicating that altering haptic feedback changed the way typists reacted to errors (Crump & Logan, 2013). There was little evidence that disabling associations between keys and finger movements affected hierarchical control. RT and IKSI were shorter for words than for nonwords with both keyboards. Moreover, the string length effect was smaller for words than for nonwords with both keyboards, and the string length effect did not differ between the regular and laser keyboards when typing words. These results suggest that altering haptic feedback did not increase the number of motor chunks for words, implying that keystrokes were programmed in the inner loop for both keyboards. The analysis of post-error slowing also appears to agree with this conclusion. Although the smaller magnitude of post-error slowing for the laser keyboard could reflect a greater “cognitive slack” with the laser keyboard that absorbed a larger portion of the slowing, the persistence of the slowing after an error keystroke could reflect the possibility that the outer loop took control of keystrokes away from the inner loop after an error. This would imply that the inner loop still controls keystrokes before an error. More broadly, the results suggest that altering haptic feedback did not force the outer loop to control the execution of each keystroke. Instead, it required the outer loop to monitor keystrokes, slowing the inner loop but still allowing it to prepare and execute the usual motor chunks.

Experiment 4

Experiment 4 disabled associations between keys and finger movements to examine their effects on chunking in short-term memory. Experiment 2 dissociated chunking in motor planning from chunking in short-term memory. Retrieval of motor chunks occurs in the interface between the outer loop and the inner loop, whereas short-term retention of words and letters occurs in the outer loop (Logan & Crump, 2011). Thus, we might expect no effect of disabling motor associations on chunking in short-term memory. Words would be represented as single chunks, so short-term retention should not be affected by word length. However, as Experiment 3 suggests, altering haptic feedback forces the outer loop to monitor keystrokes, so chunking in short-term memory may be disrupted. Thus, words would be represented as several chunks, and short-term retention should be worse for longer words than for shorter words.

Experiment 4 was similar to Experiment 2, except that typists typed with the regular and laser keyboards while performing a concurrent memory task. We used only words and assessed whether chunking in short-term memory was disrupted by typing on the laser keyboard by looking at the effect of word length on memory performance.

Method

Subjects

Twenty four touch typists were newly recruited from the Vanderbilt University community. They were paid $12 for participation. All typists typed with the conventional finger placements on the QWERTY keyboard. The mean typing speed and accuracy in the typing test were 81.71 WPM (*SD* = 1.77) and 94.16% (*SD* = 0.41), respectively. These typists reported having 4.80 months (*SD* = 0.71) of formal training and 11.42 years (*SD* = 0.67) of typing experience, and spending 4.25 hours per day (*SD* = 0.37) in front of computer.

Apparatus, Stimuli, and Procedure

The apparatus was identical with that used in Experiment 2, except that there were two types of keyboard, the regular keyboard and the laser keyboard used in Experiment 3. Stimuli were words also used in Experiment 2, and the procedure followed that experiment as well.

Each typist performed two separate phases with the two keyboard types. Each phase consisted of two blocks of 8 practice trials (one with low memory load and one with high memory load) and four blocks of 44 test trials (two blocks for each memory load). Half the typists had the low memory load condition in the first and third test blocks and the high memory load condition in the second and fourth blocks; the other half had the high memory load condition in the first and third blocks and the low memory load condition in the second and fourth blocks. The timing in each trial was also identical with the timing in Experiment 2, except that the go signal remained on the screen for 5,000 ms or until typists made as many keystrokes as the number of letters in the to-be-typed word (in Experiment 2, the interval was fixed at 3,000 ms). This modification was made due to the slower typing rate with the laser keyboard. In addition, because the laser keyboard was not equipped with a numeric keypad, a separate numeric keypad was placed on the location roughly the same as the position of the number pad equipped on the regular keyboard.

Results

The data were analyzed in the same manner as in Experiment 2. PE_{recall}, RT, IKSI, and PE_{typing} are plotted in Figure 8. They were submitted to 2 (Keyboard Type: regular vs. laser) x 2 (Word Length: 3 letter vs. 5 letter) x 2 (Memory Load: high vs. low) ANOVAs. The results are summarized in Table 4. As in the preceding experiments, differences discussed below are significant in the ANOVAs unless noted otherwise.

Chunking in short-term memory

We expected that PE_{recall} would be affected by word length for the laser keyboard if altering haptic feedback increased the number of chunks in short-term memory. The results showed little effect of word length, indicating that the laser keyboard did not affect chunking in short-term memory.

PE_{recall} was larger for the laser keyboard (M = 10.00%; SE = 1.18) than for the regular keyboard (M = 8.17%; SE = 1.15), but there was little evidence that the laser keyboard altered hierarchical control. PE_{recall} was generally larger for 5-letter words than for 3-letter words, but this word length effect was not modulated by keyboard type. Also, PE_{recall} increased with memory load (*M*s = 2.35% and 15.82% for low and high loads, respectively; *SE*s = 0.28 and 2.01), but the memory load effect was not modulated by keyboard type either.

There was an interaction between memory load and word length, reflecting a larger word length effect in the high load condition (*M*s = 13.07% and 18.56 for 3- and 5-

letter words, respectively; *SE*s = 1.71 and 2.39) than in the low load condition (*M*s = 1.61% and 3.10%; *SE*s = 0.32 and 0.48). The interaction may reflect the possibility that longer words exceed short-term memory capacity more than shorter words when memory load is high. This outcome is consistent with Experiment 2.

Chunking in motor planning

We assessed chunking in motor planning by examining the word length effect in RT. Experiment 3 suggested that altering haptic feedback did not increase the number of motor chunks, so we expected that the word length effect would be the same for the two types of keyboard. The results confirmed the prediction.

RT was generally longer with the laser keyboard (*M* = 720 ms; *SE* = 35) than with the regular keyboard (*M* = 510 ms; *SE* = 26). RT did not depend on word length, consistent with Experiment 3 and suggesting that the number of motor chunks did not increase with the laser keyboard. RT increased for high memory load, and the increase was larger for the laser keyboard (*M* = 256 ms; *SE* = 33) than for the regular keyboard (*M* = 142 ms; *SE* = 22).

IKSI was also longer with the laser keyboard (*M* = 231 ms; *SE* = 13) than with the regular keyboard (*M* = 146 ms; *SE* = 6). IKSI was not affected by memory load. IKSI showed different patterns of word length for the two keyboards: With the regular keyboard, the word length effect was 3 ms/letter (*SE* = 1); with the laser keyboard, the word length effect was –11 ms/letter (*SE* = 3). The reason for the decreasing word length effect with the laser keyboard is not clear. It is unlikely that the laser keyboard reduced the number of motor chunks for longer words, so the result may simply be due to chance. The important point is that there was little evidence indicating that the number of motor chunks increased for the laser keyboard.

PE_{typing} was larger for the laser keyboard (*M* = 15.11%; *SE* = 1.78) than for the regular keyboard (*M* = 5.03%; *SE* = 5.03), and it was also larger for longer words (*M* = 13.36%; *SE* = 1.11) than for shorter words (*M* = 6.78%; *SE* = 0.96). The effect of word length was larger with the laser keyboard (*M*s = 10.42% vs. 19.80% for 3- and 5-letter words; *SE*s = 1.88 and 1.92) than with the regular keyboard (*M*s = 3.14% vs. 6.92% for 3- and 5-letter words; *SE*s = 0.52 and 0.88).

Discussion

The present experiment provided little evidence that disabling associations between keys and finger movements alters chunking in short-term memory. Although recall errors increased somewhat with the laser keyboard, the word length effect was the same with both keyboards, suggesting that monitoring keystrokes did not affect the units of short-term memory. Consistent with Experiment 3, the laser keyboard did not increase the word length effect in RT, supporting the conclusion that disabling associations between keys and finger movements did not affect chunking in motor planning.

General Discussion

Hierarchical control enables rapid implementation of complex skills by allowing multiple component processes to operate concurrently. Chunking plays a critical role in enabling concurrent processing (e.g., Bryan & Harter, 1989; Lashley, 1951; Sternberg et al., 1978; Rhodes et al., 2004). Chunking develops over practice, so we can study it by comparing skilled and unskilled performance. To do so, we pushed skilled typists back on the learning curve by degrading two out of three types of associations that support skilled typewriting: associations between words and keys, and associations between keys and finger movements (we did not degrade associations between letters and keys). We examined contributions of these associations to chunking in three different processes underlying skilled typing.

Experiments 1 and 2 examined the contribution of associations between words and letters by scrambling the order of letters in words. Experiment 1 demonstrated that scrambling word order altered units of encoding. When typing words, stimulus noise increased RT, but it did not influence IKSI, indicating that encoding occurred once for each word before the first keystroke. When typing nonwords, stimulus noise increased RT and IKSI, indicating that encoding occurred after the first keystroke is initiated. Thus, skilled typewriting involves chunking in perception. Experiment 2 demonstrated that scrambling word order altered units of short-term memory. In the concurrent memory task, performance was not affected much by the number of letters in words, but was greatly disrupted by the number of letters in nonwords. Thus, skilled typewriting involves chunking in short-term memory. Furthermore, both experiments demonstrated that scrambling word order altered units of motor planning. RT increased as the number of letters in nonwords increased, and this increase was much larger than the increase as the number of letters in words increased. Thus, skilled typewriting involves chunking in motor planning. This chunking in motor planning was dissociated from chunking in perception in Experiment 1 and from chunking in short-term memory in Experiment 2.

Experiments 3 and 4 examined contributions of associations between keys and finger movements by altering haptic feedback to the fingers. Experiment 3 demonstrated that altering haptic feedback slowed typing, but typing words was still faster than typing nonwords. Also, string length increases RT when typing words with the laser keyboard no more than when typing words with the regular keyboard. Thus, altering haptic feedback did not alter chunking in motor planning. Experiment 4 demonstrated that word length affected concurrent memory performance to the similar extent with the two types of keyboard. Thus, altering haptic feedback did not alter chunking in short-term memory. We discuss implications of these results about the role of automatic processes in hierarchical control of skilled performance.

The Role of Automaticity in Hierarchical Control of Skill

Automatization of component processes precedes the development of hierarchical control (e.g., Abrahamse et al., 2013; Bryan & Harter, 1899; LaBerge & Samuels, 1974; Rhodes et al., 2004; Vallacher & Wegner, 1987). Automaticity develops by strengthening the associations that underlie the skill, and hierarchical processing emerges when the associations become strong enough to support performance without conscious control (LaBerge & Samuels, 1974; Logan, 1988; Schneider & Shiffrin, 1977). Hierarchical control involves executing different levels of processing in parallel, and there are strict limits on the ability to perform cognitive processes in parallel (Pashler, 1998; Welford, 1952). Thus, automaticity seems to be necessary to execute component processes in parallel (e.g., Greenwald & Shulman, 1973; Hazeltine, Teague, & Ivry, 2002; Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008; Schumacher et al., 2001; Shaffer, 1975b).

In the Introduction, we proposed that skilled typing depends on automatizing three types of association: associations between words and letters, associations between letters and keys, and associations between keys and finger movements. Associations between words and letters automatize retrieval of individual letters, so typists do not have to attend each letter they type; associations between letters and keys automatize retrieval of keystroke schemata, so typists do not have to attend to the translation of individual letters to the corresponding keystrokes; and associations between keys and fingers automatize implementation of keystrokes, so typists do not have to attend to each keystroke. In the present study, we examined the role of associations between words and letters and associations between keys and fingers in enabling hierarchical control of skilled typewriting, and showed that the former are critical in enabling hierarchical control but latter are not.

Associations between words and letters enable hierarchical control by supporting chunking. Through associative learning, a single word becomes associated with each of the letters that comprise it, producing a one-to-many mapping that is characteristic of hierarchical control (Logan & Crump, 2011; Miller et al., 1960). Chunking benefits touch typing because it compresses data (Klapp, 1995) and allows higher- and lower-level processes to operate in parallel (Rhodes et al., 2004). This reduces cognitive load and increases the speed of processing (De Kleine & van der Lubbe, 2011). Chunking increases distinctiveness of memory representations, and distinctiveness increases as the size of chunks increase (Newell & Rosenbloom, 1981). This reduces interference when retrieving the relevant chunk and increases the accuracy of performance.

The associations between keys and fingers are not necessary for chunking in skilled typewriting. We were surprised to find that haptic feedback did not disable hierarchical control because the inner loop depends on haptic feedback from the keyboard (Crump & Logan, 2010c; Gordon & Soechting, 1995). Our results suggest that altering haptic feedback compromised the inner loop's ability to monitor keystrokes, so that the outer loop had to take over. Thus, motor chunks remained intact, but keystrokes were slowed to allow the outer loop to monitor them (Logan & Crump, 2009; Snyder & Logan, 2013). Our analysis of post-error slowing in Experiment 3 supports this conclusion. For the regular keyboard, post-error slowing was strong but dissipated quickly after an error, indicating suppression of an automatic tendency to correct the error (Crump & Logan, 2013). For the laser keyboard, post-error slowing dissipated slowly after an error, indicating a strategic adjustment that was intended to prevent further errors (Crump & Logan, 2013). The sustained pattern with the laser keyboard reflects the involvement of the outer loop in monitoring keystroke errors. One of our ongoing projects tested and confirmed the involvement of the outer loop in monitoring keystrokes with the laser keyboard. We have not yet published those results, so we will not discuss them further.

The present study did not examine the role of associations between letters and keys for skilled typewriting. These associations support another component of the inner loop control that remained intact in the present study: the selection of keystrokes for each letter. We suggest that these associations might support motor chunking. Future studies are needed to address the role of letter-key associations in skilled typewriting.

On the Constituents of Chunks in Skilled Typing

The present study provided several indications of chunking in skilled typing that depended on the typing material. There was a clear advantage of words over nonwords, suggesting that chunking differed between materials, but the results do not reveal the constituents of chunking. The nonwords we used scrambled the order of letters in words, and that destroys sequential dependencies between letters and positional frequencies of letters as well as the meaningful form of words. Thus, we cannot distinguish between several possible constituents of chunks in skilled typing, such as syllables, morphemes, and digraphs. Previous studies have indicated that some of these constituents contribute to typing performance (e.g., Fendrick, 1937; Gentner et al., 1988; Inhoff, 1991; Shaffer & Hardwick, 1970; West & Sabban, 1982), but these studies do not indicate the level of processing at which these factors affect typing.

Logan and Crump (2011) assumed that words are single chunks in the outer loop. However, we found that typing words sometimes produced a string length effect, which suggests that the number of motor chunks may be larger for longer words than for shorter words or larger for unfamiliar words than for familiar ones. Also, the string length effect for words may be due to the size of the motor chunks rather than the number of motor chunks (Klapp, 1995; Wright et al., 2004).

We found a string length effect in IKSI for nonwords (also see Sternberg et al., 1978; Verwey, 1996; Verwey, Eikelboom, 2003; Rhodes et al., 2004), which bears on the nature of chunking in nonwords. The string-length effect may reflect increased time in retrieving motor chunks from a buffer (Sternberg et al., 1978) or the segmentation of an unfamiliar sequence into multiple groups (e.g., Verwey, 2003; Verwey & Eikelboom, 2003). In either case, typing nonwords may involve units that are intermediate between single words and single letters (e.g., syllables, digraphs, etc.). This possibility is left for future investigations.

Concluding Remarks

In the present study, we considered three types of association that support skilled typewriting and manipulated two types: associations between words and letters, and associations between keys and finger movements. We disabled associations between words and letters by scrambling letter orders, and found that is critical in chunking in perception, short-term memory, and motor planning. Thus, typing familiar words is special, compared to typing unfamiliar nonwords. We also disabled associations between keys and finger movements by altering the haptic feedback that the inner loop relies on by using the laser keyboard. Typing was much slower and less accurate with the laser keyboard, but altering haptic feedback did not disable chunking in any of the three processes. These results suggest that associations between words and letters underlie skilled typing and support hierarchical control, whereas associations between keys and finger movements are not important for hierarchical control. Future research will reveal whether the third type of association, that between letters and keys, contributes to the hierarchical control of skilled typewriting.

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Appendix A

Word and Nonword Lists Used in the Present Study

Table A1. Word Stimuli Used in Experiments 1-4.

3 Letters									
ACT	BED	CUP	FAN	GYM	JOG	MUD	PEW	RYE	TIN
AGE	BEG	CUT	FAR	HAM	JOY	MUG	PIE	SAD	TIP
AID	BET	DAD	FAT	HAT	JUG	NET	PIG	SAP	TOE
AIM	BID	DAY	FEE	HAY	KEY	NEW	PIN	SEA	TON
AIR	BIG	DIE	FEW	HEN	KID	NOD	PIT	SEE	TOP
ALE	BIN	DIM	FIR	HOG	LAP	NOW	POT	SEX	TOW
ANT	BIT	DIP	FLY	HOP	LAW	NUN	PUP	SIN	TOY
APE	BOW	DOG	FOE	HOT	LAX	OAK	PUT	SIT	TRY
ARC	BOX	DOT	FOG	HUE	LAY	OAT	RAP	SKI	TWO
ARK	BOY	DRY	FOX	HUT	LED	OFF	RAT	SKY	URN
ARM	BRA	DYE	FUN	ICE	LEG	OIL	RAW	SOB	VAN
ART	BUD	EAR	FUR	INK	LIE	OLD	RAY	SON	VET
ASH	BUY	EAT	GAS	INN	LIP	OUT	RED	SUE	VOW
AXE	CAN	EEL	GEM	ION	LOG	OWL	RIB	SUM	WAR
AYE	CAP	EGG	GET	IVY	MAD	PAN	RIM	SUN	WAX
BAD	CAR	EGO	GIG	JAM	MAN	PAT	ROB	TAP	WAY
BAG	CAT	ELF	GIN	JAR	MAP	PEA	ROD	TAR	WEB
BAR	COW	ELM	GOD	JAW	MAT	PEG	ROE	TAX	WET
BAT	CRY	END	GUN	JET	MAY	PEN	RUG	TEA	WIG
BAY	CUE	EYE	GUY	JOB	MOP	PET	RUM	TIE	WIN
4 Letters[a]									
ABLE	CAMP	DEAR	FILM	HAZE	LAMB	ONCE	SCUD	TAKE	USER
AREA	CANE	DEEP	FISH	HELD	LAST	PART	SEAT	TALK	VARY
AURA	CART	DEFT	FIST	HELP	LESS	PATH	SECT	TAME	VEIN
BABE	CELL	DISC	FOLD	HERO	LIVE	PECK	SEEK	TAPE	VINE
BALD	CHEF	DISK	FOOL	HIDE	LOCK	PICK	SEND	TAXI	WAIT
BALL	CHEW	DOES	FOUL	HILL	LOOT	PILL	SHOE	THEM	WARE
BARE	CLAD	DONE	FRAY	HINT	LUCK	POEM	SIZE	THUD	WEAR
BEAM	CLAN	DOOM	GAIN	HOLD	LULL	POND	SLID	TIDE	WERE
BELT	CLUE	DRIP	GALE	HOUR	MEAT	PREY	SLIM	TILT	WHOM
BITE	COIN	DROP	GALL	IRIS	MEET	PUNK	SLIP	TIRE	WILD
BOLD	COST	DUCT	GASH	IRON	MERE	PUTT	SNOW	TOIL	WINE
BOND	COVE	DUDE	GATE	JILL	MILE	RACK	SODA	TONE	WINK
BRAN	CREW	DUKE	GLAD	JUMP	MOCK	RAGE	SOFA	TOSS	WIRE

BREW
BULB
BULK
BUNK
BURN
CAGE
CAME
CROW
CURE
DAME
DARK
DART
DATE
DEAL
DUST
EACH
EARN
EPIC
FACE
FEET
FEUD
HAIL
HAIR
HALL
HALO
HANG
HARD
HAWK
JURY
KEEP
KICK
KNEE
KNOB
KNOW
LACK
MORE
MUCK
NEAR
NICE
NINE
OBEY
OILY
RATE
RIND
RISE
RODE
ROOM
SAID
SAME
SOLD
SOME
SOON
SOOT
STAR
STAY
SWAP
TOWN
TRAP
TRAY
TREE
TRIM
TYPE
UGLY
WISH
WOOD
WORK
WORN
WRAP
WREN
YELL

5 Letters

AISLE
ALGAE
ALIEN
ALLEY
AMUSE
ANGLE
ANKLE
ARGUE
ARMOR
AUDIT
AWAIT
BASIC
BASIN
BATON
BEGAN
BELOW
BIBLE
BIRTH
BISON
BLUNT
BOARD
BRUTE
BUILD
BUNCH
BUYER
CANAL
CAROL
CAUSE
CHAIR
CHAOS
CLASP
CLEAN
CLOSE
COAST
COLOR
COMES
CRANK
DEATH
DECOY
DIRTY
DONOR
DOUGH
DREAM
EASEL
EAVES
ELBOW
EQUAL
ESSAY
FABLE
FALSE
FAULT
FIGHT
FINAL
FIRST
FLAME
FLOOD
FLOOR
FLORA
FORCE
FRAIL
FRAME
FRESH
GAUDY
GEESE
GLORY
GRATE
GRIEF
GUESS
GUEST
HAPPY
HAVOC
HONEY
HORSE
JUICE
KNOWN
LAUGH
LEARN
LEASE
LEVER
LINKS
LITER
MERIT
METAL
MIMIC
MINER
MONEY
MOTOR
MOUSE
MOUTH
MUDDY
NASTY
NERVE
NEVER
NIGHT
NOISY
NOVEL
NURSE
OLDER
ONION
OPIUM
ORDER
ORGAN
PAINT
PANIC
PAPER
PARTY
PEACH
PEDAL
PENNY
PHONE
PLACE
PLANE
PLANT
PLEAD
POINT
PORCH
POWER
PRIME
PRIOR
QUAIL
QUAKE
QUILT
RABBI
RANCH
RAZOR
RHYME
RIFLE
RIGHT
ROUGH
ROUND
SANDY
SAUCE
SCALE
SCENE
SENSE
SHEEP
SHEER
SHELL
SHIRT
SHOCK
SHOWN
SIEGE
SINCE
SKATE
SKULL
SLEPT
SLICE
SLIDE
SLOPE
SMACK
SMELL
SPADE
SPEAK
SPICE
SPRAY
STAIR
STALK
STEAK
STILL
STING
STORE
STRAW
STRUT
SWAMP
TALLY
TENSE
THING
THINK
THREE
THUMB
TIGER
TITLE
TOUGH
TRACE
TRADE
TRASH
TRIED
TRUCK
TULIP
TWIST
UNION
UNITE
URBAN
USUAL
VAULT
VENOM
WAIVE
WATCH
WATER
WHEEL
WHERE
WHIFF
WHITE
WITCH
WOMAN
WORSE
WORTH
WOULD
WOUND
YOUTH

[a] 4-letter words were not used in Experiments 2 and 4.

Table A2. Nonword Stimuli Used in Experiments 1-3.

3 Letters									
ACR	CEU	EEF	GWI	MSU	NTI	PPU	TAH	VTA	YAB
ADB	CTU	EES	HRA	MYA	NTO	PRA	TBI	VYI	YAE
AES	DAS	EEY	HSA	MYG	NUF	PTI	TDO	WAJ	YDA
AET	DBI	EGB	IAR	NCA	NUS	RBA	TEJ	WFE	YED
AGS	DBU	EHU	IET	NDE	NVA	RBO	TEO	WLA	YEK
AMH	DDA	FFO	ILE	NGI	NWI	RDA	TEV	WLO	YGU
ANF	DEO	GBA	IMA	NGU	OBJ	REO	TFA	WNE	YHA
APL	DFA	GDO	IMR	NHE	ODG	RFU	TGE	WNI	YJO
APM	DIK	GEA	JMA	NIB	OEG	RGU	THU	WOB	YLA
APN	DLE	GEP	KAE	NIO	OFE	RIF	TIS	WOC	YLF
ARF	DMA	GFO	KAR	NKI	OTH	RJA	TMA	WOT	YOB
ARH	DMU	GGE	KIS	NMA	OTP	RMU	TNE	WOV	YOT
ATB	DNO	GGI	KOA	NNI	OWT	RTA	TPA	WPE	YRA
ATO	DOL	GHO	KYS	NNU	PCA	RTE	TPE	WRA	YRC
AXL	DRE	GIP	LFE	NPE	PCU	RWA	TPI	XAW	YRD
BGI	DRO	GJO	LIO	NPI	PDI	RYA	TPO	XEA	YRE
BIR	EAO	GJU	LME	NRU	PEI	RYT	TPU	XOB	YUB
BSO	EAP	GLE	LRE	NSI	PHO	SEU	TSV	XOF	YWA
BTE	EBW	GLO	MDI	NSO	PLI	SRE	TWE	XSE	ZPS
CEI	EDB	GMU	MGE	NTA	PMO	TAE	UTO	XTA	ZPT
4 Letters[a]									
ABDL	DERO	FASO	KDIS	LIOT	MTHE	NWEI	RHAI	STEA	TSRA
ACTR	DFUE	FECA	KLTA	LJLI	NAEC	NWSO	RIWE	STOS	UDED
AEAR	DHEI	FHEC	KLUC	LKBU	NBAR	OMOR	RMIT	TAED	UTCD
ASME	DHRA	FHSI	KNIW	LLBA	NBKU	PDIR	RNBU	TAEP	VOEC
BAML	DILW	FLOO	KPEC	LLGA	NCOE	PEHL	RNEW	TAPR	WATI
BBAE	DKEU	GELA	KSEE	LLIH	NCOI	PJUM	RODP	TARD	WBRE
BEIT	DLAC	GERA	KWOR	LLLU	NDSE	PKEE	ROWC	TDSU	WHEC
BEOY	DLSI	GNIA	LADE	LLYE	NEIV	PLIL	RPWA	TEAG	WNOK
BKON	DMEA	HESO	LADG	LNAC	NEKE	PMAC	RSIE	TELB	WRAE
BLBU	DMOO	HKWA	LALH	LODF	NEVI	PTAR	RTEE	TEMA	WSAP
CDSU	DNEO	HLED	LBAE	LPIS	NGHA	RAEB	RUHO	TFED	XAIT
CEHA	DOLH	HLIA	LCEU	LTTI	NIEC	RAUA	RWEE	TFEE	YLOI
CGEA	DONP	HPTA	LCLE	LVEI	NITH	RCEW	SCDI	TMEE	YPET
CIKP	DOWO	HSWI	LDOB	LYUG	NNIE	REAN	SERU	TOLO	YRAF
CIPE	DPEE	HWMO	LDSO	MCEA	NOET	REAW	SHGA	TOOS	YRUJ
COKL	DRAK	IRNO	LEIM	MCKU	NOWT	RECU	SIIR	TPUT	YSTA
CRAK	DSIA	KAET	LFMI	MEBA	NRDI	REEM	SITF	TREA	YTRA

DASO	DTEI	KCIK	LFUO	MPOE	NREA	REHO	SLSE	TSCE	YVRA
DBNO	DUTH	KCLA	LHOA	MSEO	NROW	RETI	SODE	TSLA	ZEAH
DERA	ERMO	KCMO	LIMS	MTAE	NUKP	REYP	SONO	TSOC	ZIES
5 Letters									
AEESV	CPLEA	GESTU	KNACR	LOSEP	NAYDS	OOMRT	RLTIE	SRTIA	UKRTC
AETCR	CSELA	GETRI	KRTUC	LRFAI	NCELA	ORWPE	ROALF	STCOA	UQALE
AICBS	CSENE	GIRTH	KSEAP	LRIEF	NDOUW	OTHUY	ROFLO	SYION	USNER
AITAW	CWHTI	GNHTI	KWEAU	LSEIM	NEESS	PCEIS	ROPRI	TAKSL	VENER
AKSTE	DHUGO	GTHFI	LAEGN	LSPAC	NEIAL	PEALD	RPAEP	TAPIN	VNERE
ALNAC	DRORE	GURAE	LAYTL	LTNBU	NESET	PEONH	RTEAW	TBERU	VOACH
AOCSH	DRTEI	HCPEA	LCOAR	LTUQI	NHCBU	PPYAH	RTEHE	TDERA	VRLEE
APLTN	DTUIA	HEDAT	LDUWO	LUAIQ	NHYOE	PTULI	RUTTS	TLEPS	VWEAI
ASEDP	DYDUM	HESRF	LEAES	LUUAS	NIFLA	QAELU	RYOGL	TMEIR	WBEOL
ASKMC	EPDLA	HGUAL	LEHEW	LVEON	NINOO	RANLE	SBION	TOWHR	WETHI
ASTWR	EPMIR	HITGN	LESID	LYELA	NLSIK	RAODB	SCEOM	TPOIN	WIFFH
BIARB	ERYHM	HITRB	LFEAM	MAWON	NNOWK	RAROM	SEEGI	TRESO	WMAPS
BLIEB	ESALE	HNTKI	LFODO	MEADR	NOAGR	RAYTP	SELAF	TRSHI	WOBLE
CAESU	EUCAS	HOSNW	LFUTA	MEALT	NOIUN	RCOOL	SERHO	TSFIR	YASRP
CHIRA	FALEB	HPESE	LHLES	MEONV	NSECI	RDOON	SESUG	TSNGI	YBERU
CHPRO	FEMRA	HUTOM	LISEC	MIPUO	NSIBA	RDYIT	SEYAS	TTELI	YCODE
CMIIM	FIGRE	HWACT	LIUDB	MRENI	NSUER	REEWH	SLEIA	TTWIS	YOMEN
CNAIP	GABEN	KAEST	LLSTI	MSAEU	NTOAB	REFCO	SNYAT	TUENI	YPNEN
CNHRA	GELAA	KCHSO	LNEPA	MUTBH	OESUM	RETGA	SREHE	UETBR	YUGDA
COESL	GESEE	KEALN	LODRE	NAURB	OGUHR	RHTAS	SREWO	UGOHT	ZARRO

[a] 4-letter nonwords were not used in Experiment 2.

Table 1. ANOVA Results for Response Times (RT), Interkeystroke Interval (IKSI), and Percentage Errors (PE) in Experiment 1.

Factor	*df*	*F*	*MSE*	*p*	η_p^2
			RT		
Stimulus Quality (SQ)	1, 23	129.07	1,071	< .001	.849
Stimulus Type (ST)	1, 23	277.62	4,933	< .001	.923
String Length (SL)	2, 46	66.14	881	< .001	.742
SQ x ST	1, 23	4.17	857	.053	.153
SQ x SL	2, 46	1.26	886	.293	.052
ST x SL	2, 46	20.91	554	< .001	.476
SQ x ST x SL	2, 46	2.76	621	.074	.107
			IKSI		
SQ	1, 23	13.89	201	.001	.377
ST	1, 23	188.28	836	< .001	.891
SL	2, 46	45.26	186	.001	.663
SQ x ST	1, 23	4.87	104	.038	.175
SQ x SL	2, 46	3.37	76	.043	.128
ST x SL	2, 46	51.54	110	< .001	.691
SQ x ST x SL	2, 46	2.53	63	.091	.099
			PE		
SQ	1, 23	9.72	11.98	.005	.297
ST	1, 23	110.49	8.57	< .001	.828
SL	2, 46	39.23	9.81	< .001	.630
SQ x ST	1, 23	7.48	11.85	.012	.246
SQ x SL	2, 46	<1	15.56	.925	.003
ST x SL	2, 46	<1	17.55	.616	.021
SQ x ST x SL	2, 46	<1	15.40	.662	.018

Table 2. ANOVA Results for Percent Recall Errors (PE_{recall}), Response Times (RT), Interkeystroke Interval (IKSI), and Percent Typing Errors (PE_{typing}) in Experiment 2.

Factor	*df*	*F*	*MSE*	*p*	η_p^2
			PE_{recall}		
Stimulus Type (ST)	1, 23	83.63	76.35	< .001	.784
Memory Load (ML)	1, 23	77.51	219.86	< .001	.771
String Length (SL)	1, 23	103.88	45.48	< .001	.819
ST x ML	1, 23	37.56	54.41	< .001	.620
ST x SL	1, 23	61.36	35.30	< .001	.727
SL x ML	1, 23	22.49	28.98	< .001	.494
ST x ML x SL	1, 23	6.45	24.75	.018	.219
			RT		
ST	1, 23	51.17	2,307	< .001	.690
ML	1, 23	30.07	25,732	< .001	.567
SL	1, 23	1.26	3,021	.273	.052
ST x ML	1, 23	18.03	1,835	< .001	.439
ST x SL	1, 23	5.65	2,382	.026	.197
SL x ML	1, 23	1.50	1,697	.233	.061
ST x ML x SL	1, 23	<1	1,714	.697	.007
			IKSI		
ST	1, 23	158.79	432	< .001	.873
ML	1, 23	<1	1,572	.330	.041
SL	1, 23	34.16	429	< .001	.598
ST x ML	1, 23	6.06	93	.022	.209
ST x SL	1, 23	42.75	163	< .001	.650
SL x ML	1, 23	2.55	191	.124	.100
ST x ML x SL	1, 23	<1	176	.545	.016
			PE_{typing}		
ST	1, 23	52.82	56.67	< .001	.697
ML	1, 23	50.4	22.66	< .001	.687
SL	1, 23	73.38	49.23	< .001	.759
ST x ML	1, 23	53.35	22.15	< .001	.699
ST x SL	1, 23	25.52	46.23	< .001	.526
SL x ML	1, 23	23.32	19.27	< .001	.503
ST x ML x SL	1, 23	27.42	15.30	< .001	.544

Table 3. ANOVA Results for Response Times (RT), Interkeystroke Interval (IKSI), and Percentage Errors (PE) in Experiment 3.

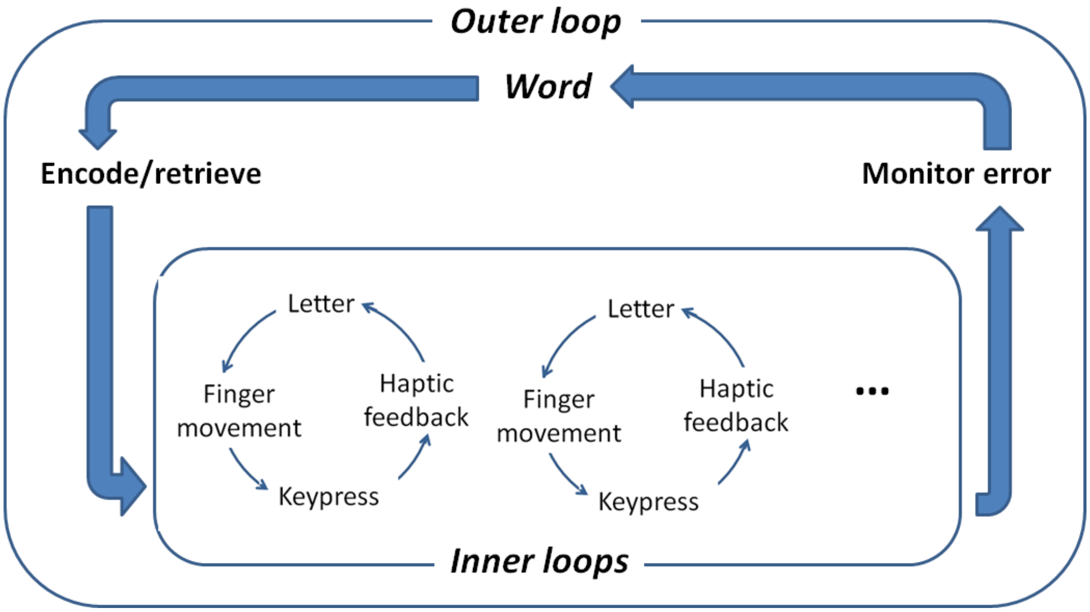
Factor	*df*	*F*	*MSE*	*p*	η_p^2
			$\text{PE}_{\text{recall}}$		
Keyboard Type (KT)	1, 23	4.52	35.32	.044	.164
Memory Load (ML)	1, 23	51.08	170.31	< .001	.690
String Length (SL)	1, 23	33.39	17.50	< .001	.592
KT x ML	1, 23	<1	28.77	.554	.015
KT x SL	1, 23	<1	34.27	.648	.009
SL x ML	1, 23	11.2	17.18	.003	.327
KT x ML x SL	1, 23	<1	20.39	.608	.012
			RT		
KT	1, 23	64.78	36,346	< .001	.738
ML	1, 23	71.07	26,741	< .001	.756
SL	1, 23	<1	1,800	.687	.007
KT x ML	1, 23	12.82	12,052	.002	.358
KT x SL	1, 23	<1	874	.472	.023
SL x ML	1, 23	<1	1,294	.676	.008
KT x ML x SL	1, 23	<1	2,716	.761	.004
			IKSI		
KT	1, 23	233.74	6,305	< .001	.910
ML	1, 23	3.02	1,124	.095	.116
SL	1, 23	10.00	350	.004	.303
KT x ML	1, 23	1.99	521	.171	.080
KT x SL	1, 23	20.59	438	< .001	.472
SL x ML	1, 23	1.85	207	.188	.074
KT x ML x SL	1, 23	1.97	208	.174	.079
			$\text{PE}_{\text{typing}}$		
KT	1, 23	30.79	158.23	< .001	.572
ML	1, 23	3.61	28.85	.070	.136
SL	1, 23	87.63	23.71	< .001	.792
KT x ML	1, 23	<1	36.57	.759	.004
KT x SL	1, 23	11.48	32.78	.003	.333
SL x ML	1, 23	<1	21.81	.860	.001
KT x ML x SL	1, 23	<1	27.76	.702	.006

Table 4. ANOVA Results for Percent Recall Errors (PE_{recall}), Response Times (RT), Interkeystroke Interval (IKSI), and Percent Typing Errors (PE_{typing}) in Experiment 4.

Factor	*df*	*F*	*MSE*	*p*	η_p^2
			RT		
Keyboard Type (KT)	1, 23	291.78	26,704	< .001	.927
Stimulus Type (ST)	1, 23	152.19	5,938	< .001	.869
String Length (SL)	2, 46	45.4	1,511	< .001	.664
KT x ST	1, 23	<1	2,077	.666	.008
KT x SL	2, 46	6.32	1,435	.004	.216
ST x SL	2, 46	16.71	1,090	< .001	.421
KT x ST x SL	2, 46	4.40	1,169	.018	.160
			IKSI		
KT	1, 23	176.11	21,185	< .001	.884
ST	1, 23	77.32	1,460	< .001	.771
SL	2, 46	25.03	487	< .001	.521
KT x ST	1, 23	5.22	568	.032	.185
KT x SL	2, 46	<1	384	.718	.014
ST x SL	2, 46	48.82	261	< .001	.680
KT x ST x SL	2, 46	11.27	336	< .001	.329
			PE		
KT	1, 23	44.51	197.04	< .001	.659
ST	1, 23	2.90	34.42	.102	.112
SL	2, 46	41.06	20.57	< .001	.641
KT x ST	1, 23	5.63	30.26	.026	.197
KT x SL	2, 46	7.17	34.48	.002	.238
ST x SL	2, 46	<1	24.19	.856	.007
KT x ST x SL	2, 46	<1	18.56	.473	.032

Figure 1. The two-loop theory of skilled typewriting: (a) schematic illustrations of control loops, and (b) processing units in the outer loop and the inner loop.

(a)



(b)

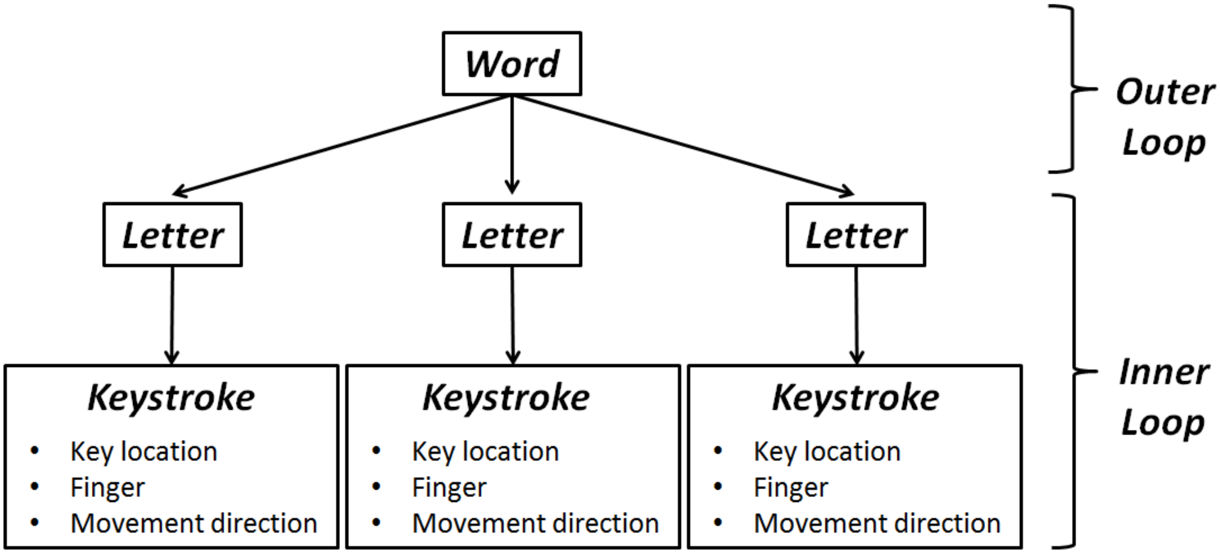


Figure 2. Hierarchical and non-hierarchical control of typing performance.

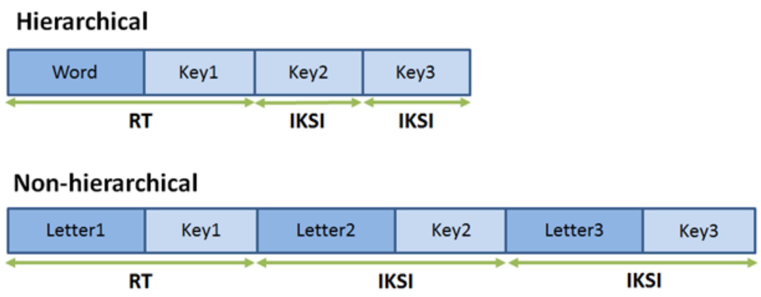


Figure 3. Examples of masked stimuli used in Experiment 1.

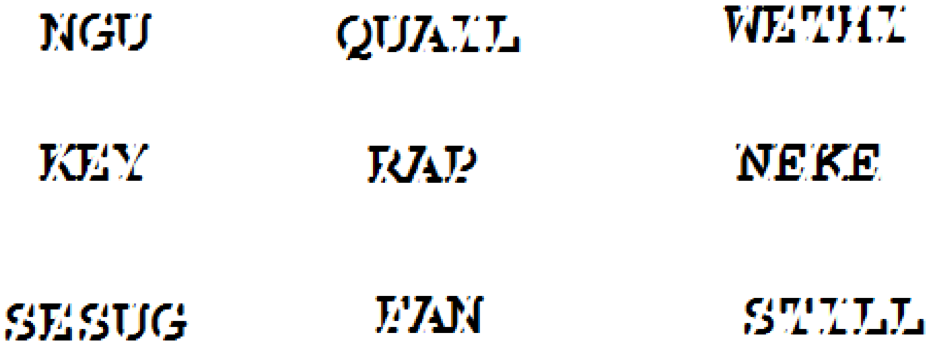


Figure 4. Mean response times (RT), interkeystroke interval (IKSI), and percentage errors (PE) in Experiment 1 (error bars represent standard errors of the means).

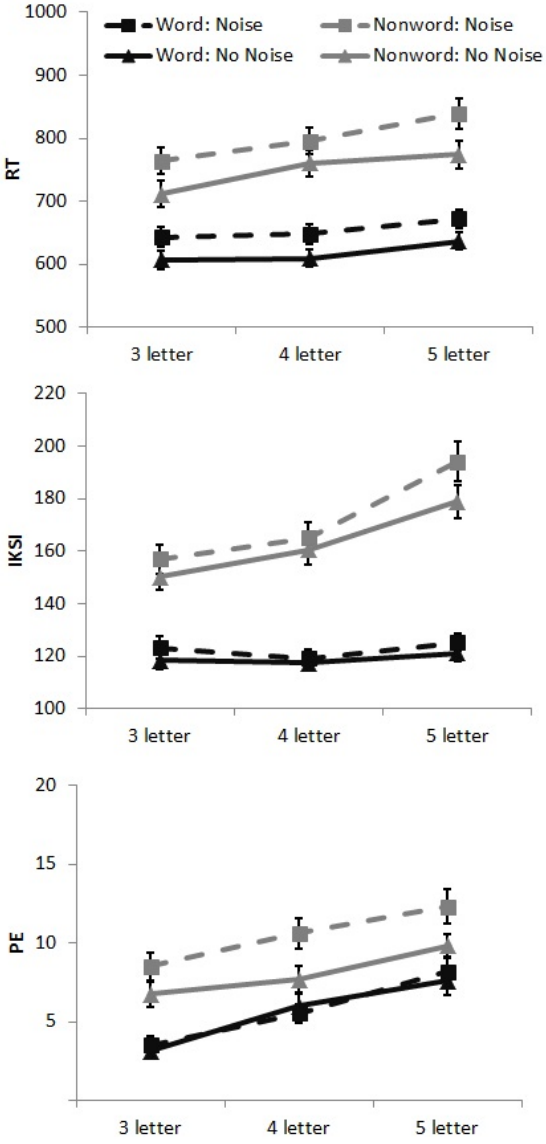


Figure 5. Mean percentage errors in recall ($\text{PE}_{\text{recall}}$), percentage errors in typing ($\text{PE}_{\text{typing}}$), response times (RT), and interkeystroke interval (IKSI) in Experiment 2 (error bars represent standard errors of the means).

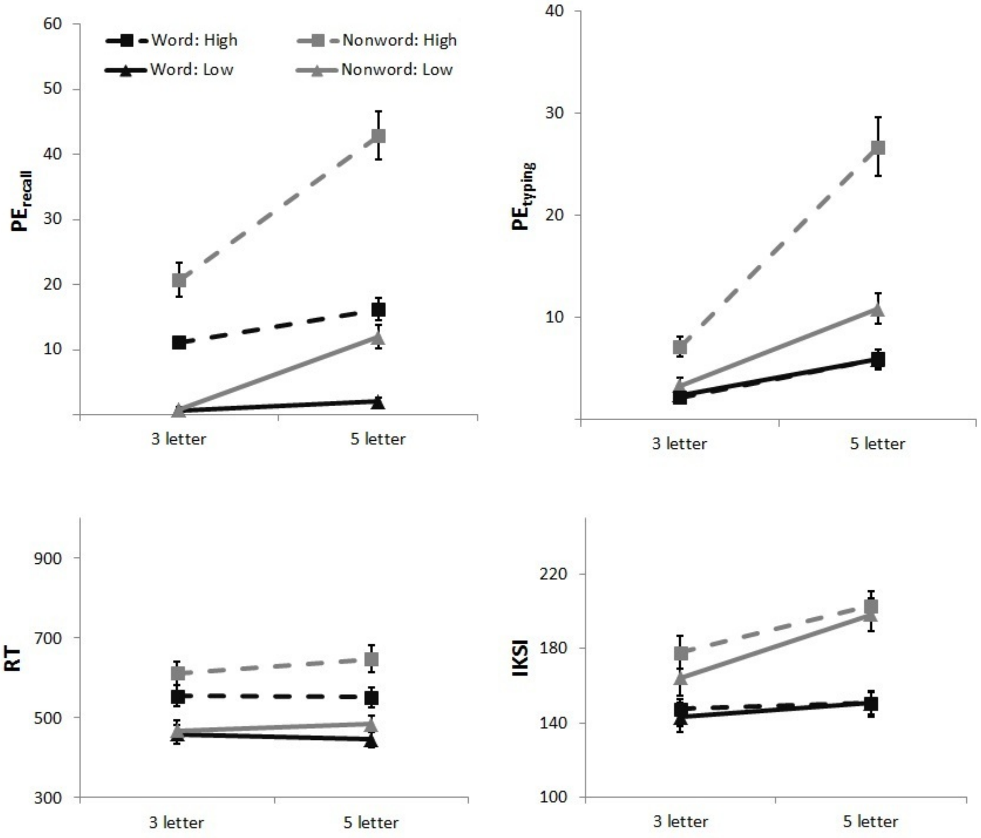


Figure 6. Mean response times (RT), interkeystroke interval (IKSI), and percentage errors (PE) in Experiment 3 (error bars represent standard errors of the means).

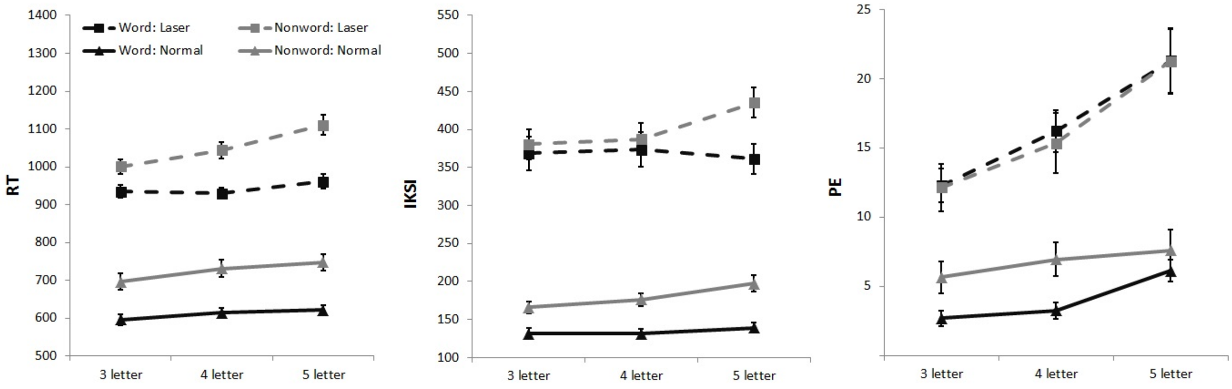


Figure 7. Interkeystroke interval (IKSI) for error trials as a keystroke position relative to the first error keystroke (E = error keystroke; E–*n* = *n* keystrokes before the error; E+*n* = *n* keystrokes after the error: error bars represent standard errors of the means).

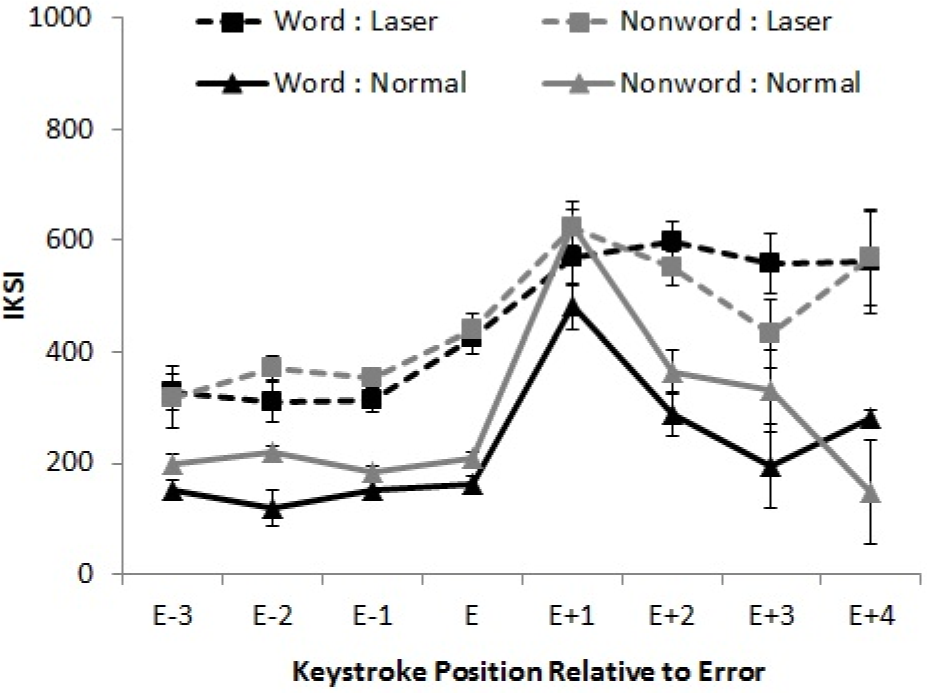


Figure 8. Mean percentage errors in recall (PE_{recall}), percentage errors in typing (PE_{typing}), response times (RT), and interkeystroke interval (IKSI) in Experiment 4 (error bars represent standard errors of the means).