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Pushing Typists Back on the Learning Curve: Memory Chunking in the Hierarchical Control of Skilled Typewriting

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Hierarchical control of skilled performance depends on the ability of higher level control to process several lower level units as a single chunk. The present study investigated the development of hierarchical control of skilled typewriting, focusing on the process of memory chunking. In the first 3 experiments, skilled typists typed words or nonwords under concurrent memory load. Memory chunks developed and consolidated into long-term memory when the same typing materials were repeated in 6 consecutive trials, but chunks did not develop when repetitions were spaced. However, when concurrent memory load was removed during training, memory chunks developed more efficiently with longer lags between repetitions than shorter lags. From these results, it is proposed that memory chunking requires 2 representations of the same letter string to be maintained simultaneously in short-term memory: 1 representation from the current trial, and the other from an earlier trial that is either retained from the immediately preceding trial or retrieved from long-term memory (i.e., study state retrieval).

Keywords: skill acquisition, chunking, spacing effect, concurrent memory load, typing

Although computer technologies have made automation of complex tasks possible, many human activities still require expert skills. The acquisition of these skills depends on extended training, and the nature of the acquisition process remains of great interest in educational and professional contexts as well as in ordinary households. For instance, schoolchildren spend much of their days learning new skills, such as numeracy and literacy skills, that will be the bases of their success in the future. One such basic skill that has become prevalent in modern society is typewriting. Many aspects of everyday activities rely on computers that require typing on a keyboard. In industrialized countries, people start typing at the age of 10 or younger and have about 10 years of experience by the time they enter college. In the United States, the majority of college students are highly skilled typists, having a semester of typing lessons and capable of typing at a rate of 70 words per minute on average (Logan & Crump, 2011). As much as typewriting is of practical importance for everyday activities, it has also been of interest to researchers, as it provides a useful test-bed for understanding the mechanisms underlying the acquisition and the control of skilled performance. Typewriting is particularly an ideal subject for the purpose of understanding the acquisition of complex motor skill, because of its prevalence and the amount of training. Therefore, the present study aimed at gaining the understanding of complex skills by investigating the process by which typing skill is acquired.

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Chunking in Hierarchical Control of Skilled Performance

Novice typists start with a typing method known as *hunt-and-peck*, by which they search the keyboard for an appropriate key and move a finger to the key location, typically using only the index fingers (Shaffer, 1986). This typing method requires deliberate effort to translate each letter to a keystroke. Skilled typists use a typing method known as *touch typing*, by which they use all fingers from both hands and navigate the fingers to the appropriate keys without looking at the keyboard. Skilled typing translates a group of letters into multiple keystrokes in parallel (Logan, Miller, & Strayer, 2011). This simultaneous activation of multiple keystrokes is made possible by hierarchically structured control processes in which different levels of processing divide the labor in typewriting (Logan & Crump, 2011; Rumelhart & Norman, 1982). A major challenge that typists face in transitioning from novices to experts is to acquire this hierarchical structure in the control system that enables concurrent processing of letters and keystrokes.

Although the notion of hierarchical control of expert skill goes back more than a century (Bryan & Harter, 1899), it has remained controversial in the contemporary cognitive science (Botvinick & Plaut, 2004; Cooper & Shallice, 2006; Elman, 1990). However, hierarchical control has been less controversial in the study of skilled typewriting (Logan & Crump, 2011; Rumelhart & Norman, 1982; Salthouse & Saults, 1987; Shaffer, 1975; Sternberg, Knoll & Turock, 1990). Skilled typing takes words as input (Fendrick, 1937; Shaffer & Hardwick, 1968; West & Sabban, 1982; Yamaguchi & Logan, 2014b; Yamaguchi, Logan, & Li, 2013) and produces a series of keystrokes that correspond to the letters in the word as output. Hence, input units have to be decomposed into several output units in the process of typing, implying a hierarchical structure in the underlying control processes.

Although the concept of hierarchical control has a long history, studies have not addressed the issue of how different levels of processing are interfaced. For instance, in skilled typewriting, the higher level processing forms an *outer loop* that operates on the word-level processing, whereas the lower level control forms an *inner loop* that operates on the letter- or keystroke-level processing (Logan & Crump, 2011). The interface between the two control levels requires a representation that bridges the two different processing units. This is achieved by chunking, whereby a single outer-loop unit (word) is mapped onto several inner-loop units (letters or keystrokes). Chunking in skilled typewriting depends on the knowledge of familiar words (Yamaguchi & Logan, 2014b). If skilled typists are required to type unfamiliar letter strings, the outer loop has to process each letter individually and their typing performance is degraded. Therefore, the development of chunks is an essential part of the acquisition of hierarchical control.

A previous study of ours (Yamaguchi & Logan, 2014b) utilized three manipulations to reveal chunking in perceptual, memory, and motor processes in skilled typewriting. At the perceptual stage, stimuli are compounds of perceptual elements that are processed separately at first and combined to form a unified representation at a later stage (McClelland & Rumelhart, 1981; Treisman & Gelade, 1980). Thus, the perceptual hierarchy involves a many-to-one mapping. At the motor stage, a coarse motor command is composed of finely tuned motor elements that are executed as a single unit as the coarse motor command (Klapp & Jagacinski, 2011; Schmidt, 1975). Thus, the motor hierarchy involves a one-to-many mapping. To close the perception-action link, the perceptual elements could be mapped one-to-one, directly onto the corresponding motor elements without chunks, but this creates a large cognitive load. The development of memory chunks bridges these input and output hierarchies and closes the perception-action link more economically without having to translate each perceptual element to the corresponding motor element.

Chunking of letters in words depends on the knowledge of the words; typists have to process letters in unfamiliar nonwords as separate chunks. Thus, typists are unable to utilize their typing skill when typing nonwords, which pushes typists back on the learning curve (Yamaguchi & Logan, 2014a, 2014b). The present study investigated the development of chunks by having typists type nonwords. Previous studies have provided evidence for the development of chunks in action sequences after extended practice in telegraphic encoding and decoding (Bryan & Harter, 1899) and novel keying sequences (Verwey, 1996). More recent studies demonstrated the development of chunks in skilled typewriting at the level of keystrokes (Ashitaka & Shimada, 2014; Yamaguchi & Logan, 2014a). The present study focused specifically on memory chunks in skilled typewriting.

The Present Study

In the present study, we used the concurrent memory load procedure (Yamaguchi & Logan, 2014b) to target memory chunks specifically. In this procedure, typists maintain a number of digits in short-term memory while typing, and they recall the digits later. The number of chunks that can be maintained in short-term memory is limited (Cowan, 2001; Miller, 1956), so concurrent memory performance depends on how many chunks have to be maintained in short-term memory in order to type a given typing material. When the typing material imposes a large short-term memory demand, concurrent memory performance would be worse when the typing material imposes a smaller short-term memory demand. Chunking reduces short-term memory demand (Miller, 1956), so concurrent memory performance should improve if the typing material is represented by fewer chunks. Our previous study showed that concurrent memory performance is better when typing words than when typing nonwords, even if the numbers of letters in words and nonwords is the same; concurrent memory performance also depends on the number of letters in nonwords, but not much by the number of letters in words (Yamaguchi & Logan, 2014b). These findings imply that words are represented by single chunks in short-term memory, and nonwords are represented by several chunks, perhaps one for each letter. The main purpose of the present study was to investigate the development of memory chunks by having typists type unfamiliar nonwords repeatedly under concurrent memory load (Experiments 1–3) or without concurrent memory load (Experiments 4 and 5).

The first two experiments were designed to establish the basic patterns of results for the development of memory chunks under a concurrent memory load; these experiments differed as to whether typing materials were repeated immediately (massed training) in Experiment 1 or with longer lags (spaced training) in Experiment 2. In Experiment 1, skilled typists typed words and nonwords under a concurrent memory load of five unique digits. The digits were recalled at the end of the trial to observe the amount of interference from typing. Digit strings were chosen randomly on each trial, but the same word or nonword was presented in six consecutive trials, providing a massed training condition. Shiffrin and his associates have found that perceptual chunks developed with five repetitions of the same nonwords (Feustel, Shiffrin, & Salasoo, 1983; Salasoo, Shiffrin, & Feustel, 1985). Experiment 1 tested whether six repetitions of the same nonword would produce memory chunks.

Experiment 2 was identical with Experiment 1, except that the same words and nonwords were presented on six trials that were distributed across different blocks, providing a spaced training condition. The average number of spaces between repetitions was 20 trials (Lag 20) or 60 trials (Lag 60). In both experiments, digit recall should become more accurate over six repetitions of the same nonwords if the nonwords get chunked with repetition. The accuracy of digit recall should remain unchanged across repetitions if the nonwords do not get chunked. For words, little change in digit recall would be expected over six repetitions, as the words are already chunked. In addition, learning is typically more efficient when there are more intervening trials between repetitions of the same study material, producing the *spacing effect* (for reviews, see Cepeda, Pashler, Vul, Wixted, & Rohrer, 2006; Hintzman, 1974; Ruch, 1928). Memory chunks should develop better with spaced repetitions of Experiment 2 than with massed repetitions of Experiment 1, and with longer lags than with shorter lags in Experiment 2.

Experiment 3 examined whether memory chunks are maintained only temporarily in short-term memory or are consolidated in long-term memory. A session was divided into the training phase and the test phase. The training phase was essentially the same as Experiment 1, in which typists typed words and nonwords under a concurrent memory load for six consecutive trials. After the training phase, there was a block of 120 intervening trials for which typists typed a new set of words and nonwords. This block was then followed by the test phase in which the trained set of words and nonwords were again presented under a concurrent memory load. If memory chunks are consolidated in long-term memory, they can be utilized after performing the intervening trials. Concurrent memory performance in the test phase should be at the same level as that on the later repetitions in the training phase, but should be better than that on the early repetitions if memory chunks are consolidated in long-term memory. If memory chunks are only transient, concurrent memory performance in the test phase should return to the level at the first repetition in the training phase.

Experiments 4 and 5 removed the concurrent memory task during training to examine the influence of a memory load on the development of memory chunks. Both experiments involved the training phase, in which typists typed words and nonwords without the concurrent memory task, and the test phase, in which they typed trained and new words and nonwords with the concurrent memory task to assess memory chunks. As in Experiment 2, the average numbers of intervening trials (lag) were varied across typing materials to examine the effect of spacing on the development of memory chunks. Experiment 4 compared the average lags of 20 and 60 trials (as in Experiment 2); Experiment 5 compared the average lag of 10 trials to immediate repetitions (Lag 0). The results of these experiments are contrasted to the findings in the first three experiments with concurrent memory load to evaluate the contribution of attention to the development of hierarchical control.

Experiment 1

The main purpose of the present experiment was to observe the development of memory chunks and provide a basis for the subsequent experiments. Skilled typists typed words and nonwords under a concurrent memory load of unique five digits on each trial. The influence of typing on concurrent memory performance (digit recall) indicates memory chunks in typing. Typing should interfere with concurrent memory performance more when it requires more memory chunks to be maintained in short-term memory. Hence, the development of memory chunks would be implied if digit recall improves over trials. The results of previous studies on sequence learning provide several possible outcomes. Some suggest that sequence learning does not take place under a secondary task demand (Nissen & Bullemer, 1987), but others indicate that it depends on a number of factors (Cohen, Ivry, & Keele, 1990; Frensch, Lin, & Buchner, 1998; Stadler, 1993, 1995). Thus, it is important to first demonstrate that memory chunks develop under a concurrent memory load in the present paradigm.

In addition to concurrent memory performance, the present experiment also examined typing performance. The task involved a discrete typing task, in which typists typed a single word or nonword on each trial. This task provided two typing measurements: response time (RT) and interkeystroke interval (IKSI). RT is the interval between onset of a word or nonword and the first keystroke. IKSI is the interval between successive keystrokes. According to the aforementioned two-loop theory (Logan & Crump, 2011), the outer loop first encodes a word and passes it to the inner loop, which decomposes the word into letters and translates the letters into keystrokes. Thus, the outer loop operates only once for each word before the first keystroke, whereas the inner loop operates for every single keystroke. Therefore, RT involves outer-loop processing (e.g., encoding a word or nonword) and one cycle of inner-loop processing (executing the first keystroke), and IKSI reflects one cycle of inner-loop processing (see also Yamaguchi, Logan, et al., 2013). In unskilled typing, IKSI would also involve outer-loop processing, as letters and keystrokes have to be processed in serial.

With the present concurrent memory procedure, it is difficult to interpret RT because typists first encoded typing materials and started typing them when a "go" signal occurred, which would allow outer-loop processing to be complete partly or fully before the start of RT. On the other hand, memory chunks should facilitate inner-loop processing, as they are required to retrieve letters and translate them into keystrokes in parallel (Crump & Logan, 2010; Logan, 2003; Logan et al., 2011). Thus, we expected that IKSI would decrease with more practice with nonwords. Note, however, that typing involves perceptual and motor chunks that may be learned at the same time as the memory chunks. These perceptual and motor chunks may be dissociable from memory chunks, so different patterns of results may be obtained between typing and concurrent memory performance (Yamaguchi & Logan, 2014b). The experiment focused primarily on memory chunking and concurrent memory performance.

Method

Subjects. Twenty-four typists were recruited from the Vanderbilt University community. They received either $12 or experimental credits toward their psychology courses for participation. All typists were required to be able to perform touch typing with the conventional finger placement on the QWERTY keyboard. All typists also reported having normal or corrected-to-normal visual acuity and having English as their native language. Their typing performance was assessed by using the typing test developed by Logan and Zbrodoff (1998), administered at the beginning of each session. They also filled out a questionnaire concerning their typing background. These data are summarized in Table 1, which shows similar typing backgrounds and skill levels across the five experiments.

Apparatus and stimuli. The apparatus consisted of a 19-in. color VGA monitor and a personal computer. For the concurrent memory task, stimuli were a string of five unique digits that were randomly chosen on each trial. The digits were presented in the Courier New font in 18 point and were arrayed horizontally at the center of screen. For the typing task, stimuli were words or nonwords consisting of three or five letters. There were 200 words for each string length, and the nonword stimuli were constructed

Table 1
Typing Backgrounds of Participant Typists (Values in Parentheses are Standard Deviations)

Experiment	Typing rate (WPM)	Typing accuracy (%)	Years of typing	Months of formal training	Hours per day using computer
1	77.42 (4.08)	94.46 (.80)	12.04 (.95)	6.48 (1.03)	4.33 (.39)
2	83.72 (3.16)	94.24 (.76)	12.92 (.65)	4.63 (.43)	4.35 (.52)
3	80.08 (3.76)	93.78 (.75)	13.65 (.67)	4.19 (.45)	4.65 (.53)
4	85.19 (3.63)	94.11 (.74)	12.79 (.63)	4.69 (.49)	4.08 (.43)
5	80.49 (2.72)	95.21 (.58)	11.54 (.57)	5.13 (.66)	3.81 (.40)

Note. WPM = words per minute.

by scrambling the order of letters in the word stimuli randomly (see Yamaguchi & Logan, 2014b). The word and nonword stimuli were printed in the 24-pt Courier New font in white against a black background. All letters were uppercase. Responses were registered by using a QWERTY keyboard; the backspace key was disabled so that typists were not able to correct their errors during the experiment.

Procedure. The experiment was conducted individually in a cubicle under normal fluorescent room lighting. Typists were seated in front of the computer monitor and read on-screen instructions. They first performed one block of 12 practice trials and three blocks of 120 test trials. On each trial, typists performed two tasks: a concurrent memory task, in which typists remembered a string of five unique digits and recalled later, and a typing task, in which typists typed a single word or nonword as quickly and as accurately as they could. The digit strings were chosen randomly on every trial. In the practice block, the same word or nonword stimulus appeared in three consecutive trials, whereas in the test blocks, the same word or nonword stimulus appeared in six consecutive trials. For each typist, there were 15 different words and nonwords each for the two string lengths, randomly chosen from the lists of 200 items.

At the beginning of each trial, typists were first presented with a word or nonword stimulus for 500 ms, followed by a 750-ms blank display. The stimulus occurred at the upper portion of the screen (6.5 cm above the screen center). Then, a string of five digits appeared at the center of screen for 1,000 ms, which were replaced by a 500-ms blank screen. Typists were prompted to start typing with a go signal ("GO") that also appeared at the screen center, printed in blue. The go signal was erased after 500 ms. As typists made keystrokes, typed letters were echoed at the lower portion of the screen (6.5 cm below the screen center) in lowercase. There was a 3,000-ms time window to complete typing the word or nonword. After the last keystroke (i.e., the third or fifth keystroke, depending on the number of letters in the word or nonword) was made, the typed letters stayed on the screen for 200 ms and were then erased, so that a blank display remained until the 3,000-ms time window elapsed. Typists were then prompted to enter the string of digits by the message "Enter the digits!" They used their right hand to enter digits on a standard number pad equipped to the right of the keyboard; they were given a 5,000-ms time window. The entered digits were also echoed at the same way as the letters for typing. As the fifth digit was entered or 5,000 ms elapsed, 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.

RT for typing was the interval between word or nonword onset and a depression of the first key. IKSI was the interval between two successive keystrokes. For the typing task, a trial was considered correct only if all letters were correctly typed in the correct order. For the memory task, a trial was considered correct only if all digits were entered in the correct order. Each of the six test blocks ended with a display of the accuracy scores for the two tasks, showing the percentages of correct responses in that block separately for the two tasks. An experimental session lasted less than an hour.

Results

Trials were discarded if either or both of the two responses were omitted or if RT was less than 200 ms (2.53% of all trials). Concurrent memory performance was examined in terms of percentages of error trials for digit recall (PE_{recall}), and typing performance was examined in terms of RT, IKSI, and percentage typing errors (PE_{type}). Figure 1 summarizes the results.

Development of memory chunks. Memory chunks were assessed in terms of concurrent memory performance; PE_{recall} should decrease as typing the same materials repeatedly requires fewer memory chunks.

Concurrent memory performance was generally better for words (M = 13.22%) than for nonwords (M = 23.11%), indicating that words were represented with fewer chunks than nonwords. String length affected concurrent memory load when typing nonwords (Ms = 15.26% vs. 30.95% for 3-letter and 5-letter nonwords, respectively), and it did to a smaller extent when typing words (Ms = 11.82% vs. 14.61%, for 3-letter and 5-letter words, respectively). The differences between typing words and typing nonwords was especially large in early repetitions (mean difference [MD] = 7.89% vs. 35.66% for 3-letter and 5-letter, respectively, for the first repetition), and the differences decreased in later repetitions (MD = 4.15% and 11.69% for 3-letter and 5-letter, respectively, in the sixth repetition; see Figure 1). These observations were supported statistically by a 2 (Typing Material: word vs. nonword) × 2 (String Length: 3-letter vs. 5-letter) × 6 (Trial Repetition: 1–6) ANOVA (see Table 2). The outcomes indicate that nonwords were represented with fewer chunks over repetitions, reducing short-term memory load.

Typing performance. RT, IKSI, and PE_{type} were also analyzed in terms of 2 (typing material: word vs. nonword) × 2 (string length: 3-letter vs. 5-letter) × 6 (trial repetition: 1–6) ANOVAs (see Table 2). Typing performance was expected to be better initially when typing words than when typing nonwords, but the

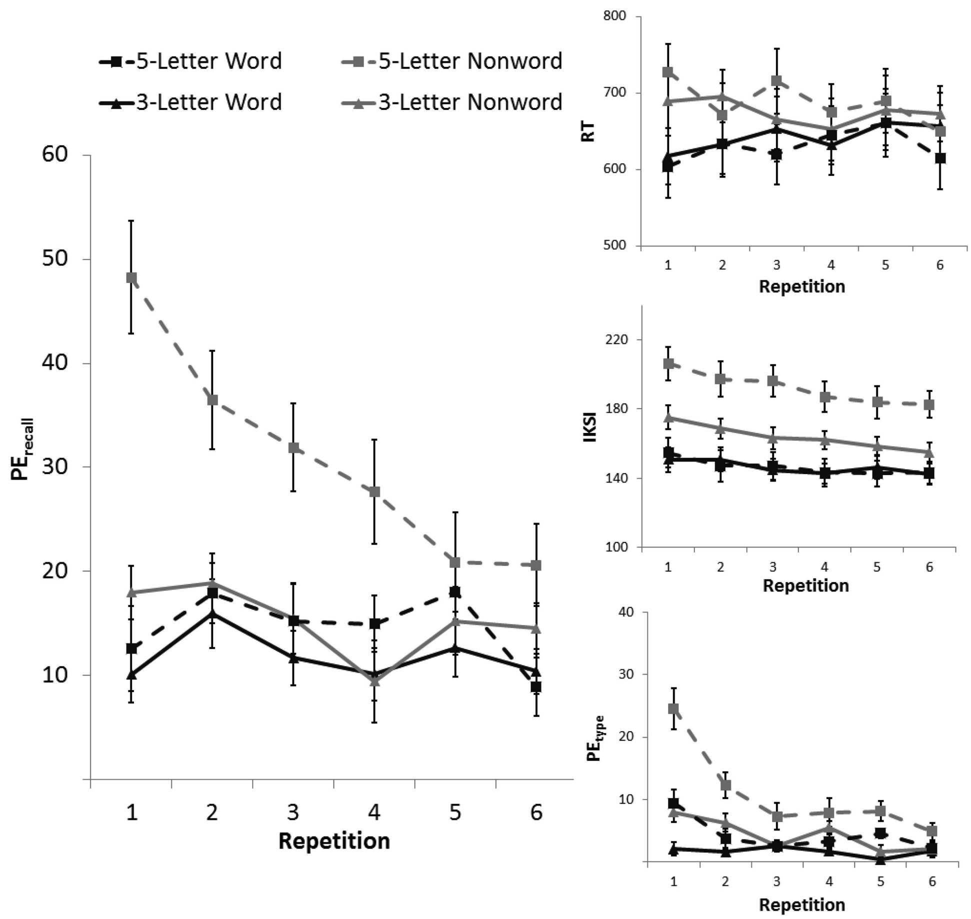

Figure 1. Percentage of error trials for the memory task (PE_{recall}) and response time (RT), interkeystroke interval (IKSI), and percentage of error trials (PE_{type}) for the typing task over six repetitions in Experiment 1 (error bars represent standard errors of the means).

differences between typing words and typing nonwords would decrease as memory chunks develop.

RT was shorter initially for words than for nonwords ($MD = 87$ ms in the first repetition), but the difference became smaller at later repetitions ($MD = 16$ ms in the sixth repetition). Some of the difference may have been absorbed into the waiting period between the presentation of the word or nonword and the go signal. IKSI also showed larger differences between words and nonwords at early repetitions ($MD = 39$ ms in the first repetition) than at later repetitions ($MD = 26$ ms in the six repetition). IKSI was shorter for 3-letter nonwords than for 5-letter nonwords ($MD = 30$ ms), but there was little difference between 3-letter and 5-letter words ($MD < 1$ ms). Overall, there was a steady decline in IKSI over repetitions (see Figure 1). Finally, PE_{type} was larger for nonwords than for words, but the difference decreased over repetitions ($MD = 10.48\%$ vs. 1.50% for the first repetition and the sixth repetition, respectively). Typing errors were more frequent for 5-letter nonwords than for 3-letter nonwords ($MD = 6.49\%$), which was also true for words but to a smaller extent ($MD = 2.62\%$). The error rates were generally smaller for 3-letter words and nonwords, but the error rates for 5-letter words and nonwords decreased more quickly over repetitions (see Figure 1).

Discussion

Concurrent memory performance was worse when typing nonwords than when typing words, and it depended on the length of nonwords more than on the length of words. These outcomes indicate that there are more memory chunks to be maintained in short-term memory when typing nonwords than when typing words (Yamaguchi & Logan, 2014b). One difference between typing words and typing nonwords is that typists can rely on their knowledge of the words, but they cannot do so for nonwords. Typing a word is guided by the preexisting memory chunk representing the word that is retrieved from long-term memory, but typing a nonword is guided by the preexisting memory chunks representing individual letters in the nonword. The present results also provided evidence that nonwords were represented with fewer memory chunks after six consecutive trials of typing. Concurrent memory performance was initially better when typing words than when typing nonwords, but the difference decreased over repetitions. These findings imply that nonwords were chunked after repeated trials. Typing performance (RT, IKSI, and PE_{type}) also improved over repetitions, which corroborated the results of concurrent memory performance. However, it should also be noted that the

Table 2
Results of ANOVAs on Percentage Error Trials for Digit Recall (PE_{Recall}), Response Time (RT), Interkeystroke Interval (IKSI), and Percentage Error Trials for Typing (PE_{Type}) in Experiment 1

Factor	*df*	*MSE*	*F*	*p*	η_p^2
			PE_{recall}		
Typing material (TM)	1, 23	325	43.32	<.001	.653
String length (SL)	1, 23	277	44.32	<.001	.658
Trial repetition (TR)	5, 115	142	8.55	<.001	.271
TM × SL	1, 23	268	22.32	<.001	.492
TM × TR	5, 115	162	6.30	<.001	.215
SL × TR	5, 115	188	3.05	.013	.117
TM × SL × TR	5, 115	175	2.86	.018	.111
			RT		
TM	1, 23	11,612	23.03	<.001	.500
SL	1, 23	17,079	<1	.743	.005
R	5, 115	10,356	<1	.444	.040
TM × SL	1, 23	10,390	2.17	.154	.086
TM × R	5, 115	6,433	2.91	.016	.112
SL × R	5, 115	9,018	1.43	.219	.058
TM × SL × R	5, 115	8,131	1.15	.340	.047
			IKSI		
TM	1, 23	1,373	107.39	<.001	.824
SL	1, 23	2,044	16.57	<.001	.419
TR	5, 115	209	17.53	<.001	.433
TM × SL	1, 23	1,210	27.37	<.001	.543
TM × TR	5, 115	227	3.23	.009	.123
SL × TR	5, 115	222	1.56	.176	.064
TM × SL × TR	5, 115	231	<1	.748	.023
			PE_{type}		
TM	1, 23	149	20.40	<.001	.470
SL	1, 23	68	43.72	<.001	.655
TR	5, 115	50	17.39	<.001	.431
TM × SL	1, 23	62	8.76	.007	.276
TM × TR	5, 115	48	5.85	<.001	.203
SL × TR	5, 115	46	7.85	<.001	.254
TM × SL × TR	5, 115	49	1.08	.375	.045

Note. df = degrees of freedom; MSE = mean squared error.

improvement of typing performance could reflect other types of learning (e.g., developing perceptual and motor chunks). Note that, in the present experiment, the same typing materials were repeated in six consecutive trials and they were never tested again later. It still remains to be tested as to whether these chunks were actually learned and consolidated in long-term memory for later use. This issue is addressed in Experiments 2 and 3.

Experiment 2

The present experiment asked whether memory chunks can develop when trials are distributed across blocks, rather than repeating consecutively. This modification results in spaced repetitions of typing materials, as opposed to massed repetitions in Experiment 1. Spacing is one of the most robust principles in the learning literature: Learning is more efficient when study items are presented with other items intervening between repetitions than when they are presented with no intervening items (Cepeda et al., 2006; Dempster, 1989; Hintzman, 1974; Ruch, 1928). Based on this principle, we expected that memory chunks would develop better when there are longer lags between repetitions. However, if memory chunks developed in Experiment 1 were only transient representations in short-term memory that resulted from consecutively repeating the same materials, concurrent memory performance should remain unchanged over repetitions at the longer lags in the present experiment.

In the present experiment, two different sets of words and nonwords were presented with different average lags between repetitions. One set of words and nonwords were repeated six times within two blocks of 60 trials; thus, there was the average lag of 20 trials (Lag 20). The other set of words and nonwords were repeated six times within six blocks; thus, there was the average lag of 60 trials (Lag 60). If a typical spacing effect is obtained, memory chunks would develop more efficiently with Lag 60 than with Lag 20. However, if memory chunks are only transient representations, they should not develop in the present experiment.

Method

Subjects. A new group of 24 touch-typists were recruited from the same subject pool (see Table 1).

Apparatus, stimuli, and procedure. Stimuli were digits and 5-letter words and nonwords, and the procedure closely followed that of Experiment 1, with the following modifications. Each typist performed one block of 12 practice trials and six blocks of 60 test trials. In each block, half trials required typing 5-letter words and the other half required typing 5-letter nonwords. For each stimulus type, half of the stimuli appeared only once in each of the six blocks; there were 60 trials between two repetitions for these stimuli (Lag 60) on average. The other half appeared three times in each of the two consecutive blocks (the first and second blocks, third and fourth blocks, or fifth and sixth blocks); there were 20 trials between two repetitions for these items (Lag 20) on average. All stimuli appeared six times in total.

Results

The same criteria as in Experiment 1 were used to filter out trials (4.32% of all trials were discarded). The results are summarized in Figure 2.

Development of memory chunks. Memory performance was better when typing words ($M = 16.46\%$) than when typing nonwords ($M = 34.85\%$), but there were no clear effects of repetition or lag. A 2 (typing materials: word vs. nonword) × 2 (lag length: Lag 20 vs. Lag 60) × 6 (trial repetition: 1–6 repetitions) ANOVA on PE_{recall} showed a significant main effect of typing material (see Table 3), supporting the better digit recall performance when typing words than nonwords. There was a significant interaction among the three factors and marginal main effects of lag length and trial repetition, but this outcome depended on a single data point (the second repetition with Lag 60 for nonword; see Figure 2); no effects emerged when this data point was removed, $ps > .1$, except the main effect of typing material, $F(1, 23) = 83.98$, $MSE = 472.04$, $p < .001$, $\eta_p^2 = .785$. The results indicate that memory chunks did not develop with spaced repetitions.

Typing performance. RT, IKSI, and PE_{type} were submitted to separate 2 (typing material: word vs. nonword) × 2 (repetition interval: Lag 0 vs. Lag 10) × 6 (trial repetition: 1–6) ANOVAs (see Table 3).

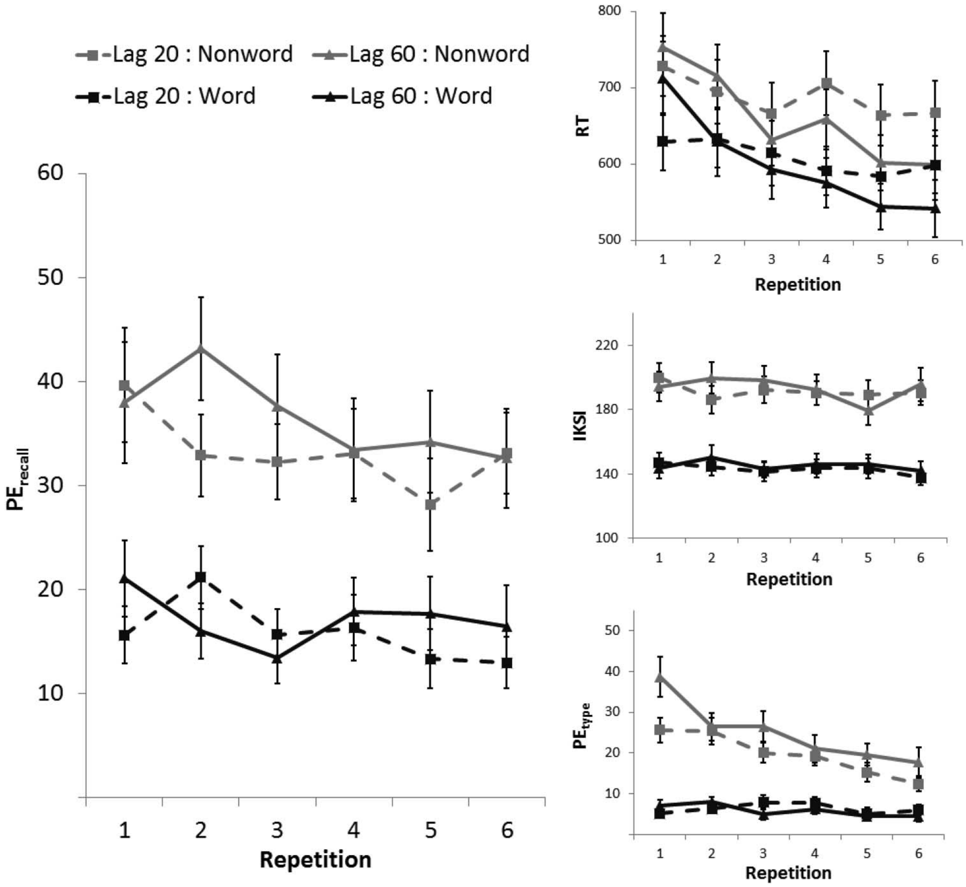

Figure 2. Percentage of error trials for the memory task (PE_{recall}) and response time (RT), interkeystroke interval (IKSI), and percentage of error trials (PE_{type}) for the typing task over six repetitions in Experiment 2 (error bars represent standard errors of the means).

RT was longer for nonwords than for words (*M*s = 673 ms vs. 603 ms), and for Lag 20 than for Lag 60 (*M*s = 648 ms vs. 629 ms). The latter effect depended on repetitions: RT was initially shorter for Lag 20 than for Lag 60 (*M* = 732 ms vs. 878 ms for the first repetition), but it became longer for Lag 20 than for Lag 60 at the sixth repetition (*M*s = 632 ms vs. 570 ms). As trials for Lag 60 were distributed across six blocks, the improvement in RT may reflect learning unspecific to the repeated items. When RT was analyzed in terms of blocks rather than repetitions in terms of a 2 (typing materials: word vs. nonword) × 2 (lag length: Lag 20 vs. Lag 60) × 6 (block: 1–6) ANOVA, there was a decrease in RT over blocks (*M*s = 729 ms vs. 583 ms, for first and sixth blocks), $F(5, 115) = 11.99$, $MSE = 23{,}791.67$, $p < .001$, $\eta_p^2 = .343$. This effect was not different between Lag 20 and Lag 60, as indicated by the nonsignificant interaction between lag length and block, $F(5, 115) = 1.54$, $MSE = 7{,}172.16$, $p = .182$, $\eta_p^2 = .063$.

IKSI for nonwords decreased more than IKSI for words (see Table 3), suggesting the development of motor chunks or some other form of learning. There was an interaction between lag length and repetition, but, as in PE_{recall}, this effect depended only on the second repetition and disappeared when that data point was removed. PE_{type} also showed larger reductions over repetitions for nonwords than for words. PE_{type} decreased more for Lag 60 than for Lag 20, and this effect remained significant when the data were analyzed in terms of blocks rather than repetitions, $F(5, 115) = 4.69$, $MSE = 180.50$, $p <$ .041, $\eta_p^2 = .169$. For nonwords, PE_{type} was larger for Lag 60 and for Lag 20 (*M*s = 24.95% vs. 19.55%); for words, there was little difference (*M*s = 5.78% vs. 6.32%, for Lag 60 and Lag 20). PE_{type} decreased over blocks more for nonwords (*M*s = 22.85% for the first block and 11.00% for the sixth block) than for words (*M*s = 14.73% for the first block and 10.62% for the sixth block).

Discussion

The present results showed that memory chunks did not develop after six spaced repetitions of the same nonwords. Although there was an improvement of typing performance over blocks, it was not specific to repeated typing materials. The outcomes are surprising from the view that the spacing effect is robust across different learning conditions and materials (Cepeda et al., 2006; Hintzman, 1974). Consequently, the results of the present experiment suggest that memory chunks observed in Experiment 1 may only be transient entities maintained temporarily in short-term memory. Yet it is also possible that spacing between repetitions somehow prevented memory chunks from developing at all, because memory chunking requires two representations of the same

Table 3
Results of ANOVAs on Percentage Error Trials for Digit Recall (PE_{Recall}), Response Time (RT), Interkeystroke Interval (IKSI), and Percentage Error Trials for Typing (PE_{Type}) in Experiment 2

Factor	*df*	*MSE*	*F*	*p*	η_p^2
PE_{recall}					
Typing material (TM)	1, 23	540.44	90.09	<.001	.797
Lag length (LL)	1, 23	201.46	3.7	.067	.138
Trial repetition (TR)	5, 115	226.69	2.16	.064	.086
TM × LL	1, 23	94.1	1.64	.213	.067
TM × TR	5, 115	118.93	<1	.491	.037
LL × TR	5, 115	132.4	<1	.833	.018
TM × LL × TR	5, 115	132.71	3.08	.012	.118
RT					
TM	1, 23	18,997	37.11	<.001	.617
LL	1, 23	6,040	8.04	.009	.259
TR	5, 115	11,176	14.68	<.001	.390
TM × LL	1, 23	3,401	3.64	.069	.137
TM × TR	5, 115	6,884	1.05	.394	.043
LL × TR	5, 115	10,150	4.35	.001	.159
TM × LL × TR	5, 115	6,253	<1	.614	.030
IKSI					
TM	1, 23	2,240	149.55	<.001	.867
LL	1, 23	497	1.2	.286	.049
TR	5 ,115	391	1.43	.219	.059
TM × LL	1, 23	470	<1	.935	<.001
TM × TR	5, 115	237	2.95	.015	.114
LL × TR	5, 115	258	2.67	.026	.104
TM × LL × TR	5, 115	254	1.13	.347	.047
PE_{type}					
TM	1, 23	618.53	61.32	<.001	.727
LL	1, 23	180.62	4.63	.042	.168
TR	5, 115	68.22	16.05	<.001	.411
TM × LL	1, 23	119.95	10.38	.004	.311
TM × TR	5, 115	64.62	12.27	<.001	.348
LL × TR	5, 115	62.79	2.53	.033	.099
TM × LL × TR	5, 115	58.85	1.82	.115	.073

Note. df = degrees of freedom; MSE = mean squared error.

typing material in short-term memory. When the typing materials are repeated in consecutive trials, a memory trace from the previous trial is still in short-term memory on the current trial when the same typing material is encoded into short-term memory. With longer lags between repetitions, the memory trace in short-term memory is different from the typing material on the current trial, so chunking will not occur unless an earlier study episode is retrieved from long-term memory (Benjamin & Tullis, 2010; Ross, 1984). Concurrent memory load might have prevented such retrieval of an earlier episode. If this hypothesis is correct, memory chunks that develop with immediate repetitions should still be consolidated in long-term memory. This was examined in Experiment 3.

Experiment 3

The present experiment examined whether memory chunks developed in six consecutive trials were consolidated in long-term memory. Salasoo et al. (1985) found that perceptual chunks developed with five repetitions of the same nonwords and were retained at least for a year, indicating that they were consolidated in long-term memory. This finding supports the possibility that memory chunks acquired in Experiment 1 were retained in long-term memory. To test this prediction, a session was divided into two phases: training and test. The training phase was essentially the same as Experiment 1, in which typists typed words and nonwords under a concurrent memory load, and the same typing material was repeated in six consecutive trials. After the training phase, typists typed a new set of words and nonwords under a concurrent memory load for 120 trials. Following these intervening trials, typists typed the words and nonwords from the training phase under a concurrent memory load. This last block of trials served as a test for the consolidation of memory chunks in long-term memory. Performance in the test phase was compared with the initial performance (the first repetition) and the final performance (the sixth repetition) in the training phase. If memory chunks developed, final performance should be better than initial performance, as in Experiment 1. If all memory chunks were consolidated in long-term memory during the training phase, test performance should be better than the initial performance and equivalent to the final performance. If only some memory chunks were consolidated in long-term memory, test performance should be better than the initial performance but poorer than the final performance. If none of the chunks were consolidated in long-term memory, test performance should be as poor as the initial performance.

Method

Subjects. Twenty-four new typists participated in the experiment (see Table 1).

Apparatus, stimuli, and procedure. The procedure closely followed that of Experiment 1, with a few modifications. Each typist performed one block of 12 practice trials and six blocks of 30 test trials. Only 5-letter words and nonwords were used in the present experiment. In the first three test blocks (the training phase), the same word or nonword appeared on six consecutive trials. There were 15 words and nonwords, randomly selected from the word lists for each typist, constituting a total of 180 trials (30 × 6 trials). The next two blocks were filler trials, in which typists typed 60 unique words and nonwords (120 trials) that had never appeared in the preceding three blocks. The last block was divided into two subblocks of 30 trials each (the test phase), which was unknown to typists. The 30 words and nonwords that occurred in the first three blocks were presented once in each subblock. Consequently, each word or nonword occurred eight times in total throughout a session.

Results

The data were analyzed in the same manner as in Experiments 1 and 2 (2.65% of all trials were discarded). The results are summarized in Figure 3.

Development and retention of memory chunks. As in Experiment 1, error rate for digit recall was generally higher for nonwords (M = 34.79%) than for words (M = 15.04%), and this disadvantage for words decreased over repeated trials (MD = 27.21% vs. 13.03% in the first and sixth repetitions, respectively). A 2 (typing material: word vs. nonword) × 6 (trial repetition: 1–6)

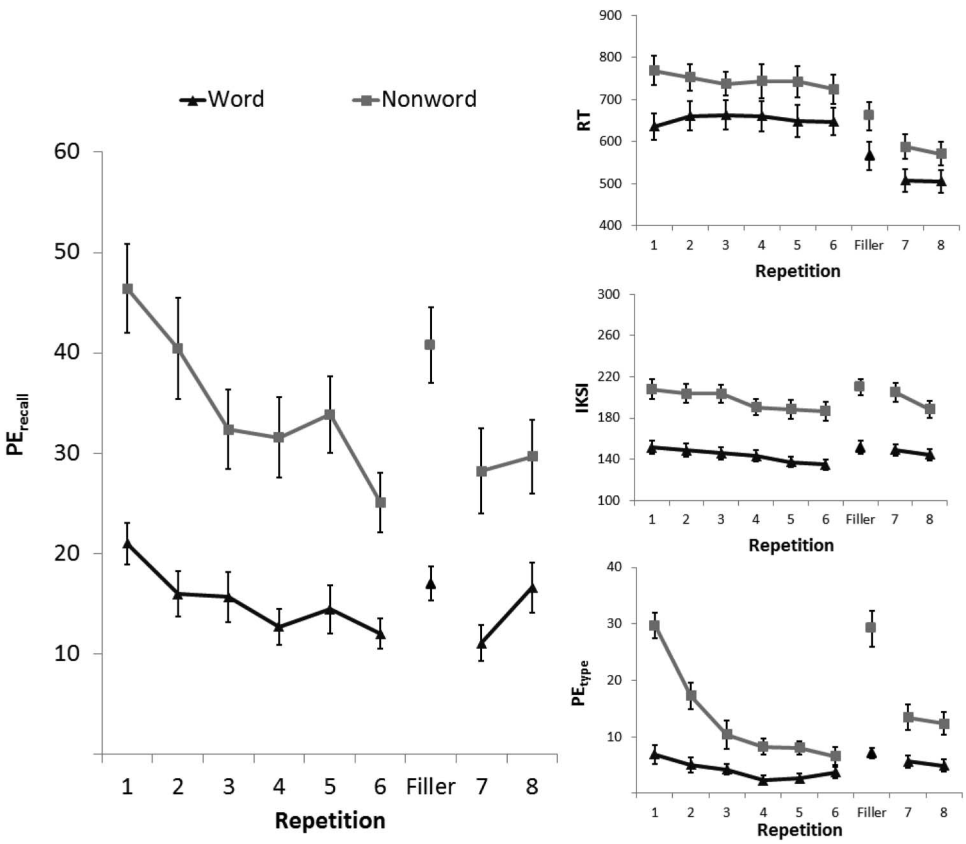

Figure 3. Percentage of error trials for the memory task (PE_{recall}) and response time (RT), interkeystroke interval (IKSI), and percentage of error trials (PE_{type}) for the typing task in the training phase (Repetitions 1–6) and the test phase (Repetitions 7 and 8) of Experiment 3. Error bars represent standard errors of the means. "Filler" indicates the summary of 60 word and nonword trials that did not appear during the training phase.

ANOVA confirmed the observation (see Table 4); the interaction between typing material and trial repetition indicated the development of memory chunks.

To examine the retention of developed chunks, digit recall was compared between the first repetition in the training phase and the first repetition in the test phase (i.e., first vs. seventh repetitions in Figure 3) in a 2 (typing material: word vs. nonword) × 2 (trial repetition: first repetition vs. seventh repetition) ANOVA (see Table 5). For both words and nonwords, digit recall was better for the first repetition in the test phase (*M*s = 10.43% for words and 28.55% for nonwords) than for the first repetition in the training phase (*M*s = 20.54% for words and 47.75% for nonwords). Similarly, the last repetition in the training phase and the first repetition in the test phase (i.e., sixth vs. seventh repetitions) were compared in a 2 (typing material: word vs. nonword) × 2 (trial repetition: sixth repetition vs. seventh repetition) ANOVA (see Table 5). There was little difference between these repetitions for typing words (*M*s = 11.46% vs. 10.43% for sixth and seventh repetitions) and for typing nonwords (*M*s = 24.49% vs. 28.55% for sixth and seventh repetitions). Therefore, the level of recall performance that was reached at the last repetition in the training phase was maintained in the test phase, consistent with the expected outcome if *all* of the chunks that developed in training were consolidated in long-term memory.

Typing performance. In the training phase (see Table 4), RT was generally longer for nonwords (*M* = 755 ms) than for words (*M* = 662 ms). Although RT decreased over six repetitions for nonwords and words (see Figure 3), the decrease was not statistically significant. IKSI in the training phase was also longer for nonwords (*M* = 195 ms) than for words (*M* = 144 ms), and IKSI decreased over repetitions; there was little difference in the reduction of IKSI between words and nonwords. PE_{type} was larger for nonwords (*M* = 13.27%) than for words (*M* = 3.99%), and it decreased over repetitions more for nonwords than for words.

The comparison between the first and seventh repetitions revealed a significant reduction in RT from the first repetition to the seventh repetition (see Table 5). This effect was larger for nonwords (*M* = 779 ms vs. 599 ms) than for words (*M*s = 641 ms vs. 515 ms). The comparison between the sixth and seventh repetition also revealed longer RT for the sixth repetition (*M* = 694 ms) than for the seventh repetition (*M* = 557 ms), and longer RT for nonwords (*M* = 666 ms) than for words (*M* = 585 ms); there was no interaction between these two factors (see Table 5). For IKSI, there was little reduction from the first repetition (*M* = 178 ms) to the seventh repetition (*M* = 174 ms), but the comparison between the sixth and seventh repetitions showed an increase, rather than a decrease, in IKSI (*M*s = 160 ms vs. 174 ms for sixth and seventh repetitions). For $PE_{type,}$ the comparison between the first and

Table 4
Results of ANOVAs on Percentage Error Trials for Digit Recall (PE_{Recall}), Response Time (RT), Interkeystroke Interval (IKSI), and Percentage Error Trials for Typing (PE_{Type}) in the Training Phase of Experiment 3

Factor	*df*	*MSE*	*F*	*p*	η_p^2
PE_{recall}					
Typing material (TM)	1, 23	567	49.52	<.001	.683
Trial repetition (TR)	5, 115	126	11.8	<.001	.339
TM × TR	5, 115	130.05	2.42	.040	.095
RT					
TM	1, 23	27,240	22.89	<.001	.499
TR	5, 115	5,362	<1	.725	.024
TM × TR	5, 115	6,554	1.32	.262	.054
IKSI					
TM	1, 23	1,380	137.57	<.001	.857
TR	5, 115	187	14.55	<.001	.387
TM × TR	5, 115	138	1.17	.327	.048
PE_{type}					
TM	1, 23	88.26	70.19	<.001	.753
TR	5, 115	55.37	20.55	<.001	.472
TM × TR	5, 115	52.73	11.99	<.001	.343

Note. df = degrees of freedom; MSE = mean squared error.

seventh repetitions showed a larger reduction for nonwords (*M*s = 28.83% vs. 13.15%) than for words (*M*s = 6.04% vs. 5.32%). PE_{type} increased from the sixth repetition (*M* = 5.15%) to the seventh repetition (*M* = 9.23%).

Discussion

The results of the present experiment are consistent with Experiment 1, showing that memory chunks developed as the same nonword was typed repeatedly on consecutive trials. They further demonstrated that the developed memory chunks were consolidated in long-term memory: Concurrent memory performance was better after 120 intervening trials than the initial performance level, and was maintained at the level that was reached at the final repetition during training (cf. Salasoo et al., 1985). Therefore, the lack of memory chunking in Experiment 2 was not because memory chunks were only transient representations in short-term memory, but because their development was prevented when repetitions were spaced.

The failure to find evidence for memory chunking with spaced repetitions is counterintuitive (Cepeda et al., 2006; Hintzman, 1974), but the result may be a consequence of the concurrent memory load procedure. It was proposed earlier that chunks develop when short-term memory contains a representation of a prior episode as well as a representation of the current one. This provides contiguity, which is essential for learning (e.g., Hebb learning; Hebb, 1961). It has been suggested that the spacing effect depends on retrieval of prior presentations of the study materials (i.e., study state retrieval; Benjamin & Tullis, 2010; Greene, 1989). With spaced repetitions of Experiment 2, a concurrent memory load would prevent retrieval of prior episodes and, therefore, would prevent the development of memory chunks. With massed repetitions of Experiments 1 and 3, a concurrent memory load may not erase the representation of the previous trial completely, so chunks may develop. If concurrent memory load is responsible for the lack of memory chunking with spaced repetitions, memory chunks should develop when there is no concurrent memory load during training, even though materials are repeated with long lags. Experiments 4 and 5 tested this prediction.

Experiment 4

To assess the influence of a concurrent memory load on the development of memory chunks, the present experiment trained typists on nonwords without a concurrent memory load and then tested them with a concurrent memory load in the final block to determine whether memory chunks developed. During the training phase, one set of words and nonwords was distributed across two

Table 5
Results of ANOVAs on Percentage Error Trials for Digit Recall (PE_{Recall}), Response Time (RT), Interkeystroke Interval (IKSI), and Percentage Error Trials for Typing (PE_{Type}) in the Test Phase of Experiment 3

Factor	*df*	*MSE*	*F*	*p*	η_p^2
PE_{recall}: First vs. seventh repetition					
Typing material (TM)	1, 23	227.79	54.13	<.001	.702
Trial repetition (TR)	1, 23	159.21	32.4	<.001	.585
TM × TR	1, 23	82.05	6.04	.022	.208
PE_{recall}: Sixth vs. seventh repetition					
TM	1, 23	107.55	54.13	<.001	.702
TR	1, 23	121.79	<1	.508	.019
TM × TR	1, 23	140.04	1.11	.302	.046
RT: First vs. seventh repetition					
TM	1, 23	6,510	45.37	<.001	.664
TR	1, 23	6,953	81.36	<.001	.780
TM × TR	1, 23	3,198	5.78	.025	.201
RT: Sixth vs. seventh repetition					
TM	1, 23	5,151	30.93	<.001	.573
TR	1, 23	6,489	69.04	<.001	.750
TM × TR	1, 23	4,063	<1	.897	.001
IKSI: First vs. seventh repetition					
TM	1, 23	481	139.98	<.001	.859
TR	1, 23	227	1.51	.232	.061
TM × TR	1, 23	129	<1	.789	.003
IKSI: Sixth vs. seventh repetition					
TM	1, 23	688	92.29	<.001	.801
TR	1, 23	193	24.53	<.001	.516
TM × TR	1, 23	144	<1	.718	.006
PE_{type}: First vs. seventh repetition					
TM	1, 23	107.58	52.27	<.001	.694
TR	1, 23	79.7	20.25	<.001	.468
TM × TR	1, 23	73.88	18.15	<.001	.441
PE_{type}: Sixth vs. seventh repetition					
TM	1, 23	56.96	12.09	.002	.344
TR	1, 23	26.44	15.12	<.001	.397
TM × TR	1, 23	56	2.63	.119	.103

Note. df = degrees of freedom; MSE = mean squared error.

blocks of 60 trials each (Lag 20), and the other set was distributed across six blocks (Lag 60). During the test phase, typists typed the trained materials and new materials that never appeared in the training phase while retaining a concurrent memory load. If memory chunks develop during the training phase, concurrent memory performance in this test phase would be better when typing trained nonwords than when typing new nonwords. Following the literature on the spacing effect, memory chunks should develop better with longer lags between repetitions in the present experiment. Concurrent memory performance should be better when typing nonwords with longer lags (Lag 60) than with shorter lags (Lag 20). Observing these effects would be consistent with our suggestion that concurrent memory load during training prevents the development of chunks with spaced training in Experiment 2.

Method

Subjects. Twenty-four new touch-typists participated (see Table 1).

Apparatus, stimuli, and procedure. The same stimuli and apparatus as those in Experiment 2 were used. The only difference was that typists typed words and nonwords during the training phase without the concurrent memory task, which was introduced in the additional test block in which typists typed words and nonwords with the concurrent memory task to examine the development of chunks. The test block consisted of 90 trials. Typists typed a new set of words and nonwords in one third of trials, and typed words and nonwords that appeared during the training phase in the remaining trials (15 words and 15 nonwords for Lags 20 and 60). There was a practice block of 12 trials (6 new words and 6 nonwords) before the test block to familiarize typists with the concurrent memory procedure.

Results

With the filtering criteria used in Experiments 1 to 3, 3.06% of trials were discarded.

Development of memory chunks. To examine the development of memory chunks, the analysis focused on PE_{recall} in the test block (see Figure 4A). Concurrent memory performance was better for words (M = 9.96%) than for nonwords (M = 31.40%). It was best for Lag 60 (M = 16.90%), intermediate for Lag 20 (M = 20.29%), and worst for new materials (M = 24.84%). The effect of lag between repetitions was more apparent for nonwords than for words. The results of a 2 (typing material: word vs. nonword) × 3 (lag length: Lag 60 vs. Lag 20 vs. new) ANOVA confirmed these observations, revealing significant main effects of typing material and lag length as well as the interaction between the two factors (see Table 6).

Typing performance. RT, IKSI, and PE_{type} are summarized in Figure 5. For the training phase, these measurements were submitted to separate 2 (typing material: word vs. nonword) × 2 (repetition interval: Lag 20 vs. Lag 60) × 6 (trial repetition: 1–6) ANOVAs. For the test phase, they were submitted to 2 (typing material: word vs. nonword) × 3 (lag length: Lag 60 vs. Lag 20 vs. new) ANOVAs. The results are summarized in Table 6.

For the training phase, RT was shorter for words (M = 439 ms) than for nonwords (M = 480 ms), and there were reductions of RT over repetitions for both material types, but to a larger extent for nonwords than for words (see Figure 5). Overall, RT for nonwords

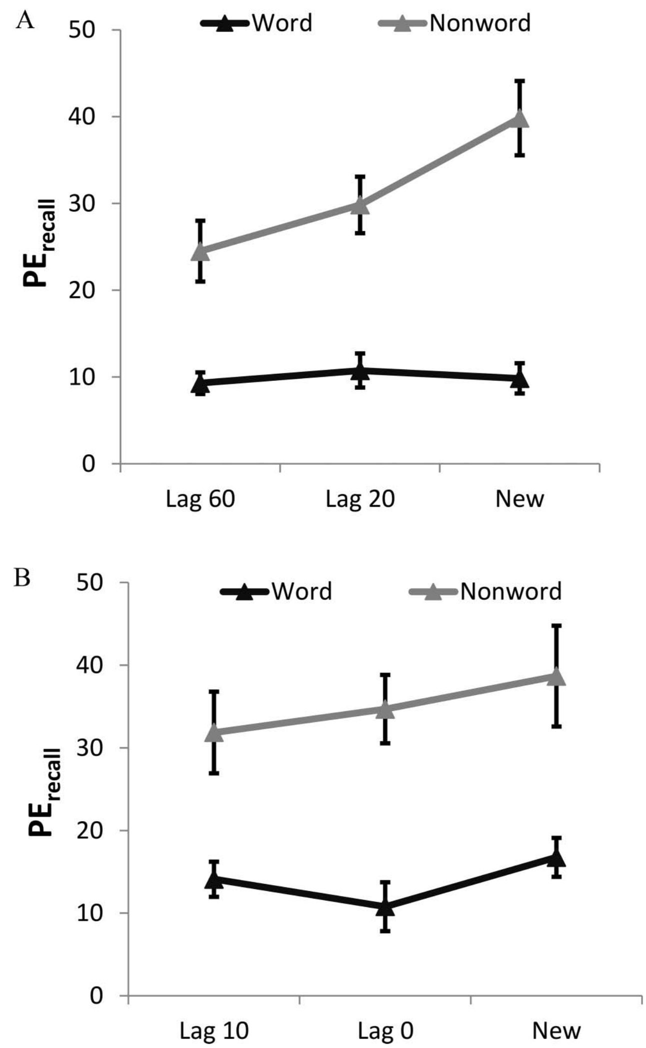

Figure 4. Percentage of Error trials for the concurrent memory task in the test block of Experiment 4 (A) and Experiment 5 (B). Error bars are standard errors of the means.

was shorter for the shorter lag between repetitions (M = 472 ms for Lag 20) than for the longer lag (M = 488 ms for Lag 60), but there was little difference for words (Ms = 439 ms for Lag 20 and Lag 60). There were larger reductions of RT for longer lags than for shorter lags (see Figure 5), but this effect was not dependent on typing materials. For the test phase, RT was still shorter for words (M = 572 ms) than for nonwords (M = 624 ms). RT for words appeared to be shorter for Lag 20 (M = 545 ms) than for Lag 60 or new words (Ms = 581 ms and 589 ms, respectively), but RT for nonwords was similar for the three conditions (Ms = 620 ms, 639 ms, and 613 ms). Thus, there was little evidence for a systematic effect of spacing between repetitions.

As in RT, IKSI for the training phase was shorter for words (M = 127 ms) than for nonwords (M = 157 ms), and it reduced across repetitions to a larger extent for nonwords than for words (see Figure 5). There was little effect of spacing. However, for the test phase, the lag length affected IKSI for nonwords: IKSI was shortest for Lag 60 (M = 170 ms), intermediate for Lag 20 (M =

Table 6
Results of ANOVA on Percentage Error Trials for Digit Recall (PE_{Recall}) in the Test Phase, and Response Time (RT), Interkeystroke Interval (IKSI), and Percentage Error Trials for Typing (PE_{Type}) in the Training and Test Phases of Experiment 4

Factor	*df*	*MSE*	*F*	*p*	η_p^2
PE_{recall}: Test phase					
Typing material (TM)	1, 23	166	99.69	<.001	.813
Lag length (LL)	2, 46	114	6.69	.003	.225
TM × LL	2, 46	127	5.55	.007	.194
RT: Training phase					
Trial Repetition (TR)	5, 115	4,681	31.32	<.001	.577
TM	1, 23	15,538	15.69	.001	.405
LL	1, 23	2,899	3.22	.086	.123
TM × LL	1, 23	1,627	5.01	.035	.179
TM × TR	5, 115	2,085	7.29	<.001	.241
LL × TR	5, 115	3,396	2.46	.037	.097
TM × LL × TR	5, 115	1,512	<1	.874	.015
RT: Test phase					
TM	1, 23	7,788	12.64	.002	.355
LL	2, 46	4,568	<1	.767	.011
TM × LL	2, 46	5,126	3.17	.051	.121
IKSI: Training phase					
TR	5, 115	202	8.30	<.001	.265
TM	1, 23	961	135.94	<.001	.855
LL	1, 23	302	<1	.931	<.001
TM × LL	1, 23	298	2.01	.170	.080
TM × TR	5, 115	112	6.63	<.001	.224
LL × TR	5, 115	95	<1	.793	.020
TM × LL × TR	5, 115	107	1.17	.329	.048
IKSI: Test phase					
TM	1, 23	593	164.22	<.001	.877
LL	2, 46	352	6.73	.003	.226
TM × LL	2, 46	298	7.93	.001	.256
PE_{type}: Training phase					
TR	5, 115	32.68	7.47	<.001	.245
TM	1, 23	62.64	16.21	.001	.413
LL	1, 23	59.15	<1	.504	.020
TM × LL	1, 23	32.92	1.86	.186	.075
TM × TR	5, 115	24.20	1.15	.338	.048
LL × TR	5, 115	29.10	<1	.933	.011
TM × LL × TR	5, 115	28.21	1.20	.315	.049
PE_{type}: Test phase					
TM	1, 23	163.15	28.22	<.001	.551
LL	2, 46	72.79	11.85	<.001	.340
TM × LL	2, 46	58.37	6.93	.002	.231

Note. df = degrees of freedom; MSE = mean squared error.

180 ms), and longest for new nonwords (M = 197 ms). IKSI for words did not differ among the three conditions (Ms = 132 ms, 129 ms, 131 ms, for Lag 60, Lag 20, and new words, respectively). IKSI was generally shorter for words (M = 131 ms) than for nonwords (M = 183 ms).

PE_{type} in the training phase was smaller for words (M = 3.52%) than for nonwords (M = 6.17%), and there were reductions over repetitions (see Figure 5). Again, there was no effect of spacing in the training phase, but there was in the test phase: PE_{type} for nonwords was smaller for Lag 60 (M = 12.12%) and for Lag 20 (M = 13.7%) than for new nonwords (M = 25.20%); PE_{type} for words also showed a similar pattern but to a smaller extent (Ms = 5.10%, 4.72%, and 7.28%, for Lag 60, Lag20, and new words). PE_{type} was generally smaller for words (M = 5.70%) than for nonwords (M = 17.01%).

Discussion

The present experiment showed that memory chunks do develop with lags between repetitions, and that the development of memory chunks showed the usual spacing effect when there is no concurrent memory load during the training phase. During the test phase, typing interfered with concurrent memory performance less when nonwords had occurred in the training phase than when they had not, indicating memory chunks developed while typing nonwords without concurrent memory load. Furthermore, interference with concurrent memory load was smaller when there were longer lags than when there were shorter lags, yielding a spacing effect. Similar spacing effects were also obtained in typing performance, including IKSI and typing error rates, but not in RT. The outcomes are in a sharp contrast to the findings in Experiments 1 to 3, which suggested that memory chunks develop under concurrent memory load with massed repetition but not with spaced repetition. Thus, these experiments collectively suggest that memory load is a determining factor in the development of memory chunks when repetitions are spaced. We have suggested that memory chunking may require two copies of the same representation to be present in short-term memory. Spacing between repetitions would erase the representation from a preceding trial, as in Experiment 2, but another representation can be retrieved from a prior episode in long-term memory instead when the capacity of short-term memory is freed up as a concurrent memory load is removed.

The discrepancy between RT and IKSI is interesting from the perspective of the two-loop theory of skilled typewriting (Logan & Crump, 2011), as they suggest that spacing affected the outer loop and the inner loop differently. The spacing effect was only obtained in IKSI, which reflects inner-loop processing (keystrokes). This finding may reflect the development of chunks of keystrokes (e.g., motor chunks). On each trial, words and nonwords are presented well before a go signal that instructs typists to start typing. Thus, much of the outer-loop processing might have been completed when the go signal was presented (Yamaguchi, Crump, & Logan, 2013). Also, this concurrent memory procedure was introduced in the test phase for a first time, so typists were not used to the procedure, slowing RT significantly and possibly wiping out the effect of spacing.

Experiment 5

The final experiment tested whether there is any benefit of massed repetitions (Lag 0) of typing materials without a concurrent memory load during the training phase compared with longer lags. Experiments 1 to 3 suggested that massed repetition was necessary to develop memory chunks with a concurrent memory load. The present experiment assessed whether this holds for training without a concurrent memory load. The experiment was the same as Experiment 4, except that the two lags were Lag 0 (six massed repetitions) and Lag 10 (six spaced repetitions in a block of 60 trials). If two representations are simply required in short-

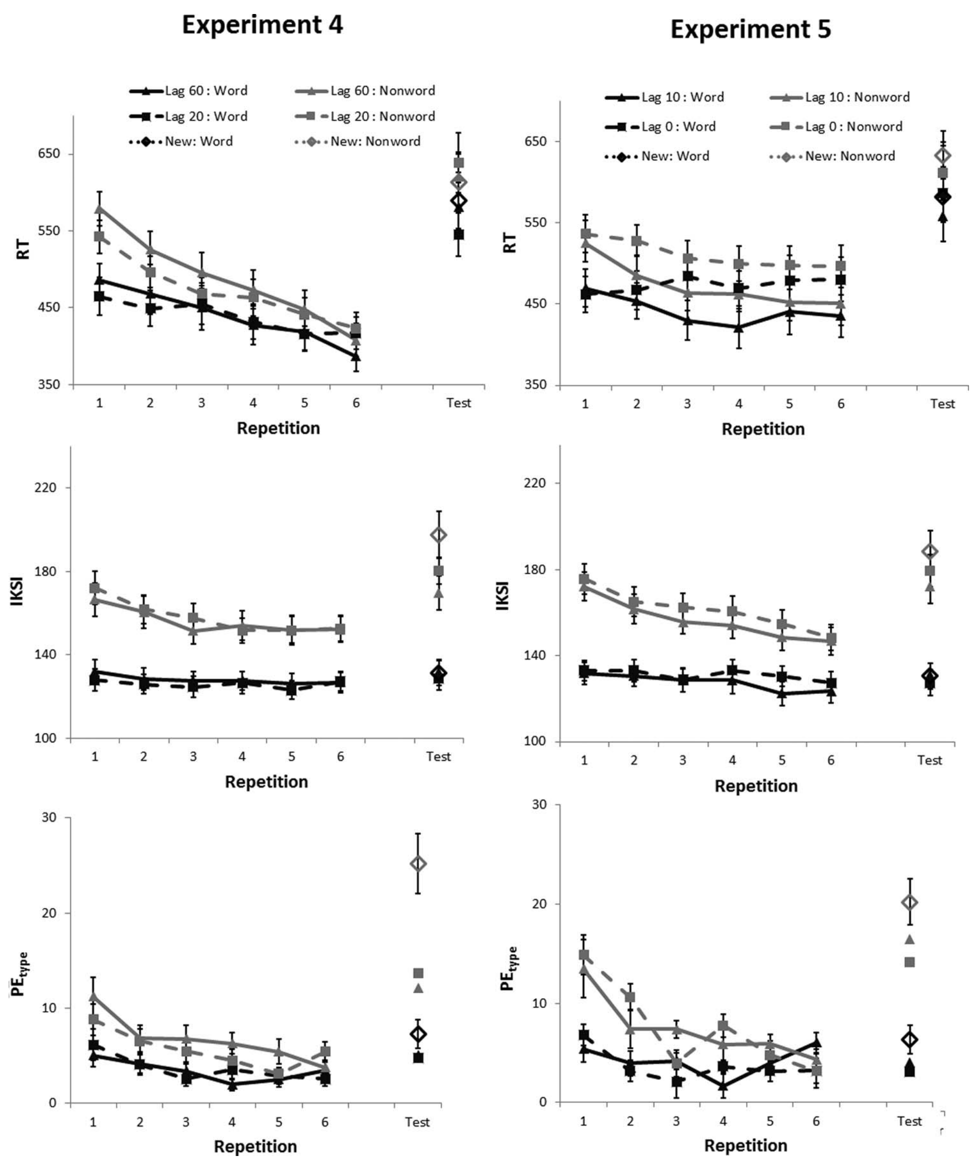

Figure 5. Response time (RT), interkeystroke interval (IKSI), and percentage of error trials (PE_{type}) for the typing task over six repetitions in the training phase and the test phase of Experiment 3. Error bars represent standard errors of the means.

term memory, we expected that massed repetitions would benefit memory chunks only under a concurrent memory load. Thus, memory chunks would develop for both Lag 0 and Lag 10 in the present experiment, and there would be a typical spacing effect that learning would be less efficient with Lag 0 than with Lag 10.

Method

Subjects. Twenty-four new typists participated (see Table 1).

Apparatus, stimuli, and procedure. The experiment was similar to Experiment 4, with the following changes. The six training blocks consisted of two different types of trials, which alternately appeared after the other condition in separate blocks (three blocks each). In the first condition, the same typing materials appeared in six consecutive trials (Lag 0). Each block included five words and five nonwords (6 repetitions × 10 items = 60 trials). In the second condition, there were also five words and five nonwords in each block, but a block was divided into a subblock of 10 trials, and each item appeared once in each subblock; on average, there were 10 trials between two repetitions of the same item (Lag 10). After the training phase, typists performed the test block, in which one third of the items were new, the other third were those from Lag 0, and the remaining third were those from Lag 10.

Results

With the same filtering criteria as the preceding experiments, 2.92% of all trials were discarded.

Development of memory chunks. As in Experiment 4, the analysis focused on memory performance in the test block (see Figure 4B). Digit recall was better when typing words (M = 13.89%) than when typing nonwords (M = 35.07%). There was not much difference between Lag 0 (M = 22.74%) and Lag 10 (M = 22.98%), which were still better than new materials (M = 27.72%). Supporting these observations, a 2 (typing material: word vs. nonword) × 3 (lag length: Lag 10 vs. Lag 0 vs. new) ANOVA (see Table 7) showed a significant main effect of typing material and only a marginal effect of lag length. Planned contrasts showed that memory performance for new items was significantly worse than the average of Lag 0 and Lag 10, $F(1, 23) = 6.66$, MSE = 170.09, $p = .017$, $\eta_p^2 = .224$, but memory performance was not different between Lag 0 and Lag 10, $F(1, 23) < 1$, $p = .914$. These outcomes suggest little evidence for the advantage of massed repetition, or vice versa.

Table 7
Results of ANOVA on Percentage Error Trials for Digit Recall (PE_{Recall}) in the Test Phase, and Response Time (RT), Interkeystroke Interval (IKSI), and Percentage Error Trials for Typing (PE_{Type}) in the Training and Test Phases of Experiment 5

Factor	*df*	*MSE*	*F*	*p*	η_p^2
PE_{recall}: Test phase					
Typing material (TM)	1, 23	475	34.00	<.001	.597
Lag length (LL)	2, 46	116	3.25	.048	.124
TM × LL	2, 46	134	<1	.423	.037
RT: Training phase					
Trial repetition (TR)	5, 115	3,418	5.11	<.001	.182
TM	1, 23	6,429	26.28	<.001	.533
LL	1, 23	7,679	22.75	<.001	.497
TM × LL	1, 23	2,162	<1	.482	.022
TM × TR	5, 115	1,803	4.81	<.001	.173
LL × TR	5, 115	2,275	3.27	.009	.124
TM × LL × TR	5, 115	1,156	1.36	.243	.056
RT: Test phase					
TM	1, 23	8,234	8.31	.008	.265
LL	2, 46	5,423	1.10	.342	.046
TM × LL	2, 46	4,020	<1	.464	.033
IKSI: Training phase					
TR	5, 115	144	23.76	<.001	.508
TM	1, 23	1,089	115.56	<.001	.834
LL	1, 23	462	5.14	.033	.183
TM × LL	1, 23	502	<1	.724	.006
TM × TR	5, 115	89	12.39	<.001	.350
LL × TR	5, 115	142	<1	.715	.025
TM × LL × TR	5, 115	72	<1	.508	.036
IKSI: Test phase					
TM	1, 23	398	230.95	<.001	.909
LL	2, 46	314	2.56	.089	.100
TM × LL	2, 46	283	3.05	.057	.117
PE_{type}: Training phase					
TR	5, 115	51	9.93	<.001	.302
TM	1, 23	62	<1	.760	.004
LL	1, 23	47	38.33	<.001	.625
TM × LL	1, 23	30	<1	.477	.022
TM × TR	5, 115	42	5.49	<.001	.193
LL × TR	5, 115	39	2.37	.044	.093
TM × LL × TR	5, 115	40	<1	.736	.023
PE_{type}: Test phase					
TM	1, 23	97	57.74	<.001	.715
LL	2, 46	67	4.02	.025	.149
TM × LL	2, 46	45	<1	.599	.022

Note. df = degrees of freedom; MSE = mean squared error.

Typing performance. RT, IKSI, and PE_{type} are summarized in Figure 5. For the training phase, these measurements were submitted to separate 2 (typing material: word vs. nonword) × 2 (repetition interval: Lag 0 vs. Lag 10) × 6 (trial repetition: 1–6) ANOVAs. For the test phase, they were submitted to 2 (typing material: word vs. nonword) × 3 (lag length: Lag 10 vs. Lag 0 vs. new) ANOVAs. The results of ANOVAs are summarized in Table 7.

The results are similar to those of Experiment 4. For the training phase, RT was shorter for words (M = 458 ms) than for nonwords (M = 492 ms), and there were larger reductions of RT over repetitions for nonwords than for words (see Figure 5). RT was shorter for Lag 10 (M = 457 ms) than for Lag 0 (M = 492 ms), and there were larger reductions of RT for longer spacing than for shorter spacing. For the test phase, RT was still shorter for words (M = 576 ms) than for nonwords (M = 619 ms), but there was no effect of spacing.

IKSI for the training phase was shorter for words (M = 129 ms) than for nonwords (M = 159 ms), and there were larger reductions for nonwords than for words (see Figure 5). IKSI was shorter for Lag 10 (M = 142 ms) than for Lag 0 (M = 146 ms). For the test phase, IKSI was shorter for words (M = 130 ms) than for nonwords (M = 180 ms). There was a statistically marginal effect of spacing on IKSI for nonwords (Ms = 172 ms, 180 ms, and 188 ms, for Lag 10, Lag 0, and new nonwords, respectively), but not for words (Ms = 131 ms, 127 ms, and 130 ms).

PE_{type} in the training phase was smaller for words (M = 3.93%) than for nonwords (M = 7.47%), and there were larger reductions for nonwords than for words (see Figure 5). There were larger reductions of PE_{type} for shorter spacing than for longer spacing. For the test phase, PE_{type} was smaller for words (M = 4.48%) than for nonwords (M = 16.95%). PE_{type} was also smallest for shorter spacing (M = 8.63%), intermediate for longer spacing (M = 10.24%), and largest for new words and nonwords (M = 13.28%).

Discussion

The development of memory chunks was no more efficient with massed repetitions (Lag 0) than with spaced repetitions (Lag 10), although the latter was not better than the former either. This implies that the advantage of massed repetition observed in the first three experiments of the present study is unique to chunking under concurrent memory load. Although there was not much benefit of spacing in typing performance during the test phase, there were the spacing effects in RT and IKSI during training. As discussed in Experiment 4, these effects in typing performance may reflect the development of memory chunks or other types of learning.

General Discussion

The present study investigated the acquisition of hierarchical control of skilled performance in the context of typewriting. A core property of hierarchical control is that single processing units for the higher level control translate into several processing units for the lower level control. A core property of the acquisition of hierarchical control is the development of chunks that reduce several higher level units into a single higher level unit with training, which can be translated into the corresponding lower level units in the lower level control process. Typewriting starts with encoding a group of letters and translating them into a series of keystrokes. When typing familiar words, perceptual chunks allow a group of letters to be encoded as a unit, and motor chunks allow a series of keystrokes to be planned as a unit; memory chunks bridge between perceptual and motor chunks to allow an efficient translation between them. The present study focused on the development of memory chunks when typing unfamiliar nonwords to reveal the process of acquiring hierarchical control of typing skill.

The development of memory chunks was examined by observing the influences of typing on concurrent memory performance. The results showed that, under a concurrent memory load, memory chunks for typing nonwords developed with massed repetitions (Experiment 1) but not with spaced repetitions (Experiment 2), and the developed memory chunks were consolidated in long-term memory (Experiment 3). The lack of memory chunking with spaced repetitions is counterintuitive, as spacing typically improves learning. Researchers have remarked that failing to find the spacing effect is important in its own right, given the robustness of the effect under a variety of different conditions (Greene, 1989; Hintzman, 1974). However, when a concurrent memory load was removed during training, memory chunks developed with spaced repetitions (Experiments 4 and 5), and they developed more efficiently with longer lags (Experiment 4) and provided little advantage of massed repetitions over spaced repetitions (Experiment 5). Therefore, the main question concerns why spacing prevented memory chunking under a concurrent memory load.

The lack of memory chunking with spacing in Experiment 2 was surprising, especially having observed memory chunking with massed practice in Experiment 1. We suggested that two representations of the same typing material have to be present in short-term memory for the elements of the typing materials to be chunked. Consistent with this idea, we found that memory chunks under a concurrent memory load were consolidated in long-term memory and utilized for later use (Experiment 3). It has been suggested that the spacing effect requires retrieval of a prior study state from long-term memory (Benjamin & Tullis, 2010; Ross, 1984; Thios & D'Agostino, 1976; Verkoeijen, Rikers, & Schmidt, 2005). This study state retrieval integrates a greater number of contextual cues into the memory trace of the study item. These contextual cues serve as retrieval cues at test, and the study item is retrieved more successfully when the item is associated with a greater number of contextual cues. According to this account, spaced repetitions improve learning because the contexts associated with the memory trace are more variable when there are longer lags between repetitions (Bower, 1972; Kahana & Greene, 1993; Landauer, 1969; Raaijmakers, 2003; Verkoeijen, Rikers, & Schmidt, 2004). When there is no concurrent memory load, a prior study state is retrieved, and a spacing effect occurs for memory chunking. But when there is a concurrent memory load, prior study states cannot be retrieved, preventing the development of memory chunks. With massed repetitions, however, the prior study state is still in short-term memory,[1] mimicking study state retrieval and allowing memory chunks to develop.

Several different accounts of the spacing effect have also been proposed (see Delaney, Verkoeijen, & Spirgel, 2010; Dempster, 1989; Hintzman, 1974, for reviews) that emphasize the role of attention. Study items receive more attention when there are lags between repetitions than when there is no lag, which results in more elaborated encoding and consolidation of the study items into long-term memory at the second presentation of the same study item (Bahrick & Hall, 2005; Bjork & Allen, 1970; Braun & Rubin, 1998; Delaney & Knowles, 2005; Elmes, Greener, & Wilkinson, 1972; Hintzman, 1974; Metcalfe & Xu, 2015). The reasons for spaced repetitions receiving more attention vary across accounts (e.g., failure to retrieve prior episodes, false confidence with massed repetitions, study items appearing more interesting with spaces, or more mind-wandering with massed than spaced repetitions). However, the present results cannot be explained based solely on such accounts. If concurrent memory load interrupted attention to the second and subsequent presentations of the same typing materials, there should be no learning regardless of whether repetitions were massed or spaced. Therefore, we propose that the core mechanism behind memory chunking requires two representations: a representation from the current trial, and the other representation from a previous trial, to be maintained in short-term memory.

We are suggesting that typists have to "notice" that the same typing material was repeated (either with or without spacing) in order to chunk it. Studies have assessed the effects of spacing on recognition with conscious recollection and recognition without conscious recollection by using the remember-know paradigm (Parkin, Gardiner, & Rosser, 1995; Parkin & Russo, 1993). They found that spaced repetitions increased the frequency of recognition with conscious recollection, whereas massed repetitions increased the frequency of recognition based on familiarity. Thus, spaced repetitions enhance recollection (explicit memory), whereas massed repetitions enhance familiarity (implicit memory). Another study also showed that performances of explicit memory tasks were affected by spacing, but performances of implicit memory tasks were not (Parkin, Reid, & Russo, 1990), and several studies have shown that the spacing effect is enhanced by informing learners of the possible repetitions of the same materials (intentional learning) compared with when they are not informed of them (incidental learning; e.g., Greene, 1990; Toppino & Bloom, 2002; Verkoeijen et al., 2005). A secondary task demand eliminates the spacing effect with intentional learning, but it does not affect the spacing effect with incidental learning (Russo, Parkin, Taylor, & Wilks, 1998). These findings suggest that the major component of the spacing effect depends on explicit learning. As memory chunking is still subject to a spacing effect when there is no concurrent memory load, but not when there is a concurrent

[1] In the procedure of Experiment 1, typists had to maintain both letter string (word or nonword) and digit string (concurrent memory load) in short-term memory on each trial. The letter string was then carried over to the next trial, which mimicked study state retrieval when the same letter string was presented on the next trial (i.e., massed repetition). However, if there were spaces between repetitions, letters and digits memorized on a trial would be overwritten by a new letter string before the same letter string occurs again.

memory load, memory chunking seems to be a form of explicit learning.

Hierarchical theories of skilled performance suggest that different levels of processing in the hierarchy divide the labor required in a task, and they operate autonomously (Logan & Crump, 2011). The inner loop is informationally encapsulated such that the outer loop does not have access to operations of the inner loop (Logan & Crump, 2009). Outer-loop processing is explicit to typists, whereas inner-loop processing is implicit (Snyder, Logan, & Yamaguchi, 2015). Consequently, memory chunks that depend on an explicit form of learning develop in the outer loop and are required to interface between the outer loop and the inner loop. There are several other forms of chunking involved in skilled typewriting (Yamaguchi & Logan, 2014b). Perceptual chunks allow a number of letters to be encoded as a unit. Motor chunks allow a group of keystrokes to be prepared and implemented in a temporally overlapping manner. Memory chunks bridge these chunks, allowing a number of letters to be maintained and retrieved as a single unit, enabling the letters to be translated into keystrokes in parallel. Whether these chunks are different manifestations of the same cognitive representation or stem from different mechanisms is still an open question. It is possible that different chunks are only different manifestations of the same representational structure (Chase & Simon, 1973), but it is also possible that there are different representational structures corresponding to different types of chunks. In recent studies, there was evidence of chunking at the inner loop (i.e., keystroke level), but not in the outer loop, when skilled typists learned typing with a new key position of a letter on the keyboard (Yamaguchi & Logan, 2014a). Such chunks are likely distinct from memory chunks that we investigated in the present study. Future investigations may tell us whether the development of different types of chunks can be dissociated empirically.

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