The Problem of Serial Order in Skilled Typing

Kristy M. Snyder and Gordon D. Logan
Vanderbilt University

We address the problem of serial order in skilled typing, asking whether typists represent the identity and order of the keystrokes they type jointly by linking successive keystrokes into a chained sequence, or separately by associating keystrokes with position codes. In 4 experiments, typists prepared to type a prime word and were probed to type a target word. We varied the overlap between the identity and order of keystrokes in the prime and the target. Experiment 1 tested whether the identity of keystrokes can be primed separately from their order. Experiments 2 and 3 tested whether keystroke positions can be primed out of sequence. Experiment 4 tested whether keystrokes are primed equally across serial positions. The results were consistent with chaining theories: Keystroke identities were not primed separately from their order, keystroke positions were not primed out of sequence, and priming was graded across the keystroke sequence and depended on the number of keystrokes that were primed in sequence. We conclude by discussing the possibility that the problem of serial order may be solved differently for different sequential tasks.

Keywords: serial order, motor control, chaining, position coding, skill

Many of the tasks we accomplish every day require the execution of specific sequences of actions. To accomplish sequential tasks, the cognitive system must control the order in which the requisite actions are executed. How the cognitive system is able to accomplish such a feat is known as the problem of serial order (Lashley, 1951). Many psychologists have studied the problem of serial order in speech production (Dell, 1986, 1990; Levelt, 1989; Mackay, 1987; O'Seaghdha & Marin, 2000; Sevald & Dell, 1994; Stemberger, 1985, 1990) and serial recall (Botvinick & Plaut, 2006; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Conrad, 1965; Crossman, 1961; Estes, 1972; Grossberg, 1978; Hartley & Houghton, 1996; Healy, 1974; Henson, 1998; Lee & Estes, 1977, 1981; Melton & Irwin, 1940; Murdock, 1983; Page & Norris, 1998; Wickelgren, 1965). These studies typically contrast two classic theoretical perspectives: chaining and position coding. Most of this work suggests that the cognitive system solves the problem of serial order with position coding rather than chaining (but see Botvinick & Plaut, 2006).

The purpose of the present study is to test the generality of this conclusion by investigating the problem of serial order in skilled typing. Typing is an important test case for generalization because it is ubiquitous in the modern world. It is the gateway to computer literacy. Most college students are expert typists, typing as quickly and accurately as the professional typists of yesteryear (50–100 words per minute [WPM]; Logan & Crump, 2011). Successful generalization would expand the scope of position coding theories

to an important new task with billions of practitioners. A failure to generalize would be a significant exception to the rule and a significant boost for serial chaining theories.

The Problem of Serial Order: One Problem or Many?

Studies of serial order often seem to assume that all sequential behaviors pose the same problem. However, complex behaviors like speaking may pose at least two problems of serial order. One problem is maintaining an explicit representation of a novel but linguistically structured sequence of words in short-term memory (STM). The other problem is maintaining an implicit representation of well-learned sequences of speech movements in a motor buffer. The nature of the representations and the mechanisms that maintain them differ, so the mechanisms that solve the problem of serial order in STM and in motor control may differ as well.

Skilled typing is similar to speaking, in that it also requires the maintenance of serial order information in STM and in a motor buffer. For both tasks, the problem of serial order in STM is to maintain a sequence of linguistically structured words, so the cognitive system is likely to solve this problem in the same way. For both tasks, the problem of serial order in the motor buffer is to maintain a sequence of well-learned actions. However, the actions in speech require the coordination of the lips, tongue, jaw, and larynx to express phonemes and produce sounds. The actions in typing require the bimanual coordination of eight fingers to express letters and produce visual shapes on a computer screen. The effectors, actions, and intended outcomes differ, so the mechanisms that solve the problem of serial order may differ as well.

Theories of Serial Order

Classic chaining theories assume that serial order is represented by a chain of directional associations between successive items (Washburn, 1916). Each link in the chain connects two items or actions. Sequences are produced in the correct serial order because

---

Kristy M. Snyder and Gordon D. Logan, Department of Psychology, Vanderbilt University.

Correspondence concerning this article should be addressed to Kristy M. Snyder, Department of Psychology, Vanderbilt University, 111 21st Avenue South, Wilson Hall 631, Nashville, TN, 37240. E-mail: kristy.m.snyder@vanderbilt.edu

each item serves as the cue that retrieves the item that follows it. Modern chaining theories assume that serial order is represented by compound associations between prior items in a sequence and the context (Botvinick & Plaut, 2004, 2006; Chance & Kahana, 1997; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Murdock, 1993; Yamashita & Tani, 2008). Sequences are produced in the correct serial order because the prior items and context serve as the cues that retrieve the next item. Chaining theories represent item and order information jointly: Each link in the chain represents an item and the sequence of links represents serial order.

Classic position coding theories assume that serial order is represented by associating items with ordinal position codes (Conrad, 1965; Crossman, 1961). Items are not associated directly with each other. Rather, they are associated directly with position codes, and each position code is associated with the next one in the sequence. Modern position coding theories assume that the order of the position codes is represented by a magnitude representation or by a gradient of activation called a primacy gradient (Brown et al., 2000; Bullock & Rhodes, 2003; Burgess & Hitch, 1999; Crowder, 1982; Glenberg & Swanson, 1986; Grossberg, 1978; Hartley & Houghton, 1996; Murdock, 1960; Page & Norris, 1998; Rhodes, Bullock, Verwey, Averbeck, & Page, 2004). Sequences are produced by stepping through the position codes in serial order, retrieving, and then producing the item associated with each position code. Position coding theories assume that item and order are represented separately: Each position code provides a "slot" that is temporarily filled by an item and the sequence of position codes is used to control serial order.

Serial Order and Errors

Psychologists have used many strategies in their quest to understand how the cognitive system solves the problem of serial order. One of these strategies is to examine tasks like serial recall, in which a failure to maintain sequential information results in errors. Serial recall tasks are commonly used to study serial order in STM (Botvinick & Plaut, 2006; Brown et al., 2000; Burgess & Hitch, 1999; Conrad, 1965; Crossman, 1961; Estes, 1972; Grossberg, 1978; Hartley & Houghton, 1996; Healy, 1974; Henson, 1998; Lee & Estes, 1977, 1981; Melton & Irwin, 1940; Murdock, 1983; Page & Norris, 1998; Wickelgren, 1965). Serial recall tasks require subjects to recall lists of verbal items in the order in which they were presented. When order information is not maintained properly, transposition errors occur, resulting in exchanges of adjacent items or exchanges of nonadjacent items that occupy equivalent positions. Item information is often lost in these tasks, resulting in omission and insertion errors.

Lashley (1951) claimed that classic chaining theories are unable to account for transpositions. Classic chaining theories assume that each item serves as the cue for the subsequent item, so items within a sequence cannot be exchanged (adjacent transpositions) and items from different sequences cannot be exchanged (nonadjacent transpositions).

Position coding theories were then proposed as an alternative to classic chaining theories (Brown et al., 2000; Bullock & Rhodes, 2003; Burgess & Hitch, 1999; Conrad, 1965; Crossman, 1961; Crowder, 1982; Glenberg & Swanson, 1986; Grossberg, 1978; Hartley & Houghton, 1996; Murdock, 1960; Page & Norris, 1998; Rhodes et al., 2004). Position coding theories account for trans-

positions by assuming that items are temporarily associated with position codes, so noise in the system can cue an item associated with a different position code within the sequence (adjacent transpositions) or cue an item associated with the same position code from another sequence (nonadjacent transpositions).

Psychologists then proposed extensions to chaining theory to account for transpositions (Botvinick & Plaut, 2004, 2006; Chance & Kahana, 1997; Keele et al., 2003; Murdock, 1993; Yamashita & Tani, 2008). Modern chaining theories assume that compound associations among all prior items and the context cue each successive item in the sequence, so the compound associations can cue items from the sequence out of order (adjacent transpositions) or cue an item from a different sequence that is embedded in a similar context (nonadjacent transpositions).

Serial Order and Rapid Execution

Another strategy for investigating how order information is represented is to examine tasks in which serially ordered sequences are produced at a high rate. Lashley (1951) argued that classic chaining theories could not account for the rapid execution of skilled tasks, like speaking, typing, and playing piano. Classic chaining theories assume that feedback from the current action triggers the next action in the sequence, so execution rates would be limited by the time it takes to receive afferent information that indicates the current action has been executed. However, modern chaining theories assume that feedback from the motor command, rather than the action, serves as the stimulus for the subsequent action (efference copy; Desmurget & Grafton, 2000). Position coding theories assume that the cueing of sequential position codes triggers each associated action, so execution can proceed as rapidly as each successive position code can be cued. The system does not have to wait for the item associated with the position code to be accessed before cueing the next position code.

Priming Motor Programs

Theories of skilled typing assume that reaction time (RT) for the first keystroke reflects the time it takes to encode the material to be typed, prepare a motor program to type it, and implement the first step of the program (i.e., execute the first keystroke). Interkeystroke latencies reflect the time it takes to implement each successive step of the program (Crump & Logan, 2010; Logan & Crump, 2011; Salthouse, 1986). Motor programs are representations that specify the movements to be executed to achieve a goal and their order of execution (Keele, Cohen, & Ivry, 1990; Miller, Galanter, & Pribram, 1960). The assumption that motor programs specify all of the movements before the first movement is executed is supported by at least three lines of evidence: The time it takes to begin an action increases with the complexity of the action, consecutive movements are frequently coarticulated, and initial movements frequently respect end-state rather than beginning-state comfort (Keele, 1968; Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007; Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993; Rosenbaum, Hindorff, & Munro, 1987).

Crump and Logan (2010) used a priming task to show that motor programs specify the identity and the order of the keystrokes typists type. They presented a prime word followed by a probe—a single letter or a word—which typists had to type as quickly and

accurately as possible. RT was faster when probe letters were from the primed word than when they were not, suggesting that the prime word activated all of the constituent letters in parallel.

We adapted Crump and Logan's (2010) priming paradigm to investigate the problem of serial order in skilled typing. Skilled typists were shown a prime word and were then probed to type a target word. We varied the overlap between the identity and the order of letters in the prime and target. We focused primarily on RT, defined as the interval between the onset of the probe and the execution of the first keystroke, because it reflects the time it takes to create a motor program (plus the time for word encoding and executing the first keystroke). Following Crump and Logan, we assumed that the prime would activate the motor program required to type it, and that would affect the time required to create and implement the motor program for the target. The greater the overlap between prime and target, the less time required to program the target, and the shorter the RT.

The Present Study

We conducted four experiments using the priming paradigm to distinguish between chaining and position coding theories of serial order in skilled typing. First, we asked whether keystroke identities could be primed separately from the position they occupy in a sequence. Experiment 1 compared the RT of probed target words that were preceded by identity, anagram, and unrelated primes. The results indicated that keystroke identities could not be primed separately from their order. Second, we asked whether keystroke identities could be primed in the correct order but out of sequence. Experiment 2 compared priming the first two keystrokes with priming the last two keystrokes. The results indicated that keystroke identities could be primed when they occur in the correct order at the beginning of the sequence, but not when they occur at the end of the sequence. Experiment 3 compared priming the first and last keystrokes with priming the middle two keystrokes. The results indicated that priming the first and last keystrokes produced an RT advantage, but priming the middle two keystrokes did not. The RT advantage observed when the first two keystrokes were primed in Experiment 2 was more pronounced than the RT advantage observed when the first and last keystrokes were primed in Experiment 3. Experiment 4 asked whether priming has a graded influence that depends on the number of keystrokes that are primed in sequence. We compared RT for probed target words that were preceded by primes that shared the first one, two, three, or four keystrokes with the target. The results indicated that priming increased with the number of keystrokes that were primed in sequence and was graded across the keystroke sequence, with less priming in later positions.

Experiment 1

The purpose of Experiment 1 was to determine whether keystroke identities can be primed separately from their order. Position coding theories of serial order suggest that item and order information are represented separately, so priming a sequence of keystrokes should activate the identities of all the keystrokes separately from their order. Chaining theories suggest that item and order information are represented jointly, so priming a sequence of keystrokes should activate keystroke identities only in the sequence that was primed.

On each trial, typists were presented with a prime word and were told to prepare to type it (see Figure 1). When typists prepare to type a word, the motor system activates the relevant item and order information and maintains this information in a motor program. To ensure that the typists prepared to type the prime, the prime was followed by a go signal (i.e., *****) that prompted the typists to type the prime in 25% of the trials. In the remaining trials, the prime was followed by a target that was identical to the prime, an anagram of the prime, or a word that was unrelated to the prime.

When the target is identical to the prime, the motor system only needs to execute the motor program that was prepared for the prime. When the target is unrelated to the prime, the motor program that was prepared for the prime is no longer appropriate, so the motor system needs to generate a new motor program by activating and ordering a new set of keystrokes. As a result, RT should be shorter when targets follow identical primes than when they follow unrelated primes. When the target is an anagram of the prime, the motor program that was prepared for the prime activated all of the keystrokes necessary to type the target, but in an inappropriate order. Thus, the motor program needs to be changed. The cognitive system may do this by creating a new program or revising the existing program. In either case, the residual activation of the shared keystrokes will affect RT differently depending on whether item and order information are represented jointly or separately.

If item and order are represented jointly, as serial chaining theories suggest, the motor system would need to activate a chain of keystrokes that are linked in a specific sequence, just as it would when targets follow unrelated primes. Thus, RT should be as long when targets follow anagram primes as when targets follow unrelated primes. If item and order are represented separately, as position coding theories suggest, the motor system would need to associate the active keystrokes with different position codes. The activation of the keystrokes may decrease the amount of time it takes to create a motor program for the target, so RT may be shorter when targets follow anagram primes than when they follow unrelated primes. However, the activated keystrokes may have to be dissociated from the positions codes they were associated with and reassigned to new position codes. That may increase the time it takes the motor system to create a motor program for the target,
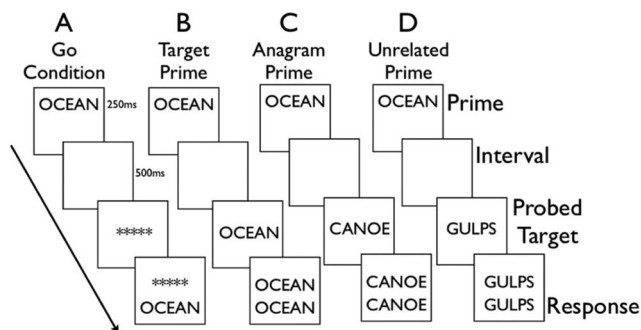

Figure 1. Schedule of events that took place in each trial during Experiment 1. Go trials are depicted in Panel A. Target prime trials are depicted in Panel B. Anagram prime trials are depicted in Panel C. Unrelated prime trials are depicted in Panel D.

so RT may be longer when targets follow anagram primes than when they follow unrelated primes (Neill & Mathis, 1998; Neill, Valdes, Terry, & Gorfein, 1992). In either case, the motor system has to associate the keystrokes with the appropriate position codes, so RT should be longer when targets follow anagram primes than when they follow identical primes.

Method

Subjects. We recruited 17 typists who had formal training in touch typing and the self-reported ability to type 40 WPM. We did not use the data from one typist who did not follow task instructions. We verified their typing skill with a typing test (for details, see WPM Logan & Zbrodoff, 1998). Their average typing speed was 72.2 WPM (range = 43.6–121.5 WPM) and their mean accuracy was 93.4% (range = 82.9%–100%). They received course credit or $12 for 60 min of participation.

Apparatus and materials. We compiled a pool of 194 five-letter words from the MRC Psycholinguistic Database (Wilson, 1987). The mean word frequency per million words was 52.0 (range = .01–1139.2), as verified by the Corpus of Contemporary American English (Davies, 2008). Each word was an anagram of another word in the list (see Appendix A). No anagrams shared first letters.

The experiment took place on a personal computer programmed in LIVECODE (http://livecode.com) using a 15-in. SVGA monitor. Typists sat about 57 cm from the monitor. Responses were registered on a standard QWERTY keyboard. The program blackened the screen and displayed a 24.1 cm × 19.7 cm gray window. The prime word was displayed 5.1 cm from the top of the window in black 40-point Helvetica font. The probe was presented 6.4 cm from the top of the window in the same font. Typists' responses were echoed 3.8 cm below the probe.

Procedure. At the beginning of each trial, a prime word was displayed for 250 ms. It was subsequently removed. After a 500-ms blank interval, the probe was displayed. The probe was either a go stimulus (i.e., *****) or a target word. There were four conditions (see Figure 1). In the *go* condition, typists were primed with a word and probed with the go stimulus (Figure 1, Panel A). In the *target prime* condition, typists were primed with the target word and probed with the target word (Figure 1, Panel B). In the *anagram prime* condition, typists were primed with an anagram of

Reaction Time

Figure 2. Average reaction time for each condition in Experiment 1. Error bars display Fisher's least significant difference for *p* < .05.

Table 1

Summary Tables for One-Way Analyses of Variance (ANOVA) Conducted on Response Times (RTs) and Error Rate (ER) Data From Experiment 1

Measure	MSE	F	η_p^2
RT	7178.5	19.6*	.566
ER	4.9	<1	.057

Note. Degrees of freedom for each effect = 3,45. *F* = F statistic; *MSE* = mean standard error.
* *p* < .05.

the target word and probed with the target word (Figure 1, Panel C). In the *unrelated prime* condition, typists were primed with a randomly selected word that was not the target word or an anagram of the target word, and then probed with a target word (Figure 1, Panel D). Each of the 194 words served as a prime four times, once per condition, resulting in a total of 776 trials.

Typists were instructed to pay attention to the prime word and to prepare to type it as soon as the go stimulus appeared. If a word was displayed instead of the go stimulus, typists were to type that word as quickly and accurately as possible. The backspace key was disabled, so typists were not able to correct their responses. Typists pressed the spacebar to move on to the next trial. Once typists finished the experiment, they completed the typing test.

Results and Discussion

We calculated mean RT from correct trials. We excluded RTs that were more than 2.5 standard deviations from the mean (Van Selst & Jolicoeur, 1994). This excluded 2.6% of the data. We also calculated mean error rates (i.e., percentage of trials in which at least one typing error was committed) for each condition for each typist. Mean RTs across typists are presented in Figure 2. We conducted one-way analyses of variance (ANOVAs) on the RT and error rates. The summary tables for the ANOVAs are presented in Table 1.

ANOVA revealed that RT differed significantly between the conditions. To determine which differences were significant, we calculated Fisher's least significant difference (LSD), which was 60 ms for *p* < .05. We also calculated the Bonferroni-corrected minimum mean difference, which was 83 ms for the adjusted alpha level of .008 per test (.05/6). Using either criterion, RT did not differ significantly between go (*M* = 558 ms) and target prime trials (*M* = 521 ms), which suggests that typists were prepared to type the prime. RT in unrelated prime trials (*M* = 692 ms) was significantly longer than both go and target prime trials. RT in anagram prime trials (*M* = 706 ms) was significantly longer than in target prime trials. RT did not differ significantly between anagram and unrelated trials (*M* = 692 ms). These findings indicate that it takes the motor system approximately the same amount of time to reorder a set of previously activated keystrokes as it does to activate and order a new set of keystrokes. These results are consistent with the notion that item and order information are represented jointly, not separately, in skilled typewriting. There were no significant differences in error rates between the conditions (go: *M* = 10.1%; target: *M* = 9.2%; anagram: *M* = 10.3%; unrelated: *M* = 10.3%).
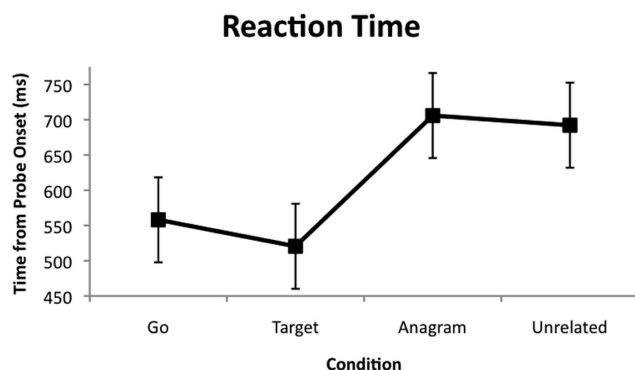
Experiment 2

The results of Experiment 1 indicated that key identities were not primed separately from their order. The findings were more consistent with chaining theories than position coding theories, but they do not rule out position coding theories entirely. Although keystroke identities were the same in target and anagram primes, the keystrokes that were associated with position codes differed. If typists represent serial order by position coding, priming may be produced only when keystroke identities are associated with the same position code in the prime and the target.

In Experiment 2, we tested whether a prime would facilitate RT if two of the keystroke identities in the prime and target were associated with the same position codes, but occurred in different sequences. We compared primes in which keystroke identities were the same as the target in the first two positions but differed in the last two positions (SSDD trials), primes in which keystroke identities were the same as the target in the last two positions but differed in the first two positions (DDSS trials), primes in which keystroke identities were the same as the target in all four positions (SSSS trials), and primes in which the keystroke identities differed from the target in all four positions (DDDD trials), in which S and D indicate whether the keystroke identity associated with a position was the same (S) or different (D) in the prime and target.

If serial order is represented by position coding, RT should be faster for targets that follow both SSDD and DDSS primes than for targets that follow DDDD primes. When targets follow SSDD and DDSS primes, the associations between two keystrokes and two positions are the same in the prime and the target. The activation in these positions should reduce the amount of time needed to prepare a motor program for the target. If serial order is represented by chaining, RT should be faster for targets that follow SSDD primes than for targets that follow DDDD primes, but RT should not be faster targets that follow DDSS primes than for targets that follow DDDD primes. Chaining theories assume that motor programs are prepared from the beginning of the sequence. In SSDD trials, the first two links in the chain are primed, which should reduce the amount of time needed to prepare them. In DDSS trials, the last two keystrokes are primed, but they follow two unprimed keystrokes. A new chain would need to be established from the beginning of the sequence, so the advantage of priming would be lost.

It is possible that the priming effects on RT reflect visual priming that reduces the time it takes to encode the target. We did not think that visual priming was likely because Peressotti and Grainger (1999) found no priming from visual primes that partially overlapped with targets in a recognition task, and Crump and Logan (2010) found equivalent priming with visual and auditory primes in a typing task. Nevertheless, we thought it was important to determine whether the priming effects are visual or motor, so we ran two groups of typists. One group received a visual prime, as in Experiment 1 and the experiments that follow. The other group received an auditory prime. If the priming is visual and perceptual, rather than motor, there should be no priming in the auditory group. If priming is motor, there should be priming in both the visual and auditory groups.

Priming effects in RT reflect the time it takes to prepare a motor program and implement the first step in program. To determine whether priming affects the implementation of subsequent steps in the program, we analyzed interkeystroke latencies. The second keystroke latency (L2) corresponds to the interval between the first and second keystroke. The third keystroke latency (L3) corresponds to the interval between the second and third keystroke. The fourth keystroke latency (L4) corresponds to the interval between the third and fourth keystroke. We focused our analyses on L3, which reflects the latency before the first unprimed keystroke in SSDD trials and before the first primed keystroke in DDSS trials.

Both serial chaining and position coding predict that L3 would be longer in SSDD trials than in DDDD trials. The first two keystrokes are primed in SSDD trials but not in DDDD trials, so the second keystroke should be executed faster in SSDD than in DDDD trials. Serial chaining predicts that L3 should not differ between DDSS and DDDD primes because the motor system would need to prepare a new chain of four keystrokes in both conditions. Position coding predicts that L3 will be shorter in DDSS than in DDDD trials because the last two keystrokes are primed in DDSS trials but not in DDDD trials.

Method

Subjects. Two new groups of 16 skilled typists were recruited from the same population as Experiment 1. For the visual prime group, average typing speed was 77.8 WPM (range = 46.5–119.3 WPM). Average typing accuracy was 93.8% (range = 86.4%–97.3%). For the auditory prime group, average typing speed was 83.9 WPM (range = 50.0–113.5 WPM). Average typing accuracy was 93.2% (range = 84.8%–98.2%).

Apparatus, stimuli, and procedure. The priming procedure was the same for both groups, except for the presentation of the prime. We compiled a pool of 100 four-letter words from the MRC Psycholinguistic Database (Wilson, 1987). The mean word frequency per million words was 108.3 (range = .41–4788.3), as verified by the Corpus of Contemporary American English (Davies, 2008). Word selection was based on the following criteria: the word consisted of four different letters, the word shared no letters with at least one other word in the list, the word shared only the first two letters with another word in the list, and the word shared only the last two letters with another word in the list (see Appendix B).

There were five conditions. The go condition occurred on 20% of the trials. In go trials, the target word was presented as the prime. A series of four asterisks was presented as the probe. In SSSS, SSDD, DDSS, and DDDD trials, a word was presented as the probe. In SSSS trials, the probe was the same as the prime (e.g., busy => busy). In SSDD trials, the first two letters of the prime were the same as the target, and the last two letters of the prime were different from the target (e.g., busy => burn). In DDSS trials, the first two letters of the prime differed from the target, and the last two letters of the prime were the last two letters of the target (e.g., busy => easy). In DDDD trials, all four of the prime's letters differed from the target (e.g., busy => wait). Each of the 100 words served as a prime in each of the five conditions, which resulted in a total of 500 trials. All other apparatuses and procedures were the same as Experiment 1.

For the auditory prime group, synthesized versions of the prime words were generated using the Apple Macintosh voice synthesizer (Apple Corp., Cupertino, CA). The average duration of the synthesized primes was 530 ms (range = 416–643 ms; standard

deviation = 45 ms). Auditory primes were played through headphones. The probe was presented visually 750 ms after the onset of the auditory prime to match the stimulus onset asynchrony between the visual prime and the target. All other aspects of the procedure were the same as in the visual prime group.

Results and Discussion

Visual prime group. We calculated error rate and mean RT for correct trials for each condition for each typist. We removed RTs that were more than 2.5 standard deviations from the mean (Van Selst & Jolicoeur, 1994), which excluded 2.7% of the data. Mean RTs across typists are displayed in Figure 3 (solid line). We conducted one-way ANOVAs on the RTs and error rates. The summary tables for the ANOVAs are presented in Table 2.

There were significant differences in RT between the conditions. Fisher's LSD for $p < .05$ was 29 ms. Bonferroni-corrected minimum mean difference was 42 ms for the adjusted alpha level of .005 (.05/10). Using either criterion, RT was significantly shorter in go trials ($M = 583$ ms) than in DDDD trials ($M = 659$), indicating that typists were prepared to type the prime. RT was significantly shorter in SSSS ($M = 512$ ms) than SSDD trials ($M = 581$ ms), and significantly shorter in SSDD than in DDSS ($M = 660$ ms). RT did not differ significantly between DDSS and DDDD trials ($M = 659$ ms). These findings indicate that priming the keystrokes in the first two, but not the last two, positions reduces the amount of time it takes to prepare the motor program for the target word and execute the first keystroke. This suggests that skilled typists represent order with serial chaining and not position coding. There were no significant differences in error rate between the conditions (Go: $M = 8.6\%$; SSSS: $M = 8.3\%$; SSDD: $M = 7.3\%$; DDSS: $M = 6.8\%$; DDDD: $M = 7.1\%$).

Interkeystroke latencies were calculated from correct trials for each condition for each typist. One-way ANOVAs conducted on the mean L2, L3, and L4 measures indicated significant differences between conditions for all three intervals (see Table 2). We focused on L3 because it was the interval before the first unprimed keystroke in SSDD trials and before the first primed keystroke in DDSS trials. Average L3 for each condition are displayed with a solid line in Figure 4. L3 was calculated by subtracting the RT of

the third keystroke (RT3) from the RT of the second keystroke (RT2). Outlier analyses excluded 2.6% of the data. Fisher's LSD for $p < .05$ was 5 ms. Bonferroni-corrected minimum mean difference was 7 ms for the adjusted alpha level of .005 (.05/10). Using either criterion, L3 was significantly longer in SSDD ($M = 132$ ms) than in DDDD trials ($M = 122$ ms). L3 did not differ significantly between DDDD and DDSS ($M = 120$ ms) trials. These results are consistent with serial chaining.

Auditory prime group. Mean RTs, L3, and error rates were calculated as before. Outlier analyses excluded 2.6% of the RT data and 2.6% of the L3 data. Mean RTs across typists are displayed in Figure 3 (dashed line). The summary tables for the ANOVAs conducted on RTs, L3, and error rates are presented in Table 2.

Auditory primes produced the same differences in RT between conditions as visual primes. Fisher's LSD for $p < .05$ was 23 ms. Bonferroni-corrected minimum mean difference for was 34 ms for the adjusted alpha level of .005 (.05/10). Using either criterion, RT was significantly shorter in go trials ($M = 577$ ms) than in DDDD trials ($M = 693$). RT was significantly shorter in SSSS ($M = 506$ ms) than SSDD trials ($M = 585$ ms), and significantly shorter in SSDD than in DDSS ($M = 693$ ms). RT did not differ significantly between DDSS and DDDD trials. These findings indicate that

Table 2

Summary Table for One-Way ANOVAs Conducted on Response Time (RT), Latencies Between Successive Keystrokes (L2, L3, and L4), and Error Rate (ER) Data From Experiment 2

Measure	Visual prime			Auditory prime		
	MSE	F	η_p^2	MSE	F	η_p^2
RT	1667.6	37.4*	.713	1062.2	99.6*	.869
L2	43.6	4.3*	.223	72.9	9.0*	.374
L3	43.3	12.4*	.452	101.2	13.4*	.471
L4	55.2	4.9*	.245	64.8	2.4	.139
ER	5.9	1.6	.099	19.1	8.6*	.364

Note. Degrees of freedom for each effect = 4,60. F = F statistic; MSE = mean standard error.
* $p < .05$.

Figure 3. Average reaction time (RT) for each condition in Experiment 2. Visual prime RTs are represented with the solid line. Auditory prime RTs are represented with the dashed line. Error bars display Fisher's least significant difference for $p < .05$.
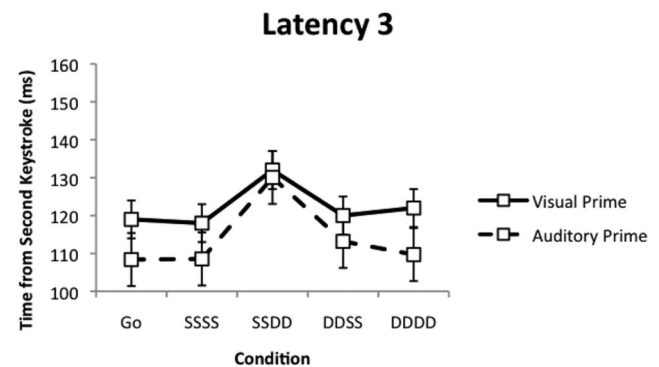
Figure 4. Average interkeystroke latency between the second and third keystroke (L3) for Experiment 2. Visual prime reaction times (RTs) are represented with the solid line. Auditory prime RTs are represented with the dashed line. Error bars display Fisher's least significant difference for $p < .05$.

auditory and visual primes affected RT in the same way, which suggest that the locus of the priming effect is motor rather than visual.

There were significant differences in error rate between auditory prime conditions. Fisher's LSD was 3.1%. Bonferroni-corrected minimum mean difference for was 4.5%. Using either criterion, error rates in go trials ($M = 17.4\%$) were higher than error rates in SSSS trials ($M = 9.2\%$), SSDD trials ($M = 10.1\%$), DDSS trials ($M = 12.5\%$), and DDDD trials ($M = 12.3\%$). Using the Fisher's LSD criterion, errors rates were marginally higher in DDSS and DDDD trials than in SSSS trials.

Average L3 across conditions are displayed in Figure 4 (dashed line). Fisher's LSD was 7 ms. Bonferroni-corrected minimum mean difference for was 11 ms. Again, the L3 results for the auditory prime group mirrored the L3 results for the visual prime group. Using either criterion, L3 was significantly longer in SSDD ($M = 130$ ms) than in DDDD trials ($M = 110$ ms). L3 did not differ significantly between DDDD and DDSS ($M = 113$ ms) trials.

The effects of visual versus auditory primes. To assess the effects of visual versus auditory primes, we conducted ANOVAs on RT, L3, and error rate, with prime group as a between-subjects factor. The interaction was not significant for RT, $F(4, 120) < 1$, $MSE = 1364.9$, $p = .06$, or L3, $F(4, 120) = 1.8$, $MSE = 72.3$, $p = .14$, but it was significant for error rate, $F(4.120) = 5.9$, $MSE = 12.5$, $p < .001$. Typists in the auditory prime group may have had difficulty discerning some of the synthesized words, which could have led to higher error rates, especially in go trials.

Experiment 3

In Experiment 3, we continued to test whether priming some of the keystrokes would facilitate the preparation and implementation of the sequence. In Experiment 2, the first (SSDD) or second (DDSS) half of a keystroke sequence was primed. In Experiment 3, the beginning and end (SDDS) or the middle (DSSD) of a keystroke sequence was primed. The auditory primes in Experiment 2 established that priming was motor and not visual, so we used visual primes in Experiment 3 and subsequent experiments. Targets could also follow primes that shared all four keystrokes (SSSS) or none of the keystrokes (DDDD). If keystroke order is represented by position coding, RT should not differ between SDDS and DSSD trials, and RT in SDDS and DSSD trials should be shorter than RT in DDDD trials. If keystroke order is represented by serial chaining, RT should be shorter in SDDS than in DSSD and DDDD trials, and RT should not differ between DSSD and DDDD trials.

In addition to RT, we analyzed L2 and L4 keystroke latencies to compare primed and unprimed keystrokes. If keystroke order is represented by position coding, L2 should be shorter in DSSD than in DDDD trials, and L4 should be shorter in SDDS than in DDDD trials. If keystroke order is represented by serial chaining, L2 should not differ between DSSD, and DDDD trials and L4 should not differ between SDDS and DDDD trials.

Method

Subjects. A new group of 16 skilled typists was recruited from the same population as the previous experiments. Their average typing speed was 77.3 WPM (range = 52.8–95.5 WPM). Their average accuracy was 94.0% (range = 87.9%–100%).

Apparatus, stimuli, and procedure. We compiled a new pool of 100 four-letter words from the MRC Psycholinguistic Database (Wilson, 1987). The mean word frequency per million words was 61.1 (range = .01–970.2), as verified by the Corpus of Contemporary American English (Davies, 2008). Word selection was based on the following criteria: the word consisted of four different letters, the word shared no letters with at least one other word in the list, the word shared only the first and fourth letters with another word in the list, and the word shared only the second and third letters with another word in the list (see Appendix C).

There were five conditions, and each occurred on 20% of the trials: go, SSSS, SDDS, DSSD, and DDDD. The go, SSSS, and DDDD conditions were the same as in Experiment 2. In the SDDS condition, the first and fourth letters of the prime matched the target, and the second and third letters were different (e.g., fire => fuse). In the DSSD condition, the first and fourth letters of the prime differed from the target, and the second and third letters of the prime matched the target (e.g., fire => girl). Each of the 100 words served as a prime in each of the five conditions, which resulted in a total of 500 trials. All other apparatuses and procedures were the same as in Experiment 2.

Results and Discussion

Error rates and mean RT for correct trials were calculated for each condition for each subject. Mean RTs across typists are displayed in Figure 5. Figure 6 displays mean L2 (A) and L4 (B), averaged across typists. We conducted one-way ANOVAs on the RT, L2, L3, L4, and error rate data. The summary tables for the ANOVAs are presented in Table 3.

Outlier analyses excluded 2.8% of the RT data. RTs differed significantly between conditions. Fisher's LSD for $p < .05$ was 29 ms. Bonferroni-corrected minimum mean difference was 43 ms for the adjusted alpha level of .005 (.05/10). Using either criterion, RT was significantly shorter in SSSS trials ($M = 508$ ms) than in SDDS trials ($M = 630$ ms) trials, and significantly shorter in SDDS trials than in DSSD trials ($M = 694$ ms). RT did not differ significantly between DSSD and DDDD ($M = 678$ ms) trials. These findings are consistent with serial chaining.

L2 was calculated by subtracting the RT of the second keystroke (RT2) from the RT of the first keystroke (RT). Outlier analyses
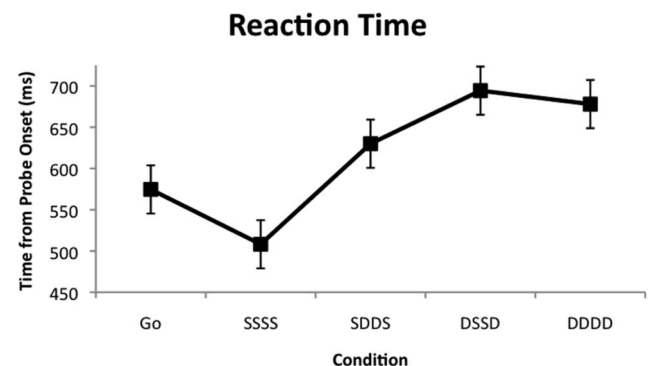

Figure 5. Average reaction time for each condition in Experiment 3. Error bars display Fisher's least significant difference for $p < .05$.

excluded 2.8% of the RT2 data. The ANOVA conducted on the L2 data indicated that L2 differed marginally between conditions. Fisher's LSD for $p < .05$ was 4 ms. Bonferroni-corrected minimum mean difference for the adjusted alpha level of .005 (.05/10) was 6 ms. Using either criterion, L2 was significantly longer in SDDS ($M = 143$ ms) trails than in SSSS ($M = 120$ ms), DSSD ($M = 128$ ms), or DDDD ($M = 124$ ms) trials. This result is consistent with both serial chaining and position coding theories. The Fisher LSD criterion suggests that L2 was marginally longer in DSSD than in DDDD trials. This result is inconsistent with both theories: Chaining theories would predict that L2 should not differ between DSSD and DDDD trials. Position coding theories would predict that L2 should be shorter in DSSD than in DDDD trials.

L3 was calculated by subtracting the RT of the fourth keystroke (RT4) from the RT of the third keystroke (RT3). Outlier analyses excluded 2.8% of the RT3 data and 2.6% of the RT4 data. The ANOVA conducted on the L4 data indicated no significant differences between the conditions. Fisher's LSD for $p < .05$ was 5 ms. Bonferroni-corrected minimum mean difference was 7 ms for adjusted $p < .005$. Using this criterion, L4 did not differ significantly between SSSS ($M = 128$ ms), SDDS ($M = 129$ ms), DSSD ($M = 125$ ms), and DDDD ($M = 127$ ms) trials. Position coding predicts that priming keystrokes that occur in common positions facilitates keystroke execution, so these null results are more consistent with serial chaining than with position coding. There were also no significant differences in error rates between the conditions (go: $M = 8.3\%$; SSSS: $M = 8.5\%$; SDDS: $M = 8.1\%$; DSSD: $M = 10.3\%$; DDDD: $M = 7.3\%$).
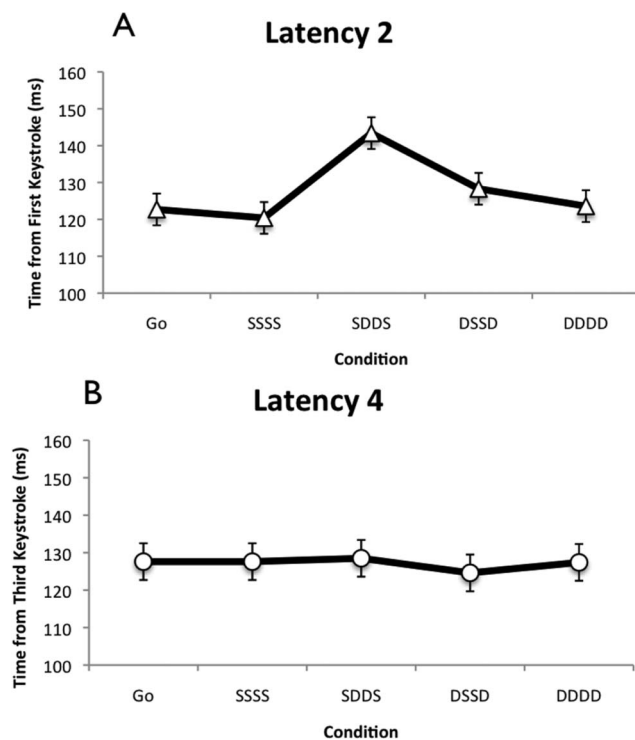

Figure 6. Average interkeystroke latencies for Experiment 3. Panel A depicts the average latency between the first and second keystroke (L2). Panel B depicts the average latency between the third and fourth keystroke (L4). Error bars display Fisher's least significant difference for $p < .05$.

Table 3

Summary Tables for One-Way ANOVAs Conducted on Response Time (RT), Latencies Between Successive Keystrokes (L2, L3, and L4), and Error Rate (ER) Data From Experiment 3

Measure	MSE	F	η_p^2
RT	1704.3	55.2*	.786
L2	37.2	4.0	.211
L3	65.9	1.3	.082
L4	47.8	<1	.047
ER	9.3	2.0	.119

Note. Degrees of freedom for each effect = 4,60. F = F statistic; MSE = mean standard error.
* $p < .05$.

Experiment 4

The RT results of Experiments 2 and 3 were consistent with chaining theories of serial order. The L3 results of Experiment 2 and the L2 results of Experiment 3 were also consistent with serial chaining. However, the L4 analyses of Experiment 3 were not entirely consistent with serial chaining or position coding.

These conclusions are based on the assumption that priming influences each item in a sequence equally. However, this may not be the case. Priming may influence items in a sequence differentially. The results of Experiments 2 and 3 suggest that priming may depend on at least two factors. First, priming may be stronger when more keystrokes are primed consecutively. The RT difference between SSDD and DDDD trials in the visual prime group of Experiment 2 (78 ms) was 30 ms larger than the RT difference between SDDS and DDDD trials in Experiment 3 (48 ms). Second, priming may be stronger for earlier positions in sequence than for later positions. The L2 difference between SDDS and DDDD trials in Experiment 3 (21 ms) was 11 ms larger than the L3 difference between SSDD and DDDD trials in the visual prime group of Experiment 2 (10 ms). L4 differences in Experiment 3 were not larger than 4 ms. The purpose of Experiment 4 was to test, within subjects, whether keystrokes are primed equally across serial positions.

In Experiment 4, we varied the number of keystrokes that were primed in sequence. Typists were primed with words that shared all keystrokes (SSSS), the first three keystrokes (SSSD), the first two keystrokes (SSDD), the first keystroke (SDDD), or no keystrokes (DDDD) with the target word. If priming depends on the number of keystrokes that are primed in sequence, RT should be shorter when more keystrokes are primed than when fewer keystrokes are primed. If priming depends only on priming the first keystroke, RT should not differ between SSSS, SSSD, SSDD, and SDDD trials. If priming affects keystrokes more at the beginning of a sequence than at the end of a sequence, the L2 difference between SDDD and DDDD trials should be larger than the L3 difference between SSDD and DDDD trials, and the L3 difference should be larger than the L4 difference between SSSD and DDDD trials.

Method

Subjects. A new group of 17 typists was recruited from the same population as before. We excluded data from one typist who

did not follow task instructions. Average typing speed was 66.3 WPM (range = 47.2–107.9 WPM). Average typing accuracy was 92.6% (range = 87.2%–99.1%).

Apparatus, stimuli, and procedure. We compiled a pool of 104 four-letter words from the MRC Psycholinguistic Database (Wilson, 1987). The mean word frequency per million words was 158.2 (range = .29–4864.9), as verified by the Corpus of Contemporary American English (Davies, 2008). Word selection was based on the following criteria: the word consisted of four different letters, the word shared no letters with at least one other word in the list, the word shared only the first letter with another word, the word shared only the first and second letters with another word, and the word shared the first, second, and third letters with another word (see Appendix D).

There were six conditions, and each occurred on one sixth of the trials: go, SSSS, SSSD, SSDD, SDDD, and DDDD. The go, SSSS, DDDD, and SSDD trials were the same as in Experiment 2. In SSSD trials, the first, second, and third letters of the prime were the same as the target, and the last letter was different (e.g., hair => hail). SDDD trials, the first letter of the prime was the same as the target, and the second, third, and fourth letter were different (e.g., hair => hunk). Each of the 104 words served as a prime in each of the six conditions, which resulted in a total of 624 trials. All other apparatuses and procedures were the same as the previous experiments.

Results and Discussion

Figure 7 displays mean RT averaged across typists for each condition. Figure 8 displays mean L2 (A), L3 (B), and L4 (C) averaged across typists. We conducted one-way ANOVAs on the RT, error rate, L2, L3, and L4 data (see Table 4). Only RT and interkeystroke latency data from correct trials were analyzed.

We excluded RTs that were more than 2.5 standard deviations from the mean (3.0% of the data). RTs differed significantly between the conditions, decreasing monotonically with the number of primed keystrokes. We assessed the significance of the monotonic decrease with a linear trend test, which was highly significant, $F(1, 75) = 145.42$, $p < .001$. Error rates differed marginally across conditions (go: $M = 6.3\%$; SSSS: $M = 8.6\%$; SSSD: $M = 7.9\%$; SSDD: $M = 7.1\%$; SDDD: $M = 6.9\%$; DDDD: $M = 9.1\%$).

L2 was calculated by subtracting the RT of the second keystroke (RT2) from the first keystroke (RT). L3 was calculated by sub-

Figure 8. Average interkeystroke latencies for Experiment 4. Panel A depicts the average L2. Panel B depicts the average L3. Panel C depicts the average L4. Error bars display Fisher's least significant difference for $p < .05$.

tracting the RT of the third keystroke (RT3) from RT2. L4 was calculated by subtracting the RT of the fourth keystroke (RT4) from RT3. Outlier analyses excluded 2.9% of the RT2 data, 2.8% of the RT3 data, and 2.9% of the RT4 data. Latencies for the first unprimed keystroke, or S-D transition, decreased monotonically across positions. L2 in SDDD trials was 151 ms, L3 in SSDD trials was 140 ms, and L4 in SSSD trials was 136 ms. We assessed the significance of this monotonic decrease with a linear trend test, using a one-way ANOVA on the relevant S-D transitions (i.e., SDDD L2, SSDD L3, and SSSD L4) data. The contrast was significant, $F(1, 30) = 5.2$, $MSE = 346.1$, $p < .05$.

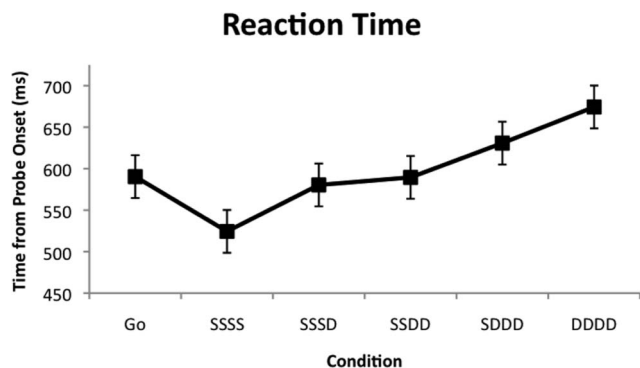Figure 9 displays the interkeystroke latencies for SSSS, DDDD, and the relevant S-D transitions. A 3 (condition: SSSS vs. DDDD

Figure 7. Average reaction time for each condition in Experiment 4. Error bars display Fisher's least significant difference for $p < .05$.
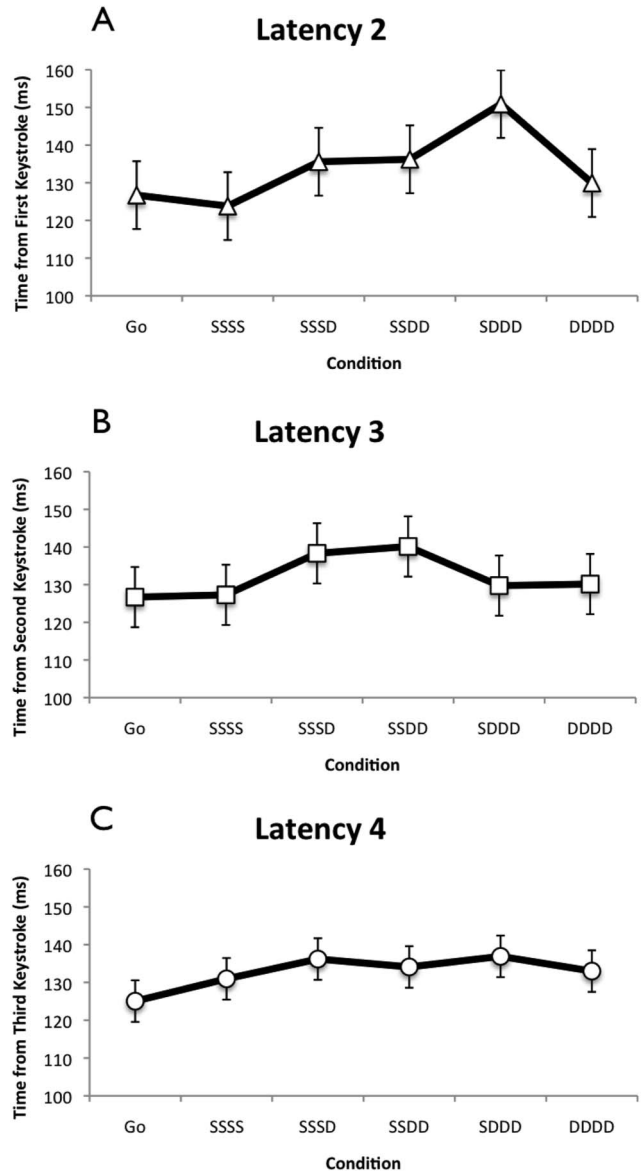
Table 4

Summary Table for One-Way ANOVAs Conducted on Response Time (RT), Latencies Between Successive Keystrokes (L2, L3, and L4), and Error Rate (ER) Data From Experiment 4

Measure	MSE	F	η_p^2
RT	1340.1	30.1[*]	.786
L2	175.2	8.5[*]	.211
L3	130.6	4.0[*]	.082
L4	61.2	4.9[*]	.047
ER	7.9	2.3[*]	.119

Note. Degrees of freedom for each effect = 5,75. F = F statistic; MSE = mean standard error.
[*] $p < .05$.

vs. S-D transition) × 3 (transition: L2 vs. L3 vs. L4) ANOVA revealed a significant effect of condition, $F(2, 30) = 10.0$, $MSE = 295.5$, $p < .001$, and nonsignificant effect of latency, $F(2, 30) < 1$, $MSE = 369.6$, $p = .834$. However, the interaction was significant, $F(4, 60) = 5.5$, $MSE = 101.5$, $p < .001$. Fisher's LSD for $p < .05$ was 7 ms. Bonferroni-corrected minimum mean difference was 9 ms for adjusted $p < .008$. We tested the difference in the linear trends of the S-D transitions and the corresponding latencies in DDDD trials. The contrast was significant, $F = 186.4$, $p < .001$. This result indicates a graded reduction in the effect of priming across serial positions. We also tested the difference in the linear trends of the S-D transitions and the corresponding latencies in SSSS trials. The contrast was significant, $F = 180.8$, $p < .001$. This result indicates a graded reduction in the amount of time needed to implement an unprimed keystroke across serial positions. Thus, whether priming is defined as decreased RT for primed versus unprimed responses, or as increased RT for unprimed versus primed responses, our findings indicate that there is a graded reduction in the effect over serial positions.

General Discussion

We investigated the problem of serial order in skilled typing by asking how typists represent the identity and order of the keystrokes they type. We conducted four experiments that were designed to test whether keystroke identity and order are represented jointly, as chaining theories suggest, or separately, as position coding theories suggest. All four experiments showed that keystrokes primed in the correct order and sequence produced an RT advantage. Experiment 1 showed that keystrokes primed out of order do not produce an RT advantage. Experiments 2 and 3 showed that keystrokes primed in the correct order, but out of sequence, did not produce an RT advantage. Experiment 4 showed that priming is graded across the keystroke sequence and that the RT advantage is modulated by the number of keystrokes that are primed in sequence.

Serial Order by Chaining

Chaining theories provide a good account of our findings. Chaining theories assume that keystroke identity and order are represented jointly. Preparing a sequence of keystrokes requires linking a specific sequence of keystrokes into a chain, so there should be no benefit of priming the appropriate keystrokes in an

inappropriate order. Accordingly, RTs did not differ between anagram prime and unrelated prime trials in Experiment 1. In addition, there should be no benefit of priming keystrokes in the correct order but out of sequence. Accordingly, RTs did not differ between DDSS and DDDD prime trials in Experiment 2, or between DSSD and DDDD prime trials in Experiment 3. It takes time to add different links to a chain, so RT should be shorter when fewer links need to be added to the chain. Accordingly, RTs were shorter when more keystrokes were primed in sequence in Experiment 4.

Lashley (1951) identified three problems that challenge classic chaining theories as viable means of controlling serial order. One problem is that skilled keystrokes are executed too rapidly for afferent information from each keystroke to serve as the stimulus for the next keystroke (Keele, 1968; Lashley, 1951). However, keystrokes can be executed rapidly if the motor command for each keystroke serves as the stimulus for the next keystroke, as modern chaining theories suggest (Desmurget & Grafton, 2000). Another problem is that items should never be produced out of order (i.e., transpositions), because each item cues the next item in the sequence. However, items can be produced out of order if compound associations link all items in a sequence to the prior context, as modern chaining theories suggest (Botvinick & Plaut, 2004, 2006; Chance & Kahana, 1997; Keele et al., 2003; Murdock, 1993; Yamashita & Tani, 2008).

A third problem is that classic chaining theories do not account for recovery from errors. Each item cues the next item in a sequence, so a transposition, omission, or insertion error would not cue the right item. Modern chaining theories can be extended to account for recovery from errors if we assume the cognitive system reinstates the prior context and works back through the chain. Skilled typists prefer to correct errors, moving automatically to press the backspace key (Crump & Logan, 2013), deleting back to the error or deleting the entire word. Both strategies reset the context, and provide cues that retrieve the right sequence.

Serial Order by Position Coding

Classic position coding theories do not account for our findings. Position coding theories assume that keystroke identity and order
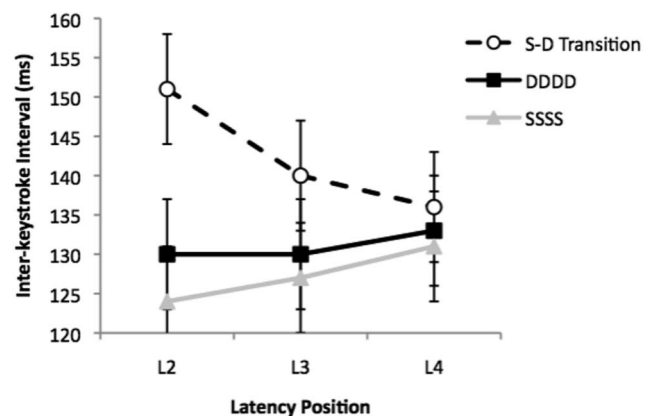

Figure 9. Average interkeystroke latencies for SSSS, DDDD, and S-D transition (i.e., SDDD L2, SSDD L3, and SSSD L4). Error bars display Fisher's least significant difference for $p < .05$.

are represented separately. Preparing a motor program requires activating keystroke identities and associating them with position codes or slots. This predicts a benefit of priming the appropriate identities in an inappropriate order. We should expect priming from anagrams and from the middle and last letters of words, but we found no such priming in Experiments 1 through 3. Modern, position coding theories that incorporate primacy gradients (Brown et al., 2000; Bullock, & Rhodes, 2003; Burgess & Hitch, 1999; Grossberg, 1978; Hartley & Houghton, 1996; Marshuetz, 2005; Page & Norris, 1998; Rhodes et al., 2004) may be better able to account for our results than their classic predecessors, but they still predict nonzero priming for anagrams, and for keystrokes in the middle and last positions of words, which we did not find. Thus, the results seem more consistent with chaining.

The Problem of Serial Order: One Problem or Many?

The overarching purpose of our study was to test the generality of the conclusion, drawn from studies of serial recall and speech, that the problem of serial order is solved by position coding. We found that this conclusion does not generalize to typing. Our results suggest that the problem of serial order in typing is controlled by serial chaining. Thus, the cognitive system appears to solve different problems of serial order in different ways.

The different solutions seem tailored to the demands of the tasks. Serial recall tasks are prone to both item and order errors, so recovery from errors is an important problem. The cognitive system may prefer position coding because it makes recovery from errors easier. By contrast, typing is very accurate and recovery from errors is easy—press the delete key to erase the error, then start over—so recovery from errors is less of a problem (Crump & Logan, 2013). Typing tasks usually present familiar words that have been typed many times before. Each repetition strengthens sequential associations between keystrokes, forming a chain. The cognitive system may prefer serial chaining for skilled typing because the sequential associations speed typing. By contrast, serial recall tasks present new unstructured lists on each trial. There is no repetition of the sequence that would produce chaining, so there is no reason for the cognitive system to prefer it over position coding, which allows rapid recovery from errors.

We might expect speech to be like typing because it is also fast and the materials are familiar words. However, speech differs from typing in two ways that might favor different solutions to the problem of serial order. First, speech is much faster than typing. People speak approximately 150 WPM, producing about 660 phonemes per minute (Levelt, 1999). Typists type approximately 75 WPM, producing about 375 keystrokes per minute. Chaining may be fast enough for typing—the efference copy of one command may be the stimulus for generating the next command—but it may not be fast enough for the high rates of speech. Lashley (1951) suggested hierarchical control could overcome the speed constraint, and position coding is hierarchical, representing order at one level and items at another. Consistent with this speculation, Yamaguchi, Crump, and Logan (2013) pressed typists to trade accuracy for speed, and found that typists seemed unable to type faster than 100 ms per keystroke. Serial chaining may not support faster responding, and that may invite the control system to consider position coding as a way around this limit. However, the 18- to 20-year-old typists we tested had a lot less practice typing than

speaking. They started typing around 10 years old (Logan & Crump, 2011), but begin speaking at 1 year. This doubling of the amount of practice may be responsible for speech being faster. We may see a transition from position coding when the response is so unfamiliar it must be maintained in STM, to serial chaining at intermediate levels of practice when sequential associations are available to support performance, to position coding at high levels of skill when serial chaining is not fast enough to support the desired level of performance.

Second, speech is more complex than typing. Speech contains units at three hierarchical levels—words, syllables, and phonemes—and this may invite position coding (Dell, 1986, 1990; Levelt, 1989; Mackay, 1987; O'Seaghdha & Marin, 2000; Sevald, & Dell, 1994; Stemberger, 1985, 1990). Syllabic structure is important in speech because it organizes articulation and, at the same time, expresses pragmatics through prosody. The order of syllables may be represented by position codes within words, and the order of phonemes may be represented by position codes within syllables. By contrast, typing contains units at two hierarchical levels—words and letters. Syllables are not important in the motor component of typing (Gentner, Larochelle, & Grudin, 1988), and the mapping from phonemes to graphemes is only partially consistent (in English). Words activate keystrokes directly (Crump & Logan, 2010; Logan & Crump, 2011). The cognitive system may prefer to use position coding to represent the more complex structure in spoken words, and serial chaining to represent the less complex structure in typed words (Keele et al., 2003).

Concluding Remarks

Different tasks pose different problems of serial order. Previous research showed that problems of serial order in serial recall and speech were solved by position coding, which suggested that all problems of serial order may be solved by position coding. Our experiments tested the generality of this conclusion in skilled typing by adapting a priming procedure that varied the overlap between primes and targets. We found consistent evidence for serial chaining, which suggests that the cognitive system can solve different problems of serial order in different ways.

References

Botvinick, M., & Plaut, D. C. (2004). Doing without schema hierarchies: A recurrent connectionist approach to normal and impaired routine sequential action. *Psychological Review, 111,* 395–429. doi:10.1037/0033-295X.111.2.395

Botvinick, M. M., & Plaut, D. C. (2006). Short-term memory for serial order: A recurrent neural network model. *Psychological Review, 113,* 201–233. doi:10.1037/0033-295X.113.2.201

Brown, G. D. A., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. *Psychological Review, 107,* 127–181. doi:10.1037/0033-295X.107.1.127

Bullock, D., & Rhodes, B. J. (2003). Competitive queuing for planning and serial performance. In M. A. Arbib (Ed.), *The handbook of brain theory and neural networks* (2nd ed., pp. 241–244). Cambridge, MA: MIT Press.

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review, 106,* 551–581. doi:10.1037/0033-295X.106.3.551

Chance, F. S., & Kahana, M. J. (1997). Testing the role of associative

interference and compound cues in sequence memory. In J. Bower (Ed.), *Computational neuroscience, trends in research* (pp. 599–603). New York, NY: Plenum Press. doi:10.1007/978-1-4757-9800-5_93

Conrad, R. (1965). Order error in immediate recall of sequences. *Journal of Verbal Learning & Verbal Behavior, 4,* 161–169. doi:10.1016/S0022-5371(65)80015-9

Crossman, E. R. F. W. (1961). Information and serial order in human immediate memory. In C. Cherry (Ed.), *Information theory* (pp. 147–159). Lon, UK: Butterworths.

Crowder, R. G. (1982). Demise of short-term memory. *Acta Psychologica, 50,* 291–323. doi:10.1016/0001-6918(82)90044-0

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

Crump, M. J. C., & Logan, G. D. (2013). Prevention and correction in post-error performance: An ounce of prevention and a pound of cure. *Journal of Experimental Psychology: General, 142,* 692–709. doi:10.1037/a0030014

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

Dell, G. S. (1986). A spreading activation theory of retrieval in language production. *Psychological Review, 93,* 283–321. doi:10.1037/0033-295X.93.3.283

Dell, G. S. (1990). Effects of frequency and vocabulary type on phonological speech errors. *Language and Cognitive Processes, 5,* 313–349. doi:10.1080/01690969008407066

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4,* 423–431. doi:10.1016/S1364-6613(00)01537-0

Estes, W. K. (1972). An associative basis for coding and organization in memory. In A. W. Melton & E. Martin (Eds.), *Coding processes in human memory* (pp. 161–190). Washington, DC: Winston.

Gentner, D. R., Larochelle, S., & Grudin, J. (1988). Lexical, sublexical, and peripheral effects in skilled typewriting. *Cognitive Psychology, 20,* 524–548. doi:10.1016/0010-0285(88)90015-1

Glenberg, A. M., & Swanson, N. G. (1986). A temporal distinctiveness theory of recency and modality effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12,* 3–15. doi:10.1037/0278-7393.12.1.3

Grossberg, S. (1978). A theory of human memory: Self-organization and performance of sensory-motor codes, maps, and plans. In R. Rosen & F. Snell (Eds.), *Progress in theoretical biology* (Vol. 5, pp. 233–374). New York, NY: Academic Press. doi:10.1016/B978-0-12-543105-7.50013-0

Hartley, T. A., & Houghton, G. (1996). A linguistically constrained model of short-term memory for nonwords. *Journal of Memory and Language, 35,* 1–31. doi:10.1006/jmla.1996.0001

Healy, A. F. (1974). Separating item from order information in short-term memory. *Journal of Verbal Learning & Verbal Behavior, 13,* 644–655. doi:10.1016/S0022-5371(74)80052-6

Henson, R. N. A. (1998). Short-term memory for serial order: The start-end model. *Cognitive Psychology, 36,* 73–137. doi:10.1006/cogp.1998.0685

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

Keele, S. W., Cohen, A., & Ivry, R. B. (1990). Motor programs: Concepts and issues. In M. Jennerod (Ed.), *Attention & performance XIII: Motor representation and control* (pp. 77–110). Hillsdale, NJ: Erlbaum.

Keele, S. W., Ivry, R. B., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review, 110,* 316–339. doi:10.1037/0033-295X.110.2.316

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

Lee, C. L., & Estes, W. K. (1977). Order and position in primary memory for letter strings. *Journal of Verbal Learning & Verbal Behavior, 16,* 395–418. doi:10.1016/S0022-5371(77)80036-4

Lee, C. L., & Estes, W. K. (1981). Item and order information in short-term memory: Evidence for multilevel perturbation processes. *Journal of Experimental Psychology: Human Learning and Memory, 7,* 149–169. doi:10.1037/0278-7393.7.3.149

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA: MIT Press.

Levelt, W. J. M. (1999). Models of word production. *Trends in Cognitive Sciences, 3,* 223–232. doi:10.1016/S1364-6613(99)01319-4

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

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

Mackay, D. G. (1987). *The organization of perception and action: A theory for language and other cognitive skills*. New York, NY: Springer. doi:10.1007/978-1-4612-4754-8

Marshuetz, C. (2005). Order information in working memory: An integrative review of evidence from brain and behavior. *Psychological Bulletin, 131,* 323–339. doi:10.1037/0033-2909.131.3.323

Melton, A. W., & Irwin, J. M. (1940). The influence of degree of interpolated learning on retroactive inhibition and the overt transfer of specific responses. *The American Journal of Psychology, 53,* 173–203. doi:10.2307/1417415

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

Murdock, B. B. (1960). The immediate retention of unrelated words. *Journal of Experimental Psychology, 60,* 222–234. doi:10.1037/h0045145

Murdock, B. B. (1983). A distributed memory model for serial-order information. *Psychological Review, 90,* 316–338. doi:10.1037/0033-295X.90.4.316

Murdock, B. B. (1993). TODAM2: A model for the storage and retrieval of item, associative, and serial order information. *Psychological Review, 100,* 183–203. doi:10.1037/0033-295X.100.2.183

Neill, W. T., & Mathis, K. M. (1998). Transfer-inappropriate processing: Negative priming and related phenomena. In D. L. Medin (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 38, pp. 1–44). San Diego, CA: Academic Press. doi:10.1016/S0079-7421(08)60182-6

Neill, W. T., Valdes, L. A., Terry, K. M., & Gorfein, D. S. (1992). Persistence of negative priming: II. Evidence for episodic trace retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 993–1000. doi:10.1037/0278-7393.18.5.993

O'Seaghdha, P., & Marin, J. W. (2000). Phonological competition and nonsequential processes in word production. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 57–73.

Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105,* 761–781. doi:10.1037/0033-295X.105.4.761-781

Peressotti, F., & Grainger, J. (1999). The role of letter identity and letter priming in orthographic priming. *Perception & Psychophysics, 61,* 691–706. doi:10.3758/BF03205539

Rhodes, B. J., Bullock, D., Verwey, W. B., Averbeck, B. B., & Page, M. P. A. (2004). Learning and production of movement sequences: Behavioral, neurophysiological, and modeling perspectives. *Human Movement Science, 23,* 699–746. doi:10.1016/j.humov.2004.10.008

Rosenbaum, D. A., Cohen, R. G., Jax, S. A., Weiss, D. J., & van der Wel, R. (2007). The problem of serial order in behavior: Lashley's legacy. *Human Movement Science, 26,* 525–554. doi:10.1016/j.humov.2007.04.001

Rosenbaum, D. A., Engelbrecht, S. E., Bushe, M. M., & Loukopoulos, L. D. (1993). Knowledge model for selecting and producing reaching movements. *Journal of Motor Behavior, 25,* 217–227. doi:10.1080/00222895.1993.9942051

Rosenbaum, D. A., Hindorff, D. A., & Munro, E. M. (1987). Scheduling and programming of rapid finger sequences: Tests and elaborations of the hierarchical editor model. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 193–203. doi:10.1037/0096-1523.13.2.193

Salthouse, T. A. (1986). Perceptual, cognitive, and motoric aspects of transcription typing. *Psychological Bulletin, 99,* 303–319.

Sevald, C. S., & Dell, G. S. (1994). The sequential cuing effect in speech production. *Cognition, 53,* 91–127.

Stemberger, J. P. (1985). An interactive activation model of language production. In W. W. Ellis (Ed.), *Progress in the psychology of language* (Vol. 1, pp.143–186). Hillsdale, NJ: Erlbaum.

Stemberger, J. P. (1990). Wordshape errors in language production. *Cognition, 35,* 123–157. doi:10.1016/0010-0277(90)90012-9

Van Selst, M., & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 47,* 631–650. doi:10.1080/14640749408401131

Washburn, M. F. (1916). *Movement and mental imagery: Outlines of a motor theory of the complexer mental processes.* Boston, MA: Houghton Mifflin Company. doi:10.1037/11575-000

Wickelgren, W. A. (1965). Distinctive features and errors in short-term memory for English vowels. *Journal of Acoustical Society of America, 39,* 388–398. doi:10.1121/1.1909900

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

Yamaguchi, M., Crump, M. J. C., & Logan, G. D. (2013). Speed-accuracy trade-off in skilled typewriting: Decomposing the contributions of hierarchical control loops. *Journal of Experimental Psychology: Human Perception and Performance, 39,* 678–699. doi:10.1037/a0030512

Yamashita, Y., & Tani, J. (2008). Emergence of functional hierarchy in a multiple timescale neural network model: A humanoid robot experiment. *PLoS Computational Biology, 4,* e1000220. doi:10.1371/journal.pcbi.1000220

(*Appendices follow*)

Appendix A

Target Words Used in Experiment 1 Displayed as Anagram Pairs

	Target	Anagram
1	ADORN	RADON
2	AGREE	EAGER
3	ALERT	LATER
4	ALLOY	LOYAL
5	ALOFT	FLOAT
6	AMBER	BREAM
7	AMBLE	BLAME
8	AMPLE	MAPLE
9	ANGER	RANGE
10	ATTIC	TACIT
11	BELOW	ELBOW
12	BLEAT	TABLE
13	BRAID	RABID
14	BROTH	THROB
15	BRUSH	SHRUB
16	BUDGE	DEBUG
17	CANOE	OCEAN
18	CHARM	MARCH
19	CHEAP	PEACH
20	CHEAT	TEACH
21	CLASP	SCALP
22	CLEAN	LANCE
23	CRUEL	ULCER
24	DICER	CRIED
25	DOZEN	ZONED
26	DUSTY	STUDY
27	EARNS	SNARE
28	EARTH	HEART
29	EASEL	LEASE
30	EQUIP	PIQUE
31	FIBER	BRIEF
32	FLESH	SHELF
33	FLIER	RIFLE
34	GABLE	BAGLE
35	GIRTH	RIGHT
36	GROWN	WRONG
37	GULPS	PLUGS
38	HATED	DEATH
39	HORSE	SHORE
40	HOSES	SHOES
41	IDEAS	AIDES
42	INFER	FINER
43	INURE	URINE
44	ITEMS	MITES
45	LAPSE	PEALS
46	LAYER	EARLY
47	LEASH	SHALE
48	LEAST	SLATE
49	LEMON	MELON
50	MANOR	ROMAN
51	MAYBE	BEAMY
52	MEDAL	LAMED
53	MERIT	TIMER
54	MOIST	OMITS
55	NAKED	KNEAD
56	NAMES	MEANS
57	NEEDS	DENSE
58	NIGHT	THING

(*Appendices continue*)

Appendix A (*continued*)

	Target	Anagram
59	NORTH	THORN
60	ONSET	STONE
61	ORGAN	GROAN
62	OUTER	ROUTE
63	PASTE	SPATE
64	PETAL	LEAPT
65	PHASE	SHAPE
66	POSTS	STOPS
67	PROSE	SPORE
68	PURSE	SUPER
69	RAISE	ARIES
70	RINSE	SIREN
71	ROBED	BORED
72	ROPES	PORES
73	RUNTS	TURNS
74	SCARE	ACRES
75	SERVE	VERSE
76	SHARE	HEARS
77	SLEPT	PELTS
78	SLIME	MILES
79	STAGE	GATES
80	STEAM	MATES
81	STRAP	PARTS
82	SWEAR	WARES
83	SWEAT	WASTE
84	TACOS	COATS
85	TAKES	STEAK
86	TASTE	STATE
87	THROW	WORTH
88	TOWER	WROTE
89	TRADE	DATER
90	TRAMS	SMART
91	VEILS	LIVES
92	VOTER	OVERT
93	VOTES	STOVE
94	WADES	SAWED
95	WARTS	STRAW
96	WORDY	DOWRY
97	ZEBRA	BRAZE

(*Appendices continue*)

Appendix B

Target Words and Paired SSDD, DDSS, and DDDD Primes Used in Experiment 2

	Target	SSDD	DDSS	DDDD
1	BANG	BASE	WING	WOVE
2	BASE	BANG	WISE	WORD
3	BLOT	BLUR	SPOT	WARM
4	BLUR	BLOT	SPUR	WAND
5	BOAR	BOLT	FEAR	SUIT
6	BOLT	BOAR	FELT	WARE
7	BURN	BUSY	EARN	SOAK
8	BUSY	BURN	EASY	WAIT
9	CALM	CASH	FILM	VOTE
10	CASH	CALM	FISH	VOID
11	CHAP	CHOW	SLAP	TOWN
12	CHOW	CHAP	SLOW	SEAT
13	COAL	CORK	PEAL	TINY
14	CORK	COAL	PERK	PLAN
15	CRAB	CROP	STAB	SPOT
16	CROP	CRAB	STOP	TAME
17	DECK	DENY	TICK	PART
18	DENY	DECK	TINY	FAST
19	DIME	DISK	TAME	TASK
20	DISK	DIME	TASK	PEAL
21	DRAG	DRIP	FLAG	STOP
22	DRIP	DRAG	FLIP	STAB
23	DUKE	DUMP	RAKE	SWAY
24	DUMP	DUKE	RAMP	GRAY
25	EARN	EASY	BURN	SOFT
26	EASY	EARN	BUSY	ROUT
27	FACE	FAST	MICE	SLOW
28	FAST	FACE	MIST	DENY
29	FEAR	FELT	BOAR	SHUT
30	FELT	FEAR	BOLT	SHAM
31	FILM	FISH	CALM	SANK
32	FISH	FILM	CASH	ROAM
33	FLAG	FLIP	DRAG	SPUR
34	FLIP	FLAG	DRIP	SCAN
35	FOND	FORM	WAND	RAMP
36	FORM	FOND	WARM	SALE
37	GOAT	GOLF	SEAT	MICE
38	GOLF	GOAT	SELF	RAKE
39	GRAY	GRIM	SWAY	DUMP
40	GRIM	GRAY	SWIM	SLAP
41	HARD	HAVE	WORD	PLUM
42	HAVE	HARD	WOVE	TOMB
43	HUGE	HURT	PAGE	TICK
44	HURT	HUGE	PART	WISE
45	LAMB	LAWN	TOMB	PERK
46	LAWN	LAMB	TOWN	SURE
47	LEAK	LEFT	SOAK	MIST
48	LEFT	LEAK	SOFT	MAID
49	MAID	MATE	VOID	LEFT
50	MATE	MAID	VOTE	PINK
51	MICE	MIST	FACE	GOAT
52	MIST	MICE	FAST	LEAK
53	PAGE	PART	HUGE	SWIM
54	PART	PAGE	HURT	DECK
55	PEAL	PERK	COAL	DISK
56	PERK	PEAL	CORK	LAMB
57	PILE	PINK	SALE	SCUM
58	PINK	PILE	SANK	MATE

(Appendices continue)

Appendix B (*continued*)

	Target	SSDD	DDSS	DDDD
59	PLAN	PLUM	SCAN	CORK
60	PLUM	PLAN	SCUM	HARD
61	RAKE	RAMP	DUKE	GOLF
62	RAMP	RAKE	DUMP	FOND
63	ROAM	ROUT	SHAM	FISH
64	ROUT	ROAM	SHUT	EASY
65	SALE	SANK	PILE	FORM
66	SANK	SALE	PINK	FILM
67	SCAN	SCUM	PLAN	FLIP
68	SCUM	SCAN	PLUM	PILE
69	SEAT	SELF	GOAT	CHOW
70	SELF	SEAT	GOLF	WING
71	SHAM	SHUT	ROAM	FELT
72	SHUT	SHAM	ROUT	FEAR
73	SLAP	SLOW	CHAP	GRIM
74	SLOW	SLAP	CHOW	FACE
75	SOAK	SOFT	LEAK	BURN
76	SOFT	SOAK	LEFT	EARN
77	SPOT	SPUR	BLOT	CRAB
78	SPUR	SPOT	BLUR	FLAG
79	STAB	STOP	CRAB	DRIP
80	STOP	STAB	CROP	DRAG
81	SUIT	SURE	WAIT	BOAR
82	SURE	SUIT	WARE	LAWN
83	SWAY	SWIM	GRAY	DUKE
84	SWIM	SWAY	GRIM	PAGE
85	TAME	TASK	DIME	CROP
86	TASK	TAME	DISK	DIME
87	TICK	TINY	DECK	HUGE
88	TINY	TICK	DENY	COAL
89	TOMB	TOWN	LAMB	HAVE
90	TOWN	TOMB	LAWN	CHAP
91	VOID	VOTE	MAID	CASH
92	VOTE	VOID	MATE	CALM
93	WAIT	WARE	SUIT	BUSY
94	WAND	WARM	FOND	BLUR
95	WARE	WAIT	SURE	BOLT
96	WARM	WAND	FORM	BLOT
97	WING	WISE	BANG	SELF
98	WISE	WING	BASE	HURT
99	WORD	WOVE	HARD	BASE
100	WOVE	WORD	HAVE	BANG

Appendix C

Target Words and Paired SDDS, DSSD, and DDDD Primes Used in Experiment 3

	Target	SDDS	DSSD	DDDD
1	BAIT	BELT	HAIR	MUCH
2	BANK	BULK	LAND	ROSE
3	BATH	BUSH	GATE	WORE
4	BEAR	BLUR	MEAK	WHIM
5	BELT	BAIT	SELF	GOWN
6	BLOW	BREW	PLOT	TUNE
7	BLUR	BEAR	GLUE	WIFE
8	BOND	BRAD	PONY	HAUL
9	BRAD	BOND	TRAY	CLIP
10	BREW	BLOW	FRET	TIDY
11	BULK	BANK	MULE	RIDE
12	BUSH	BATH	FUSE	VENT
13	CALF	CHEF	SALT	PONY
14	CASE	CUTE	TASK	JUNK
15	CHAP	CLIP	SHAM	FIST
16	CHEF	CALF	WHEY	LAND
17	CHIN	CORN	WHIM	LARK
18	CITY	COPY	SITE	HOWL
19	CLIP	CHAP	SLIM	BRAD
20	COLD	CURD	VOLT	PIES
21	COPY	CITY	MOPE	SELF
22	CORN	CHIN	SORT	LIFT
23	CURD	COLD	SURF	LOST
24	CUTE	CASE	DUTY	GRIN
25	DAMP	DRIP	TAME	FERN
26	DENY	DUTY	VENT	LICK
27	DRIP	DAMP	GRIN	FAUN
28	DUTY	DENY	CUTE	LAWN
29	FAUN	FERN	HAUL	DRIP
30	FERN	FAUN	JERK	DAMP
31	FILM	FOAM	SILK	TASK
32	FIRE	FUSE	GIRL	TUCK
33	FIST	FRET	RISE	CHAP
34	FLAT	FORT	PLAY	JERK
35	FOAM	FILM	GOAL	SITE
36	FORT	FLAT	WORE	LIEN
37	FRET	FIST	BREW	SILK
38	FUSE	FIRE	BUSH	TRAY
39	GATE	GLUE	BATH	SLIM
40	GIRL	GOAL	FIRE	TAME
41	GLUE	GATE	BLUR	WAVY
42	GOAL	GIRL	FOAM	SURF
43	GOWN	GRIN	HOWL	BELT
44	GRIN	GOWN	DRIP	CUTE
45	HAIR	HOUR	BAIT	NOTE
46	HAUL	HOWL	FAUN	BOND
47	HOUR	HAIR	LOUD	SAVE
48	HOWL	HAUL	GOWN	CITY
49	JERK	JUNK	FERN	FLAT
50	JUNK	JERK	TUNE	CASE
51	LAND	LOUD	BANK	CHEF
52	LARK	LICK	WARM	CHIN
53	LAWN	LIEN	PAWS	DUTY
54	LICK	LARK	NICE	DENY
55	LIEN	LAWN	PIES	FORT
56	LIFT	LOST	WIFE	CORN
57	LOST	LIFT	ROSE	CURD
58	LOUD	LAND	HOUR	SHAM

(*Appendices continue*)

Appendix C (*continued*)

	Target	SDDS	DSSD	DDDD
59	MEAK	MINK	BEAR	VOLT
60	MINK	MEAK	PINT	WHEY
61	MOPE	MULE	COPY	SALT
62	MOTH	MUCH	NOTE	RACE
63	MUCH	MOTH	TUCK	BAIT
64	MULE	MOPE	BULK	PAWS
65	NICE	NOTE	LICK	SORT
66	NOTE	NICE	MOTH	HAIR
67	PAWS	PIES	LAWN	MULE
68	PIES	PAWS	LIEN	COLD
69	PINT	PLOT	MINK	WARM
70	PLAY	PONY	FLAT	RISE
71	PLOT	PINT	BLOW	SACK
72	PONY	PLAY	BOND	CALF
73	RACE	RISE	SACK	MOTH
74	RIDE	ROSE	TIDY	BULK
75	RISE	RACE	FIST	PLAY
76	ROSE	RIDE	LOST	BANK
77	SACK	SILK	RACE	PLOT
78	SALT	SORT	CALF	MOPE
79	SAVE	SITE	WAVY	HOUR
80	SELF	SURF	BELT	COPY
81	SHAM	SLIM	CHAP	LOUD
82	SILK	SACK	FILM	FRET
83	SITE	SAVE	CITY	FOAM
84	SLIM	SHAM	CLIP	GATE
85	SORT	SALT	CORN	NICE
86	SURF	SELF	CURD	GOAL
87	TAME	TUNE	DAMP	GIRL
88	TASK	TUCK	CASE	FILM
89	TIDY	TRAY	RIDE	BREW
90	TRAY	TIDY	BRAD	FUSE
91	TUCK	TASK	MUCH	FIRE
92	TUNE	TAME	JUNK	BLOW
93	VENT	VOLT	DENY	BUSH
94	VOLT	VENT	COLD	MEAK
95	WARM	WHIM	LARK	PINT
96	WAVY	WHEY	SAVE	GLUE
97	WHEY	WAVY	CHEF	MINK
98	WHIM	WARM	CHIN	BEAR
99	WIFE	WORE	LIFT	BLUR
100	WORE	WIFE	FORT	BATH

(*Appendices continue*)

Appendix D

Target Words and Paired SSSD, SSDD, SDDD, and DDDD Primes Used in Experiment 3

	Target	SSSD	SSDD	SDDD	DDDD
1	BOAR	BOAT	BONE	BUSH	WHIP
2	BOAT	BOAR	BOND	BURN	REND
3	BOND	BONE	BOAT	BURY	SLAY
4	BONE	BOND	BOAR	BUST	MILD
5	BURN	BURY	BUST	BOAT	PLAY
6	BURY	BURN	BUSH	BOND	SLOW
7	BUSH	BUST	BURY	BOAR	TRIO
8	BUST	BUSH	BURN	BONE	WARN
9	CAME	CAMP	CARD	CHIP	HURT
10	CAMP	CAME	CARE	CHIN	RENT
11	CARD	CARE	CAME	CHEF	WHIM
12	CARE	CARD	CAMP	CHEW	HUNK
13	CHEF	CHEW	CHIP	CARD	TRIM
14	CHEW	CHEF	CHIN	CARE	PLAN
15	CHIN	CHIP	CHEW	CAMP	MANE
16	CHIP	CHIN	CHEF	CAME	SNUB
17	DAME	DAMP	DARK	DUET	MINT
18	DAMP	DAME	DART	DUEL	SNUG
19	DARK	DART	DAME	DUMB	WHEY
20	DART	DARK	DAMP	DUMP	PINE
21	DUEL	DUET	DUMB	DAMP	LONG
22	DUET	DUEL	DUMP	DAME	SNOW
23	DUMB	DUMP	DUEL	DARK	PIES
24	DUMP	DUMB	DUET	DART	TRAY
25	FILE	FILM	FIRM	FLAP	HAZY
26	FILM	FILE	FIRE	FLAX	SNOB
27	FIRE	FIRM	FILM	FLEA	LEAP
28	FIRM	FIRE	FILE	FLEW	SLAB
29	FLAP	FLAX	FLEW	FILE	WHEN
30	FLAX	FLAP	FLEA	FILM	PIER
31	FLEA	FLEW	FLAX	FIRE	GRIT
32	FLEW	FLEA	FLAP	FIRM	THAN
33	GRAB	GRAM	GRIN	GULF	HAIL
34	GRAM	GRAB	GRIT	GULP	THEY
35	GRIN	GRIT	GRAB	GUST	WASP
36	GRIT	GRIN	GRAM	GUSH	FLEA
37	GULF	GULP	GUSH	GRAB	TRAP
38	GULP	GULF	GUST	GRAM	HAIR
39	GUSH	GUST	GULF	GRIT	RANK
40	GUST	GUSH	GULP	GRIN	THEM
41	HAIL	HAIR	HAZE	HURT	GRAB
42	HAIR	HAIL	HAZY	HUNK	GULP
43	HAZE	HAZY	HAIL	HUNG	PLUM
44	HAZY	HAZE	HAIR	HURL	FILE
45	HUNG	HUNK	HURL	HAZE	REAP
46	HUNK	HUNG	HURT	HAIR	CARE
47	HURL	HURT	HUNG	HAZY	MINK
48	HURT	HURL	HUNK	HAIL	CAME
49	LEAF	LEAP	LENS	LONE	MAID
50	LEAP	LEAF	LENT	LONG	FIRE
51	LENS	LENT	LEAF	LORD	RAIL
52	LENT	LENS	LEAP	LORE	WASH
53	LONE	LONG	LORD	LEAF	MAIL
54	LONG	LONE	LORE	LEAP	DUEL
55	LORD	LORE	LONE	LENS	MANY
56	LORE	LORD	LONG	LENT	RAIN
57	MAID	MAIL	MANY	MINK	LEAF
58	MAIL	MAID	MANE	MINT	LONE

(Appendices continue)

Appendix D (*continued*)

	Target	SSSD	SSDD	SDDD	DDDD
59	MANE	MANY	MAIL	MILD	CHIN
60	MANY	MANE	MAID	MILE	LORD
61	MILD	MILE	MINT	MANE	BONE
62	MILE	MILD	MINK	MANY	RANG
63	MINK	MINT	MILE	MAID	HURL
64	MINT	MINK	MILD	MAIL	DAME
65	PIER	PIES	PINK	PLAY	FLAX
66	PIES	PIER	PINE	PLAN	DUMB
67	PINE	PINK	PIES	PLUM	DART
68	PINK	PINE	PIER	PLUG	THAW
69	PLAN	PLAY	PLUM	PIES	CHEW
70	PLAY	PLAN	PLUG	PIER	BURN
71	PLUG	PLUM	PLAY	PINK	REAL
72	PLUM	PLUG	PLAN	PINE	HAZE
73	RAIL	RAIN	RAIN	REND	LENS
74	RAIN	RAIL	RAIL	RENT	LORE
75	RANG	RANK	RANK	REAP	MILE
76	RANK	RANG	RANG	REAL	GUSH
77	REAL	REAP	REND	RANK	PLUG
78	REAP	REAL	RENT	RANG	HUNG
79	REND	RENT	REAP	RAIL	BOAT
80	RENT	REND	REAL	RAIN	CAMP
81	SLAB	SLAY	SLOW	SNOW	FIRM
82	SLAY	SLAB	SLOT	SNOB	BOND
83	SLOT	SLOW	SLAY	SNUG	WARM
84	SLOW	SLOT	SLAB	SNUB	BURY
85	SNOB	SNOW	SNUG	SLAY	FILM
86	SNOW	SNOB	SNUB	SLAB	DUET
87	SNUB	SNUG	SNOW	SLOW	CHIP
88	SNUG	SNUB	SNOB	SLOT	DAMP
89	THAN	THAW	THEM	TRIM	FLEW
90	THAW	THAN	THEY	TRIO	PINK
91	THEM	THEY	THAN	TRAY	GUST
92	THEY	THEM	THAW	TRAP	GRAM
93	TRAP	TRAY	TRIM	THEY	GULF
94	TRAY	TRAP	TRIO	THEM	DUMP
95	TRIM	TRIO	TRAP	THAN	CHEF
96	TRIO	TRIM	TRAY	THAW	BUSH
97	WARM	WARN	WASP	WHEN	SLOT
98	WARN	WARM	WASH	WHIM	BUST
99	WASH	WASP	WARN	WHIP	LENT
100	WASP	WASH	WARM	WHEY	GRIN
101	WHEN	WHEY	WHIP	WARM	FLAP
102	WHEY	WHEN	WHIM	WASP	DARK
103	WHIM	WHIP	WHEY	WARN	CARD
104	WHIP	WHIM	WHEN	WASH	BOAR