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Simon-Type Effects: Chronometric Evidence for Keypress Schemata in Typewriting

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In 4 experiments, chronometric evidence for keypress schemata in typing was sought by presenting stimuli to be typed in positions that were displaced from a central fixation point. Reaction times were shorter when stimulus positions corresponded to keyboard locations of the letters to be typed, suggesting that position was an important part of the internal representation of the response. Experiment 1 presented single letters left and right of fixation. Experiment 2 presented single letters above and below fixation. Experiment 3 presented words left and right of fixation and found evidence of parallel activation of keypress schemata. Experiment 4 found no effect of the eccentricity of the keyboard locations and responding fingers, suggesting that response-location codes are categorical, not metric. The results are consistent with D. E. Rumelhart and D. A. Norman's (1982) theory of typewriting.

Typewriting is a recent skill in human history. The typewriter on which the common QWERTY keyboard first appeared was patented by Christopher Latham Scholes on July 14, 1868. By 1900, typewriters were in common use, and Scholes was heralded as a women's emancipator for bringing female typists into the working world (Cooper, 1983b). With the advent of personal computers in the late 1970s, typewriting became even more common. Today, computers can be found in most American homes, schools, and businesses, and many people have at least some skill at typewriting.

Typewriting has been of interest to psychologists throughout its history (e.g., Book, 1908; Lashley, 1951; Shaffer, 1976). It is a complex skill that recruits a variety of perceptual, conceptual, and motor processes and requires them to function together in an integrated fashion. Consequently, it has been a fertile ground for psychological research, producing a variety of data and several theories (for reviews, see Cooper, 1983a; Inhoff & Gordon, 1997; Salthouse, 1986). The most elaborate theory of typewriting was proposed by Rumelhart and Norman in 1982. Their theory is a computer simulation of skilled typewriting that models processing at perceptual, conceptual, and motor levels. The key idea behind their theory is that typing performance is determined primarily by the biomechanical constraints of the hands and the keyboard. Perceptual and conceptual processes contribute to performance, but the limitations that determine patterns of reaction time (RT)[1] and accuracy stem primarily from the hands and the keyboard (see also Gentner, Larochelle, & Grudin, 1988).

Rumelhart and Norman's (1982) theory assumes that typing depends primarily on three cascaded levels of processing: the word level, the keypress level, and the response level. The word level receives words as input, either from perceptual processes in copy typing or from language-production processes in composition typing. A word in the word level activates keypress schemata for its constituent letters in the keypress level, which in turn activate movement schemata in the response system. The keypress schemata represent the target position for a keypress in keyboard-centered coordinates, specifying the hand, the finger, and the nature of the movement required to reach particular keyboard locations (i.e., to press particular keys). The home row and the center columns constitute the reference frame. The movement schemata represent programs for individual keystrokes. The response system feeds back information about the current location of the fingers to the keypress system, and when a finger is within a critical distance of its intended key, a movement schema is triggered and the key is pressed. The theory proposes that several keypress schemata and movement schemata are active simultaneously, each pulling a finger and a hand toward a key. This parallel activation produces coarticulation effects that appear in RT data (Gentner, 1982; Shaffer, 1978).

One purpose of the present article is to seek chronometric evidence for the keypress schemata and the parallel activation proposed in Rumelhart and Norman's (1982) theory. Previous studies of keypress schemata in typing have relied on analyses of the errors people make while typing (Grudin, 1983; F. A. Logan, 1999) and kinematic analyses of keystrokes taken from high-speed video (Grudin, 1983; Soechting & Flanders, 1992, 1997). Evidence for parallel activation has come primarily from kinematic analyses (Gentner, Grudin, & Conway, 1980; Soechting &

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[1] The term *reaction time* is used in the present article to describe the interval between the onset of a stimulus and the time at which a key was pressed. This reflects the conventional use of the term in the literature on the Simon effect. In the literature on motor control and movement, reaction time often refers to the interval between stimulus onset and the beginning of movement, whereas *movement time* refers to the interval between the beginning of a movement and the end of that movement (i.e., the time at which a key was pressed). Thus, the present reaction-time measure equals the sum of what motor control and movement researchers would call reaction time and movement time.

Flanders, 1992, 1997). The present article seeks converging evidence for keypress schemata and parallel activation by relying on a chronometric interference effect known as the *Simon effect* (e.g., Simon & Small, 1969), which reflects interactions between spatial representations in perceptual and motor systems (for reviews, see Lu & Proctor, 1995; Simon, 1990). Another purpose of the present article is to relate the Simon effect with typewritten responses to the standard Simon effect with simple keypress responses.

Evidence for Keypress Schemata

The primary evidence for keypress schemata comes from analyses of error corpora (Grudin, 1983; Lessenberry, 1928; F. A. Logan, 1999). One of the most common kinds of error is the *substitution error* in which an incorrect letter is substituted for a correct one. The three most common kinds of substitution errors are *horizontal errors, vertical errors*, and *homologous errors.* Horizontal errors occur when the key that is struck in error is adjacent to (beside) the one that was intended to be struck (e.g., *D* or *G* for *F*). Horizontal errors accounted for 43% of the 63,000 substitution errors in Lessenberry's (1928) corpus (Grudin, 1983). Vertical errors occur when the key that is struck in error is above or below the one that was intended to be struck (e.g., *R* or *V* for *F*). Vertical errors accounted for 15% of the substitution errors in Lessenberry's corpus. Homologous errors occur when the key that is struck in error is struck with the same finger but the opposite hand as the key that was intended to be struck (e.g., *J* for *F*). Homologous errors accounted for 10% of the substitution errors in Lessenberry's corpus.

Kinematic analyses by Grudin (1983) have shown that horizontal and vertical errors are not just "clumsy" movements in which the correct finger strikes the wrong key. Instead, horizontal and vertical errors tend to be typed with the finger appropriate to the key that was struck. This suggests that horizontal errors are "finger" errors in which the "finger" feature of the keypress schema is specified incorrectly, and that vertical errors are "direction" errors in which the "direction" feature of a keypress schema (i.e., "up" vs. "down") is specified incorrectly. Homologous errors suggest that the "hand" feature of a keypress schema has been specified incorrectly.

Analyses of error corpora are difficult to carry out because errors are rare events in skilled typing. For example, in F. A. Logan's (1999) analysis of a single skilled typist, it was necessary to sample 1,300,000 keystrokes to obtain a corpus of 3,000 errors—the error rate was 0.23%. Moreover, the analysis of errors is necessarily post hoc and requires that inferences be made about what the typist had intended. The validity of such inferences may be clear in copy typing, in which the text to be typed can be compared with the text that was typed, but it will be less clear in composition typing, in which the author's intentions are not available for scrutiny. The present experiments sought evidence of keypress schemata in an experimental procedure that did not require a post hoc analysis and did not depend on inferences about typists' intentions.

Evidence for Parallel Activation

Evidence for parallel activation of keypress schemata comes primarily from kinematic analyses of finger movements. The strongest evidence comes from successive keystrokes in different hands (*hand alternations*), which are often typed much faster than successive keystrokes in the same hand (*hand repetitions*) or in the same finger (*finger repetitions*; Salthouse, 1986). Gentner et al. (1980) filmed skilled typists and found that the second movement in a hand alternation typically began before the first movement was finished (see also Soechting & Flanders, 1992, 1997). If the fingers are in motion simultaneously, then the keypress schemata that drive them must be active simultaneously as well.

Kinematic analyses suggest parallel activation most clearly with hand alternations. Hand repetitions and finger repetitions are ambiguous in this regard. It is possible that parallel activation also occurs in hand or finger repetitions, but it is also possible that parallel activation only occurs with hand alternations. Keypress schemata in hand and finger alternations may be activated in series. The present Experiment 3 sought evidence for parallel activation in hand repetitions.

The Simon Effect

The Simon effect is a spatial-compatibility effect in which a stimulus presented in one part of space is responded to faster when the response assigned to that stimulus occurs in a corresponding part of space than when it occurs in a noncorresponding part of space. The key feature that distinguishes the Simon effect from other spatial-compatibility effects is that the location of the stimulus is logically irrelevant to the task. It was first reported by Simon and Small (1969), who had subjects make left and right keypresses to high- and low-pitched tones that were presented through headphones to the left or right ear. RTs were 60 ms shorter when the ear and responding hand corresponded than when they did not, even though the ear was irrelevant to the pitch discrimination. Since then, the Simon effect has been replicated many times, most often with visual stimuli (for reviews, see Lu & Proctor, 1995; Simon, 1990). It occurs with horizontally arranged stimuli and with vertically arranged stimuli. It is explained in many ways, but the key idea in each explanation is that a spatial representation engendered by the stimulus facilitates or interferes with the spatial representation of the response. Most of the controversy regarding the Simon effect focuses on the processes involved in producing the perceptual representation; there is little controversy over the spatial representation of the response. The present article is concerned primarily with the spatial representation of typing responses, so the controversy over perceptual representations need not compromise the conclusions.

The present experiments used the Simon effect to prime spatial features of keypress schemata in typing. Experiments 1 and 3 presented stimuli to be typed on the left or right side of the display screen. According to theories of the Simon effect, stimuli presented on the left should prime left-hand responses, whereas stimuli presented on the right should prime right-hand responses. Obtaining a Simon effect with typewritten responses would indicate that the hand or the spatial location of the responding fingers was part of the keypress schemata, as Rumelhart and Norman (1982) predicted. Experiment 2 presented stimuli above and below fixation. According to theories of the Simon effect, stimuli presented above fixation should prime upward movements, whereas stimuli presented below fixation should prime downward movements. Obtaining a Simon effect with typewritten responses would indicate that upward and downward direction was part of the keypress schema, as Rumelhart and Norman (1982) predicted.

Experiments 1 and 2 presented single letters that required single keystrokes as responses. Experiment 3 sought evidence of parallel activation of keypress schemata by presenting words left and right of fixation. The words were typed all in one hand or with both hands. If keypress schemata are activated in parallel, as Rumelhart and Norman (1982) predicted, then letters beyond the first one should contribute to the Simon effect. The Simon effect should be stronger with words that are typed entirely in one hand than with words that are typed with both hands.

Experiments 1–3 differed from previous studies of the Simon effect in two ways: First, Experiments 1–3 used 22 different responses, whereas previous studies of the Simon effect have generally used only two responses (e.g., one for each side of the screen). It was not clear whether the Simon effect should generalize to this multiple-response situation. Second, Experiments 1–3 involved substantially more preexperimental practice than is typical in studies of the Simon effect. Averaged over Experiments 1–3, subjects had 6.83 years of experience with typing, whereas subjects in most studies of the Simon effect have had no experience mapping the imperative stimuli onto the required responses prior to the experiments. It was not clear whether the Simon effect would be obtained with such well-practiced subjects. Experiment 4 explored some of the differences between the Simon effect with typewriting and the Simon effect with more traditional responses.

Experiment 1

The first experiment looked for evidence of a "left versus right" feature in the keypress schemata that control typing. Single letters were presented left or right of the fixation point. Subjects were instructed to type them using the standard (and habitual) mapping of fingers onto the keyboard. Half of the letters were typed with the left hand, and half were typed with the right hand. Theories of the Simon effect predict that horizontally displaced letters should create perceptual representations that prime left and right responses. If "left" and "right" are part of the representations that are used to generate keypress responses—part of the keypress schemata—then a Simon effect should be observed. RT should be shorter when stimulus position and response hand correspond than when they do not.

Method

Subjects. The subjects were 16 students recruited from the general university community for their ability to touch type (i.e., to type with all 10 fingers without looking at the keyboard). They were paid for their participation. Their average typing speed on the typing test (described below) was 46.13 words per minute ($SD = 11.35$). Their average accuracy was 92.01% ($SD = 4.67$). They reported an average of 8.41 years of typing experience ($SD = 4.06$). All but 2 reported having some formal training in typing. They reported typing an average of 1.81 hr per day.

Apparatus and stimuli. The stimuli were displayed on Gateway 2000 Crystalscan 1024 NI monitors controlled by Gateway 2000 486 computers. Responses were collected from the computers' keyboards. The time between the onset of the letter and the pressing of the key was measured with an accuracy of 1 ms. The stimuli were the letters *Q, W, E, R, T, Y, U, I, O, P, S, D, F, G, H, J, K, L, V, B, N,* and *M,* presented as capitals in white on a black background. They corresponded to keys arranged symmetrically around the midline of the standard QWERTY keyboard (see Figure 1). Half were typed with the left hand, and half were typed with the right hand.

Each trial began with a white fixation point (.) presented in the center of a black screen for 500 ms. It was extinguished and replaced with a single letter 3 mm wide and 5 mm high that was presented 3.25 cm to the left or to the right of the central fixation point. The letter was exposed until the subject responded, whereupon the screen was extinguished and remained blank (black) for a 1,500-ms intertrial interval. Eye movements were not controlled or monitored, and subjects were given no instructions about eye movements, following typical procedures in studies of the Simon effect.

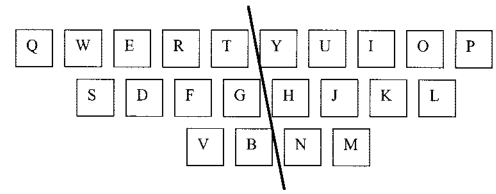

Figure 1. The keyboard locations of the letters used in the present experiments. The slanted vertical line divides the letters typed with the left hand from those typed with the right.

The typing test involved typing one paragraph of text adapted from Collier's (1995) book, *Border Collies.* The four texts I used are presented in the Appendix of G. D. Logan and Zbrodoff (1998). The texts ranged in length from 111 to 117 characters. They were presented on the computer screen, and subjects typed them on the computer keyboard. Subjects were allowed to read the text before the typing test began. When they performed the typing test, their keystrokes were not echoed on the computer screen. The computer measured the time from the first to the last keystroke. Typing speed was estimated by dividing the number of words in the text by the time (in minutes) from the first to the last keystroke. Accuracy was scored by displaying a record of the letters that subjects typed on the screen and then counting the number of words that contained errors.

Procedure. The basic design involved 44 trials. Each of the 22 letters was presented once on each side of fixation. The experiment involved 12 replications of the basic 44-trial design, for a total of 528 trials. Each letter occurred equally often in each location in each set of 132 trials. The order of trials was randomized within these constraints. The four texts for the typing test were counterbalanced across subjects, with 4 subjects receiving each text.

Subjects began by performing the typing test. First, they read through the text. Then they typed it into the computer. After completing the first typing test, subjects were told about the Simon task. Subjects were instructed to rest their fingers on the home row of the keyboard as they would if they were typing. They were told to type the letter that appeared on the screen as quickly and accurately as possible, using the finger they would use in normal typing. They were allowed brief rests every 88 trials.

Data analysis. The mean RTs were analyzed in 2 (keyboard position: left hand vs. right hand) $\times$ 2 (screen position: left side vs. right side) analyses of variance (ANOVAs). There were two ANOVAs, one with subjects as the random effect and one with items as the random effect. In the subject ANOVA, mean RTs were calculated for each subject in each cell of the 2 $\times$ 2 design by averaging over items. Keyboard position and screen position were within-subject effects. In the item ANOVA, mean RTs were calculated for each item in each cell of the 2 $\times$ 2 design by averaging over subjects. Keyboard position was a between-items effect, and screen-position was a within-item effect.

Results and Discussion

Simon effect. Mean RTs in each cell of the 2 (keyboard position) $\times$ 2 (screen position) design are presented in Figure 2. Each point in the figure is based on 2,112 observations. The data show a Simon effect: RTs to right-hand letters were 17 ms shorter when the letters were presented on the right side of the screen. RTs to left-hand letters were 19 ms shorter when the letters were presented on the left side of the screen. In the subject ANOVA, the

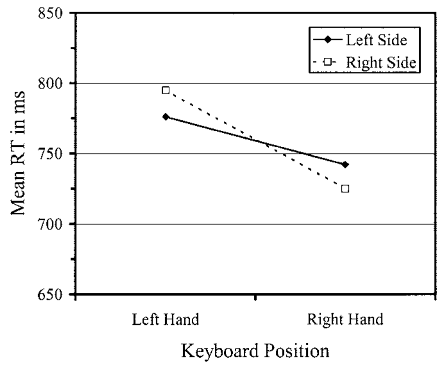

Figure 2. Mean reaction time (RT) as a function of keyboard position of the response and the side of fixation on which the letter was presented in Experiment 1.

main effect of keyboard position was significant, $F(1, 15) = 24.52$, $p < .01$, $MSE = 1{,}758.17$, reflecting shorter RTs to right-hand letters, and the interaction between keyboard position and screen position was significant, $F(1, 15) = 10.49$, $p < .01$, $MSE = 468.62$, reflecting the Simon effect. In the item ANOVA, only the interaction between keyboard position and screen position was significant, $F(1, 20) = 14.59$, $p < .01$, $MSE = 208.67$, reflecting the Simon effect.

Accuracy was high, averaging 97.14%. It was unaffected by the experimental variables. A 2 (keyboard position) × 2 (screen position) ANOVA was conducted on the accuracy scores, with subjects as a random effect. The ANOVA yielded no significant main effects and no significant interaction between keyboard position and screen position.

Simon effect for each keyboard position. The mean RTs across subjects for each keyboard position and screen position are presented in Table 1. The difference in RT to corresponding and noncorresponding screen and keyboard positions—the Simon effect—is also presented for each keyboard position in Table 1. The mean RTs in Table 1 show that responses were shorter for home-row letters ($M = 705$ ms) than for top- ($M = 779$ ms) or bottom- ($M = 835$ ms) row letters. This is a common observation in the typing literature (Salthouse, 1986). It occurs because subjects' fingers rest on the home-row keys and must move upward or downward to reach top- or bottom-row keys.

The Simon effect was about the same for top- and home-row letters ($Ms = 18$ and 21 ms, respectively) but smaller for bottom-row letters ($M = 4$ ms). Another way to view the keyboard-position effect is in terms of the fingers used to strike the keys. Keys struck with the index finger produced a smaller Simon effect ($M = 4$ ms) than keys struck with the middle, ring, and little fingers ($M = 32$ ms). Keys on the top row were struck with all fingers and so produced a substantial Simon effect, when averaged across fingers. Keys in the middle row were typed with the index, middle, and ring fingers and so produced a substantial Simon effect, averaged across fingers. Keys in the bottom row were struck only with the index fingers and so produced a negligible Simon effect.

Each subject saw each letter in each position 12 times, so I was able to test the significance of these effects with a 2 (stimulus position) × 2 (hand) × 11 (letter) ANOVA, with subjects as a random effect. I assessed the significance of the effects with contrasts, using the error term from the interaction between stimulus position, hand, and letter ($MSE = 3{,}919.58$). A contrast comparing mean RTs in the home row with mean RTs in the top and bottom rows was significant, $F(1, 150) = 180.95$, $p < .01$, as was a contrast comparing mean RTs in the top versus bottom rows, $F(1, 150) = 35.89$, $p < .01$. Contrasts evaluating the Simon effect were significant for the top row, $F(1, 150) = 6.61$, $p < .05$, and for the home row, $F(1, 150) = 7.29$, $p < .01$, but not for the bottom row, $F(1, 150) < 1$. A contrast comparing the Simon effect for

Table 1
Mean Reaction Times (in Milliseconds) to Each Letter in Experiment 1 as a Function of Screen Position (Left vs. Right) and the Difference Between Left and Right Screen Positions (Simon Effect)

Variable										
	Top row									
Variable	Q	W	E	R	T	Y	U	I	O	P
Left	904	804	710	803	747	796	803	690	751	808
Right	927	823	735	793	753	779	793	665	711	782
Simon effect	23	19	25	−10	6	17	10	25	40	26
		Home row								
		S	D	F	G	H	J	K	L	
Left		630	708	706	748	777	656	714	648	
Right		703	730	725	743	792	651	671	621	
Simon effect		73	22	19	−5	−15	5	43	27	
				Bottom row						
				V	B	N	M			
Left				934	877	772	751			
Right				938	885	784	734			
Simon effect				4	8	−12	17			

keys typed with the index fingers versus those typed with the middle, ring, and little fingers was significant, $F(1, 150) = 9.06$, $p < .01$, $MSE = 3{,}919.58$.

The variation in the Simon effect over keyboard position could have been due to the latency with which the different keypress responses were made (De Jong, Liang, & Lauber, 1994; Hommel, 1993; Roswarski & Proctor, 1996). To test this hypothesis, I correlated the Simon effect with mean RT averaged over stimulus position. The correlation was negative ($r = -.398$), indicating a smaller Simon effect with longer RTs, but it was not significant, $F(1, 21) = 3.95$.

Variation in the Simon effect over keyboard position could also have been due to differential practice. Proctor and Lu (1999) found that the Simon effect decreased but did not disappear with practice. To test this hypothesis, I correlated the Simon effect with Mayzner and Tresselt's (1965) measures of the frequency with which the letters occurred in written (i.e., typewritten) text. The correlation was negligible ($r = .0004$). As a further test, I correlated the Simon effect with measures of the frequency with which each letter occurred as the initial letter in a word, a measure also taken from Mayzner and Tresselt. This correlation was negligible as well ($r = .014$).

Conclusions

The RT data showed a Simon effect. Responses on the same side as the letter were 18 or 19 ms shorter than responses on the opposite side. Theories of the Simon effect suggest that the horizontally displaced stimuli created "left" and "right" perceptual representations that interacted with "left" and "right" motor representations of the keypress responses. This suggests that "left" and "right" are part of the keypress schemata that control typewritten responses, as Rumelhart and Norman (1982) predicted. It is not clear whether the Simon effect addressed "hand" features or "finger" features of the keypress schemata; either hypothesis could account for the results. The fact that homologous substitution errors occur frequently in typing (Grudin, 1983) suggests that "hand" and "finger" are represented separately, and that is more consistent with the hypothesis that the present Simon effect reflected the "hand" feature (which distinguishes left and right) rather than the "finger" feature (which does not distinguish left and right).

Experiment 2

The second experiment looked for evidence of a "direction" feature in the keypress schemata that control typing. Single letters were presented above or below fixation, and subjects typed them using the standard mapping for touch typing. Theories of the Simon effect suggest that letters that appear above fixation should create a perceptual representation of "up" or "above" that should prime a motor representation of "up" or "top row." Letters that are typed on the top row should benefit from this priming, whereas letters that are typed on the bottom row should suffer from it. Theories of the Simon effect suggest that letters that appear below fixation should create a perceptual representation of "down" or "below" that should prime a motor representation of "down" or "bottom row." Letters that are typed on the bottom row should benefit from this priming, whereas letters that are typed on the top row should suffer from it. Letters that are typed on the middle, or "home," row should not be associated with a direction feature (i.e., "up" or "down") and so should not show a Simon effect.

Method

Subjects. The subjects were 16 students recruited from the general university population for their ability to touch type. They were paid for their participation. None had served in Experiment 1. Their average typing speed on the typing test was 43.40 words per minute ($SD = 9.23$). Their average accuracy was 89.49% ($SD = 5.99$). Their average number of years of typing experience was 5.41 ($SD = 2.38$). All but 1 reported some formal training in typing. They reported typing an average of 2.06 hr a day.

Apparatus and stimuli. The apparatus and stimuli were the same as in Experiment 1, except that the letters appeared 1.7 cm directly above or below the fixation point (i.e., they were not displaced horizontally).

Procedure. The procedure was the same as in Experiment 1, except that the letters appeared above or below the fixation point instead of to the left or right of it. There were 528 experimental trials.

Data analysis. Mean RTs were analyzed in 3 (keyboard position: top, home, or bottom row) × 2 (screen position: above or below) ANOVAs. One ANOVA analyzed means across items, treating subjects as a random effect and keyboard position and screen position as within-subject factors. The other ANOVA analyzed means across subjects, treating items as a random effect, keyboard position as a between-items factor, and screen position as a within-item factor.

Results and Discussion

Simon effect. The mean RTs in each cell of the 3 (keyboard position) × 2 (screen position) design are presented in Figure 3. Because the number of letters in each row was different (see Figure 1) and each letter appeared equally often, the means for the rows are based on different numbers of observations. The top-row means are based on 1,920 observations, the home-row means are based on 1,536 observations, and the bottom-row means are based on 816 observations. RTs to home-row letters were shorter than RTs to top- and bottom-row letters because subjects rested their fingers on the home row (Salthouse, 1986). The top- and bottom-row letters showed a Simon effect. RTs to top-row letters were 5 ms shorter when the letters appeared above fixation, and RTs to bottom-row letters were 21 ms shorter when the letters appeared below fixation.

In the subject ANOVA, the main effect of keyboard position was significant, $F(2, 30) = 50.05$, $p < .01$, $MSE = 2{,}281.66$, and

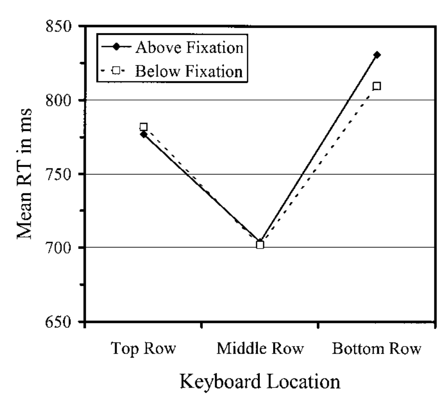

Figure 3. Mean reaction time (RT) as a function of keyboard location of the response and the location in which the letter was presented in Experiment 2.

the interaction between keyboard position and screen position was significant, $F(2, 30) = 4.25$, $p < .05$, $MSE = 325.08$, reflecting a Simon effect. The Simon effect was predicted for letters that were typed on the top and bottom rows but not for letters typed on the home row, so I computed an interaction contrast comparing corresponding and noncorresponding screen positions and top- versus bottom-row keyboard positions, using the error term from the interaction between keyboard position and screen position (i.e., 325.08). That contrast was significant, $F(1, 30) = 8.00$, $p < .01$. In the item ANOVA, the main effect of screen position, $F(1, 19) = 5.07$, $p < .05$, $MSE = 9{,}159.37$, and the interaction between keyboard position and screen position, $F(2, 19) = 4.09$, $p < .05$, $MSE = 122.64$, were significant. A contrast evaluating the Simon effect in the top and bottom rows was significant as well, $F(1, 19) = 8.15$, $p < .05$, $MSE = 122.64$.

Accuracy was high, averaging 96.71%, and was unaffected by the experimental variables. A 3 (keyboard position) $\times$ 2 (screen position) ANOVA was conducted on the accuracy scores, using subjects as a random effect. It yielded no significant main effects or interactions.

Simon effect for each keyboard position. Mean RTs for each keyboard position and each screen position are presented in Table 2, along with the Simon effect for each keyboard position. The keyboard-position effects were different than they were in Experiment 1. In this experiment, the Simon effect was smaller for the top row (5 ms) than it was for the bottom row (21 ms). In the top row, where all four fingers were used, the Simon effect did not vary across fingers. The mean Simon effect was 0.5 ms for the index fingers and 8 ms for the middle, ring, and little fingers. In the bottom row, where only the index fingers were used, the Simon effect was robust (21 ms).

In contrast with Experiment 1, the more eccentric positions showed a smaller Simon effect than the central positions. This was due in part to the fact that only the top row contributed to the eccentric positions, and the top row produced a very small Simon effect. It could also have been due to the fact that the little fingers only moved up. Consequently, they may have benefited from letters presented above fixation but not suffered cost from letters presented below fixation.

To test whether the variation in the Simon effect over keyboard position was due to differences in RT, I correlated the Simon effect with RT averaged across stimulus position. The correlation was small and nonsignificant ($r = -.011$), $F(1, 13) < 1$. To test whether variation in the Simon effect across keyboard position was due to differences in experience typing different letters, I correlated the Simon effect with letter frequency and with the frequency with which the letters appeared as the first letters of words (Mayzner & Tresselt, 1965). Both correlations were small and nonsignificant (rs = .262 and $-.016$, respectively), both Fs$(1, 13) < 1$.

Conclusions

The RT data showed a Simon effect for letters typed on the top and bottom rows of the keyboard. Letters typed in rows that corresponded to stimulus location were typed 13 ms faster than letters typed in rows that did not correspond to stimulus location. Theories of the Simon effect suggest that vertically displaced stimuli should have created perceptual representations of "up" and "down" that primed top- and bottom-row responses, respectively, speeding corresponding responses and slowing noncorresponding responses. The fact that corresponding responses were faster than noncorresponding responses suggests that the stimuli primed the "direction" feature of the keypress schemata that control typing responses, which is consistent with Rumelhart and Norman's (1982) theory.

Experiment 3

The third experiment sought evidence of parallel activation of keypress schemata. Subjects typed whole words that were pre-

Table 2
Mean Reaction Times (in Milliseconds) to Each Letter in Experiment 2 as a Function of Screen Position (Above vs. Below) and the Difference Between Above and Below Screen Positions (Simon Effect)

Variable	Top row									
	Q	W	E	R	T	Y	U	I	O	P
Above	906	836	733	801	752	788	787	671	726	787
Below	900	840	755	791	758	792	789	683	764	766
Simon effect	−6	4	22	−10	6	4	2	12	38	−21

	Home row							
	S	D	F	G	H	J	K	L
Above	638	701	732	769	786	688	678	637
Below	633	698	734	736	804	680	687	647
Above–Below	5	3	−2	33	−18	8	−9	−10

	Bottom row			
	V	B	N	M
Above	979	860	768	728
Below	942	834	761	713
Simon effect	37	26	7	15

sented left or right of fixation. Some of the words were typed entirely with one hand, and other words were typed with both hands. If keypress schemata are activated in parallel, as Rumelhart and Norman (1982) predicted, then keystrokes beyond the first letter should be primed by the stimulus representation of “left” and “right” (see also Lamberts, Tavernier, & d’Ydewalle, 1992; Roswarski & Proctor, 1996). Words that are typed with one hand should show a strong Simon effect because all keystrokes will have the same “hand” feature. Words that are typed with both hands should show a weaker Simon effect because the different keystrokes will have different “hand” features, some pulling “left” and some pulling “right.” By contrast, if keypress schemata are activated in series, then the Simon effect should depend only on the first letter of a word. It should be just as strong for words typed with two hands as it is for words typed with one hand.

The experiment used six sets of words, which are listed in the Appendix. Two sets—called *LEFT* and *right*—were typed entirely within one hand. Such words should show a strong Simon effect. Two sets of words—called *LEght* and *riFT*—were typed with both hands. The first two letters were typed with one hand, and the remaining letters were typed with the other hand. These words should also show a Simon effect, though it might not be as strong as the effect with LEFT and right words. The final two sets of words—called *Light* and *rEFT*—were also typed with both hands, but the transition from one hand to the other occurred after the first letter. The remaining letters were all typed with the other hand. These words should show the weakest Simon effect. Activation from the second and subsequent letters might overcome and possibly reverse the Simon effect.

Rumelhart and Norman’s (1982) theory predicts that the initial letters in a word will have a stronger influence than subsequent letters. It assumes that the word to be typed activates all of the keypress schemata for the letters that comprise a word but that the activation is graded by position in order to guarantee that the letters are typed in the correct serial order. Each letter schema receives equally strong activation from the word schema, but the letter schemata inhibit each other in a left-to-right direction. Each letter schema inhibits the schemata for all letters that follow it. Thus, the first letter has no inhibition from other letters and so has the strongest net activation. The second letter has inhibition from the first letter but no inhibition from the others, so it has the second strongest net activation. The third letter is inhibited by the first and second but not by the remaining letters, so its net activation is third strongest, and so on. Once the first letter is struck, it is inhibited to remove it from the competition. That makes the second letter the most strongly activated, so it is typed next. Then it is inhibited so that the third letter can be typed, and so on until all of the letters have been typed. This directional inhibition is a common feature of models that account for serial order in behavior (Dell, Burger, & Svec, 1997). The effect of the directional inhibition is to increase the influence of the initial letters relative to that of the later letters. In the present experiment, this directional inhibition might reduce the influence of the third and subsequent letters in LEght and riFT words, allowing them to produce a Simon effect equal to that found with LEFT and right words. Only Light and rEFT words might show a reduced Simon effect.

The requirement to type whole words rather than single letters allows a new dependent variable—the rate at which letters were typed within words. The Simon effect could occur in these within-word rate measures, or it could occur only in RT to the first letter. G. D. Logan and Zbrodoff (1998, 2002) ran similar experiments with the Stroop effect, displaying color words (RED, GREEN, BLUE, and YELLOW) in different colors (red, green, blue, and yellow) and requiring subjects to type the name of the color while ignoring the words themselves. They found a strong Stroop effect in the RT to the first keystroke of the word—subjects were slower to type color names that were incongruent with the word (e.g., the word GREEN in red) than to type color names that were congruent with the word (e.g., the word RED in red). However, they found no Stroop effect in the rate at which letters were typed within words. Incongruent color names were typed at the same rate as congruent color names. If the Simon effect is like the Stroop effect (see Lu & Proctor, 1995), it might also occur in the RTs to initial letters and not in subsequent interkeystroke intervals.

To summarize, parallel activation of keypress schemata predicts that the Simon effect will vary in magnitude across words that are typed with one or more hands (cf. Lamberts et al., 1992; Roswarski & Proctor, 1996). Words that are typed entirely within one hand should produce a stronger Simon effect than words whose first letters are typed with one hand and whose remaining letters are typed with the other. Words whose first two letters are typed with one hand should show an effect intermediate in size. By contrast, if keypress schemata cannot be activated in parallel, contrary to Rumelhart and Norman’s (1982) prediction, then only the first letter should matter. The Simon effect should be equally strong with all word sets.

Method

Subjects. The subjects were 16 students recruited from the general university community for their ability to touch type. They were paid for their participation. One subject had served in Experiment 1; the rest were naive. Their average speed on the typing test was 46.13 words per minute ($SD = 9.23$). Their average accuracy was 90.38% ($SD = 5.99$). Their average number of years of experience typing was 6.75 ($SD = 2.65$). All but 1 reported some formal training in typing. They reported typing an average of 2.06 hr a day.

Apparatus and stimuli. The apparatus was the same as in Experiments 1 and 2. The stimuli were different: They were 180 3-, 4- and 5-letter words composed of the 22 letters used in Experiments 1 and 2. The 180 words were divided into six sets of 30. Two sets—LEFT and right—were typed entirely with one hand. The other four sets were typed with both hands. The first two letters of LEght and riFT words were typed with one hand, and the remaining letters were typed with the other. The first letter of Light and rEFT words was typed with one hand, and the remaining letters were typed with the other. The six sets of words are presented in the Appendix, along with their mean length in letters and mean frequencies in the Francis and Kučera (1982) word-frequency count. The six sets of words were approximately equal in length and frequency. A one-way six-level ANOVA on word length showed no effect of word list, $F(5, 174) = 2.14$, $p < .10$, $MSE = 0.356$. A one-way six-level ANOVA on word frequency showed no effect of word list either, $F(5, 174) = 0.04$, $MSE = 10{,}095.01$.

The average word length was 3.8 letters, which corresponded to 1.2 cm on the computer screen. Words were presented left-justified left and right of fixation. For words presented left of fixation, the first letter appeared 2.3 cm from fixation, and the 3.8th letter (i.e., the average last letter) appeared 1.1 cm from fixation. For words presented right of fixation, the first letter appeared 1.1 cm from fixation, and the 3.8th letter appeared 2.3 cm from fixation.

Procedure. The procedure was the same as in Experiment 1, except that subjects typed words instead of single letters. Each word was presented once to the left of fixation and once to the right of fixation, for a total of 360 trials. The different word types (LEFT, right, LEght, riFT, Light, and rEFT) were intermixed randomly and were presented in a different random order for each subject.

Data analysis. The mean RTs were analyzed in 3 (word type: all letters in one hand, first two letters in one hand, or first letter only in one hand) × 2 (initial letter in left or right hand) × 2 (screen position) ANOVAs. In the subject ANOVA, mean RT was calculated across items in each cell of the design for each subject. Subjects were treated as random effects, and word type, initial letter, and screen position were within-subject factors. In the item ANOVA, mean RT was calculated for each item (i.e., each word) across subjects. Items were treated as random effects. Word type and initial letter were between-items factors, and screen position was a within-item factor.

Results and Discussion

Simon effects. Mean RTs to the initial keystroke were averaged over words for each word class (LEFT, right, LEght, riFT, Light, and rEFT) and screen position (left vs. right) for each subject. The means over subjects are plotted in Figure 4. Each point in the figure is based on 480 observations. A Simon effect was observed for words typed entirely with one hand (i.e., LEFT and right; Panel A) and for words whose first two letters were typed with one hand and whose remaining letters were typed with the other (i.e., LEght and riFT; Panel B). No Simon effect was observed for words whose first letters were typed with one hand and whose remaining letters were typed with the other (i.e., Light and rEFT; Panel C).

The subject ANOVA revealed significant main effects for screen position, $F(1, 15) = 6.98$, $p < .05$, $MSE = 1{,}348.90$, and initial letter in the left or right hand, $F(1, 15) = 4.55$, $p = .05$, $MSE = 3{,}128.78$, and significant interactions between initial letter and screen position, $F(1, 15) = 4.62$, $p < .05$, $MSE = 1{,}004.19$, and between word type and initial letter, $F(2, 30) = 7.45$, $p < .01$, $MSE = 1{,}261.42$. The three-way interaction between word type, initial letter, and screen position approached significance, $F(2, 30) = 3.05$, $p < .07$, $MSE = 312.43$. The item ANOVA revealed a significant main effect of screen position, $F(1, 174) = 14.90$, $p < .01$, $MSE = 1{,}359.18$, and a marginally significant effect of initial letter in the left or right hand, $F(1, 174) = 3.81$, $p < .06$, $MSE = 7{,}140.18$. The interactions between initial letter and screen position, $F(1, 174) = 3.64$, $p < .06$, $MSE = 1{,}359.18$, and between initial letter and word type, $F(2, 174) = 2.86$, $p < .06$, $MSE = 7{,}140.18$, were marginally significant. The three-way interaction between word type, initial letter, and screen position was not significant, $F(2, 174) = 1.35$, $MSE = 1{,}359.18$.

I tested the significance of the Simon effects within each word type by calculating interaction contrasts, using the error term from the interaction between word type, initial letter, and side of fixation. For the subject analysis, the Simon effect was significant for words typed entirely in one hand (i.e., LEFT and right), $F(1, 30) = 5.12$, $p < .05$, and for words whose first two letters were typed in one hand (i.e., LEft and riFT), $F(1, 30) = 15.68$, $p < .01$, but not for words whose first letters were typed in one hand and remaining letters were typed in the other (i.e., Light and rEFT), $F(1, 30) < 1.0$, all *MSE*s = 312.43. For the item analysis, the Simon effect was significant for words whose first two letters were typed with one hand, $F(1, 174) = 4.64$, $p < .05$, but not for words typed entirely in one hand, $F(1, 174) = 1.59$, or for words whose first letters were typed in one hand, $F(1, 174) < 1$, all *MSE*s = 1,359.18.

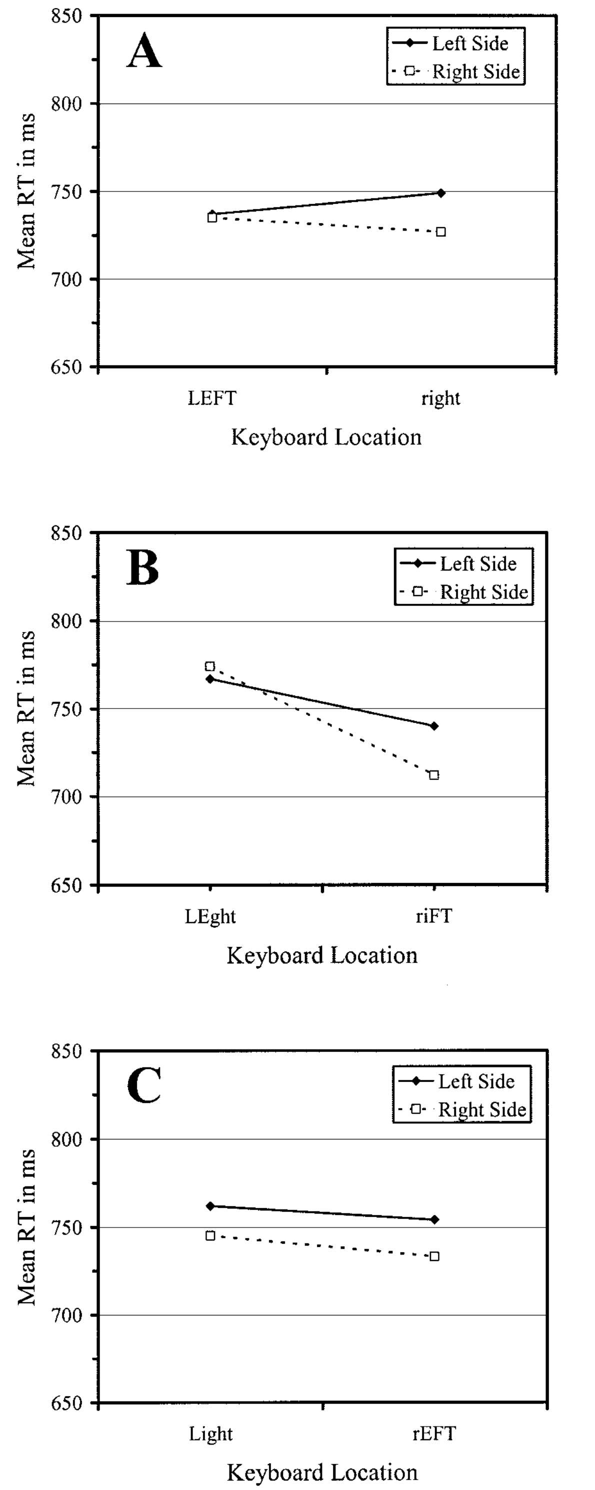

Figure 4. Mean reaction time (RT) as a function of the keyboard location of the responses and the side of fixation on which the word was presented in Experiment 3. A: Data from words that were typed with one hand (LEFT and right). B: Data from words whose first two letters were typed with one hand and whose remaining letters were typed with the other hand (LEght and riFT). C: Data from words whose first letters were typed with one hand and whose remaining letters were typed with the other hand (Light and rEFT).

The accuracy data are presented in Table 3. Accuracy was high, averaging 91.89% over word types. If the letters in each word were typed independently, then the accuracy for single letters could be derived by taking the 3.8th root of the proportion correct for words (i.e., mean word length was 3.8 and, assuming independence, P[word correct] = P[letter correct]$^{3.8}$). This calculation yields an accuracy of typing single letters of 97.80%, which is about the same as that observed in Experiments 1 and 2, in which single letters were typed. Most likely, the letters were not typed independently (see Gentner, 1982; Gentner et al., 1980; Shaffer, 1978), so this figure probably overestimates the actual accuracy of typing single letters. There were no significant effects in a 3 (word type) × 2 (initial letter) × 2 (side of fixation) ANOVA on the accuracy scores, using subjects as the random effect.

The rates at which words were typed were calculated by averaging the intervals between successive keystrokes within words. The mean rates, averaged over words within word types and side of fixation, appear in Table 3. Mean typing rate was slowest for words typed entirely within one hand (i.e., LEFT and right; M = 195 ms), intermediate for words whose first two letters were typed with one hand (i.e., LEght and riFT; M = 183 ms), and fastest for words whose first letter was typed with one hand and whose remaining letters were typed with the other (i.e., Light and rEFT; M = 172 ms). This is consistent with a general finding that hand and finger repetitions are typed more slowly than hand alternations (Salthouse, 1986). Typing rate was unaffected by the side of fixation the word was presented on (Ms = 183 ms for both sides) or by the hand with which the initial letter was typed (Ms = 183 ms for both hands). Typing rate showed no evidence of a Simon effect. Typing rate was 184 ms when the initial letter corresponded to the side of fixation the word was presented on and 182 ms when the initial letter did not correspond to that side (cf. G. D. Logan & Zbrodoff, 1998, 2002). These conclusions were confirmed in a 3 (word type) × 2 (initial letter) × 2 (side of fixation) ANOVA on the mean typing rates, with subjects as a random effect. The only significant effect in the ANOVA was the main effect of word type, $F(2, 30) = 24.75$, $p < .01$, $MSE = 336.435$.

Simon effect and individual items. Item effects were noisier in this experiment than in the previous ones because each subject typed each word only twice, once when it appeared left of fixation and once when it appeared right of fixation. Means across subjects for the item analysis are based on a maximum of 16 observations. By contrast, in Experiments 1 and 2, subjects saw each letter 24 times, 12 times in each position. Means across subjects (and presentations) in those experiments were based on a maximum of 192 observations. Moreover, in the present experiment, the initial letters of the words to be typed were not distributed over the keyboard as evenly as they were in the previous experiments. Nevertheless, I calculated item effects. The mean RTs and Simon effects for each word in each word list in each screen position are presented in the Appendix.

Averaged across word types, the Simon effect was largest for words with initial letters on the home row (M = 19 ms), intermediate for words with initial letters on the top row (M = 12 ms), and smallest for words with initial letters on the bottom row (M = −3 ms). Words with initial letters typed with the index fingers produced larger Simon effects (M = 21 ms) than words with initial letters typed with the other fingers (M = 0 ms).

I conducted stepwise multiple-regression analyses on the Simon effects with each word type, trying to predict the magnitude of the Simon effect from measures of word frequency (Francis & Kučera, 1982), the frequency with which the first letter appeared as the first letter of a word (Mayzner & Tresselt, 1965), the frequency with which the first digraph appeared as the first two letters of a word (Mayzner & Tresselt, 1965), and word length. In the six analyses, the only significant correlations between these measures and the Simon effect occurred with "right" words. In that analysis, word length correlated positively with the Simon effect ($r = .481$, $p < .01$), and the frequency of the first letter correlated negatively with the Simon effect ($r = -.430$, $p < .01$). The regression coefficients were significant for both variables.

Conclusions

RTs to the initial letters of the words showed a Simon effect for words typed entirely in one hand (i.e., LEFT and right; mean difference between corresponding and noncorresponding trials was 10 ms) but no Simon effect for words whose first letters were typed with one hand and whose remaining letters were typed with the other (i.e., Light and rEFT; mean difference between corresponding and noncorresponding trials was 2 ms). Words whose first two letters were typed with one hand and whose remaining letters were typed with the other showed the strongest Simon effect (i.e., LEght and riFT; mean difference between corresponding and noncorresponding trials was 18 ms). The contrast between words typed entirely with one hand and words whose first letters were typed with one hand and whose remaining letters were typed with the other is consistent with Rumelhart and Norman's (1982) hypothesis that keypress schemata are activated in parallel. All keypress schemata in LEFT and right words shared the same "hand"

Table 3
Mean Accuracy (Percentage Correct) and Typing Rate (in Milliseconds) as Functions of Word Type and Side of Fixation on Which the Word Was Presented in Experiment 3

Side of fixation	LEFT	right	LEght	riFT	Light	rEFT
Accuracy						
Left	89.50	91.82	91.56	93.56	92.18	92.63
Right	92.19	89.25	91.25	94.06	91.88	92.75
Typing rate						
Left	195	193	186	179	170	175
Right	197	195	182	184	168	174

feature, whereas the first and subsequent letters in Light and rEFT words had different "hand" features that counteracted each other and reduced the Simon effect.

It is not clear why words whose first two letters were typed with one hand and whose remaining letters were typed with the other showed the largest Simon effect. Rumelhart and Norman's (1982) theory predicts that the Simon effect with these LEght and riFT words should be intermediate in magnitude, smaller than the effect for LEFT and right words and larger than the effect for Light and rEFT words. Rumelhart and Norman's theory assumes a directional inhibition that reduces the influence of subsequent letters in a word and that may account for the Simon effect (i.e., the Simon effect may depend primarily on the first two letters). However, the Simon effect was not significantly larger for LEght and riFT words than it was for LEFT and right words, $F(1, 30) = 1.44$, $MSE = 312.43$, for the subject analysis and $F(1, 174) < 1$, $MSE = 1{,}359.18$, for the item analysis. Thus, the results are not entirely inconsistent with Rumelhart and Norman's theory.

The contrast between LEFT and right words and Light and rEFT words suggests parallel activation of keypress schemata for words typed entirely within one hand. This result goes beyond the kinematic evidence for parallel activation, which has been clearest for words containing hand alternations (Gentner et al., 1980; Soechting & Flanders, 1992, 1997). Together, the kinematic evidence and the present evidence from the Simon effect suggest that keypress schemata are activated in parallel in all words, however their letters are distributed across hands.

The fact that the Simon effect occurred in RTs to the initial keystrokes but not in the intervals between subsequent keystrokes is consistent with G. D. Logan and Zbrodoff's (1998, 2002) observation that the Stroop effect with typewritten responses occurred only in RTs to the first keystroke and not in the subsequent interkeystroke intervals. It is possible that the stimulus-location code decayed throughout the typing of a word as keystrokes were executed, thereby reducing the Simon effect for letters beyond the first (De Jong et al., 1994; Hommel, 1993; Roswarski & Proctor, 1996).

Experiment 4

The item analyses in Experiments 1–3 showed that the Simon effect varied considerably over keyboard position. The patterns were somewhat different in different experiments. Experiment 4 was conducted to determine whether the keyboard-position effects in Experiments 1–3 were due to eccentricity of the keys subjects pressed, to the fingers they used to press the keys, or to an interaction between response key and responding finger. The Simon effect could depend on a metric representation of keyboard position, with more eccentric keys and fingers being more strongly associated with "left" and "right" than less eccentric ones. Alternatively, the Simon effect could depend on a categorical representation of keyboard position, in which case neither key eccentricity nor finger eccentricity would have an effect. Studies of the standard Simon effect that manipulated stimulus eccentricity suggest that stimulus eccentricity is coded categorically (Hommel, 1993; Lamberts et al., 1992; Roswarski & Proctor, 1996; Stins & Michaels, 2000). Nevertheless, it is not clear that the effect of response eccentricity would be the same as the effect of stimulus eccentricity, so the interpretation of the present results remains open.

Experiment 4 was also conducted to serve as a control condition for Experiments 1–3. Touch typists always strike the same keys with the same fingers, so responding finger and keyboard location are completely confounded. Experiment 4 was designed to separate the effects of responding finger and keyboard location.

Experiment 4 involved a standard Simon task. Subjects were presented with a single letter to the left or right of fixation, and they responded to it by pressing one of two keys with one of two fingers. In different blocks, subjects pressed the *G* key or the *H* key, the *F* key or the *J* key, the *D* key or the *K* key, and the *S* key or the *L* key (see Figure 1), using their index, middle, ring, or little fingers. All 16 combinations of response key and responding finger were tested to remove the confound between response location and responding finger that is inherent in touch typing. If the Simon effect depends on eccentricity of response location, it should increase with eccentricity of the response keys, independent of the fingers used to press the keys. If the Simon effect depends on eccentricity of the responding fingers, it should be larger for middle, ring, and little fingers than it is for index fingers, independent of the response keys. If the Simon effect in touch typing reflects an interaction between response-key eccentricity and finger eccentricity, that interaction should be apparent in this experimental design.

Method

Subjects. Sixteen subjects from the general university community were paid for participating in a single session. None had served in any of the previous experiments.

Apparatus and stimuli. The apparatus and stimuli were the same as in Experiment 1, except that the stimuli were the letters *X* and *O*, presented in uppercase, and the responses were collected from the *S*, *D*, *F*, *G*, *H*, *J*, *K*, and *L* keys on the home row of the keyboard (see Figure 1). The letters appeared in the same locations as the letters in Experiment 1.

Procedure. The experiment involved 16 blocks of 60 trials, one block for each combination of finger and response key. Subjects used the same fingers for consecutive sets of four blocks, during which they cycled through the response keys. For example, one group of subjects began the experiment using their index fingers to distinguish between *X* and *O*, pressing the *G* and *H* keys in the first block, the *F* and *J* keys in the second block, the *D* and *K* keys in the third block, and the *S* and *L* keys in the fourth block. In the fifth block, they used their middle fingers to distinguish *X* from *O*, pressing the *G* and *H* keys. In the sixth through eighth blocks, they cycled through the keys, increasing eccentricity with each block. In Blocks 9 through 12, they used their ring fingers, cycling through the keys in increasing eccentricity, and in Blocks 13 through 16, they used their little fingers, cycling through the keys in increasing eccentricity.

Altogether, there were eight groups of 2 subjects, formed by the factorial combination of three counterbalancing factors: (a) Half of the subjects began with their index fingers, using their middle, ring, and little fingers (in that order) as the experiment progressed. The other half began with their little fingers and progressed through their ring, middle, and index fingers. (b) Half of the subjects began with the central (*G* and *H*) keys and progressed outward, while the other half began with the most eccentric keys (*S* and *L*) and progressed inward. (c) Half of the subjects pressed the left key for *X* and the right key for *O*, while the other half did the opposite.

Within each block of 60 trials, *X* and *O* occurred equally often on each side of the fixation point. The order of trials was randomized separately for each subject. Subjects were given instructions at the beginning of each block that told them which keys to press for *X* and *O*.

Results and Discussion

The mean RTs for each combination of finger and response key and side of presentation are presented in Table 4. Mean RT was shorter when the stimulus appeared on the right side of the screen (M = 501 ms) than when it appeared on the left side (M = 509 ms), and it was shorter when subjects responded with their right hands (M = 497 ms) than when they responded with their left hands (M = 513 ms). Overall, subjects were 31 ms faster when the stimulus side and response side were the same than when they differed, replicating the Simon effect. RT was largely unaffected by responding finger and by response location. The main exception was the little fingers: RT was longest for the little fingers in the central response locations (*G* and *H* keys) and sped up with increasing eccentricity. The slowing in the central response locations may have been due to the relatively awkward positioning of the hands when the little fingers were on the *G* and *H* keys.

The most important result was the modulation of the Simon effect by response location and responding finger. Mean RTs for each stimulus and response location (collapsed across responding finger) are plotted in Figure 5. There was no systematic modulation of the Simon effect by response location. Mean RTs for each stimulus location and responding finger (collapsed across response location) are plotted in Figure 6. The Simon effect was not modulated systematically by responding finger.

These conclusions were supported in a 2 (stimulus left or right) × 2 (response left or right) × 4 (response location: *GH*, *FJ*, *DK*, or *SL*) × 4 (responding finger: index, middle, ring, or little) ANOVA on the mean RTs, with subjects as a random effect. The

Table 4
Mean Reaction Time (RT; in Milliseconds), Percentage of Correct Responses (P[C]), and Simon Effect as Functions of Side of Presentation, Responding Finger, and Response Location in Experiment 4

Finger	Response location: S	D	F	G	H	J	K	L	Mean
Stimulus on left side									
Index									
RT	497	502	511	495	515	546	510	531	513
P(C)	97	98	98	99	94	96	95	96	97
Middle									
RT	483	520	489	485	493	500	530	483	498
P(C)	96	97	98	98	95	97	98	94	97
Ring									
RT	479	473	499	505	524	519	498	511	501
P(C)	98	100	99	99	96	97	97	97	98
Little									
RT	488	515	543	538	550	535	513	513	524
P(C)	98	98	99	100	97	96	95	99	98
Mean									
RT	487	503	511	506	521	525	513	510	
P(C)	97	98	99	99	96	97	96	97	
Stimulus on right side									
Index									
RT	532	512	511	522	475	462	457	472	493
P(C)	97	96	97	95	98	98	97	99	97
Middle									
RT	504	534	531	518	474	476	494	474	501
P(C)	99	96	96	98	99	98	98	98	98
Ring									
RT	499	510	527	512	478	468	454	482	491
P(C)	96	97	97	97	99	99	98	99	98
Little									
RT	517	544	523	598	499	492	486	495	481
P(C)	97	97	97	96	99	99	100	99	98
Mean									
RT	500	514	517	522	501	500	493	495	
P(C)	97	97	97	97	99	99	98	99	
Simon effect									
Index	35	10	0	27	40	84	53	59	39
Middle	21	14	42	33	19	24	36	9	25
Ring	20	37	28	7	46	51	44	29	33
Little	29	29	−20	60	51	43	27	18	30
Mean	26	23	13	32	39	51	40	29	

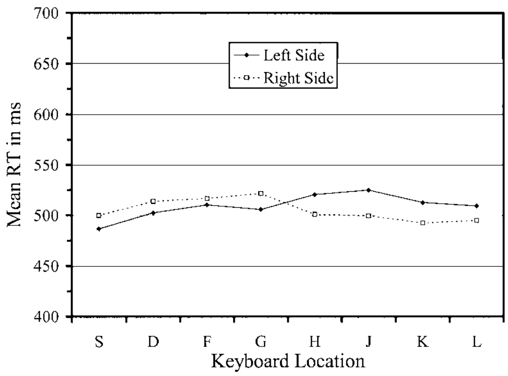

Figure 5. Mean reaction time (RT) as a function of keyboard location and stimulus position in Experiment 4.

only significant main effects were stimulus left or right, $F(1, 15) = 5.90$, $p < .05$, $MSE = 2{,}879.29$, and response left or right, $F(1, 15) = 6.78$, $p < .05$, $MSE = 9{,}437.49$. The interaction between stimulus left or right and response left or right was significant, $F(1, 15) = 36.76$, $p < .01$, $MSE = 6{,}870.63$, reflecting the Simon effect. The interaction between response location and responding finger was also significant, $F(9, 135) = 2.36$, $p < .05$, $MSE = 4{,}804.69$, reflecting the stronger response-location effect with the little fingers.

I assessed the modulation of the Simon effect by response location and responding finger with contrasts testing the difference in linear trend between corresponding and noncorresponding locations. I constructed eight contrasts testing the difference in linear trend across response locations for each finger and eight contrasts testing the difference in linear trend across responding fingers for each response location. None of the contrasts were significant. The Simon effect does not appear to be modulated by stimulus position or response finger.

Following Hommel (1993), De Jong et al. (1994), and Roswarski and Proctor (1996), I examined the relation between the magnitude of the Simon effect and RT by correlating the Simon effect with mean RT (across stimulus location) for the 32 cells in the 2 (response left or right) × 4 (response location) × 4 (responding finger) design. The correlation was negligible ($r = .007$) and nonsignificant, $F(1, 31) < 1$.

The accuracy data (percentage of correct responses) are presented along with the RTs in Table 4. The accuracy data were analyzed in a 2 (stimulus left or right) × 2 (response left or right) × 4 (response location: *GH*, *FJ*, *DK*, or *SL*) × 4 (responding finger: index, middle, ring, or little) ANOVA. The only significant effect in the ANOVA was the interaction between stimulus left or right and response left or right, $F(1, 15) = 14.99$, $p < .01$, $MSE = 57.82$, reflecting a Simon effect. Responses with the left hand were 98% correct when the stimulus was presented on the left and 97% correct when the stimulus was presented on the right. Responses with the right hand were 99% correct when the stimulus was presented on the right and 96% correct when the stimulus was presented on the left.

Conclusions

This experiment produced a robust Simon effect that was not modulated systematically by response location or by responding finger. As with manipulations of stimulus location, the Simon effect appears to depend on a categorical "left versus right" encoding of response location and of responding hand rather than a metric representation of absolute distances between stimulus and response locations (Hommel, 1993; Lamberts et al., 1992; Roswarski & Proctor, 1996; Stins & Michaels, 2000). This lack of modulation suggests that the modulation observed in the item analyses of Experiments 1–3 may be due to factors imposed by the task of typing.

General Discussion

Experiments 1–3 showed Simon effects with typewritten responses, which suggest the existence of location codes in the keypress schemata that control typing. Experiments 1 and 3 showed evidence of "left" and "right" location codes, and Experiment 2 showed evidence of "up" and "down" location codes. Experiment 3 showed evidence of parallel activation of location codes for different letters. All of these results are consistent with Rumelhart and Norman's (1982) theory of typewriting, which assumes that location codes play critical roles in keypress schemata.

The item analyses in Experiments 1–3 provided further evidence of parallel activation of keypress schemata. Mean RT to the letters that occurred in all three experiments (i.e., all letters except *Q* and *E*) was virtually identical in Experiments 1 and 2 ($r = .970$), $F(1, 19) = 304.47$, $p < .01$. However, the correlation between Experiment 1 and Experiment 3 was smaller ($r = .413$) and nonsignificant, $F(1, 19) = 3.92$, and the correlation between Experiments 2 and 3 was also smaller ($r = .444$), though it was significant, $F(1, 19) = 4.67$, $p < .05$. The change in the pattern of RTs to the initial letters in Experiment 3 must be due to the context provided by the other letters in the word (see also Gentner, 1982; Shaffer, 1978).

The present evidence for keypress schemata corroborates and complements previous evidence from analyses of error corpora (Grudin, 1983; F. A. Logan, 1999) and kinematic data (Grudin, 1983). The present evidence for parallel activation of keypress schemata complements and extends previous evidence from kinematic data (Gentner et al., 1980; Soechting & Flanders, 1992, 1997). Together, the three kinds of evidence converge on the concept of keypress schemata, demonstrating its utility and predictive power. Typing is a complex skill that manifests itself in

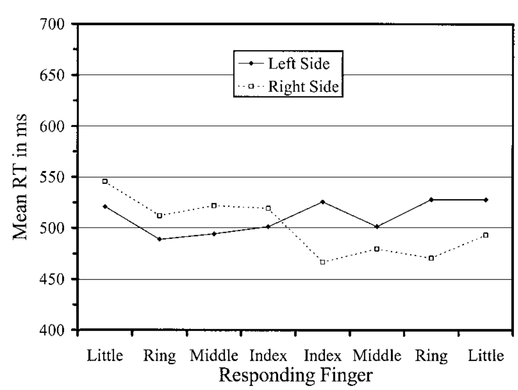

Figure 6. Mean reaction time (RT) as a function of responding finger and stimulus position in Experiment 4.

several aspects of performance, and the concept of keypress schemata accounts for many of those aspects.

The Simon Effect and Typing Skill

The Simon effect is not related to typing skill. I calculated the relation between the Simon effect and typing skill in two ways in each experiment and found no significant relation with either method. First, I calculated the correlation between speed on the typing test and the Simon effect (i.e., the interaction contrast between keyboard position and screen position). In Experiments 1 and 2, the correlation was negative (rs $= -0.378$ and -0.047, respectively) and nonsignificant, Fs$(1, 15) = 2.50$ and < 1, indicating a trend toward a smaller Simon effect in the faster typists. In Experiment 3, I calculated the correlations between the speed test and the Simon effect for each word type. They were all negative (rs $= -.412$, $-.342$, and $-.059$) and nonsignificant, Fs$(1, 15) = 3.06$, 1.98, and 0.04, for LEFT–right, LEght–riFT, and Light–rEFT words, respectively.

Second, I calculated the correlation between the Simon effect and mean RT across all conditions of the experiments. Mean RT reflects typing skill (Hayes, Wilson, & Schafer, 1977). The correlations between mean RT and speed on the typing test were significant in each experiment (for Experiments 1 and 2, rs $=$ $-.720$ and $-.553$ and Fs$[1, 15] = 16.10$ and 6.60, respectively [both ps $< .05$]; for Experiment 3, rs $= -.628$, $-.604$, and $-.646$, and Fs$[1, 15] = 9.78$, 8.63, and 10.77, for LEFT–right, LEght–riFT, and Light–rEFT words, respectively [all ps $< .01$]). In Experiment 1, the correlation between the Simon effect and mean RT was positive ($r = .210$) and nonsignificant, $F(1, 15) < 1$. In Experiment 2, the correlation was negative ($r = -.237$) and nonsignificant, $F(1, 15) < 1$. In Experiment 3, the correlations between the Simon effect and mean RT for each word type were negligible (rs $= -.001$, .036, and .007) for LEFT–right, LEght–riFT, and Light–rEFT words, respectively. None were significant: all Fs$(1, 15) < 1$.

The failure to find a correlation between the magnitude of the Simon effect and typing skill may be due to a restricted range of typing skill. Speed on the typing test ranged from 29.27 to 63.62 words per minute in Experiment 1, from 28.30 to 60.26 words per minute in Experiment 2, and from 31.70 to 60.20 words per minute in Experiment 3. It is possible that a broader range of skill would reveal a stronger relation. The trend toward a smaller Simon effect in faster typists is inconsistent with a general finding that the Simon effect is smaller for slower responses (De Jong et al., 1994; Hommel, 1993; Roswarski & Proctor, 1996). Researchers have interpreted the reduction in the Simon effect as evidence that the location code engendered by the stimulus decays over time and is less active when slower responses are selected. From this perspective, it is possible that the range of RTs was not large enough to produce a difference in decay of the location code (see Hommel, 1993). The lack of correlation between the Simon effect and typing skill is reminiscent of G. D. Logan and Zbrodoff's (1998) finding of no correlation between typing skill and the Stroop effect with typewritten responses. Perhaps congruency effects are unrelated to skill level.

The Simon Effect and Practice

The present evidence for Simon effects in typewriting also extends the literature on the Simon effect in significant directions. Experiments 1–3 demonstrated Simon effects in subjects with much more preexperimental practice with the stimulus–response mappings relevant to the task. Most studies of the Simon effect use arbitrary mappings of relevant stimulus dimensions (e.g., color) onto responses that are introduced for the first time when the subject begins the experiment. The most practice on record is 30 sessions in a single subject tested by Hommel (reported in Prinz, Aschersleben, Hommel, & Vogt, 1995). By contrast, the present subjects had an average of 6.83 years of typing experience and reported typing an average of 1.98 hr each day, in recent years at least. The present results suggest that the Simon effect can survive extensive periods of practice.

The conclusion that the Simon effect survives extensive practice is mitigated somewhat by the fact subjects in Experiments 1–3 most likely did not practice typing in conditions that would produce a Simon effect. Proctor and Lu (1999) showed that the reduction in the Simon effect with practice involves suppressing irrelevant location codes. Irrelevant location codes would be more likely to be generated in copy typing, in which subjects type visually presented text. Subjects in Experiments 1–3 reported more extensive experience with composition typing, in which they created the text to be typed, than with copy typing. It is unlikely that the "stimuli" in composition typing would produce irrelevant location codes, so it is unlikely that subjects in Experiment 1–3 had learned to suppress them. However, Hommel (personal communication, December 18, 2001) found a Simon effect in an unpublished experiment with 10 professional typists who averaged 13.4 years of copy-typing experience that may have taught them to suppress irrelevant location codes. He had them type the letters *F* and *J*, presented left or right of a fixation point, and found a 61-ms Simon effect.

The Simon Effect With Typing Versus Key Pressing

The Simon effects in Experiments 1–3, which involved typing, were smaller than the Simon effect in Experiment 4, which involved key pressing rather than typing. This difference could have been due to the number of alternative responses. There were 22 alternative responses in Experiments 1 and 2 and somewhere between 180 (the number of words on the stimulus list) and several hundred thousand (the number of words in subjects' vocabularies) in Experiment 3. There were only two alternative responses in Experiment 4. The reduction in the Simon effect could have been due to some direct effect of the number of alternative responses, or it could have been due to the increase in RT that accompanies increases in the number of alternative responses (Hick, 1952; Hyman, 1953). In Experiment 4, mean RT was 505 ms, and the Simon effect was 31 ms. In Experiments 1–3, mean RT was 760, 768, and 745 ms, respectively, and the Simon effects were 18, 13, and 10 ms, respectively. The increase in RT could allow irrelevant location codes to decay and, consequently, reduce the Simon effect (De Jong et al., 1994; Hommel, 1993).

The evidence for categorical representation of finger and key locations in Experiment 4 suggests that finger and key locations may also be represented categorically in the keypress schemata that underlie typewriting. Skilled touch typing may differ from unpracticed key pressing in the number and the specificity of the response categories, but the same categorical representation may underlie both tasks. Thus, in typing, each letter activates a particular location on the keyboard to be struck with a particular finger on a particular hand (Rumelhart & Norman, 1982). Each finger, hand, and keyboard location may be bound together in a separate response category that is encapsulated by extensive practice (Gentner et al., 1980; Long, Nimmo-Smith, & Whitefield, 1983; Soechting & Flanders, 1992, 1997). Nevertheless, the differences between skilled typing and unpracticed key pressing may be more quantitative than qualitative. Indeed, the present experiments have shown that they are both subject to the same qualitative effect of spatial correspondence between stimulus and response locations—the Simon effect prevails despite vast differences in skill.

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Appendix

Words Used in Experiment 3

LEFT and right words (Table A1) are typed entirely with one hand. The first two letters of LEght and riFT words (Table A2) are typed with one hand, and the remaining letters are typed with the other. The first letter of Light and rEFT words (Table A3) are typed with one hand, and the remaining letters are typed with the other. Length and Frequency refer to mean length in letter spaces and mean frequency in the Francis and Kučera (1982) norms. RT_{Left} and RT_{Right} are mean reaction times (in milliseconds) across subjects when the words were presented on the left and right sides of the screen, respectively. Simon effect is the RT difference between corresponding and noncorresponding stimulus and response locations.

Table A1
LEFT and right Words

	LEFT	RT_{Left}	RT_{Right}	Simon effect	right	RT_{Left}	RT_{Right}	Simon effect
	sew	713	712	−1	you	768	747	21
	dew	773	728	−45	jump	748	659	89
	wed	718	760	42	milk	690	691	−1
	bed	761	748	13	pun	786	760	26
	feed	737	718	−19	hill	727	691	36
	seed	657	626	−31	pill	783	746	37
	deer	685	690	5	pull	803	735	68
	deed	672	657	−15	lop	665	667	−2
	beer	711	734	23	lip	633	690	−57
	beet	720	723	3	nil	722	799	−77
	bet	694	722	28	pink	764	839	−75
	debt	745	817	72	lump	691	643	48
	rest	728	725	−3	pump	773	721	52
	west	793	729	−64	pool	699	713	−14
	vest	957	808	−149	hoop	775	780	−5
	deft	813	796	−17	noon	757	672	85
	test	706	701	−5	moon	708	763	−55
	web	770	777	7	limp	719	659	60
	red	733	690	−43	yolk	906	927	−21
	fed	747	717	−30	lion	699	657	42
	veer	729	828	99	hip	720	771	−51
	sewer	814	728	−86	pupil	843	766	77
	fewer	737	800	63	ion	804	751	53
	serve	694	687	−7	poppy	777	750	27
	verse	782	775	−7	pony	771	681	90
	verb	762	815	53	loop	657	665	−8
	stew	694	704	10	jolly	920	721	199
	steer	670	679	9	junk	710	692	18
	sweet	690	693	3	punk	834	757	77
Length	3.90	739	734	5	3.87	751	729	22
Frequency	58.30				56.90			

(*Appendix continues*)

Table A2
LEght and riFT Words

	LEght	RT_{Left}	RT_{Right}	Simon effect	riFT	RT_{Left}	RT_{Right}	Simon effect
	sell	671	676	5	jut	763	708	55
	fell	761	762	1	hid	783	709	74
	bell	771	679	−92	lid	656	640	16
	gem	813	758	−55	hit	777	758	19
	ten	685	722	37	lit	649	636	13
	stop	686	650	−36	kit	811	705	106
	try	737	708	−29	pit	734	697	37
	stun	698	709	11	purr	747	731	16
	drop	790	731	−59	pub	901	814	87
	veil	826	913	87	list	656	615	41
	deny	735	761	26	lost	597	612	−15
	trim	683	739	56	kiss	740	693	47
	broom	723	744	21	pure	722	718	4
	swim	781	761	−20	pore	696	699	−3
	drip	774	786	12	post	723	716	7
	groin	825	871	46	port	770	730	40
	dry	722	722	0	power	743	716	27
	grill	768	824	56	pose	738	693	45
	grip	814	823	9	pig	785	845	−60
	grim	773	856	83	miss	732	671	61
	grin	848	754	−94	hog	865	863	2
	venom	1005	1010	5	jog	880	746	134
	broil	788	728	−60	note	733	699	34
	vein	849	943	94	hut	810	785	25
	brim	787	775	−12	loft	671	657	14
	demon	755	785	30	love	635	722	−87
	rely	780	693	−87	lobe	703	693	10
	trump	729	761	32	lore	648	646	2
	gel	773	733	−40	lure	746	672	74
	drum	745	756	11	mist	713	709	4
Length	4.07	770	771	1	3.63	738	710	28
Frequency	57.90				62.56			

Table A3
Light and rEFT Words

	Light	RT_{Left}	RT_{Right}	Simon effect	rEFT	RT_{Left}	RT_{Right}	Simon effect
	tool	724	672	−52	pew	810	812	−2
	soon	699	626	−73	pet	746	689	57
	doll	835	833	−2	let	724	616	108
	toll	715	694	−21	met	701	711	−10
	till	680	710	30	net	735	731	4
	top	767	703	−64	jet	823	800	23
	tip	769	736	−33	yet	819	793	26
	rink	780	803	23	heed	887	805	82
	boil	805	728	−77	meet	661	675	−14
	dump	931	850	−81	leg	679	662	17
	sick	715	681	−34	peg	773	739	34
	fun	728	718	−10	pest	749	698	51
	bun	753	791	38	nest	747	749	−2
	gun	866	822	−44	lest	650	656	−6
	ton	716	708	−8	peer	685	664	21
	won	759	752	−7	lewd	742	675	67
	bill	785	724	−61	mere	720	697	23
	fill	676	760	84	leer	649	617	32
	gull	811	785	−26	keg	790	849	−59
	bull	757	757	0	newt	819	954	−135
	tiny	738	724	−14	lever	671	673	−2
	sink	746	709	−37	never	674	711	−37
	bin	829	794	−35	herd	779	736	43
	rim	741	759	18	ore	705	739	−34
	tin	727	674	−53	pert	759	755	4
	fool	710	789	79	meter	728	685	43
	slop	736	799	63	jeer	790	713	77
	slip	817	745	−72	heft	902	820	82
	slum	788	741	−41	user	945	791	154
	slim	761	714	−47	owe	713	856	−143
Length	3.67	762	743	−19	3.70	753	736	17
Frequency	54.43				63.60			

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