Research Article

The Left Hand Doesn't Know What the Right Hand Is Doing

The Disruptive Effects of Attention to the Hands in Skilled Typewriting

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ABSTRACT—*Everyone knows that attention to the details disrupts skilled performance, but little empirical evidence documents this fact. We show that attention to the hands disrupts skilled typewriting. We had skilled typists type words preceded by cues that told them to type only the letters assigned to one hand or to type all of the letters. Cuing the hands disrupted performance markedly, slowing typing and increasing the error rate (Experiment 1); these deleterious effects were observed even when no keystrokes were actually inhibited (Experiment 3). However, cuing the same letters with colors was not disruptive (Experiment 2). We account for the disruption with a hierarchical control model, in which an inner loop controls the hands and an outer loop controls what is typed. Typing letters using only one hand requires the outer loop to monitor the inner loop's output; the outer loop slows inner-loop cycle time to increase the likelihood of inhibiting responses with the unwanted hand. This produces the disruption.*

A world-famous rock guitarist, legendary for his dazzling speed and virtuosity, was once asked how he played so quickly. He said, "They asked me what I was doing, and I said I don't know. Then I started looking and it got confusing." His experience is shared by mere mortals in executing everyday skills: Everyone knows that attending to the details disrupts skilled performance. Surprisingly, however, there is little empirical evidence documenting this fact (but see Beilock, Carr, MacMahon, & Starkes, 2002). This article reports the effects of attention to the hands on the everyday skill of typewriting. We asked college students to

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type only the letters assigned to one hand and avoid typing the letters assigned to the other. This was very disruptive, as you can confirm by typing only the right-hand letters in this sentence.

These disruptive effects of attention to the hands are paradoxical. They suggest that the system controlling typewriting does not know what the hands are doing, yet it uses the hands correctly five to six times per second. One resolution to this paradox is to divide the control system into two hierarchical parts (Shaffer, 1976): an outer loop that transforms text or thought into a series of words and an inner loop that transforms each word into a series of keystrokes, specifying hand, finger, and direction. These two steps are common components in existing models of typewriting (John, 1996; Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008). Our novel contribution is to suggest that the loops are encapsulated: The outer loop does not know which hand types which characters, but the inner loop does. This works well in normal typewriting because it frees the outer loop from attention to details, but it creates problems when typists must type only the characters assigned to one hand. In that case, the outer loop must determine which hand types each character, and it may have to observe the inner loop's output (i.e., watch the hands make keystrokes) to do so. Then, the outer loop must inhibit unwanted responses before they are executed. Discrimination and inhibition take time (Logan, 1982), so typing must slow substantially. The duration of each keystroke must be extended to allow discrimination and inhibition to finish before the key is struck.

This analysis assumes that the outer loop must discover what the hands do by examining the inner loop's output. Another possibility is that hand information is specified in the inner loop's input (the outer loop's output). If so, the information necessary to inhibit unwanted keystrokes would be available well before the keys are struck, so typing characters in only one hand would not be as disruptive. Experiment 1 tested whether

such typing instructions are in fact disruptive. More generally, information specified in the outer loop's input, such as the color in which characters are rendered, should not be very disruptive. Experiment 2 tested the hypothesis that the requirement to attend to such information should not disrupt typewriting very much. The results of Experiments 1 and 2 suggest that the disruption caused by instructions to type only letters assigned to one hand could result from monitoring the inner loop's output and from inhibiting inner-loop processing to prevent unwanted keystrokes. Experiment 3 tested the hypothesis that monitoring is disruptive even when no keystrokes must be inhibited. Experiment 4 generalized the results to continuous typing.

EXPERIMENT 1

First, we quantified the disruptive effects of attention to the hands. Subjects typed words presented on a computer screen; a cue that preceded each word told subjects whether to type the whole word or only the letters typed with the left or right hand. If attention to the hands is disruptive, typing should be slower and more error prone when only the letters assigned to one hand are typed than when whole words are typed.

Method

Sixteen touch typists were sampled from the Vanderbilt University subject pool. Their mean speed on a typing test was 68 words per minute (wpm; range: 46–94). We asked them to type single four-letter words, presented in the center of a computer screen, and to press the space bar when they finished each trial. A cue presented 1,500 ms before each word indicated whether to type the whole word ("WHOLE") or only the letters assigned to the left ("LEFT") or right ("RIGHT") hand. The whole-word cue appeared on half of the trials; each hand cue occurred on one quarter of the trials. The words to be typed belonged to two categories: *unimanual words*, in which all letters were typed with the left hand or the right hand, and *bimanual words*, in which half the letters were typed with each hand. The sequence of left-hand (L) and right-hand (R) keystrokes defined six types of bimanual words: LLRR, LRRL, LRLR, RRLL, RLLR, and RLRL. Each subject typed 24 unimanual left-hand words, 24 unimanual right-hand words, and 48 bimanual words (8 of each type). Each word was presented four times in random order, twice with the whole-word cue and once each with the left-hand and right-hand cues. A word was exposed until the subject pressed the space bar. Subjects' responses were echoed on the bottom of the screen. There were 384 trials.

Results

We calculated the mean response time (RT) for each keystroke, relative to the onset of the word to be typed. The means across subjects are plotted as a function of position (1–4, space) in Figure 1. These data show that attention to the hands was very

disruptive. Averaged over position, RT was 506 ms (47%) longer with hand cues than with the whole-word cue.

Using the RT data, we characterized typing performance with three dependent variables: *first-position response time* (FPRT), which measured the time to encode the word and prepare the first keystroke; *interkeystroke interval* (IKSI), which measured the rate of typing once it began (the slope of a linear function relating keystrokes for Positions 1–4 to time); and *space-bar RT* (SBRT), which measured the time at which typing, monitoring, and inhibiting were finished. In addition, we calculated *error rate*, the probability that an error occurred in typing the required letters. Table 1 presents the means across subjects and inferential statistics for these four variables.

The contrast between hand cues and the whole-word cue with unimanual words measures the disruptive effects of monitoring. Subjects typed the same keystrokes with both cues (e.g., the left-hand and whole-word cues called for the same keystrokes for *dart*), yet performance was much worse with hand cues: FPRT was 233 ms (28%) longer, IKSI was 34 ms (20%) slower, and SBRT was 356 ms (23%) longer. SBRT was also longer (by 424 ms, or 28%) when subjects did not type any letters (e.g., when the right-hand cue preceded *dart*). These results suggest that subjects simulated typing to discover which letters were typed with which hand. The error rate was higher by .09 (100%) when typing was preceded by a hand cue.

The contrast between hand cues and the whole-word cue with bimanual words measures the disruptive effects of monitoring and of inhibiting unwanted keystrokes. Subjects had to inhibit two keystrokes in the case of hand cues and no keystrokes in the case of the whole-word cue. Disruption with hand cues was substantial: FPRT was 462 ms (55%) longer, IKSI was 153 ms (104%) longer, SBRT was 738 ms (50%) longer, and the error rate was .16 (200%) higher. These disruptions are more than twice as large as the ones with unimanual words, which suggests that monitoring and inhibiting were more disruptive than simply monitoring.

EXPERIMENT 2

The hierarchical control model suggests that attention to the hands disrupts typing because the outer loop has to monitor the inner loop's output to identify unwanted keystrokes. Experiment 2 tested the corollary assumption that attention to features specified in the outer loop's input will not disrupt typing much because unwanted keystrokes can be identified well before they are executed. To test this hypothesis, we presented the words in color, with some letters red and others green, and asked subjects to type all the letters, only the red ones, or only the green ones. The hierarchical control model predicts little disruption from cuing color. An alternative, dual-task-interference hypothesis predicts that attention to anything other than typing will disrupt performance, regardless of the loop in which the attended feature is specified (but see Salthouse & Saults, 1987; Shaffer,
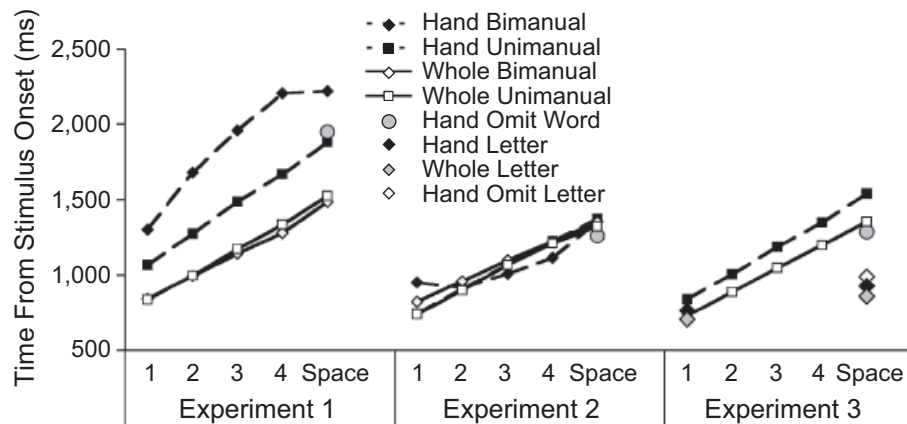
Fig. 1. Results from Experiments 1 through 3: times at which keys were struck relative to the onset of the word to be typed, as a function of letter position within the word, including the after-word space (subjects pressed the space bar when they finished typing). The data points above Position 1 are first-position response times; the slopes of the lines relating key-press time to Positions 1 through 4 are interkeystroke intervals; and the data for the space are the space-bar response times. ''Whole'' and ''hand'' refer to the cues that were presented on each trial. The former cue indicated that every letter should be typed; the hand cues indicated whether only the letters assigned to the left hand or only the letters assigned to the right hand should be typed. (In Experiment 2, hand cues were replaced by color cues; see the text.) ''Unimanual,'' ''bimanual,'' and ''letter'' refer to the properties of the stimuli to be typed—unimanual words, bimanual words, and single letters, respectively. Unimanual words were typed entirely with one hand, and bimanual words were typed with both hands. Single letters were typed with either hand. ''Omit word'' and ''omit letter'' refer to trials on which no characters were typed; subjects only pressed the space bar.

1975). Thus, according to this hypothesis, attention to color should disrupt typing as much as attention to the hands.

Method

Sixteen touch typists who had not served in Experiment 1 were recruited. Their mean typing speed was 72 wpm (range: 48–96). The method was the same as in Experiment 1 except that letters typed with the left hand were presented in one color (i.e., red or green), and letters typed with the right hand were presented in the other color (assignment of color to hand was counterbalanced); the cues were "ALL," "RED," and "GREEN," which meant "type all letters," "type only red letters," and "type only green letters," respectively. Thus, the stimuli and the required key presses were the same as in Experiment 1.

Results

Figure 1 presents the mean RTs across subjects as a function of response-sequence position (1–4, space). Means for the dependent variables and inferential statistics are in Table 2.

The results were dramatically different from those of Experiment 1. Cuing with color produced virtually no disruption. Averaged over position, RT was 3 ms faster (0.3%) with color cues than with the "ALL" cue. For unimanual words, color cues increased FPRT by 5 ms (0.7%), increased IKSI by 2 ms (1.3%), and increased SBRT by 56 ms (4.3%). The error rate decreased by .02. For bimanual words, FPRT was 129 ms (16%) longer with color cues, but this increase was not sustained at subsequent response positions: IKSI was 75 ms (56%) smaller with color cues, and SBRT was 19 ms (1.4%) longer. The error rate was unaffected. Altogether, the results show no disruption from color cuing, confirming the hierarchical control hypothesis and dis-

TABLE 1

Descriptive and Inferential Statistics for Experiment 1

| | Unimanual words | | | | | | Bimanual words | | | | | |
| | Cue type | | | | | | Cue type | | | | | |
Measure	Whole-word	Hand	$F(1, 15)$	MSE	p_{rep}	η_p^2	Whole-word	Hand	$F(1, 15)$	MSE	p_{rep}	η_p^2
Mean FPRT (ms)	832	1,065	47.91	9,050	.99	.76	838	1,300	188.77	9,050	.99	.92
Mean IKSI (ms)	168	202	4.02	2,240	.91	.21	147	300	83.80	2,240	.99	.85
Mean SBRT (ms)	1,523	1,879	143.18	7,083	.99	.91	1,482	2,220	615.5	7,083	.99	.98
Mean error rate	.09	.18	37.53	.002	.99	.71	.08	.24	106.12	9,050	.99	.88

Note. FPRT = first-position response time; IKSI = interkeystroke interval; SBRT = space-bar response time.

TABLE 2

Descriptive and Inferential Statistics for Experiment 2

Measure	Unimanual words						Bimanual words					
	Cue type						Cue type					
	"ALL"	Color	$F(1, 15)$	MSE	p_{rep}	η_p^2	"ALL"	Color	$F(1, 15)$	MSE	p_{rep}	η_p^2
Mean FPRT (ms)	736	741	< 1	1,274	.61	.01	819	948	104.59	1,274	.99	.87
Mean IKSI (ms)	159	161	< 1	448	.58	.005	134	59	100.99	448	.99	.87
Mean SBRT (ms)	1,315	1,371	12.15	2,050	.98	.45	1,363	1,382	1.37	2,050	.79	.08
Mean error rate	.11	.09	2.09	.0009	.84	.12	.10	.10	< 1	.0009	.56	.003

Note. FPRT = first-position response time; IKSI = interkeystroke interval; SBRT = space-bar response time.

confirming the dual-task-interference hypothesis (also see Salthouse & Saults, 1987; Shaffer, 1975).

EXPERIMENT 3

Experiments 1 and 2 used bimanual words to force attention to each key press. The observed disruptions could have been proactive effects of adjustments subjects made in order to attend to each key press (slowing typing rate to inhibit partial responses) or reactive effects of inhibiting familiar response sequences. In Experiment 3, we distinguished proactive from reactive effects by presenting only unimanual words (we also presented single letters). If disruption results from proactive slowing to monitor keystrokes, then we would observe it in this experiment because subjects had to monitor keystrokes. If disruption results from inhibiting familiar sequences, then we would not observe it because no familiar sequences were ever inhibited.

Method

Sixteen touch typists who had not served in Experiment 1 or 2 were tested. Their mean typing speed was 74 wpm (range: 47–110). The procedure was the same as in Experiment 1 except that the bimanual words were replaced by single letters (the first letters of the bimanual words). The cues were "LEFT," "RIGHT," and "WHOLE." After the experiment, subjects an-

swered a questionnaire that assessed what they had learned about the words.

Results

The mean RTs across subjects are plotted as a function of response position in Figure 1. Table 3 presents means for the dependent variables and inferential statistics. Attention to the hands disrupted performance in the unimanual condition: RT was 141 ms (14%) longer, FPRT was 109 ms (15%) longer, IKSI was 14 ms (9%) longer, and SBRT was 187 ms (14%) longer with hand cues than with the whole-word cue.

All the words were unimanual, so subjects could have learned to monitor only the first character and then inhibit the whole word, if appropriate. We tested for this strategy in four ways. First, we assessed the cuing effect on IKSI and SBRT. If subjects monitored only the first letter, IKSI and SBRT should have been the same for the hand and whole-word cues. The data rule this out. However, the differences (~12%) were half as large as the differences observed in Experiment 1 (~25%), so subjects may not have always monitored all the letters.

Second, as noted, we had subjects type single letters preceded by the hand and whole-word cues. The difference in FPRT between these two cue types was about half of the difference for single letters (57 ms) as for unimanual words (109 ms). This suggests that subjects looked beyond the first letter when typing the unimanual words.

TABLE 3

Descriptive and Inferential Statistics for Experiment 3

Measure	Unimanual words						Letters					
	Cue type						Cue type					
	Whole-word	Hand	$F(1, 15)$	MSE	p_{rep}	η_p^2	Whole-word	Hand	$F(1, 15)$	MSE	p_{rep}	η_p^2
Mean FPRT (ms)	726	835	182.38	518	.99	.92	702	759	50.61	518	.99	.77
Mean IKSI (ms)	158	172	4.02	66	.91	.21	—	—	—	—	—	—
Mean SBRT (ms)	1,351	1,538	472.39	591	.99	.97	854	924	67.37	591	.99	.82
Mean error rate	.09	.18	76.81	.0009	.99	.84	.03	.05	5.12	.0009	.93	.25

Note. FPRT = first-position response time; IKSI = interkeystroke interval; SBRT = space-bar response time.

Third, we included two bimanual catch trials at the end of the experiment. The first catch trial cued the right hand with an LLRL sequence (or the left hand with an RRLR sequence) and the second cued the right hand with an RRLR sequence (or the left hand with an LLRL sequence). No subject typed the letter to be withheld on both trials, and only 1 subject typed the letter to be withheld on one of these trials (1 in 32 opportunities).

Fourth, the postexperiment questionnaire asked subjects whether they knew all the words were unimanual. Only 3 of the 16 subjects reported knowing that. Subjects reported checking letters beyond the first on 80% of word trials.

EXPERIMENT 4

To generalize the results to continuous typing, we had 16 touch typists type four paragraphs from Logan and Zbrodoff's (1998) typing test under four conditions (one for each paragraph, counterbalanced): typing all letters, only left-hand letters, only right-hand letters, or every other word. Typing all letters was fast (mean = 80 wpm, range: 38–107) and accurate (mean error rate = .06, range: .01–.14). Typing left- or right-hand letters was much slower (mean = 14 wpm, range: 8–22) and less accurate (mean error rate = .33, range: .11–.47). These results suggest that attention to the hands disrupts continuous typing, in addition to single-word typing. Typing every other word was slow (mean = 43 wpm, range: 18–57) but accurate (mean error rate = .07, range: .02–.14), showing some disruption from monitoring the input to the outer loop, but not as much as from monitoring the output of the inner loop.

DISCUSSION

These four experiments show that attention to the hands paradoxically disrupts skilled typewriting. The system that controls typing knows but does not know which hand types which character. The paradox may be resolved with the hierarchical model of typewriting, in which the outer loop must monitor the inner loop's output to determine which hands are used. The model performs quickly if the output is not monitored ("WHOLE" cues) or if the input is monitored ("RED" and "GREEN" cues), but not if the output is monitored ("RIGHT" and "LEFT" cues). Hand cues require anticipatory slowing to allow enough time to detect and inhibit responses with the unwanted hand, and that is disruptive.

The theory behind the model may generalize to other skills. Paradoxical disruption may occur in all hierarchically controlled skills that have an encapsulated inner loop. If the outer loop must monitor the inner loop's output for details, it may have to slow inner-loop cycle time to see them. This would impair performance on tasks such as typing, in which speed is important. It may also impair performance on tasks such as dribbling a soccer ball through obstacles—in which accuracy is important—by disrupting critical timing (Beilock et al., 2002). More generally, monitoring the inner loop's output would impair performance on tasks that require temporal coordination, and that is a requirement of many skills.

If attention to the details is disruptive, what do people normally attend to in performing skills? What does the outer loop normally monitor? We suggest that it monitors the effects of its actions (Hommel, Müssler, Aschersleben, & Prinz, 2001). In typing, the outer loop monitors the keystrokes on the screen and asks the inner loop to make the screen look right. The hands are out of the picture. Usually, the inner loop works fluently, so the outer loop does nothing but monitor. Occasionally, when errors occur or someone asks typists what they are doing, the outer loop intervenes, and they find themselves like the rock star, confused about what their hands were doing, although they were doing it very well.

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