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Monitoring-Induced Disruption in Skilled Typewriting

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It is often disruptive to attend to the details of one's expert performance. The current work presents four experiments that utilized a monitor to report protocol to evaluate the sufficiency of three accounts of monitoring-induced disruption. The inhibition hypothesis states that disruption results from costs associated with preparing to withhold inappropriate responses. The dual-task hypothesis states that disruption results from maintaining monitored information in working memory. The implicit–explicit hypothesis states that disruption results from explicitly monitoring details of performance that are normally implicit. The findings suggest that all three hypotheses are sufficient to produce disruption, but inhibition and dual-task costs are not necessary. Experiment 1 showed that monitoring to report was disruptive even when there was no requirement to inhibit. Experiment 2 showed that maintaining information in working memory caused some disruption but much less than monitoring to report. Experiment 4 showed that monitoring to inhibit was more disruptive than monitoring to report, suggesting that monitoring is more disruptive when it is combined with other task requirements, such as inhibition.

Keywords: automaticity, hierarchical control, skilled action, implicit and explicit knowledge

The cognitive system constantly samples feedback to monitor the execution of skilled behaviors without conscious awareness and without adversely affecting performance (Logan & Crump, 2011; Rosenbaum, 2010). However, common lore and recent findings suggest that it is disruptive to direct attention to the details of a skilled behavior (Beilock, Carr, MacMahon, & Starkes, 2002; Beilock & Carr, 2001; Gray, 2004; Logan & Crump, 2009; Tapp & Logan, 2011). William James (1890) alluded to this paradox over a century ago when he noted that: "Our lower centers know the order of movements . . . But higher thought-centers know hardly anything about the matter" (p. 39). In this work, we evaluate three possible causes of monitoring-induced disruption. We propose that conscious monitoring of skilled behavior is disruptive when performance must be slowed to allow time for implicit aspects of the behavior to be made explicit. We evaluate this implicit–explicit hypothesis and two alternative hypotheses: an inhibition hypothesis, which says that disruption occurs when performance must be slowed to allow time to withhold potentially inappropriate actions (Logan & Crump, 2009), and a dual-task hypothesis, which says that disruption occurs when attention that is typically allocated to the execution of a skilled behavior is redistributed to monitor task execution (Beilock, Kulp, Holt, & Carr, 2004).

Several researchers have suggested that skilled behaviors are hierarchically controlled such that lower level processes are embedded within higher level processes (Logan & Crump, 2010, 2011; Miller, Galanter, & Pribram, 1960; Shaffer, 1976; Sternberg, Knoll, & Turock, 1990). For example, Logan and Crump (2011) proposed a two-loop theory of skilled typewriting in which processing at the highest level(s) of a control hierarchy is governed by an outer loop, whereas processing at lower levels of the control hierarchy is governed by a nested, inner loop. The outer loop is responsible for producing a word and the inner loop is responsible for decomposing the word into letters and assigning a hand and finger to type the letters. Information processed by the outer loop is directly accessible for explicit report. Information processed by the inner loop is not directly accessible for explicit report because it is informationally encapsulated (Fodor, 1983) and is therefore implicit.

The encapsulation of the inner loop is a double-edged sword. On the one hand, it facilitates performance by reducing the outer loop's processing load. On the other hand, it could impede performance when information processed by the inner loop needs to be made explicit (Logan & Crump, 2009; Tapp & Logan, 2011). For example, Logan and Crump (2009) developed a *monitor-to-inhibit* task in which skilled typists had to type only the letters of target words that are normally typed with one hand (e.g., the right) but not the other (e.g., the left). They found that typing was slower and less accurate when typists monitored the details of their performance (i.e., hand to key assignments) than when they typed normally.

Logan and Crump (2009) suggested that the monitor-to-inhibit task was disruptive because processing in the inner loop needed to be slowed down so that inappropriate keystrokes (i.e., keystrokes typed with a noncued hand) could be identified and inhibited. This account of monitoring-induced disruption contains two separate hypotheses: an implicit–explicit hypothesis and an inhibition hypothesis. The implicit–explicit hypothesis suggests that disruption occurs when implicit details of performance must be made explicit. The outer loop does not have direct access to information pro-

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cessed by the inner loop, so the outer loop must make the information explicit by monitoring the inner loop's output—by "watching" the hands and fingers move. Tapp and Logan (2011) found that the outer loop monitors the inner loop's output by looking at the hands and fingers as they strike the keyboard, but it can also monitor kinesthetic information. Because skilled keystrokes are rapidly executed, typing rate needs to be slowed down to allow enough time for the outer loop to explicitly register the keystrokes (Keele & Posner, 1968; Klemmer, 1971). The inhibition hypothesis suggests that monitoring-induced disruption results when it is necessary to adjust performance online so that inappropriate responses can be withheld if necessary. Inhibition takes time (Logan, 1982), so typing rate must be slowed to allow enough time to inhibit the inappropriate responses.

Alternatively, the monitor-to-inhibit task (Logan & Crump, 2009; Tapp & Logan, 2011) could be disruptive because it induces dual-task costs. The dual-task hypothesis suggests that when monitoring-induced disruption occurs, attention must be divided between performing a skill and attending to how the skill is executed. Monitoring is a second task, separate from the typing task, and it demands attention. Although it is commonly believed that skilled tasks do not suffer from dual-task interference, there is evidence that skilled performance is disrupted when executed with a second task. Shaffer (1975) concluded that skilled typing was not disrupted by a concurrent shadowing task, but he found that typing was 20 ms/keystroke slower when shadowing occurred than when typing alone (see also Spelke, Hirst, & Neisser, 1976). If skilled performance suffers from a redistribution of attention away from the primary typing task to the secondary monitoring task (Beilock et al., 2004; Lewis & Linder, 1997), skilled typing could be slower and less accurate when typists must monitor their performance.

The purpose of the present work was to evaluate the necessity and sufficiency of these three accounts of monitoring-induced disruption in skilled typewriting. We conducted four experiments that utilized a *monitor-to-report* task in which skilled typists had to report the sequence in which they used their hands to type a word. Experiment 1 evaluated the necessity of the inhibition hypothesis. We compared typists' normal typing performance with their performance on the monitor-to-report task, which did not require inhibition. If monitoring to inhibit is necessary to produce disruption, there should be no disruption in the monitoring-to-report task. Experiment 2 evaluated the sufficiency of the dual-task hypothesis. We compared typists' performance while they held a sequence in working memory with their performance on the monitoring-to-report task. If dual-task requirements were sufficient to produce disruption, we should see disruption in both conditions, relative to no-monitoring and no-dual-task controls. If dual-task requirements accounted for all of the disruption, then the monitor-to-report and working-memory tasks should produce the same amount of disruption. The results of Experiments 1 and 2 indicated that inhibition is not necessary to produce disruption and that dual-task costs do not account for all of the disruption observed in the monitor-to-report task. The results supported the implicit–explicit hypothesis. Experiment 3 tested the role of watching the hands while monitoring to report, asking whether disruption was greater when a box was placed over the typists' hand to restrict visual feedback than when their hands were visible. Experiment 4 evaluated the sufficiency of the implicit–explicit hypothesis, comparing the monitor-to-report task with the monitoring-to-inhibit task. If making implicit information explicit is sufficient, then the two tasks should produce the same amount of disruption.

Experiment 1

The purpose of the first experiment was to evaluate the necessity of the inhibition hypothesis by evaluating the disruption produced by a monitor-to-report task that did not require inhibition. If inhibition is necessary to produce disruption, then monitoring to report should not be disruptive. Skilled typists were asked to type target words normally (i.e., control trials) and while monitoring which hand types each of the target word's letters (i.e., monitoring trials). After monitoring trials, a probe presented a four-character sequence that represented one of the six possible combinations of right- and left-hand use (e.g., RLRL) that were required to type the target words, as dictated by standard 10-finger touch-typing protocol. Typists were given 2 s to indicate whether the presented sequence accurately represented the actual sequence of hands used to type the target word. This monitor-to-report task did not require typists to withhold any keystrokes. Therefore, if inhibition were necessary to produce monitoring-induced disruption, there should be no disruption in the monitor-to-report task.

Typing performance was measured in three ways. Reaction time of the first keystroke (RT1) was measured relative to the onset of the target word. Interkeystroke intervals (IKSIs) were measured by calculating the slope of the linear function relating each keystroke's reaction time (RT), relative to the onset of the target word, to its position in the target word. Typing-error rate was measured by calculating the proportion of words in which at least one error was made. If monitoring-induced disruption depends on the intention to inhibit a component action of a skilled behavior (Logan & Crump, 2009), then RT1, IKSI, and typing-error rate should not differ between monitoring and control trials. However, if monitoring-induced disruption results from making implicit details explicit, RT1 should be longer, IKSIs should be longer, and typing-error rate should be higher in monitoring trials than in control trials.

Method

Participants. The participants were 24 Vanderbilt University students and volunteers from the surrounding community who were recruited for the self-reported ability to touch-type 40 words per minute (WPM) or better. Typing skill was evaluated with a typing test (Logan & Zbrodoff, 1998). Mean typing speed was 70.7 WPM (range = 42.1–100 WPM) and mean accuracy was 91.7% (range = 84.6–97.4%). All participants were compensated with course credit or were paid $12 for one hour of participation. All participants had normal or corrected-to-normal vision and spoke English as a first language.

Apparatus and stimuli. A pool of 240 four-letter words was compiled from the *MRC Psycholinguistic Database* (Wilson, 1987). The mean word frequency per million words was 123.7 (range = .41–4,309.4) as verified by the *Corpus of Contemporary American English* (Davies, 2008). Each word required typing two keystrokes with each hand, as determined by standard assignments of keys to hands in touch-typing. There were six word types defined by the sequence of right-hand (R) and left-hand (L) keystrokes. The stimulus list consisted of 40 words of each type:

RRLL (mean word frequency, 231.3 ± standard deviation, 504.1), RLLR (36.9 ± 72.5), RLRL (76.7 ± 165.2), LLRR (148 ± 677.8), LRRL (117.8 ± 278.5), LRLR (133.2 ± 268.7). A one-way ANOVA determined that the word frequencies did not differ significantly between the six word types, $F(4, 235) = 1.3$, $p = .28$.

The experiment took place on a personal computer programmed in MetaCard (Boulder, CO) using a 15" super video graphics array (SVGA) monitor, from which participants sat about 57 cm. Responses were registered on a standard QWERTY keyboard. The program blackened the screen and displayed a 24.1 cm × 19.7 cm gray window. The cue (i.e., *probe* or *none*) was displayed 3.8 cm from the top of the window. The target word was presented 2.5 cm below the cue and subjects' responses were echoed 5.1 cm below the target word. The probe screen displayed the monitoring question 5.1 cm from the top of the window. Probe responses were echoed 3.8 cm below the monitoring question. All text was presented centrally in black 40-point Helvetica font.

Procedure. The sequence of events that took place during each trial is presented in Figure 1. At the beginning of each trial, a cue was presented at the top of the screen (i.e., probe or none) that told typists whether a probe would follow the upcoming target word. After 1,000 ms, a fixation point was displayed for 500 ms and subsequently replaced by a target word. Typists were told to type the target word as quickly and accurately as possible and then press the spacebar. During monitoring (i.e., probe-cued) trials, typists were instructed to attend to which hand typed each letter of the target word so that they could respond to a subsequent probe within a 2-s response deadline. The probe presented a possible sequence (e.g., RLRL) of hand use and instructed typists to type a "Y" if the sequence correctly represented the sequence of hands that was used to type the target word or type "N" if it did not. The program then progressed to the next trial after 2 s. No probe was presented during control (i.e., none-cued) trials.

Each word of the stimulus list was presented twice, once when paired with the none cue and once when paired with the probe cue. The pairs of cues and words were presented in random order. The probe displayed the correct sequence following half of the monitoring trials and a randomly selected incorrect sequence following the other half of monitoring trials. Upon completion of the total 480 trials, typists were given a typing test to assess their typing skills (Logan & Zbrodoff, 1998). The experiment lasted approximately 60 min.

Results and Discussion

The mean response times of each keystroke relative to the onset of the target word are plotted in Figure 2. Only trials in which the target words were typed correctly were included in the analyses. Analyses comparing the means of RTs and IKSIs between the monitoring and control trials included all trials in which the target word was typed correctly. Analysis of typing-error rates between monitoring and control trials included those trials in which at least one error was committed in typing a word.

RT1, which reflects the time it takes to encode the target word and to prepare the motor commands necessary to type the first keystroke, was longer on monitoring trials ($M = 875$ ms) than on control trials ($M = 717$ ms), $t(23) = 2.9$, $MS_e = 53.92$, $p < .01$. Thus, preparing to monitor the inner loop's output disrupts performance even before the skilled behavior is initiated. IKSI, which measures typing rate, was also longer on monitoring trials ($M = 247$ ms/keystroke) than on control trials ($M = 146$ ms/keystroke), $t(23) = 4.1$, $MS_e = 24.27$, $p < .001$, indicating that ongoing typing performance is disrupted when skilled typists attend to performance details that are controlled by the inner loop. Typing-error rates did not differ significantly between monitoring trials ($M = 8\%$) and control trials ($M = 9.1\%$), $t(23) = 1.9$, $MS_e = .60$, $p = .07$.

In addition to the three typing performance measures, two measures of monitoring performance were calculated: probe error rate and probe omission rate. The probe error rate was determined by calculating the proportion of monitoring trials in which an incorrect response was rendered within the 2-s probe deadline (14%). probe omission rate was determined by calculating the proportion of monitoring trials in which typists failed to respond

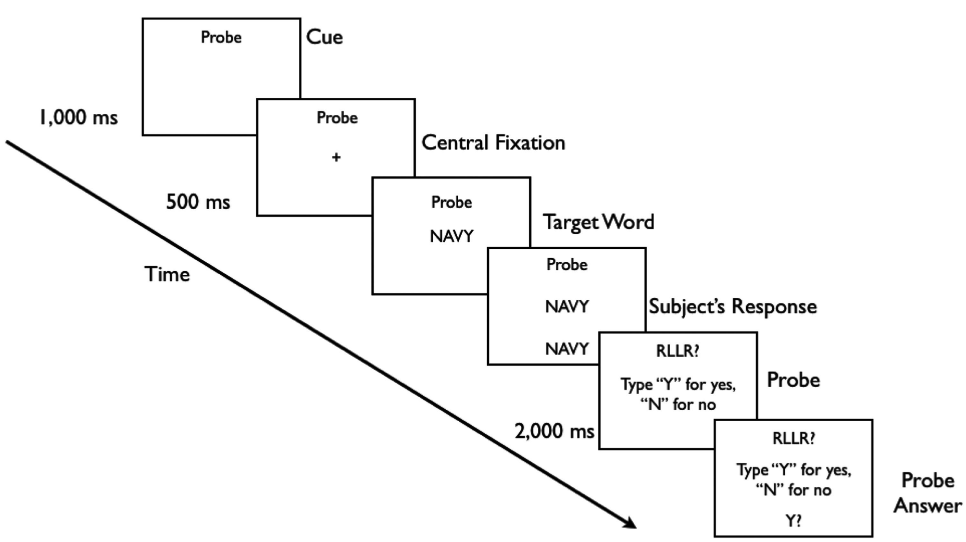

Figure 1. The sequence of events in Experiment 1.

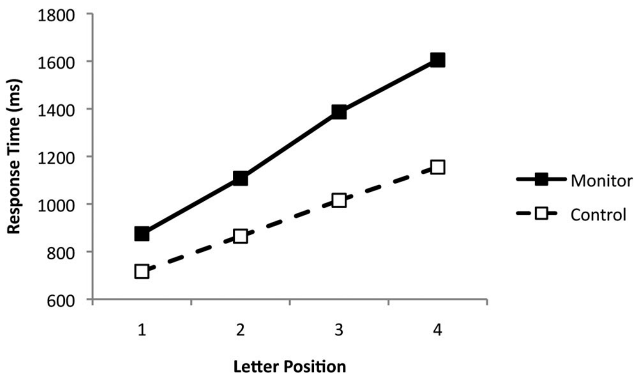

Figure 2. RTs for each keystroke relative to the onset of the target word plotted as a function of the position in the word for monitoring and control conditions in Experiment 1.

within the 2-s deadline (3.5%). Excluding data from those monitoring trials in which probe responses were either omitted or incorrect did not change the results of the RT1, IKSI, and typing-error rate analyses.

Overall, Experiment 1 demonstrated that preparing to inhibit inappropriate keystrokes is not necessary to disrupt skilled typing performance. Explicitly monitoring implicit aspects of typing is sufficient to disrupt performance.

Experiment 2

Experiment 2 was designed to evaluate the sufficiency of the dual-task hypothesis (Beilock et al., 2004; Lewis & Linder, 1997), which says that monitoring-induced disruption results when attention is taken from the typing task and given to the monitoring task. Skilled typists completed two blocks of trials: a monitoring block and a dual-task memory block. Both blocks included probe trials that required typists to type target words while holding a cued sequence in memory (e.g., RLRL). In the monitoring block, typists were asked to indicate whether the cued sequence represented the sequence of hands they used to type the target word (see Figure 3, Panel A). Unlike Experiment 1, the sequence was presented before the target word was displayed and typed. In the memory block, typists were asked to indicate whether the sequence held in memory matched a second sequence that was presented after the target word was typed (see Figure 3, Panel B). If performing a secondary task that loads working memory disrupts skilled typing, probe trials should have longer RT1s, longer IKSIs, and increased typing-error rates than control trials. If dual-task costs are sufficient to explain monitoring-induced disruption, then the disruption should not differ between the memory and monitoring blocks.

Method

Participants. We sampled 24 different typists from the same population as Experiment 1 and compensated them similarly. Mean typing speed was 70.3 WPM (range = 47.4–97.1 WPM) and mean accuracy was 93.6% (range = 83.5–99.1%).

Apparatus and stimuli. These were the same as in Experiment 1 except for the order of the displays, described below.

Procedure. A new pool of 144 four-letter words was compiled from the *MRC Psycholinguistic Database* (Wilson, 1987). The mean word frequency per million words was 88.7 (range = .41–1,836.7; Davies, 2008). There were 24 words per sequence: RRLL (137.4 ± 390.4), RLLR (23.8 ± 25.6), RLRL (63.1 ± 84.1), LLRR (47.7 ± 72.2), LRRL (151.1 ± 352.3), LRLR (109.1 ± 170.4). A one-way ANOVA determined that the word frequencies did not differ significantly between the six sequence categories, $F(4, 139) = .57$, $p = .68$.

For each subject, the experimental program randomly selected half of the words in each category to be used in one block and half of the words to be used in the other block. The order in which the two blocks were completed was counterbalanced across participants. After both blocks were completed, a typing test was administered to assess typing skill (Logan & Zbrodoff, 1998).

Monitoring block. The sequence of events that took place during monitoring trials is presented in Figure 3, Panel A. At the beginning of each trial a cue was presented for 1,500 ms. During monitoring trials, the cue displayed a sequence that represented a possible sequence of hands used to type a following target word (e.g., RLRL). During control trials, the cue displayed the word "none." A central fixation point was then displayed for 500 ms and was subsequently replaced by a target word. Typists were to type the target word as quickly and as accurately as possible and then press the spacebar. They were instructed to attend to which hand typed each letter during monitoring trials and respond to a subsequent probe within a 2-s response deadline. The probe prompted typists to type "Y" if the cued sequence matched the sequence of hands they used to type the target word or type "N" if it did not. The target words were presented four times, twice when paired with the none cue, once when paired with the correct sequence, and once when paired with a randomly selected incorrect sequence. The combinations of cues, words, and probes were displayed in random order. No probe was displayed during control trials.

Memory block. The sequence of events in the memory task is presented in Figure 3, Panel B. As in the monitoring block, each trial began with the presentation of a cue. On memory trials, the cue displayed a sequence to be remembered (e.g., RLRL). On control trials, the cue displayed the word "none." Typists were told to remember the cued sequence while they typed the target word so that they could respond to a following probe within a 2-s deadline. The probe screen presented a second sequence and prompted the typists to type "Y" if it matched the cued sequence or type "N" if it was different. The target words were presented four times, twice when paired with the none cue, once when the cue and probe matched, and once when the cue and probe did not match. The combinations of cues, targets, and probes were displayed in random order. No probe was presented during control trials.

Results and Discussion

The mean response times of each keystroke relative to the onset of the target word are plotted as a function of position in the word for each condition in Figure 4. A 2 (block: monitoring vs. memory) × 2 (trial type: probe vs. control) ANOVA was conducted on the RT1s, IKSIs, and typing-error rates. Only trials in which the target word was typed correctly and the probe was responded to correctly were included in the analysis. The ANOVA summary tables are presented in Table 1.

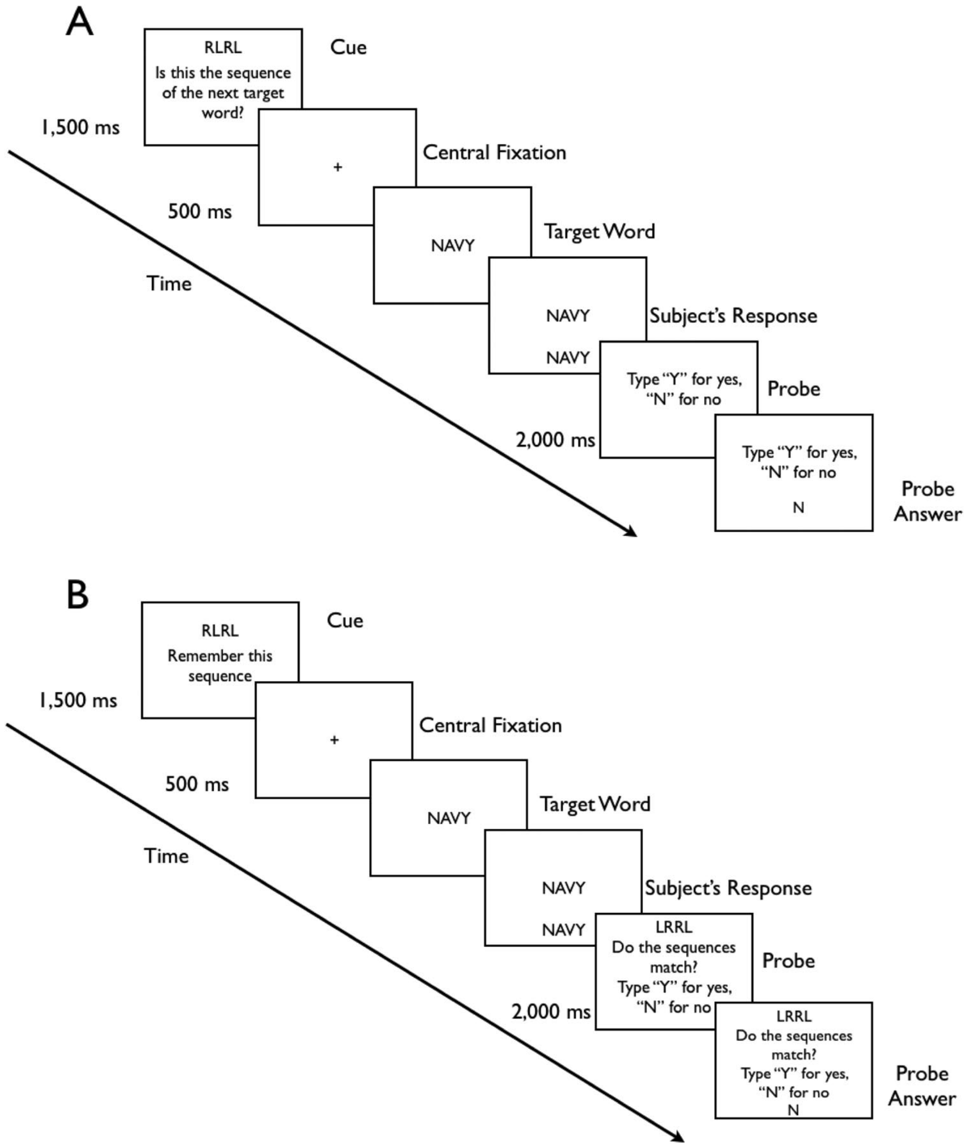

Figure 3. The sequence of events in Experiment 2. A: The monitoring condition. B: The memory condition.

RT1 was longer in probe trials ($M = 817$ ms) than in control trials ($M = 721$ ms), $F(1, 23) = 46.8$, $MS_e = 4707.6$, $p < .001$, indicating that the initiation of typing was delayed when typists hold a sequence in memory. The difference was 102 ms greater in the monitoring block (probe $M = 882$ ms vs. control $M = 735$ ms) than in the memory block (probe $M = 752$ ms vs. control $M = 707$ ms), $F(1, 23) = 53.0$, $MS_e = 2245.8$, $p < .001$. Disruption was greater when the remembered sequence was relevant to the typing task than when it was independent of the typing task.

IKSIs were also longer in probe trials ($M = 183$ ms/keystroke) than in control trials ($M = 135$ ms/keystroke), $F(1, 23) = 88.5$, $MS_e = 622.6$, $p < .001$, indicating that ongoing typing performance was slowed when typists held a sequence in memory. The difference was 54 ms/keystroke greater in the monitoring block (probe $M = 209$ ms/keystroke vs. control $M = 134$ ms/keystroke) than in the memory block (probe $M = 156$ ms/keystroke vs. control $M = 135$ ms/keystroke), $F(1, 23) = 32.3$, $MS_e = 524.7$, $p < .001$.

Typing-error rates were higher in probe trials ($M = 7.8\%$) than in control trials ($M = 4.6\%$), $F(1, 23) = 37.7$, $MS_e = 6.6$, $p < .001$. However, typing-error rates did not differ significantly between the monitoring block (probe $M = 7.8\%$ vs. control $M = 4.8\%$) and the memory block (probe $M = 7.8\%$ vs. control $M = 4.3\%$), indicating that monitoring to report did not disrupt typing accuratey more than holding a sequence in memory.

probe error rates did not differ significantly between the monitoring block ($M = 11\%$) and the memory block ($M = 12.8\%$). However, probe omission rates were significantly lower in the monitoring block ($M = 1\%$) than in the memory block ($M = 3.4\%$), $t(23) = 3.0$, $p < .01$.

In summary, Experiment 2 demonstrated that the dual-task interference is sufficient to disrupt typing (Beilock et al., 2004;

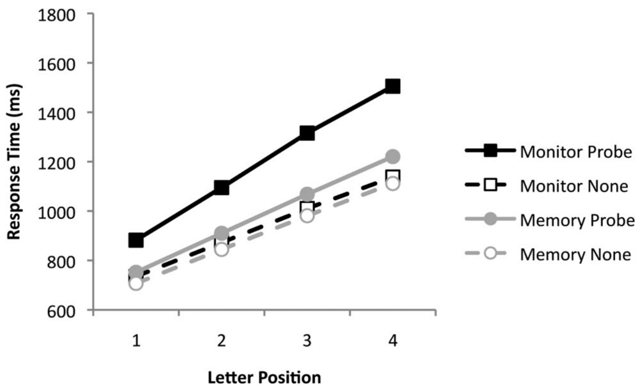

Figure 4. RTs for each keystroke relative to the onset of the word plotted as a function of the position in the word for monitoring and control and memory and control conditions in Experiment 2.

Lewis & Linder, 1997) but the dual-task hypothesis cannot account for the magnitude of monitoring-induced disruption observed in the monitor-to-report task. Explicitly monitoring implicit aspects of typing was substantially more disruptive than holding a sequence in working memory.

Experiment 3

The results of Experiments 1 and 2 were consistent with the implicit–explicit hypothesis: Monitoring was disruptive when implicit performance details needed to be made explicit. Experiment 3 addressed a key tenet of the implicit–explicit hypothesis, that the outer loop gains access to information processed by the inner loop by monitoring the inner loop's output (i.e., hand and finger movements). Logan and Crump (2009) speculated that the outer loop uses visual information about hand and finger movements (i.e., watches the hands) to determine whether a keystroke needs to be inhibited. Tapp and Logan (2011) tested this hypothesis by limiting access to visual information from the hands and keyboard by covering typists' hands while they completed a monitor-to-inhibit task. Consistent with the hypothesis, Tapp and Logan found increased disruption when the hands were covered.

Experiment 3 was conducted to determine whether visual information is also important when monitoring to report. Skilled typists completed the monitor-to-report task used in Experiment 2 with their hands and the keyboard visible for half of the trials and covered with a box for the other half of the trials. If visual information about hand and finger movements is important when monitoring to report, then RT1s should be longer, IKSIs should be longer, and typing-error rates should be higher in blocks with the hands covered than in blocks with the hands visible. However, if visual information is important only when monitoring to inhibit, then RT1, IKSIs, and typing-error rates should not differ between the hands-covered block and the hands-visible block.

Method

Participants. We sampled 24 different typists from the same population as the previous experiments and compensated them similarly. Mean typing speed was 72.2 WPM (range = 57.4–109.6 WPM) and mean accuracy was 91.4% (range = 71.7–97.2%).

Apparatus and stimuli. These were the same as in the previous experiments. The stimulus words were the same as those used in Experiment 2.

Procedure. Figure 5 displays the sequence of events in Experiment 3. At the beginning of each trial a cue was presented for 1,500 ms. During monitoring trials, the cue displayed a possible sequence of hand order that may be used to type the upcoming target word (i.e., RLRL). During control trials, the cue displayed the word "none." A central fixation was displayed for 500 ms and subsequently replaced by the target word. Typists were to type the target word as quickly and as accurately as possible and then press the spacebar. During monitoring trials, typists were instructed to attend to which hand typed each of the target word's letters in order to respond to a probe, within a 2-s response deadline, that was presented after the target word was typed. The probe prompted typists to type "Y" if the cued sequence matched the sequence of hands they used to type the target word or type "N" if it did not. The target words were presented four times, twice when paired with the none cue, once when paired with the correct sequence, and once when paired with a randomly selected incorrect sequence. No probe was displayed during control trials.

The combinations of cues, words, and probes were displayed in random order. The typists' hands and the keyboards were covered by a 10.8 cm × 27.9 cm × 44.5 cm box, which did not constrain hand movement. The order in which each subject completed the hands-visible and hands-covered block was counterbalanced. After the experiment was completed, a typing test was administered to assess typing skill (Logan & Zbrodoff, 1998).

Table 1
Summary Tables for a 2 (Block: Monitor Task vs. Memory Task) × 2 (Cue: Probe Trials vs. Control Trials) Analysis of Variance (ANOVA) on Response Time to the First Keystroke (RT1), Typing Rate (IKSI), and Typing-Error Rate (TER) for Experiment 2

	RT1			IKSI			TER		
Effect	*MSE*	*F*	η_p^2	*MSE*	*F*	η_p^2	*MSE*	*F*	η_p^2
Block (B)	9722.1	15.5*	.402	703.5	23.2*	.502	7.3	.1	.004
Cue (C)	4707.6	46.8*	.670	622.6	88.5*	.794	6.6	37.7*	.621
B × C	2246.0	27.8*	.547	524.7	32.3*	.584	6.5	.4	.015

Note. Degrees of freedom for each effect = 1, 23.
* $p < .05$.

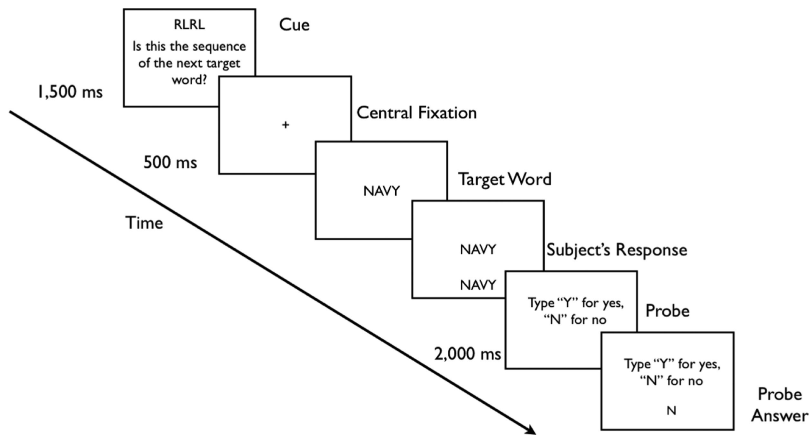

Figure 5. The sequence of events in Experiment 3.

Results and Discussion

Only correct trials were included in the analyses. The mean RTs of each keystroke relative to the onset of the target word are plotted as a function of position in the word for each condition in Figure 6. A 2 (visibility: hands visible vs. hands covered) × 2 (trial type: monitor vs. control) ANOVA was conducted on the RT1s, IKSIs, and typing-error rates. The ANOVA summary tables are presented in Table 2.

As in the first two experiments, the results showed that it is disruptive for experts to monitor the details of their skilled performance. RT1 was longer in monitoring trials ($M = 860$ ms) than in control trials ($M = 709$ ms), $F(1, 23) = 58.9$, $MS_e = 9{,}205.78$, $p < .001$. IKSIs were longer in monitoring trials ($M = 250$ ms/keystroke) than in control trials ($M = 145$ ms/keystroke), $F(1, 23) = 77.3$, $MS_e = 3.397.16$, $p < .001$. Typing-error rates were also higher in monitoring trials ($M = 13.4\%$) than in control trials ($M = 5.7\%$), $F(1, 23) = 36.0$, $MS_e = 38.69$, $p < .001$.

The crucial manipulation in Experiment 3 was restricting visual information from the hands and keyboard as the typists completed the monitor-to-report task. Overall, neither RT1s nor IKSIs were significantly longer when the hands were covered than when they were visible. However, covering the hands slowed IKSI 40 ms/keystroke more in monitoring trials (covered $M = 289$ ms/keystroke vs. visible $M = 210$ ms/keystroke) than in control trials (covered: $M = 164$ ms/keystroke vs. visible: $M = 125$ ms/keystroke), $F(1, 23) = 6.7$, $MS_e = 1361.8$, $p < .01$. Typing-error rates were not significantly higher when the hands were covered than when they were visible. However, covering the hands increased typing-error rates significantly more in monitoring trials (covered $M = 17\%$ vs. visible $M = 9.7\%$) than in control trials (covered $M = 5.1\%$ vs. visible $M = 6.2\%$), $F(1, 23) = 14.7$, $MS_e = 29.6$, $p < .001$. In addition, probe error rates were the same with the hands covered ($M = 14.1\%$) and visible ($M = 12.1\%$) and so were probe omission rates (covered $M = 2.9\%$ vs. visible $M = 2.1\%$).

The results of Experiment 3 show that monitoring-induced disruption is greater when hands are covered than when they are visible. This pattern of disruption is quantitatively similar to the disruption observed when typists monitor to inhibit inappropriate responses (Tapp & Logan, 2011). This suggests that typists rely on vision to determine which hand typed which keystroke in both tasks, although the requirements of the tasks differ after the visual information is processed. The monitor-to-report task requires typists to take note of the keystroke, whereas the monitoring-to-inhibit task requires typists to inhibit the keystroke if it is inappropriate.

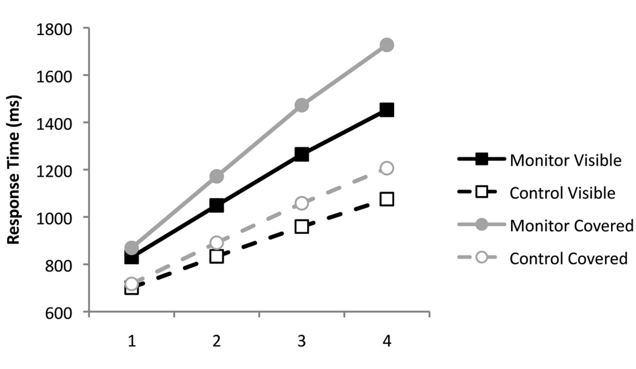

Figure 6. RTs for each keystroke relative to the onset of the word plotted as a function of the position in the word for monitoring and control in Experiment 3.

Experiment 4

The findings from the previous three experiments are consistent with the implicit–explicit account of monitoring-induced disruption in the monitor-to-report task. Experiment 4 asked whether the implicit–explicit hypothesis could account for the magnitude of disruption observed in both the monitoring to inhibit and monitor-to-report tasks. Comparing previous monitoring-to-inhibit tasks with Experiments 1–3 suggests that monitoring to inhibit is more disruptive than monitoring to report; the disruption averaged 140 ms/keystroke in Logan and Crump (2009) and Tapp and Logan (2011) compared with 87 ms/keystroke in Experiments 1–3. Experiment 4 compared the disruption from monitoring to inhibit and monitoring to report directly in the same typists.

Skilled typists completed two blocks of trials: a monitor-to-inhibit block and a monitor-to-report block. Unlike the previous studies, typists were to inhibit or monitor single fingers (e.g., left index) instead of hands. This allowed us to use the same cues for

Table 2
Summary Tables for 2 (Visibility: Hands Covered vs. Hands Visible) × 2 (Cue: Monitor Trials vs. Control Trials) ANOVA on Response Time to the First Keystroke (RT1), Typing Rate (IKSI), and Typing-Error Rate (TER) for Experiment 3

	RT1			IKSI			TER		
Effect	*MSE*	*F*	η_p^2	*MSE*	*F*	η_p^2	*MSE*	*F*	η_p^2
Visibility (V)	30305.6	.3	.111	27038.3	3.0	.115	78.0	3.0	.114
Cue (C)	9205.8	58.9*	.719	3397.2	77.3*	.771	38.7	36.0*	.610
B × C	2696.4	.0	.002	1361.8	6.7*	.226	29.6	14.7*	.389

Note. Degrees of freedom for each effect = 1, 23.
* $p < .05$.

the two monitoring tasks. In the monitor-to inhibit-block, typists were asked to withhold any keystroke that would be typed with the cued finger (see Figure 7, Panel B). We expected to see longer RT1s, longer IKSIs, and increased typing-error rates in monitoring trials than in control trials, as observed in Logan and Crump (2009) and Tapp and Logan (2011). In the monitor-to-report block, typists were asked to indicate whether the cued finger was used in typing the target word (see Figure 7, Panel A). We expected to see longer RT1s, longer IKSIs, and increased typing-error rates in monitoring trials than in control trials, as observed in the previous experiments. The question was whether monitoring to inhibit would be more disruptive than monitoring to report. If monitoring is the only cause of disruption in the two tasks, then the amount of disruption should be the same. If the intention to inhibit adds to the cost of

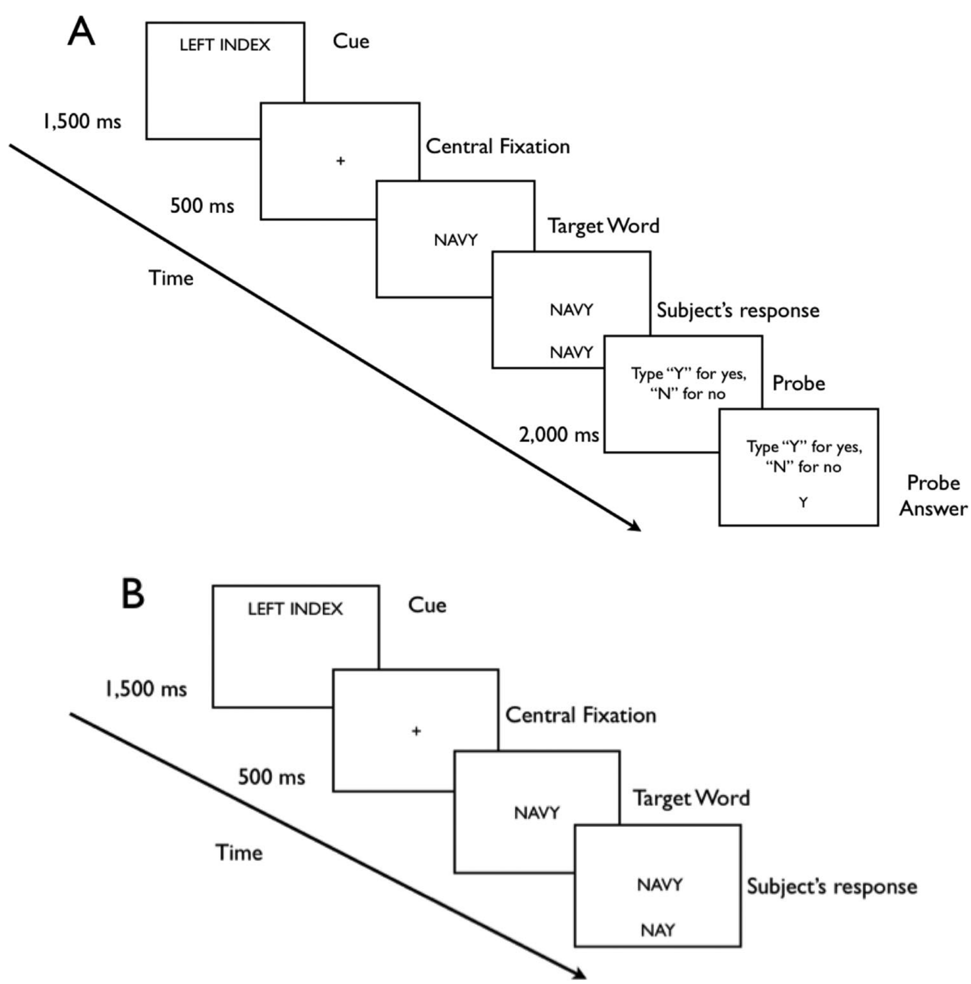

Figure 7. The sequence of events in Experiment 4. A: the monitoring to report condition. B: the monitoring to inhibit condition.

monitoring, then there should be more disruption in the monitoring-to-inhibit task than in the monitor-to-report task.

Method

Participants. We sampled 24 different typists from same population as the previous experiments and compensated them similarly. Mean typing speed was 74.4 WPM (range = 39.6–104.2 WPM) and mean accuracy was 94.1% (range = 88.0–99.1%).

Apparatus and stimuli. These were the same as in previous experiments, except as noted below. A new pool of 96 four-letter bimanual words was compiled from the *MRC Psycholinguistic Database* (Wilson, 1987). The mean word frequency per million words was 45.6 (range = .01–368.4; Davies, 2008). There were 16 words per sequence: RRLL (53.9 ± 94.3), RLLR (44.6 ± 87.2), RLRL (55.8 ± 99.5), LLRR (33.5 ± 41.0), LRRL (40.7 ± 38.1), LRLR (45.9 ± 68.8). A one-way ANOVA determined that the word frequencies did not differ significantly between the six sequence categories, $F(4, 139) = .16$, $p = .98$.

Words were selected for inclusion in the stimulus list based on hand and finger-to-key mappings as per the standard 10-finger touch-typing protocol. In addition, each word needed to serve as both a valid target and an invalid target. A word served as a valid target when one of the eight typing fingers was used only once to type the letter in a specific letter position. For example, GOAL is a valid target for the left index finger at the first position. OVAL is a valid target for the left index finger at the second position. Each word also served as an invalid target. For example, GOAL is an invalid target for the middle finger because neither middle finger is used to type any of the word's letters.

Procedure. Each word in the stimulus list was presented 16 times over the course of the experiment, eight times per block (i.e., report block and inhibit block). In each block, each word was paired with a none cue four times (i.e., control trials). Each word was also paired with one of four possible cue combinations: invalid hand and invalid finger (e.g., pairing GOAL with a right-middle cue), invalid hand and valid finger (e.g., pairing GOAL with a right-index cue), valid hand and invalid finger (e.g., pairing GOAL with a left-middle cue), and valid hand and valid finger (e.g., pairing GOAL with a left-index cue). The trials were randomly ordered within each block and the order in which the blocks were completed was counterbalanced across subjects. After both blocks were completed, a typing test was administered to assess typing skill (Logan & Zbrodoff, 1998).

Report block. Figure 7, Panel A displays the sequence of events that took place during the monitor-to-report block. At the beginning of each trial a cue was presented for 1,500 ms. During monitoring trials, the cue presented a specific hand (e.g., left or right) and a specific finger (e.g., index, middle, ring, or pinky). During control trials, the cue presented the word "none." A central fixation point was then displayed for 500 ms and was subsequently replaced by a target word. Typists were to type the target word as quickly and as accurately as possible and then press the spacebar. In monitoring trials, the typists were to monitor whether or not the cued finger of the cued hand was used to type any of the target word's letters. Once the spacebar was pressed, a probe was presented that prompted the subjects to type "Y" for yes if the cued finger was used, or "N" for no if it was not. The probe remained on the screen for 2 s, after which the program automatically progressed to the next trial. No probe was displayed during control trials.

Inhibit block. Figure 7, Panel B displays the sequence of events that took place during the monitor-to-inhibit block. Each trial began with the presentation of a cue. As in the monitor-to-report block, a specific finger was cued during monitoring trials and the word "none" was cued during control trials. A central fixation was presented for 500 ms and then replaced by the target word. Typists were to type the target word as quickly and as accurately as possible and then press the spacebar to move on to the next trial. In monitoring trials, the typists were instructed to withhold typing any letter that is typically keyed with the cued finger.

Results and Discussion

The mean response times of each keystroke relative to the onset of the target word are plotted as a function of position in the word for condition in Figure 8. A 2 (task: report vs. inhibit) × 2 (trial type: monitor vs. control) ANOVA was conducted on the RT1s, IKSIs, and typing-error rates. Only trials in which the target word was typed appropriately and the probe was responded to correctly, when applicable, were included in the analysis. The ANOVA summary tables are presented in Table 3.

As expected, RT1s and IKSIs were longer in monitoring trials than in control trials. However, the crucial comparison was in the extent of the difference between the monitor-to-inhibit and monitor-to-report blocks. The difference in RT1 was greater in the inhibit task (control $M = 714$ ms vs. monitor $M = 1261$ ms) than in the report task (control $M = 667$ ms vs. monitor $M = 844$ ms), $F(1, 23) = 40.0$, $MS_e = 20501.170$, $p < .001$. The difference in IKSIs was also longer in the inhibit block (control $M = 146$ ms/keystroke vs. monitor $M = 364$ ms/keystroke) than in the report block (control $M = 135$ms/keystroke vs. monitor $M = 208$ ms/keystroke), $F(1, 23) = 32{,}4$, $MS_e = 3873.5$, $p < .001$. These results indicate that monitoring to inhibit delays the initiation of typing and the rate at which each letter is typed more than monitoring to report.

Typing-error rates were higher in the monitoring trials (inhibit $M = 11.7\%$ vs. report $M = 7.9\%$) than in control trials (inhibit task $M = 5.8\%$ vs. report $M = 7.0\%$), $F(1, 23) = 14.2$, $MS_e = 10.8$, $p < .001$. The increase in error rates caused by monitoring was not

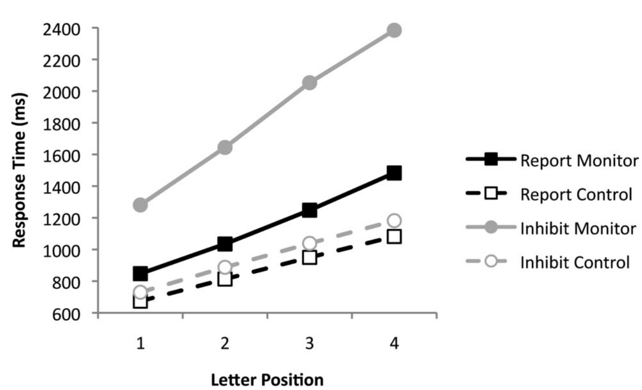

Figure 8. RTs for each keystroke relative to the onset of the word plotted as a function of the position in the word for each condition in Experiment 4.

Table 3
Summary Tables for 2 (Task: Report vs. Inhibit) × 2 (Cue: Monitor Trials vs. Control Trials) ANOVA on Response Time to the First Keystroke (RT1), Typing Rate (IKSI), and Typing-Error Rate (TER) for Experiment 4

	RT1			IKSI			TER		
Effect	*MSE*	*F*	η_p^2	*MSE*	*F*	η_p^2	*MSE*	*F*	η_p^2
Block (B)	48802.2	26.6*	.536	8909.6	19.0*	.453	26.1	1.5	.063
Cue (C)	26620.6	118.1*	.837	6760.4	75.4*	.766	15.3	18.3*	.444
B × C	20501.2	40.0*	.634	3873.5	32.4*	.585	10.8	14.2*	.381

Note. Degrees of freedom for each effect = 1, 23.
* $p < .05$.

significantly different between the inhibit block ($M = 8.8\%$) and the report block ($M = 7.5\%$). Therefore, monitoring to inhibit and monitoring to report cause approximately the same amount of disruption to the accuracy of skilled typing. In the report block, probe error rate was 21.6% and probe miss rate was 1.8%.

The results of Experiment 4 indicate that preparing to inhibit inappropriate responses online imposes additional performance costs above and beyond those induced by monitoring alone.

General Discussion

The cognitive system typically monitors skilled behavior without disrupting performance. However, there are some occasions when monitoring is disruptive. We conducted four experiments to determine the conditions under which monitoring disrupts skilled performance. Three hypotheses were tested: that (a) monitoring is disruptive when typists must withhold inappropriate responses (inhibition hypothesis), (b) monitoring is disruptive when attention must be taken away from executing the skill in order to note how it is performed (dual-task hypothesis), and (c) monitoring is disruptive when implicit details need to be made explicit (implicit–explicit hypothesis). Each experiment utilized a monitor-to-report protocol, which required skilled typists to type four-letter target words while attending to which hand executes each keystroke, so that they could report the hand sequence they used when prompted. The findings from each experiment provided consistent support for the implicit–explicit hypothesis. The findings also supported three additional conclusions: Monitoring costs are distinguishable from inhibition costs and dual-task costs, slower performance while monitoring indicates a strategic adjustment in the way skills are controlled, and timing disruptions could account for monitoring costs observed in all skills that are hierarchically controlled and rapidly executed. We discuss each of these conclusions in turn.

Monitoring Costs

Our findings indicated that monitoring costs are distinct from inhibition costs and dual-task costs. In Experiment 1, performance costs were observed even when the monitoring task did not require inhibition. In Experiment 4, performance costs were significantly larger when the monitoring task required inhibition than when the monitoring task did not require inhibition. Thus, monitoring costs are separable from the costs incurred by preparing to inhibit inappropriate responses. In Experiment 2, both the monitoring and memory tasks required typists to maintain a four-item sequence in working memory while they typed a target word. Nevertheless, performance costs were significantly larger in the monitoring task than in the memory task. Thus, monitoring costs are separable from the dual-task costs incurred by taxing working memory. Therefore, we propose that monitoring costs are distinguishable from both inhibition and dual-task costs.

Implicit–Explicit Hypothesis

Control of skilled performance requires the dynamic coordination of the perceptual, cognitive, and motor systems (Salthouse, 1986). Therefore, disrupted performance could stem from processes governed by any of these systems. Indeed, some researchers have suggested motor accounts of monitoring-induced disruption (Ehrlenspiel, 2001; Wulf, 2007). Our implicit–explicit hypothesis provides a cognitive account of monitoring-induced disruption. Whether motor and cognitive accounts contradict or complement each other is an empirical question beyond the scope of the current work. However, a consensus among many theories of monitoring-induced disruption is that monitoring is disruptive when experts attend to details of performance of which they are not typically aware (Baumeister, 1984; Beilock & Carr, 2001; Logan & Crump, 2009; Lohse, Sherwood, & Healy, 2010; Schorer, Jaitner, Wollny, Fath, & Baker, 2012; Peh, Chow, & Davids, 2011; Zentgraf et al., 2009). We suggest that attending to details is disruptive because the explicit, outer-processing loop does not have direct access to information processed by the inner loop. Therefore, the only way for the outer loop to discover how a skill is being performed is to "watch" the inner loop's output (e.g., the hands interacting with the keyboard). We found that this can be accomplished by sampling either visual or kinesthetic feedback information (Experiment 3).

Accounts of Monitoring-Induced Timing Disruptions

There are two ways that skilled performers could make implicit information explicit. Both hypotheses account for the slower performance rates commonly observed when experts attend to the details of their performance than when they do not (Beilock & Carr, 2001; Gray, 2004; Logan & Crump, 2009; Lohse et al., 2010; Schorer et al., 2012; Tapp & Logan, 2011). The restructuring hypothesis assumes that the outer loop takes control over processes that are typically controlled by the inner loop. That is, the outer loop chooses which letter to type, locates the appropriate key, selects which hand and finger will press the key, initiates the movement, and checks the movement's accuracy. Because the outer loop is explicit, restructuring control in this way would make the performance details available for explicit report. Because outer-loop processing is slow (Keele, 1968; Lashley, 1951), the restructuring hypothesis predicts slower performance rates when typing is controlled by the outer loop than when it is controlled by the inner loop. However, we believe this account is unlikely. Expert typists have poor explicit knowledge of key locations (Liu, Crump & Logan, 2010), so top-down control of finger-to-key mappings would require visual inspection of the keyboard. However, skilled typists are able to complete the monitor-to-report task (Experiment 3) and the monitor-to-inhibit task (Tapp & Logan, 2011) when view of the keyboard is restricted.

We believe the strategic slowing hypothesis (Logan & Crump, 2009) is a more likely option. This hypothesis assumes that the control structure remains hierarchical, but the outer loop strategically slows the rate at which movements are initiated in the inner loop, so that the outer loop has time to observe and register the output of the inner loop. Explicit awareness is slow (Heuer & Sulzenbruk, 2012), and encoding information into short-term memory (STM) takes time (Sperling, 1963; Woodman & Vogel, 2008), whichindicates that the slowing must be substantial. Moreover, the strategic slowing hypothesis allows for task-appropriate flexibility in keystroke execution rate. When monitoring to report, performance only needs to be slowed to allow enough time to encode the information into working memory. When monitoring to inhibit, performance needs to be slowed enough to allow for the additional time needed to inhibit potentially inappropriate responses (Logan, 1982).

Applications of the Strategic Slowing Hypothesis

We expect the strategic slowing hypothesis to account for monitoring costs observed in tasks that meet three criteria: They are hierarchically controlled, highly skilled, and rapidly executed. Monitoring-induced disruption has been observed in a number of skills that have the one-to-many task-structure characteristic of hierarchical control, such as baseball batting (Gray, 2004), golf putting (Beilock, Wierenga, & Carr, 2002), and dart throwing (Schorer et al., 2012).

It is not enough for a task to be comprised of multiple component actions; these lower order actions need to be controlled by an informationally encapsulated inner processing loop in order for the strategic slowing hypothesis to apply. Otherwise, if each component action of a behavior were controlled independently by the outer loop (e.g., following a new recipe), information about those actions would always be explicitly accessible (see Botvinick & Plaut, 2004). When a task becomes skilled, control over the performance details is delegated to the inner loop. Encapsulating information about how a task is executed reduces the processing load of the outer loop, and this allows the component actions to be completed rapidly and with less variability than actions that are consciously controlled (Lohse et al., 2010; Schorer et al., 2012). Once the performance details have been encapsulated, task execution no longer relies on explicit knowledge (Logan, 1988). As a result, the explicit knowledge may decay or become less accessible. Therefore, just as skilled typists need to "watch" their hands to discover which hand types each letter, expert baseball players and golfers also need to "watch" their performance to discover which component actions are being executed.

The final requirement necessary for our strategic slowing hypothesis to account for monitoring-induced disruption is that the component actions of the skill need to be executed rapidly. If the component actions are typically performed at a rate slow enough for the outer loop to "watch" the inner loop's output (i.e., pottery, cooking), slowing the rate of performance would be unnecessary. However, many skilled tasks are performed quickly. Skilled typists typically execute one keystroke every 130 ms. Skilled batters and golfers need to swing the bat or club rapidly in order to exert an appropriate amount of force on the ball. Because of processing limitations inherent in the cognitive system, actions that are executed in less than 200 ms occur too quickly to be explicitly monitored online (Keele, 1968; Keele & Posner, 1968; Lashley, 1951). Therefore, performance rate must be slowed down to allow the outer loop enough time to register the feedback information.

Conclusions

We reported results from a novel monitor to report protocol designed to investigate the conditions under which monitoring one's skilled performance is disruptive. We found that dual-task costs and inhibition costs both contribute to the disruption observed when skilled typists attend to the details of their performance. However, we found that monitoring costs are distinguishable from dual-task and inhibition costs. We suggest that monitoring costs occur when implicit performance details need to be made explicit. Our results are consistent with the strategic slowing hypothesis (Logan & Crump, 2009), which assumes that the outer loop reduces the rate of inner-loop processing so that inner-loop output can be noted and stored in memory. We suggest that similar strategic slowing may account for monitoring-induced disruption in tasks that are hierarchically controlled, highly skilled, and rapidly executed.

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