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## Prevention and Correction in Post-Error Performance: An Ounce of Prevention, a Pound of Cure

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# Prevention and Correction in Post-Error Performance: An Ounce of Prevention, a Pound of Cure

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Error detection serves 2 different functions: prevention and cure. Prevention engages post-error slowing to reduce future errors, whereas cure engages processes that correct the error. Thus, prevention predicts post-error slowing, and cure does not. We investigated this distinction in skilled typists in 3 experiments. In Experiment 1, post-error performance was investigated in 800 typists who completed a short continuous typing test where correction was disallowed. In Experiments 2 and 3, post-error performance and post-correction performance were investigated by manipulating whether typists were allowed to correct their mistakes. Across experiments, there was limited evidence that typists used error detection for prevention; typists preferred the cure. After making mistakes, they corrected them and rapidly resumed typing at normal rates. Post-error slowing occurred only when correction was disabled; post-error speeding occurred when correction was enabled. This finding offers support for the novel hypothesis that post-error slowing reflects the inhibition of pre-potent tendencies to correct mistakes. Error-detection processes in general will be better understood by distinguishing between tasks that allow performers to cure their errors through correction rather than reduce their errors through prevention.

*Keywords:* error detection, cognitive control, skill-acquisition, performance, typing

Everybody makes mistakes. An understanding of human error not only mitigates disastrous consequences caused by human operators (e.g., drivers, air traffic controllers, nuclear power plant operators) but also informs on the underpinnings of performance across domains in psychology and neuroscience (Reason, 1990). Errors occur at low levels of skill and drive learning, and they occur at high levels of skill and demand correction or compensation. Errors help identify neurological disorders like Broca's and Wernicke's aphasia (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997) and dementia (Carlesimo & Oscar-Berman, 1992). The nature of errors shed light on how psychological processes operate. Language errors constrain theories of production (Garrett, 1975), the pattern of slips during routine action points to hierarchically organization in planning (Botvinick & Plaut, 2004; Cooper & Shallice, 2000), and memory errors show the reconstructive nature of remembering (Bartlett, 1932). Errors are important in neuroscience. Errors in performance are marked by activation in the anterior cingulate cortex (ACC; Carter et al., 1998) and are followed by neurophysiological markers such as the error-related negativity (ERN) and positivity (Pe; Gehring, Goss, Coles, Meyer, & Donchin, 1993). In development, the nature of errors changes with developmental stage and can be used to diagnose developmental stages (e.g., the A-not-B error; Smith, Thelen, Titzer, & McLin, 1999). Across domains, major questions of interest are to understand how and why errors occur and how people respond to the consequences of their mistakes.

## Responding to Errors: Prevention Versus Cure

Everybody makes mistakes; it's what they do about them that counts. We suggest a major distinction in characterizing how people respond to errors is that of prevention and cure. Prevention refers to post-error adjustment processes that minimize or prevent future errors. Cure refers to post-error responses that correct the error. Many theories of learning invoke error-driven processes (e.g., Rescorla & Wagner, 1972) that characterize learning as an adjustment process designed to minimize and prevent future errors. In performance, from laboratory-based choice reaction time tasks (for a review, see Danielmeier & Ullsperger, 2011) to real-world tasks such as playing music (Ruiz, Strübing, Jabusch, & Altenmüller, 2011), errors are followed by slowed responding. Post-error slowing suggests prevention: People slow down to prevent errors in the future. Reactions to errors also depend on task constraints, and we suggest that these constraints can determine whether performers adopt prevention or cure strategies. Some tasks demand correction of errors and others do not allow correction. The task of typing demands correction, as the goal of typing is to produce an error-free document. Other tasks like music performance disallow correction. When a mistake is made during performance musicians must continue to play the remaining notes

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without self-repair. When the musical score is not strictly defined, musicians may attempt self-repair by repeating the error to feign intention and cast the error as part of the song. In the words of Joe Pass, “If you hit a wrong note, then make it right by what you play afterwards” (Sudo, 1998, p. 54). Speech production can allow or disallow correction. A speaker cannot take back an utterance, but he or she can attempt self-repair through utterances that repeat incorrect words or signal mistakes (e.g., “oops, I meant to say”).

## The Role of Learning and Skill in Prevention and Cure

Whether people engage in prevention or cure following errors may depend on skill level and different stages of practice. Very early in skill when people are unsure of performance requirements they make many errors. Learning processes here serve adjustment purposes and drive prevention of future errors (Rescorla & Wagner, 1972; Widrow & Hoff, 1960). At intermediate levels of skill, performers no longer make errors out of ignorance but instead slips may occur by glitches in the control processes guiding action. At this stage, performers may be learning to optimize speed-accuracy tradeoffs and engage in post-error prevention to adjust speed and increase accuracy (Rabbitt, 1966b). At high levels of skill, performers have already optimized for speed and accuracy and post-error prevention in the form of slowing or increased caution may not be useful. Highly skilled performers may accept a given error rate as inevitable and do nothing to prevent future errors. Indeed, prevention-based adjustments at high levels of skill could lead to breakdowns and cause experts to choke under pressure (Beilock, Carr, MacMahon, & Starkes, 2002; Logan & Crump, 2009). The ability to cure errors may also develop with skill. In tasks like typing, error correction via the backspace key is a common experience during practice, and these corrective actions could become automatized over the course of learning.

## The Role of Task Demands in Prevention and Cure

Prevention and cure strategies could depend on task demands as well as skill level. We suggest that task demands play a more important role in determining reaction to errors. In tasks like typing, typists at all skill levels are expected to produce perfect copy. Perfect copy can be accomplished in typing because correction is easily achieved through backspacing. Other tasks like music performance can require perfect copy, but the copy must be produced with additional temporal constraints that preclude correction attempts. When tasks demand a series of correct actions in real time, there is no opportunity for correction because the error has been committed and temporally preserved. In sports, a player cannot replay a missed shot. In speech, a speaker can attempt self-repair, but if the mistaken utterance is severe enough, what has been said has been said and cannot be taken back. In medicine, errors in diagnosis, prescription, or surgery may be corrected provided that the remedy also cures any damage incurred over time. When time is of the essence, the only response to error is acceptance and apology.

In addition to timing, there are several important related task-demands determining prevention or cure. A second demand is deadline flexibility. Tasks high in deadline flexibility are more forgiving of errors than tasks that are low in deadline flexibility. As long as errors can be corrected before a deadline, there is opportunity for a cure. For example, when speaking among friends, speech errors that are corrected through self-repair may be accepted by the audience more so than speech errors and attempts at self-repair made in formal settings such as a conferences or press releases. Similarly, in live music performance, deadline flexibility is low and errors cannot be corrected; however, in the studio, deadline flexibility is high and errors can be corrected through over-dubbing and re-recording. In sports, deadline flexibility is low when seconds count at the end of a game and missed shots lose the match; however, deadline flexibility is high throughout the game when players have the opportunity to make up for errors earlier in a match.

A third task demand is repeatability. Cures for error are possible when tasks allow mistakes to be corrected through repetition. We have already mentioned self-repair in speech and music as examples and there are many more. Failed courses can be repeated, failed driving exams can be re-scheduled, and failed culinary creations can be re-attempted. In sports, gracious golfing partners allow mulligans, and in some cases, repeated attempts are formally allowed as in the high jump and long jump. Repeated attempts allow for cure in the sense that the best attempt is taken as the final product, but they also allow for prevention-based adjustments following errors to ensure an improved final product on the next attempt.

A final task demand is deletion or erasure. Tasks allowing deletion directly cure errors by removing them from the performance record. Backspacing in typing is a clear example. Points on a driver’s license can be erased through defensive driving courses. Artists can erase badly drawn lines and paint over errant strokes. Poorly executed movie scenes are edited out from the final production. Lenient instructors may drop the lowest exam grade.

Taken together, task demands like timing, deadline flexibility, repeatability, and erasure constrain whether or not people attempt prevention or cure following errors. The role of task demands and skill level in shaping post-error prevention or cure are intertwined. Learning about and coping with task demands is part and parcel of gaining task-specific expertise. Prevention and cure are not mutually exclusive. People can rely on both or focus on one or the other depending on task demands and skill level.

The distinction between prevention and cure applies broadly to post-error performance across a wide range of tasks but most research on post-error processing has focused on prevention. The present work emphasizes cure strategies in post-error processing, focusing on typewriting, which demands cure strategies, and skilled typists, whose performance is nearly optimal and may no longer require prevention strategies.

## Contrasting Prevention Versus Cure in Skilled Typing

Typing is a model task environment to investigate a range of performance issues (for a review, see Logan & Crump, 2011a, 2011b), including those involved in error detection (Logan & Crump, 2010; Rieger, Martinez, & Wenke, 2011; Wilbert & Haider, 2012). Typing is now a common skill among undergraduates, making experts readily available. Typing involves rapid serial ordering of keystrokes, and response timing is easily measured. The goal of typing is produce perfect copy making, errors well defined as any word not correctly copied. Errors can be difficult to study when their occurrence is rare; however, in typing, errors are frequent even when error rates are low, as typists can be instructed to type texts with many words. Typing allows for both prevention and cure following errors. Typists can cure their mistakes through corrective actions like pressing the backspace key. Typists can prevent future errors by trading speed for accuracy (Gentner, 1987; Yamaguchi, Crump, & Logan, in press). The task demands of typing are lax in terms of timing, high in deadline flexibility, allow for repeated attempts, and allow for deletion to occur. These demands may lead typists of all skill levels to adopt a cure strategy following errors. Typists are also highly skilled and may be unable to further optimize speed-accuracy tradeoffs. As a result, constraints on further skill development may lead expert typists to accept their errors and avoid preventive adjustments following errors.

## Post-Error Slowing

A hallmark behavioral finding is post-error slowing: Performance is often slower following errors than before them or slower following errors than following correct responses (Laming, 1968; Rabbitt, 1966b). Post-error slowing is found across a broad range of performance tasks, and there are many views on the processes driving the effect (for a review, see Danielmeier & Ullsperger, 2011). Post-error slowing may or may not reflect processes involved in prevention of future errors. Post-error slowing could reflect a continuation of the same state of confusion that led to the initial error (Gehring et al., 1993). Post-error slowing may be driven by surprise at the mismatch between the observed error and expected performance (Notebaert et al., 2009). More in line with the prevention view, post-error slowing could reflect a generic neural system for error-detection (Gehring et al., 1993; Miltner, Braun, & Coles, 1997) or a conflict-monitoring process (Yeung, Botvinick, & Cohen, 2004) that triggers control adjustments for future performance.

Typists also exhibit post-error slowing (Logan & Crump, 2010; Salthouse, 1986). When an error occurs at the letter level, keystrokes following the error are slowed relative to pre-error keystrokes. Post-error slowing in typing could reflect post-error prevention to optimize speed-accuracy tradeoffs (Rabbitt, 1966a, 1966b, 1969; Rabbitt & Vyas, 1970). Errors may occur when typists make keystrokes too quickly, and they may slow down to avoid making future errors. However, typists are highly skilled and may already be performing with an optimized speed/accuracy tradeoff. They have learned to type rapidly and may accept the error rate that follows from their preferred typing speed. The goal of typing is to produce words and sentences, and the overall speed of this process could be hampered by lengthy recovery periods that slow down typing rate to reduce error rate. Typists could prefer to operate at top speed, correct errors as quickly as possible, and then continue typing at top speed to produce words and sentences in the most timely fashion.

## Post-Error Slowing as the Result of Inhibiting the Tendency to Cure

In tasks like typing that afford the opportunity for cure, the corrective action is also stereotyped. Typists have extensive practice with pressing the backspace key to correct their errors and, indeed, may have developed automatized routines to produce corrective actions. We suggest a new hypothesis that post-error slowing reflects the cost of inhibiting an automatic tendency to correct erroneous responses, and so reflects a frustrated attempt to cure the error instead of an attempt to prevent future errors.

Many tasks that are used to study post-error slowing (e.g., choice reaction time tasks) do not allow subjects to correct their errors. They lack the possibility for deletion or erasure, and often encourage subjects to respond as quickly and accurately as possible, thereby creating a task that has timing constraints and is low in deadline flexibility. These task demands encourage adoption of prevention strategies following errors. At the same time, errors in choice-reaction time tasks are not always followed by post-error slowing, but instead by fast correct responses that were presumably prepared and competed for action when the error was committed (Rabbitt, 1966a, 1966b; Ullsperger, Nittono, & von Cramon, 2007). These spontaneous corrections hint at what may be an automatic tendency to engage in correction following errors, even in tasks that discourage cure.

In order for errors to automatically trigger correction or prevention, some process must first detect the error and signal a reaction to the error. There is broad support across the domains of motor control and cognitive control for rapid error detection processes. Motor control theories posit feed-forward and inverse models that allow for fast and rapid adjustment based on perceptual and simulated feedback (Jordan & Rumelhart, 1992; Wolpert, Ghahramani, & Jordan, 1995). As well, higher-level and more generic error-detection processes are evidenced by ACC activation in functional magnetic resonance imaging (fMRI) and electrophysiological measures (e.g., ERN and Pe). How these perspectives as well as error-detection theories from the speech production domain fit with the prevention versus cure distinction are reviewed in the General Discussion section.

## The Present Experiments

The general aim of the present work was to determine whether error detection processes in skilled typing address prevention or cure: Do they lend themselves to the prevention of future errors, or to the correction of current errors? Experiment 1 investigated post-error performance in a large database of 800 typists who performed a continuous typing task. We report the first distributional analyses of post-error slowing within and across individuals, and we examine whether typing errors are followed by more cautious and accurate typing that would be characterized by a prevention strategy. Experiments 2 and 3 investigated post-error performance in continuous typing tasks that manipulated whether or not typists were allowed to correct their mistakes by pressing the backspace key to test the novel hypothesis that post-error slowing may result from inhibiting the automatic tendency to correct errors. We report surprising new evidence for post-error speeding in tasks that allow for corrective responses. Taken together, our findings strongly support the view that error-detection processes in skilled typing are used for cure and not prevention. They allow typists to correct their mistakes rather than cause typists to adjust their performance to prevent future errors.

## Experiment 1

Over the past 4 years, we collected data from 800 typists who completed a short paragraph typing test (approximately 115 words long) developed to measure normal typing speed (Logan & Zbrodoff, 1998). This database provides a unique opportunity to investigate how skilled performers make adjustments following errors. Specifically, we can characterize the temporal properties of the recovery period following errors. If typists engage in prevention, then the recovery period following errors should be marked by slower and more accurate performance. These predictions are investigated first by measuring post-error slowing at the word level, as well as post-error accuracy and error clustering or grouping. Next, we investigate distributional properties of post-error slowing at the letter level to determine whether post-error slowing occurs following all errors, whether post-error slowing occurs across all individuals, and whether post-error slowing changes as a function of typing skill level.

### Method

**Subjects.** Eight-hundred volunteers from the Vanderbilt community were recruited for their self-reported ability to type 40 words per minute (WPM). Their mean typing speed was 68 WPM (range = 21–127 WPM); their mean typing error rate was 7%. All subjects were compensated $12 for 1 hr of participation. All subjects had normal or corrected-to-normal vision and spoke English as a first language.

**Apparatus and stimuli.** Typing tests were conducted on a PC using a 15-in. (38.1-cm) SVGA monitor controlled by METACARD software. Typing responses were registered on a standard QWERTY keyboard. Each phase in the typing task involved copy-typing one of four short paragraphs (115 words in length), taken from Logan and Zbrodoff (1998).

**Procedure.** The typing tests were administered as a part of ongoing typing experiments. The typing test lasted approximately 5 min and was presented to participants after they completed the main experimental session. For each test, typists were presented with a short paragraph on a computer screen. An text box was displayed below the paragraph, in which their keystrokes were echoed. Typists were instructed to type the entire paragraph as quickly and accurately as possible. Typists were informed that the backspace key was disabled and that it would not correct their errors. In the event of an error, typists were instructed to continue typing as normal.

### Results and Discussion

Our general aim was to determine whether post-error performance shows evidence for a recovery period that is sustained or transient. If typists use a prevention strategy, and slow down and increase vigilance following errors to reduce future errors, then we would expect post-error slowing to appear at the word level. If typists successfully use a prevention strategy, then they will be more accurate following errors. Thus, a prevention strategy predicts that errors should be grouped sparsely.

**Word-level post-error slowing.** To measure word-level post-error slowing, the database was filtered with the following constraints. For each typist, each erroneous word was found. We then computed the average inter-keystroke-interval (IKSI) for the error word (E), average IKSI for the preceding correctly spelled word (E − 1), and average IKSI for the following correctly spelled word (E + 1). IKSIs reflect the average time taken to type each letter in a word. Average IKSIs for each word were found by computing the slope of the line that best fit the individual RTs for each letter in the word. Only words that had at least three letters were used to compute slopes. With these constraints, 765 typists contributed data to the analysis.

Mean IKSIs were 151 ms, 287 ms, and 155 ms for the E − 1, E, and E + 1 conditions, respectively. Error (E) words were typed slower than E − 1 words, $F(1, 764) = 778.47$, $MSE = 9{,}094.34$, $\eta_p^2 = .50$, and E + 1 words, $F(1, 764) = 701.21$, $MSE = 9{,}510.90$, $\eta_p^2 = .48$. Importantly, there was no evidence for post-error slowing at the word level: Words following errors (E + 1) were not typed slower than words preceding errors (E − 1), $F(1, 764) = 1.97$, $p < .16$, $\eta_p^2 = .003$.

The absence of word-level post-error slowing shows either no evidence for a recovery period, or evidence that the recovery period was short-lived and did not persist across words. If typists were attempting to prevent future errors by slowing down they appear only to do so within the context of the remaining letters in the word that they typed incorrectly.

**Error grouping.** Typists may not have slowed down following errors, but perhaps they increased vigilance and focused more on the task to prevent future errors. Such a prevention strategy would reduce the probability that errors are spaced closely together: Words following errors will be more often typed correctly than incorrectly. Typists may not engage in prevention; they may simply resume typing at their normal speed and continue to make errors at their normal rate.

To test for prevention, we computed whether errors are more likely to occur following errors or following correctly typed words, and whether correctly typed words are more likely to follow correctly typed words or errors. Given that word N was typed correctly, the probability that word N + 1 was correct or erroneous was .91 and .09, respectively. Given that word N was an error, the probability that word N + 1 was correct or erroneous was .91 and .09, respectively. The probabilities were identical. Typists were equally likely to make errors following correct or incorrectly typed words. This shows that typists did not become more vigilant following errors, and errors did not seem to result from a sustained confused state, as this would have increased error likelihood following errors.

To provide a more fine-grained test for prevention, we assessed error grouping. We measured distances between errors in the data, and we compared the observed distributions of distances with predicted distributions from a stochastic model, which assumed that errors are distributed randomly within a paragraph. The analysis involved all 800 typists, who were further binned into four groups defined by overall error rate: <.05 ($N = 244$), .05–.10 ($N = 349$), .10–.15 ($N = 157$), and .15–.20 ($N = 36$). For each typist, each word-level error was assigned a number indicating its position in the paragraph (e.g., if the 20th word was in error, then this error was assigned the number 20). Starting from the second error, the distance between each error and the previous error was found. Distance refers to the number of words between successive errors. For each group, the probability of making an error at a given error distance is plotted in Figure 1. As the group error rate

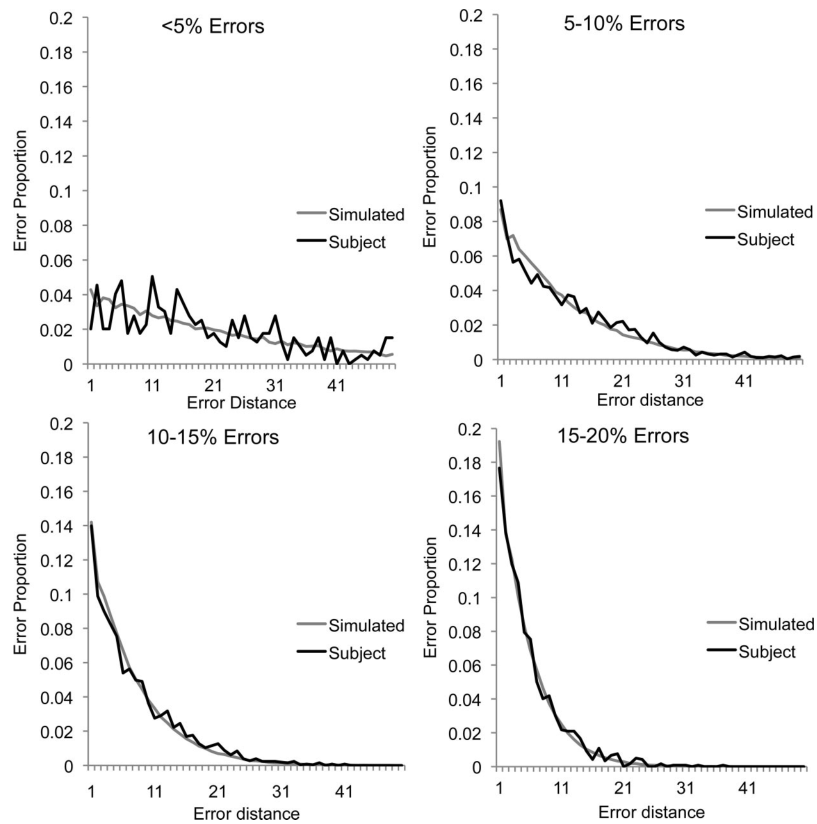


*Figure 1.* Probabilities of word level errors as a function of error distance. Error distance is the number of words intervening between each error. Typists are binned by overall error rates of <.05, .05–.1, .1–.15, and .15–.2. The black line reflects actual subject data. The gray line reflects simulated data from the stochastic model, which assumes errors are distributed randomly in each paragraph.

increases, the proportion of errors that involve short distances increases. The critical question is whether these distributions of error groupings are different from what would be expected by chance.

The distributions of error groupings that would be expected by chance were simulated in the following way. Four simulations were conducted assuming different overall rates (<.05, .05–.10, .10–.15, and .15–.20). A paragraph of 100 words was modeled as a vector with 100 units. The vector was populated with 0s and 1s, with 0s reflecting correctly spelled words, and 1s reflecting errors. Each model involved 10,000 simulated subjects. For each simulation, the overall error rate was determined by picking a random value between the error-rate bin limits. This number defined how many 1s would be inserted into the vector. After insertion, the positions of the 1s within the vector were randomized. Next, the distances between successive 1s in the vector were found. These simulated distances were used to construct model predictions for the probability of making an error for different error distances. The simulated distributions are plotted in Figure 1. The model fits were $R^2$ = .46, .97, .99, and .99 for the <.05, .05–.10, .10–.15, and .15–.20 groups, respectively. With the exception of the <.05 group (which appears to be the most noisy), the model fit the data remarkably well.

If typists became more vigilant following errors, then the error probability for short distances (e.g., 1–10) should be lower than would be predicted by the chance model. Instead, for all groups, the predicted probabilities closely matched the observed probabilities across error distances. Both the actual and predicted data show that error probability for short distances increases as the overall error rate increases across groups. These findings emerge from the constraints of populating a limited space with errors. The paragraphs contained 100–115 words. Increasing error rate populates the paragraph with more errors, and this naturally increases the probability that errors will be more closely packed.

When post-error performance was analyzed at the word level, we found no evidence of post-error slowing. We found no evidence that errors are grouped differently than would be expected from chance. Both of these findings argue against a view that typists were engaging in sustained prevention strategies to reduce future errors. They did not slow down, and they did not improve accuracy following errors at the word level. There was no evidence for a recovery period following errors. Next, we investigate post-error performance in a more fine-grained manner, at the level of letters and keystrokes.

**Letter-level post-error slowing.** Data from 800 typists were included in the analysis. For each typist, all erroneous words were found. For each word, we restricted analysis to the keystrokes surrounding the first erroneous letter. Figure 2A displays mean IKSIs collapsed across 800 typists for keystrokes surrounding an error (E − 1, Error, E + 1, and E + 2). We defined post-error

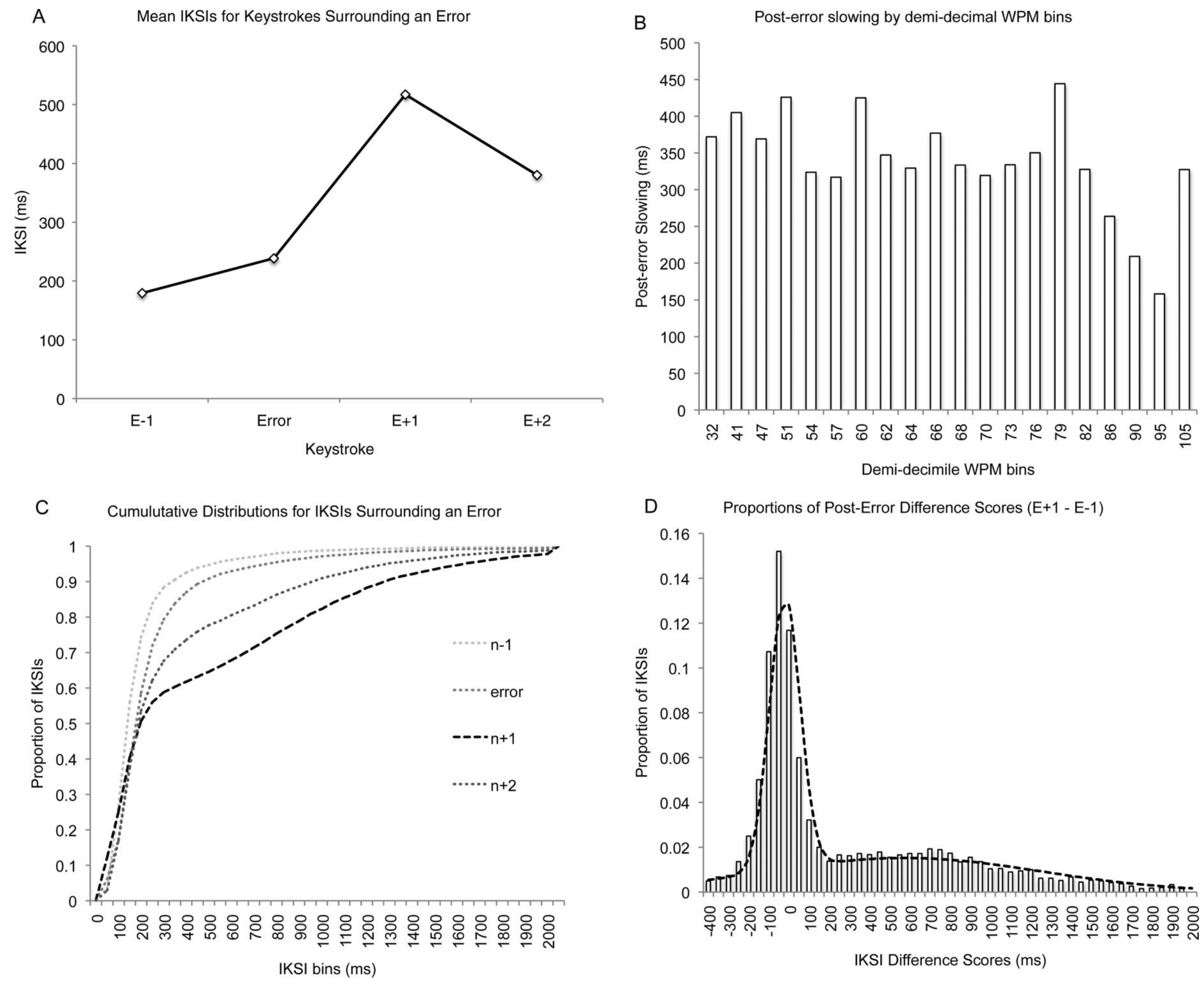


*Figure 2.* (A) Mean inter-keystroke-intervals (IKSIs) surrounding errors collapsed across all typists and errors. E − 1 is the keystroke prior to the error. E + 1 and E + 2 are letter keystrokes following uncorrected errors. (B) Mean post-error slowing for individual subjects by demi-decimal words per minute (WPM) bins; the *x*-axis shows mean WPM for each 40-subject bin. (C) Cumulative distributions showing proportions of IKSIs surrounding errors in bins of 100 ms. (D) Histogram showing the distribution of post-error scores [(E + 1) – (E − 1)] collapsed across typists. The dotted line shows the fit for a mixture of two normal distributions.

slowing as the difference in IKSI between keystrokes following an error (E + 1, mean IKSI = 517 ms) and keystrokes preceding an error (E − 1, mean IKSI = 180 ms). The mean difference was significant, $F(1, 799) = 991.89$, $MSE = 46{,}060.20$, $\eta_p^2 = .55$. In contrast to the word-level analysis, the average data here show robust post-error slowing for the keystroke following an error.

**Letter-level post-error slowing and skill level differences.** The large database offers a first opportunity to investigate individual differences in post-error slowing. As mentioned in the introduction, whether typists adopt prevention or cure-based strategies following errors may depend partly on task demands and on skill level. First, we measured the prevalence of post-error slowing at the letter level across all typists by calculating post-error slowing scores [(E + 1) − (E − 1)] for each typist. The vast majority of typists (98.6%) showed greater than zero post-error slowing; the remaining (11/800 typists) showed post-error speeding. Post-error slowing is ubiquitous in the average across typists.

We looked at post-error slowing as a function of WPM to determine whether post-error performance changes with skill level. Figure 2B shows post-error slowing scores as a function of WPM in demi-decile bins (40 typists each) and clearly shows that typists of all skill-levels show sizable post-error slowing. We analyzed skill level differences in post-error slowing in two ways. First, a median split comparing the slowest and fastest typists showed significantly larger post-error slowing for the slow (369 ms) than fast typists (307 ms), $F(1, 798) = 8.52$, $MSE = 91{,}261.88$, $p < .005$, $\eta_p^2 = .01$. Second, WPM and post-error slowing scores for all 800 typists were submitted to a linear regression, which showed a significant negative linear trend, $F(1, 798) = 15.09$, $MSE = 90{,}523.24$, $p < .0001$, $R^2 = .02$. The intercept was 493 ms, and the slope was –2.29, showing that post-error slowing was generally smaller for faster than slower typists.

The smaller post-error slowing with faster typists suggest smaller absolute adjustments, but they could also reflect constant or larger relative adjustments. We addressed this issue with a proportional analysis in which each typist's post-error slowing score was normalized by their average IKSI for typing the entire paragraph. The proportional analyses showed opposite effects. A median split comparing the slowest and fastest typists showed significantly larger proportional post-error slowing for the fast (2.07) than slow (1.64) typists, $F(1, 798) = 11.59$, $MSE = 3.20$, $p < .001$, $\eta_p^2 = .01$. A regression of WPM and proportion post-error slowing scores for all 800 typists showed a significant positive linear trend, $F(1, 798) = 14.27$, $MSE = 2{,}546.06$, $p < .0005$, $R^2 = .02$. The intercept was .95, and the slope was .01, again showing a trend for the fast typists to have larger proportional post-error slowing than slow typists.

Overall, the magnitudes of differences in post-error slowing between slow and fast typists were very small both absolutely and proportionally, and both slow and fast typists showed sizeable post-error slowing effects. This fits with the view that task demands in typing rather than skill level determine how typists respond following errors. The interpretation of the skill-related differences depends on whether absolute or proportional differences are more valid measures of post-error slowing. If absolute differences matter, then the data suggest that slower typists inhibited correction more than faster typists. If proportional differences matter, then the data suggest that faster typists may have inhibited correction strategies more than slower typists. Future research will be required to distinguish these possibilities.

**Distributional analysis of letter-level post-error slowing.** Next, we investigated whether post-error slowing always occurs following errors at the keystroke level. We measured IKSIs for keystrokes surrounding every error made by every typist. Figure 2C shows cumulative distributions for E − 1, Error, E + 1, and E + 2 IKSIs, collapsed across all typists. All distributions appear to start at a common minimum and rise at the same rate until about the 50th percentile. After that, IKSIs immediately following an error (E + 1, and to some extent E + 2) show marked departures from the E − 1 and Error distributions. Most of the IKSIs for the E − 1 and Error distributions occur within 300 ms, whereas a large proportion of IKSIs for the E + 1 distribution occurs later than 300 ms. This suggests that the distribution of post-error (E + 1) IKSIs is a mixture of IKSIs that are fast like normal IKSIs (e.g., E − 1) and IKSIs that are extremely slow.

The evidence for a mixture distribution can be seen in the histogram of post-error slowing difference scores [(E + 1) – (E − 1)] for each error, plotted in Figure 2D. The histogram is bi-modal, which is characteristic of distributions of extreme mixtures (Yantis, Meyer, & Smith, 1991). To estimate the mixture probability and the parameters of the parent distributions contributing to the mixture, we fit a mixture of two normal distributions to the data using maximum likelihood estimation. The best fitting mixture probability was 0.47, indicating that almost half of the IKSIs came from the fast distribution. This provides the first evidence that post-error slowing does not occur following every error. Instead, it occurs following approximately half of the errors. The fast peak had a mean of –20 ms and a standard deviation of 76 ms. This mean was significantly smaller than zero, suggesting that half of the keystrokes following errors are actually faster than normal keystrokes, $t(5890) = -20.35$, $p < .01$. The slow peak was best fit with a mean of 574 ms and a standard deviation of 677 ms.

Taken together, these distributional analyses are the first to establish that post-error slowing does not occur after every error, although it occurs in almost all typists. The data show that post-error slowing occurs about half of the time following an error, and when it does not occur, there is some evidence of post-error speeding (the mean of the fast post-error distribution was 159 ms/keystroke, whereas the mean for pre-error IKSIs was 179 ms/keystroke).

Our finding that post-error slowing and speeding both occur is very important. It suggests that previous accounts of post-error slowing are inadequate because they imply that post-error slowing should occur after every error (Gehring et al., 1993; Miltner et al., 1997; Notebaert et al., 2009; Yeung et al., 2004). This calls for a different perspective on post-error processing that would explain why slowing occurs after some errors and speeding occurs after others.

We propose the novel hypothesis that post-error slowing results from inhibiting the automatic tendency to correct errors. It is important to note that in these typing tests we prevented typists from correcting their errors by disabling the backspace key. Instead, typists were instructed to type through errors without correcting them. We suggest that post-error slowing occurs following errors that elicited a corrective movement toward the backspace key that had to be inhibited. Indeed, it is possible that typists struck the backspace key following some errors. This hypothesis may account for post-error slowing in other tasks where participants are not allowed to correct their errors and may have to suppress their natural tendency to do so.

## Experiment 2

Experiment 1 showed that typists do not engage in prolonged prevention to reduce future errors. Typing speed briefly slows following errors at the keystroke level, but returns to normal by the next word. All of these data were collected in a typing test that disabled the backspace key. The aim of Experiment 2 was to investigate post-error performance in a continuous typing test that allowed typists to use the backspace key to correct their errors. If post-error slowing results from inhibiting the tendency to correct errors, we should see no post-error slowing when typists are allowed to correct their errors.

We used the same typing test as above with the following changes. Each typist completed 24 paragraphs. The backspace key was enabled for all paragraphs, and typists were not allowed to use the mouse to correct their mistakes. We assumed that typists would occasionally fail to correct errors, and we anticipated situations where typists would attempt to backspace through several words to correct a prior word. We preempted this by manipulating post-view across six conditions. For each post-view condition, typists could only view their most recent 5, 10, 15, 20, 25, or 30 keystrokes. As they continued typing, letters displayed as visual feedback that were beyond the post-view window were erased from the screen.

Enabling the backspace key allows us to measure several aspects of post-error performance in typing. First, we can measure the latency and probability of error detection. We assumed that typists would detect and correct some errors very rapidly, striking the backspace key immediately after the error, would detect and correct other errors slowly, striking several keys before striking the backspace key, and miss some errors entirely, never striking the backspace key. We assumed that any errors that were followed by a backspace or series of backspaces were explicitly detected, and the number of keystrokes between the error and the first backspace indicates latency of explicit error detection. The post-view manipulation was intended to provide converging evidence for this latency measure. Typists should not correct errors whose latencies were longer than the post-view. Thus, the proportion of errors that were detected in each post-view condition can be used to estimate the proportion of the error-detection latency distribution that fell within the number of post-viewed keystrokes.

Second, we can measure timing of post-error performance for keystrokes following errors that were not immediately corrected. Post-error slowing at the keystroke level could reflect an implicit error detection process that slows typing to prevent errors on the following keystroke. On this view, post-error slowing should be observed at the keystroke level for keystrokes following uncorrected errors. We suggested that the post-error-slowing observed in Experiment 1, where backspacing was not allowed, could reflect inhibition of the automatic tendency to correct errors by pressing the backspace key. In Experiment 2, typists were allowed to press the backspace button and would have no reason to inhibit this tendency. With this procedure, the cure perspective predicts an absence of post-error slowing for keystrokes following errors that were not immediately corrected.

Finally, the timing of corrective responses (pressing the backspace key) and the time to resume normal typing following correction can be measured. If typists engage in prevention following error detection, then they may slow down following errors. On the other hand, typists may not engage in prevention when they have the opportunity to correct their mistakes. After correcting their errors they may quickly resume typing at normal speed.

## Method

**Subjects.** Subjects were 18 students from Vanderbilt University who were recruited for their self-reported ability to type 40 WPM. Their mean typing speed was 80 WPM (range = 49–103 WPM); their mean typing error rate was 22% (range = 15%–38%). All subjects were compensated $12 for 1 hr of participation. All subjects had normal or corrected-to-normal vision and spoke English as a first language.

**Apparatus and stimuli.** The experiment was conducted on a PC using a 15-in. (38.1-cm) SVGA monitor controlled by METACARD software. Typing responses were registered on a standard QWERTY keyboard. Each phase in the typing task involved copy-typing one of six short paragraphs (115 words in length), taken from Logan and Zbrodoff (1998).

**Procedure.** Each typist transcribed 24 paragraphs. Each paragraph was chosen from among the six total paragraphs so that across the session each typists typed each paragraph four times. For each, the paragraph was presented above a text-box that gave visual feedback during copy typing. Typists could see the letters they typed and the letters they deleted when backspacing, as would normally be the case when using a word-processor. However, unlike a word-processor, the number of letters displayed as feedback was restricted to 30, 25, 20, 15, 10, or 5, of the most recent letters. Visual feedback of letters was updated continuously during typing, with trailing letters outside of the post-view window blanked out with subsequent keystrokes. Paragraphs were randomly assigned to the restricted post-view conditions. The order of post-view conditions was assigned randomly for each typist. For all paragraphs, typists were instructed to type as quickly and accurately as possible, and to correct any errors that they noticed by using the backspace key.

## Results

**Explicit error detection and correction.** We first investigate explicit error detection and correction as measured by backspace key presses. For each error, we measured the number of keystrokes intervening between the erroneous keystroke and the backspace key. Collapsing across all typists, Figure 3B shows the proportion of errors that were corrected immediately following the error (zero) up to nine intervening keystrokes before the backspace key was pressed, for each of the restricted post-view conditions. Visual inspection of the figure shows a similar pattern across post-view conditions. Collapsing across post-view conditions, .46 of the errors were corrected immediately following the error, .28 were corrected with one intervening keystroke, .11 were corrected with two intervening keystrokes, .07 were corrected with three intervening keystrokes, and the remaining errors were corrected with four or more intervening keystrokes. These probabilities reflect the rates of detected errors that were detected at a given lag. Overall, typists detected and corrected 93% of their errors. The findings show that latency of error detection was relatively short, and usually shorter than our shortest post-view. Approximately half of the time, typists corrected their errors immediately, suggesting that explicit error detection can operate fairly quickly. However, the other half of the time, typists missed their errors as evidenced by the additional keystrokes that intervened prior to backspacing.

**Keystroke timing.** Figure 3A shows mean IKSIs for keystroke positions surrounding errors grouped by errors that were corrected with a zero to four keystroke correction delay. IKSIs were collapsed across the post-view restriction conditions. The keystroke positions are ordered but not always in immediate temporal order for each of the correction delays.

Correct keystrokes preceding the error (E − 1 = 154 ms) were faster than erroneous keystrokes (E = 201 ms), $F(1, 17) = 35.06$, $MSE = 2{,}814.55$, $\eta_p^2 = .67$. Some errors were not immediately corrected, so the figure next plots keystrokes E + 1 to E + 4, which involve intervening letters that were pressed prior to backspace. Interestingly, keystrokes following the error (E + 1 = 123 ms) were faster than keystrokes preceding the error (E − 1 = 154 ms), $F(1, 17) = 64.05$, $MSE = 595.24$, $\eta_p^2 = .79$. This is the first demonstration of a complete absence of post-error slowing following errors at the keystroke level. When typists are allowed to correct their mistakes, they show post-error speeding following uncorrected errors. Post-error speeding occurs on trials where an error was not immediately corrected, and typists may have been unaware that these errors occurred. Post-error speeding may also be accounted for by a trial-selection artifact. When an error is committed and subsequently detected, the need for a new corrective action arises. On some trials, typists may fail to stop the next letter press before pressing the backspace key, and this is more likely to happen when the next letter press has a fast than slow finishing time.

The slowest keystroke was the first backspace press (B1 = 416 ms). B2–B5 represent subsequent backspaces that were necessary for the one to four correction delay conditions. The

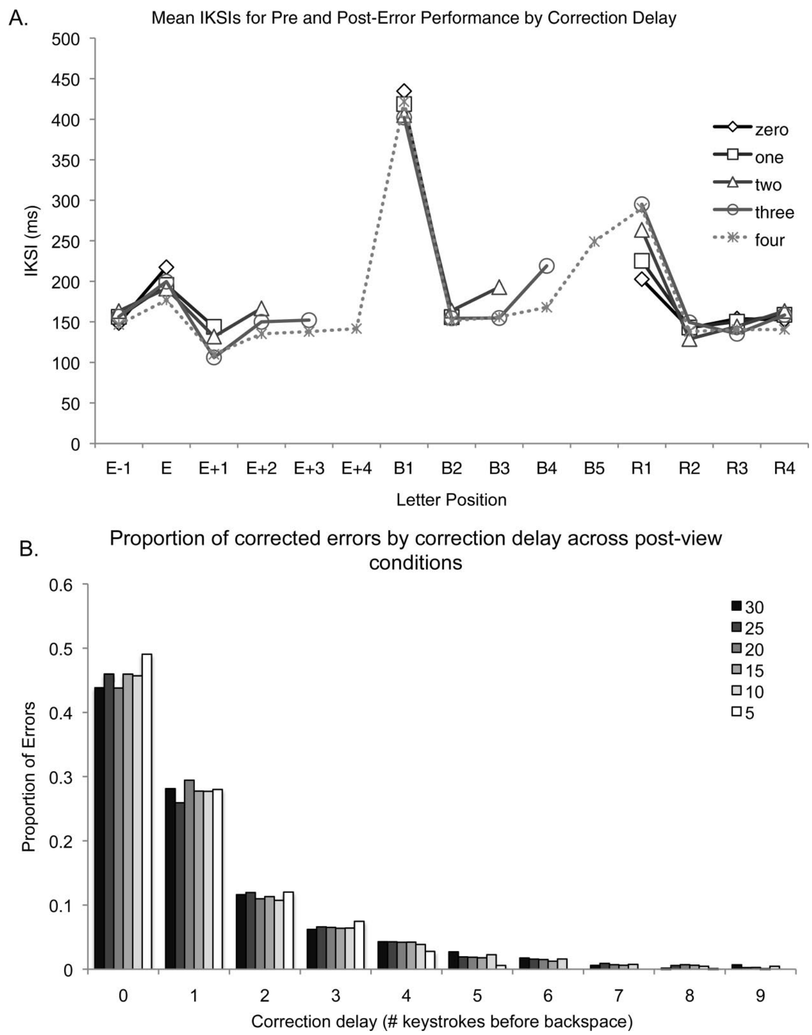


*Figure 3.* (A) Mean inter-keystroke-intervals (IKSIs) surrounding errors, collapsed across post-view conditions, for errors that were corrected with zero to four correction delay. Zero represents errors that were corrected immediately following the error. E − 1 is the keystroke prior to the error (E). E + 1 to E + 4 are letter keystrokes following uncorrected errors. B1 is the first backspace press to correct the error, and B2–B5 are successive backspace presses. R1 is the first correct keystroke following the final backspace press, and R2–R4 are the subsequent correct letter keystrokes. (B) Proportion of errors in each post-view condition that was corrected immediately or was delayed in correction by intervening keystrokes.

first backspace press is presumably slowest because it reflects both the time required for error detection and the time required to move the right hand little finger to press the backspace key. The figure shows that subsequent backspaces were made rapidly, and the rate of backspacing began to slow as the typist approached the incorrect letter.

When typists resumed typing, the first correct keystroke following the final backspace press (R1 = 255 ms) was slower than pre-error keystrokes (E − 1 = 154 ms), $F(1, 17) = 45.89$, $MSE = 10{,}075.1$, $\eta_p^2 = .73$. However, the next keystroke (R2 = 140 ms) was faster than pre-error keystrokes, $F(1, 17) = 6.19$, $MSE = 1{,}355.93$, $\eta_p^2 = .27$. It would appear that typists take approximately one keystroke to get back on track. However, resumption time may be even swifter. It takes time to move the right hand toward the home row and away from the backspace key. R1 slowing could be driven entirely by keystrokes that are made with the right hand. We examined this possibility looking at R1 IKSIs for left versus right hand keystrokes. We included only IKSIs from the zero correction delay condition as these had the largest number of observations per cell. Mean IKSIs for R1 right hand keystrokes (263 ms) were slower than pre-error IKSIS, $F(1, 17) = 60.98$, $MSE = 1{,}680.26$, $\eta_p^2 = .78$. Interestingly, Mean IKSIs for R1 left hand keystrokes (157 ms) were not significantly different from pre-error IKSIS, $F < 1$, $\eta_p^2 = .002$. Right hand keystrokes were presumably slower than left hand owing to the fact that the right hand takes time to move away from the backspace key. Looking only at the left hand responses, we see no evidence of a recovery period following error correction. After hitting bump and correcting for it, typists immediately put the pedal to the metal.

## Discussion

There are three important findings in Experiment 2. First, we found that typists detected half of their errors immediately before striking the next key. This value corresponds well with the estimate of the mixture probability in the distributional analysis, suggesting that error detection can occur quickly for some errors. This finding also fits well with prior work showing fast corrective responses following errors in choice-reaction time (RT) tasks (Rabbitt, 1966a, 1966b).

Second, we found post-error speeding instead of post-error slowing. Post-error slowing was observed only for backspace key presses, and those may have long latencies for physical reasons: The backspace key is located beyond the upper right corner of the keyboard and requires a stretch of the right-hand little finger to strike it. Post-error speeding was a very surprising result. It is consistent with the mixture-distribution fits in our distributional analysis in Experiment 1, which found a fast mode with a mean of –20 ms, suggesting post-error speeding for undetected errors. Post-error speeding is also consistent with our hypothesis that post-error slowing results from the requirement to inhibit the natural tendency to correct errors in experiments in which error correction is prevented. We allowed error correction in this experiment and found post-error speeding instead of post-error slowing. Post-error speeding is inconsistent with theories that assume post-error slowing results from persistence of the state of confusion that led to an error (Gehring et al., 1993), adjustments following error detection (Miltner et al., 1997), adjustments following conflict detection (Yeung et al., 2004), or surprise (Notebaert et al., 2009).

Third, this experiment is the first to report resumption times following error correction. We showed that typists immediately resume typing at their normal rate following error correction. This finding provides more evidence that typists do not engage in sustained prevention to reduce future errors.

# Experiment 3

Across Experiments 1 and 2, we showed that post-error performance in skilled typing depends strongly on whether typists can correct their mistakes. The purpose of Experiment 3 was to replicate these findings in a within-subject design. Experiment 3 was the same as Experiment 2 except that the backspace key was disabled for half of the paragraphs and was enabled for the other half. As well, a single post-view restriction condition (15 letters) was used for all paragraphs.

An overarching goal of Experiment 3 was to better establish relationships between the distributional analysis of post-error performance from Experiment 1 and the findings of Experiment 2. The distributional analyses showed post-error speeding for approximately half of all errors, and post-error slowing the other half. It is tempting to relate these findings to the probability of immediate error correction from Experiment 2, where we showed that approximately half of errors are detected immediately. Both of these findings speak to the reliability of the processes detecting errors. Error detection is reliable in the sense that typists detected and corrected most of their errors overall; however, the speed with which errors are detected is variable. Typists failed to immediately detect errors approximately half of the time. We suggested that the post-error slowing observed for half of the errors in Experiment 1 was the result of an inhibition process. When typists were not allowed to correct their errors they inhibited the automatic tendency to press the backspace button. The data imply variability in the retrieval of backspace presses following an error as post-error slowing only occurred half of the time. In Experiment 2, typists were allowed to correct their errors. They did so 93% of the time, and they did so immediately about half of the time, presumably on occasions where the error successfully retrieved the backspace press. When typists failed to detect their error immediately, they showed post-error speeding rather post-error slowing: They failed to retrieve backspace key presses and so did not need to inhibit them. Experiment 3 tests this hypothesis in a within-subjects design. We expected the same typists to show post-error slowing when they were not allowed to correct errors and post-error speeding when they were allowed to correct errors.

We registered use of the backspace key in both conditions of Experiment 3. In all of our previous experiments in which typists were not allowed to correct errors, we completely disabled the backspace key, and the computer did not record these key presses if they were made. It is possible that our previous evidence of post-error slowing can be explained by spurious keystrokes to the disabled backspace key. For example, the post-error slowing in Experiment 1 may be driven by typists noticing their errors and then attempting to press the backspace key. The backspace was not recorded, but pressing the key would cause time to elapse and produce the observed post-error slowing. In Experiment 3, we recorded all backspace key presses, even when typists were not allowed to correct errors. In the condition where typists were not allowed to use the backspace key, we expected post-error slowing. If post-error slowing results from spurious backspace key presses, we should see post-error slowing only when typists spuriously type the backspace key. If post-error slowing results from inhibiting the tendency to correct errors, we should see post-error slowing when typists do not strike the backspace key.

## Method

**Subjects.** Subjects were 18 students from Vanderbilt University who were recruited for their self-reported ability to type 40 WPM. Their mean typing speed was 91 WPM (range = 89–133 WPM); their mean typing error rate was 10% (range = 3%–20%). All subjects were compensated $12 for 1 hr of participation. All subjects had normal or corrected-to-normal vision and spoke English as a first language.

**Apparatus and stimuli.** The experiment was conducted on a PC using a 15-in. (38.1-cm) SVGA monitor controlled by METACARD software. Typing responses were registered on a standard QWERTY keyboard. The typing task involved copy-typing one the same paragraphs used in Experiment 2.

**Procedure.** For all paragraphs, post-view was restricted to 15 letters. Typists transcribed 24 total paragraphs taken from the six paragraphs used in Experiment 2. Each of the paragraphs was typed twice with the backspace key enabled and twice with the backspace key disabled. When backspace was enabled, typists were instructed to correct their mistakes. When backspace was disabled, typists were instructed to ignore their mistakes, continue typing as normal, and avoid pressing the backspace key. In the backspace disabled condition, the backspace key did not delete letters from the screen; however, presses to this button were registered by the computer. Backspacing was enabled or disabled in a blocked design. Typists completed one group of 12 paragraphs with one instruction, the remaining group with the other instruction. Whether typists received enabled or disabled paragraphs first was randomized. For each paragraph, typists were given on screen instructions indicating whether backspacing was enabled or disabled. These instructions remained onscreen throughout typing of each paragraph.

## Results

Our primary aim was to determine whether post-error slowing depends on the task demand to allow or disallow correction via backspacing. Figures 4 and 5A show mean IKSIs surrounding errors for backspace disabled and enabled conditions, respectively. Visual inspection shows post-error slowing when the backspace key was disabled, and post-error speeding when the backspace key was enabled, replicating the patterns Experiment 1 and 2 within individual typists.

**Backspace disabled paragraphs.** The overall word-level error rate for the backspace disabled paragraphs was .10, or 11.1 incorrectly typed words per paragraph. For each typist and for each paragraph, we measured the prevalence of spurious backspace presses as the number of backspace presses divided by the total number of errors. For each error, the average rate of spurious backspace presses was .10, or .96 spurious backspace presses per paragraph. Spurious backspaces presses did occur, but they did not occur very often.

We note that typists were explicitly instructed not to press the backspace key, and there was a constant on screen reminder present during the paragraph typing task. In addition, the backspace disabled paragraphs were presented in a blocked fashion. Typists had experience with 12 successive paragraphs under the same task instructions. Consequently, there was sufficient time for each typist to adjust to the task demand. The fact that spurious backspacing exists, despite ample preparation, instruction, and immediate feedback that the backspace was disabled, further demonstrates the pre-potent nature of the backspace response following errors.

Importantly, keystroke times for words where typists pressed the backspace key were not included in analysis of post-error performance. Figure 4 shows mean IKSIs for pre- and post-error performance. Mean IKSIs were 169 ms, 200 ms, 390 ms, 314 ms, 261 ms, 216 ms, and 199 ms in the E − 1, E, E + 1, E + 2, E + 3, E + 4, and E + 5 conditions, respectively. Replicating the pattern from Experiment 1, we show significant post-error slowing: The keystroke following the error was slower than the keystroke preceding the error, $F(1, 17) = 88.58$, $MSE = 4{,}987.62$, $\eta_p^2 = .84$. We also see that typists somewhat gradually resume normal typing over several keystrokes. Even by E + 5 they are not fully back to pre-error speeds, $F(1, 17) = 14.25$, $MSE = 577.63$, $\eta_p^2 = .46$. However, we know from Experiment 1 that post-error slowing does not persist across words, so overall the recovery remains fairly rapid.

**Backspace enabled paragraphs.** The overall word-level error rate for the backspace disabled paragraphs was .13, or 14.57 incorrectly typed words per paragraph. Figure 5A shows mean IKSIs for the keystrokes surrounding errors for the backspace-enabled paragraphs. The overall pattern replicates the basic findings from Experiment 2 shown in Figure 3A. Owing to a small number of observations per cell, the data from the correction delay four condition were not included in the analysis.

We focus on the most important finding: Post-error slowing was not observed for keystrokes following errors that were not immediately corrected. Instead, we again found evidence of post error speeding. E + 1 IKSIs (138 ms) were faster than E − 1 IKSIs (160 ms), $F(1, 17) = 4.30$, $MSE = 3{,}119.00$, $p < .06$, $\eta_p^2 = .20$.

The remaining timing data replicated the pattern of findings from Experiment 2. Mean E IKSIs (207 ms) were slower than E − 1 IKSIs, $F(1, 17) = 13.53$, $MSE = 5{,}374.72$, $\eta_p^2 = .44$. The first

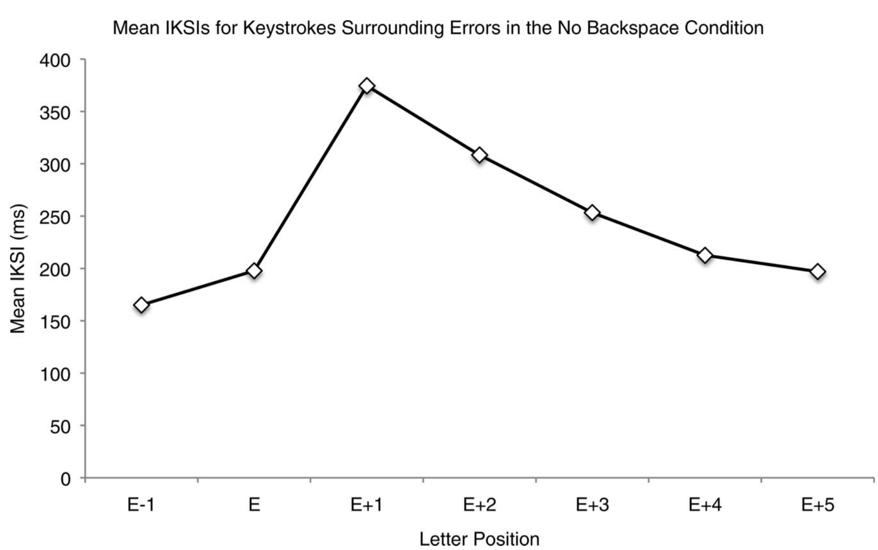


*Figure 4.* Mean inter-keystroke-intervals (IKSIs) for keystrokes surrounding errors in the backspace disabled condition. E − 1 is the keystroke prior to the error (E). E + 1 to E + 5 are letter keystrokes following uncorrected errors.

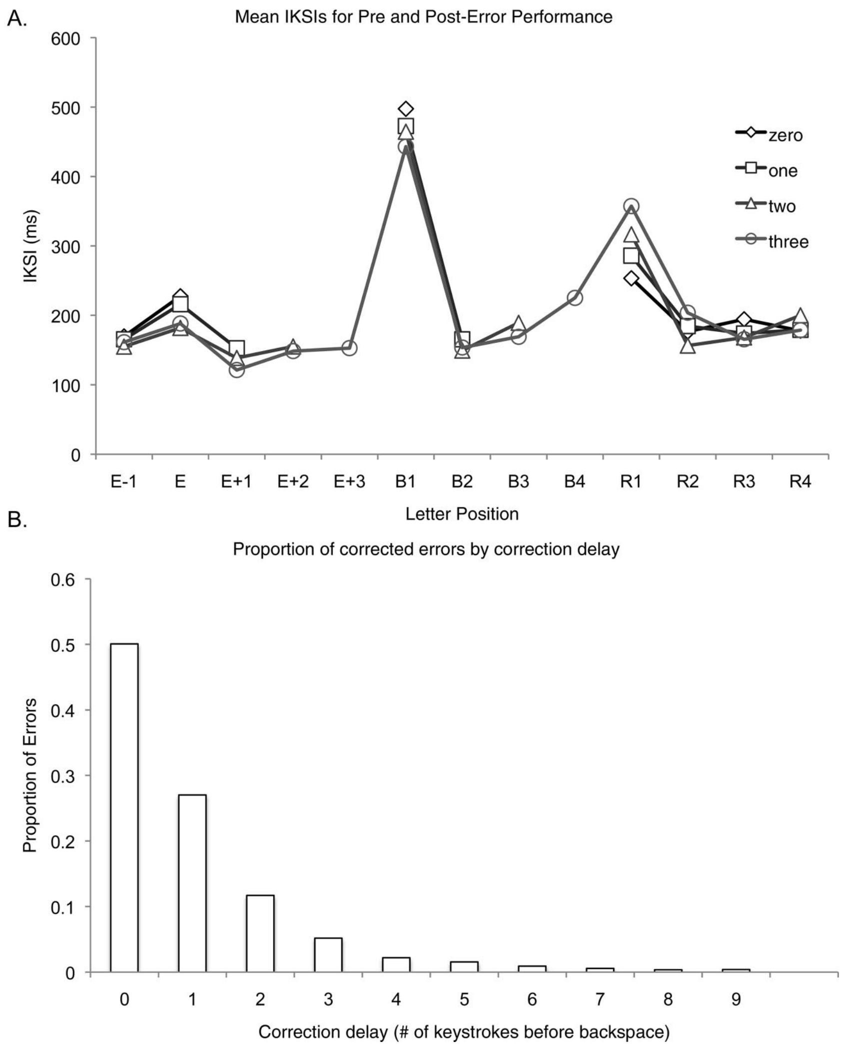


*Figure 5.* (A) Mean inter-keystroke-intervals (IKSIs) for keystrokes surrounding errors in the backspace enabled condition. E − 1 is the keystroke prior to the error (E). E + 1 to E + 3 are letter keystrokes following uncorrected errors. B1 is the first backspace press to correct the error, and B2–B3 are successive backspace presses. R1 is the first correct keystroke following the final backspace press, and R2–R4 are the subsequent correct letter keystrokes. (B) Proportion of errors that was corrected immediately or was delayed in correction by intervening keystrokes.

backspace press was the slowest response (B1 = 469 ms). The first resumed response (R1 = 303 ms) was slower than pre-error IKSIs, $F(1, 17) = 64.47$, $MSE = 11{,}111.80$, $\eta_p^2 = .79$, and the next response (R2 = 180 ms) was not significantly different from pre-error IKSIs, $F(1, 17) = 1.11$, $MSE = 11{,}703.4$, $p < .31$, $\eta_p^2 = .06$.

As with Experiment 2, we report variability in explicit error detection by measuring the number of keystrokes intervening between the erroneous keystroke and the backspace key. Collapsing across all typists, Figure 5B presents the proportion of errors that were corrected immediately following the error (zero) up to nine intervening keystrokes before the backspace key was pressed. Visual inspection shows similar results to those found in Experiment 2. Overall, 86% of errors were corrected; of these, 50% of the errors were corrected immediately following the error, 22% were corrected with one intervening keystroke, 12% were corrected with two intervening keystrokes, 5% were corrected with three intervening keystrokes, and the remaining errors were corrected with four or more intervening keystrokes.

## Discussion

Post-error slowing was observed when the backspace key was disabled, and typists were instructed to continue typing following an error without pressing the backspace key. Post-error speeding was observed when the backspace key was enabled, and typists were instructed to correct their mistakes. These findings support the novel hypothesis that post-error slowing results from inhibiting the automatic tendency to correct errors. The results rule out the possibility that post-error slowing results from spurious pressing of the disabled backspace key. Spurious backspace key presses were rare, and post-error slowing was observed when the backspace key was not pressed.

## General Discussion

Our findings support a distinction between prevention and cure in post-error performance. Across three experiments, typists showed no evidence of prevention following errors. They did not slow down or improve accuracy following errors. Instead, typists showed evidence of a cure perspective. When they were allowed to correct their mistakes, they typed at their normal rate unless they were in the process of correcting their error. The action to correct an error was slow, but there was no speed cost in resuming typing following correction.

We show that post-error slowing, which is a ubiquitous phenomenon across many performance tasks, does not occur following every error. We demonstrate that allowing typists to correct their mistakes causes dramatic changes in post-error performance. When typists were allowed to correct their mistakes, we found significant post-error speeding. When typists were not allowed to correct their mistakes, we found significant post-error slowing. The data support a new cure perspective on post-error slowing in skilled typing: Post-error slowing reflects inhibition of the pre-potent tendency to make corrective actions following an error.

### Explicit and Implicit Error Detection Processes

We have proposed that error-detection in skilled typing is controlled hierarchically by two processing loops (Logan & Crump, 2010, 2011a, 2011b). The outer loop monitors feedback from the screen and mediates awareness of the error. The inner loop is sensitive to kinesthetic feedback and mediates post-error slowing. Our prior work supported this division of labor by dissociating illusions of error awareness from post-error slowing in typing performance. Our present findings further support an inner-loop error-detection process and suggest that rapid detection of errors activates pre-potent responses to the backspace key. When typists are not allowed to make corrective actions, they exhibit post-error slowing driven by inhibition of the pre-potent backspace response.

Our findings raise important questions about the relationship between explicit and implicit error detection processes. We found that explicit error detection can occur immediately following an error, but often occurs with some delay. It is tempting to speculate that implicit error detection processes provide signals to explicit processes that play a role in determining the speed of explicit detection. When typists can correct their mistakes, they do so immediately about half of the time. When typists cannot correct their mistakes, post-error slowing is observed about half of the time. Putting these observations together suggests that variability in implicit error detection processes controls the speed of explicit error detection. That is, rapid corrective actions in continuous typing may be triggered by signals produced by implicit error detection processes.

We suggest that implicit error detection develops alongside skill in normal typing. Early in learning, typists make many mistakes, and they make voluntary corrective actions to fix them. The same learning processes that automatize typing would also automatize the actions necessary for corrections. In this way, implicit error-detection abilities emerge and become automatized as a by-product of explicit monitoring throughout skill learning.

### Implications for Other Tasks

Although we have focused specifically on skilled typing, our approach has wider implications for research into error detection and performance monitoring in general. In most laboratory tasks, participants are asked to make a single response to a target. They either make the correct response or they make a mistake, and there is no opportunity for corrective action. Similarly, in some real-world tasks like music, dance, or sports, the performer is not able to repeat actions to correct a mistake but must continue their performance after an error is committed. Our findings show that giving participants the opportunity to correct their mistakes can strikingly alter post-error performance. Post-error slowing was not observed when typists were allowed to correct their mistakes. By contrast, post-error slowing was observed when typists were not allowed to correct their mistakes. We speculate that observations of post-error slowing in other tasks may owe to task demands that prevent performers from correcting their mistakes.

In the Introduction, we identified several general task demands that shape whether post-error performance shows prevention or cure. We described how demands such as timing, deadline flexibility, repeatability, and deletion/erasure guide post-error performance. Tasks high in timing constraints, where actions must be performed in precise time steps, offer little opportunity for correction; tasks low in timing constraints may allow and encourage correction. Tasks high in deadline flexibility allow mistakes to be corrected before deadlines, whereas tasks low in deadline flexibility do not. Tasks high in repeatability allow repeated actions to stand for prior actions, whereas tasks low in repeatability do not. Tasks allowing deletion ensure that errors can be wiped from the performance record, whereas tasks disallowing deletion ensure that errors are preserved in the record. Different tasks stress different task demands and can lead performers to adopt prevention or cure following errors.

### The Role of Error Detection in Skilled Performance

In addition to task demands, error detection could have different functions across levels of skill. Novices are slow and error prone compared to experts, and error detection helps novices learn the speed/accuracy tradeoff function. Errors show the learner that components of their skill need further training. Rabbitt and Vyas (1970) described this process as tracking. In choice-RT tasks, participants are often instructed to respond quickly and accurately; however, participants may not know their limits in terms of speed and accuracy. Participants can home in on their perceived optimal speed and accuracy level by speeding up to the point of making errors and then backing off a little, using errors to discover their own speed/accuracy tradeoff function. They may adopt a heuristic to slow down after errors and speed up after correct responses as a kind of staircase tracking procedure to reach optimal levels of responding. In this way, error-detection during skill acquisition can play a pivotal role in the learning processes shaping the skill. This also fits with conventional views of human and animal learning processes that rely on error signals to update associations between predictions and outcomes during performance (Rescorla & Wagner, 1972; Widrow & Hoff, 1960).

Highly skilled performers may not use error detection for prevention and adjustment because their skill is already fully optimized. Experts "know" their current speed/accuracy tradeoff function, and as a result, they may cease to make prevention adjustments following errors (Rabbitt, 1969; Welford, 1967). However, even experts make mistakes, and a challenge for experts is to determine whether their errors are expected or unexpected given a particular level of skill. For example, a basketball player with a free throw percentage of 80% would expect to miss 20% of the time. After missing a shot the player may accept the error as expected given their level of skill, and continue to play without making post-error adjustments—after all, their unadjusted level of performance will produce 80% baskets over the long run. The terms expected versus unexpected are used to refer specifically to errors that should or should not occur given a performers level of skill. This is unrelated to the question of whether performers can predict and perhaps prevent upcoming errors.

Determining whether an error is expected or unexpected is a metacognitive performance problem (Dunlosky & Metcalfe, 2009). Expected errors do not reflect deterioration in skill and they ought not lead to performance adjustments. Unexpected errors indicate a drop in performance level. If the above basketball player misses 40 out of 100 free throws, perhaps performance adjustments are required. Failing to distinguish between errors that are expected and unexpected may lead performers to make post-error adjustments when they are not required. Treating an expected error as unexpected may lead the performer to adjust their performance to focus attention on component skills and cause further deterioration of performance (Beilock et al., 2002; Logan & Crump, 2009). Treating unexpected errors as expected may induce a temporary illusion that performance is not suffering, and prolong the period before adjustments are made. Skilled performers must monitor their own performance and balance the need for adjustment following unexpected errors and the need for persistence following expected errors.

We suggest that acts of correction—in tasks where correction can be accomplished——or acts that simulate correction—in tasks where correction is not possible—allow skilled performers to balance their response to expected and unexpected errors. Our findings show that errors in typing automatically retrieve corrective actions in skilled typists. Corrective responses are also rapidly retrieved following errors in choice-RT tasks (Rabbitt, 1966a, 1966b). We suspect that errors in other skilled domains also automatically retrieve corrective actions, or retrieve what would have been the correct action. In typing, we found that about half of the errors triggered immediate correction. We suggest there may be similar variability for other skills. Expected errors emerge as part of a performer's current skill level and may be associated with corrective responses. These errors are most familiar and are likely to be corrected frequently. Unexpected errors emerge when skilled performance shifts away from optimal, and may not be familiar and may not be strongly associated with corrective responses. Performers may rely on the availability of corrective responses following errors as a cue to determine whether they engage in prevention following the error, or whether they correct the error and persist in their current mode of performance without further adjustment.

## Error Detection and Correction Across Domains

Research into error detection processes spans multiple domains and levels of analysis. Three major domains include motor control, speech production, and cognitive control. Within each domain, error detection has been investigated at the behavioral, computational, and neurophysiological levels. A full review of the advances in each domain is beyond the scope of this article; nevertheless, it is worth highlighting different perspectives on error detection processes across literatures as they relate to the prevention versus cure distinction.

## Error Detection and Correction in Motor Control

A broad range of tasks with different task demands, from typing, talking, and walking, to reaching, touching, and grasping, engage motor control. Whether prevention or cure follows errors in performance depends on how each task balances timing, deadline flexibility, repeatability, and deletion demands. Everyday movements like reaching for and grasping a cup of coffee require coordination between multiple sub-processes involved in action planning, action execution, and online monitoring systems mediating rapid, on-the-fly adjustments to ongoing actions. Highly trained movements, like those involved in typing, additionally involve adaptive longer-term learning and memory processes that stabilize adjustments to planning and execution processes.

Computational accounts of motor control systems invoke error detection as a fundamental processing principle guiding coordination of these motor control sub-systems (Jordan & Rumelhart, 1992; Wolpert et al., 1995). For example, when motor plans for action are translated into motor effector movements, the sensory effects of the movement provide feedback signals that may or may not match well with the predicted outcome of the intended action. Evaluation of such discrepancy signals is one form of error detection that can be used to modify motor plans for future action. Error detection based solely on sensory feedback can involve too much temporal delay for the feedback to adaptively control more rapid movements, such as those found in typing or music performance (Lashley, 1951). Control of rapid movements can be achieved computationally through an internal (forward) model or simulation of the action. Here, motor plans feed both action execution and action simulation processes. Error signals based on feedback from the simulation can be used to predict future action states and make online adjustments to the motor plans controlling current movements. Such internal models have increased neurophysiological support and account for online adjustments in reaching and grasping tasks (for a review, see Davidson & Wolpert, 2005). Finally, longer-term adjustments to motor plans involved in motor learning can also be computationally specified in terms of internal models that rely on similar error detection signals (Jordan & Rumelhart, 1992; Miall & Wolpert, 1996).

From the perspective of motor control, error detection is a general processing principle mediating transient (online) and long-term (learning-based) adjustments to performance. Error detection involves a comparison between intended and observed or simulated actions. The comparison generates an error signal controlling adjustments to current or future actions. From this view, error detection involves both prevention and cure. Mistakes in ongoing actions can be immediately adjusted to correct errors, and adjustments can carry forward to prevent future errors. Longer-term motor learning processes create stable action plans that accomplish environment-specific goals. In the context of typing, we assume that the same learning processes guiding fingers to correct keyboard locations are also at play in correcting errors. Typists have extensive experience with correct and incorrect keystrokes, and we assume they have developed learned action plans for corrective keystrokes (e.g., pressing the backspace button) in response to errors. Indeed, when typists are prevented from making backspace presses, we assume that observed post-error slowing reflects inhibition of the pre-potent corrective response.

## Error Detection and Correction in Speech Production

Like speaking, the act of typing is a form of language production. Speakers and typists make mistakes during production and in both domains corrective actions are possible. In typing, correction is achieved via the backspace key. In speech production, correction or self- repair occurs less directly. For example, speakers may immediately follow an incorrect utterance by the correct utterance, or they may signal their correction using a corrective phrase (e.g., "oops, I meant to say . . .") indicating their following utterance will be a correction. Different speaking situations balance timing, deadline flexibility, repeatability, and deletion task demands differently and may lead speakers to engage in more or less prevention and correction. Informal speaking situations where a friendly audience is prepared for verbal slips may encourage correction and discourage prevention. Mistaken utterances can be repaired by self-repairing correct statements without penalty, and speakers may not attempt to adjust their speaking style because they are confident that the audience understands the relevant portions of dialogue. Formal speaking situations can be less forgiving, and verbal slips could encourage prevention and adjustment. Here, verbal slips or poorly chosen words could be followed by a period of composure and then by slower, re-formed, well-articulated statements that better convey intended meaning.

There are several theories of error detection and correction in speech production (for a review, see Postma, 2000). Prominent theories of error detection and correction in speech production (Levelt, 1983) share many similarities with the outer/inner loop theory of typing (Logan & Crump, 2011a, 2011b). Like typing, speech production is controlled by hierarchically organized processing loops involved in conceptualizing the meaning of a sentence, sentence construction, and lower level loops involved in production of utterances. Error detection occurs through self-monitoring at various levels of processing. Speakers may monitor the auditory feedback from their own verbal output, or they may monitor simulated verbal output using inner speech. There is ample support for the notion that error detection is not driven by a specialized process but instead is achieved through the same speech comprehension process employed in understanding the speech of others. Speakers simply monitor their own speech and employ their own comprehension system to detect errors and initiate self-repair.

More recently, Nozari, Dell, and Schwarz (2011) have suggested that in addition to self-monitoring, error detection in speech production can be accomplished through more generic error detection systems involved in cognitive control that are summarized in the next section.

Self-monitoring during speech production affords both prevention and cure. Errors in speech detected by the comprehension system could signal adjustments to speech that allow speakers to construct error free utterances. Errors detected by comprehension can also signal self-repair and thereby provide an immediate cure for the mistake. Like typing, speech is an acquired skill. We assume that learning processes involved in correct speech production are also involved in self-repair and that self-repair attempts may be highly automatized. In the present experiments, we show that preventing participants from making corrections dramatically disrupts post-error performance. We imagine that similar disruptions would occur in speech production if speakers were instructed to inhibit self-repair attempts or were penalized for making self-repair attempts following errors, as speakers would need to inhibit the pre-potent self-repair actions. If self-repair in speech is automatized through skill learning, as we assume with backspacing in typing, then we would expect that speech disruptions due to self-repair prevention ought to scale with skill level. Curing speech errors through self-repair may not be routinized in early or second language learners, as a result self-repair may both be less frequent following errors, and less disruptive to speech in tasks requiring blocking of self-repair attempts.

## Error Detection and Correction in Cognitive Control

Errors in performance are a general phenomenon, and research on cognitive control has focused on generic error detection processes that apply across performance domains. Monitoring and adjustment processes have been studied across a range of traditional cognitive tasks from simple and choice RT tasks to Stroop and Flanker tasks involving selective attention demands. Participants in these studies are often new to the task, and in general the balance of timing, deadline flexibility, repeatability, and deletion task demands fit better with prevention than cure. Task instructions usually stress speed and accuracy, thus emphasizing both precise timing and limiting deadline flexibility. Typically, a single response is required for each trial and there is no opportunity for correction, thus limiting repeatability and deletion.

Behavioral measures consistently show post-error slowing across tasks (Danielmeier & Ullsperger, 2011). Neurophysiological measures have identified ERP components such as the error-related negativity (ERN) and error-related positivity (Pe) involved in error detection, and fMRI studies have localized error-detection signals to a network of brain regions including the anterior cingulate cortex (ACC) and posterior medial frontal cortex (pMFC; for a review, see Ullsperger, Harsay, Wessel, & Ridderinkhof, 2010). Error detection could rely on a monitoring system that detects mismatches between action outcomes and expected outcomes (Falkenstein, Hohnsbein, Hoorman, & Blanke, 1990; Gehring et al., 1993) and on monitoring of conflicting responses competing for action (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Holroyd, Yeung, Coles, & Cohen, 2005). These error detection processes are generic in the sense that they operate across tasks. And, they are hierarchical as they operate in concert with lower-level error detection processes involved in motor control (Krigolson & Holroyd, 2006, 2007).

Much of the work on error detection in cognitive control has employed reaction time tasks that do not allow participants to make corrective responses. As a result, investigations have focused on error detection for preventing future errors rather than correcting current errors. For example, error-detection signals are thought to drive adjustments to processes controlling performance to reduce future errors. These adjustments may come in the form of post-error slowing, or in the form of increased attention to task relevant information (Maier, Yeung, & Steinhauser, 2011). Error-detection signals are used for adjustment and do not simply signal that an error occurred. For example, the size of the ERN following errors correlates with the amount of post-error slowing (Holroyd et al., 2005), suggesting that the strength of error-detection signals drives the amount of post-error adjustment. And, the ERN and Pe are both larger for detected than undetected errors (Steinhauser & Yeung, 2010).

Although there has been more focus on error detection processes from a prevention perspective than a cure perspective, the cognitive control literature has made efforts to understand processes involved in making corrective actions. In early behavioral work, Rabbitt (1966a, 1966b) showed both post-error slowing following errors but also demonstrated that participants often follow errors with fast correct responses (Rabbitt, 2002). These correct responses could be the driven by the output of an error detection process or could be driven by response priming.

More recent studies have shed new light on connections between error-detection and correction processes. By varying task-demands like repeatability, the rate of corrective responding can come under voluntary control and can be in increased or decreased through task instruction (Fiehler, Ullsperger & Von Cramon, 2004, 2005; Rodríguez-Fornells, Kurzbuch, & Münte, 2002). Corrective responses are faster for incidental corrections produced by participants who were not instructed to make corrections than participants who were instructed to make corrections (Fiehler et al., 2004, 2005). ERN amplitude is larger for corrected than uncorrected errors (Gehring et al., 1993; Rodríguez-Fornells et al., 2002). Finally, correction-related ERNs occur for incidental and fast and slow instructed corrections, and they are delayed for slow than fast instructed corrections (Fiehler et al., 2005).

Taken together, these findings show two important insights. First, error detection processes are involved in signaling the need for corrective actions. Second, corrective actions can be controlled voluntarily and involuntarily. Evidence for voluntary control comes from the finding that task instructions change the rate of corrective responding. Evidence for involuntary control comes from the finding that correction-related ERNs occur even when corrections are made incidentally.

Our findings fit well with these prior observations and suggest interesting extensions. Our results show that post-error slowing in typing is driven by inhibition of the automatic tendency to correct by pressing the backspace key. We assume that error detection processes automatically trigger the need for a corrective response. The corrective actions in our task involved pressing a backspace key following an error, whereas corrective actions in the previously described forced-choice RT tasks involved repeating a correct response following an error. The nature of our task permits us to conclude that our corrective actions were not simply primed correct responses but were instead corrective actions taken to repair errors. We also show variability in the error detection and correction. When the backspace key is disabled, we show that post-error slowing occurs following approximately half of all errors, and when the backspace key is enabled, we show that typists correct their errors immediately on the next keystroke about half of the time. We assume that post-error slowing following errors in the disabled conditions and that fast immediate corrections in the enabled conditions are driven by an involuntary error detection process. For delayed corrections in the backspace enabled conditions, we assume that voluntary processes monitoring visual feedback detect the error and signal the need for correction. This fits with our assumption that error detection in typing involves hierarchical processing loops (Logan & Crump, 2010, 2011a, 2011b) and that error detection more generally is hierarchical involving lower-level action systems and higher-level cognitive control systems (Krigolson & Holroyd, 2006, 2007).

## Unifying Approaches to Error Detection

We have described several perspectives on error detection and correction across the domains of motor control, speech production, and cognitive control. There are domain-specific and general approaches, and there is much overlap between perspectives across domains. The cognitive control literature in particular has identified a generic error-detection system that operates across tasks. This both presents the possibility of a unified approach to error-detection across domains and raises questions about how error detection is optimized for tasks where error detection serves different functions like prevention and cure.

In summarizing perspectives on error detection across motor control, speech production, and cognitive control domains, it is clear that error detection processes operate at multiple levels. There are domain-specific error detection processes. For example, the error-detection processes guiding reaching and grasping movements are different from the comprehension processes detecting errors in speech production. At the same time, there are domain-general error detection processes. For example, conflict-monitoring processes can signal errors across a range of lower level motor tasks, attention and performance tasks, and higher-level cognitive tasks like speech production. All of these error detection processes can be thought of as working in concert in a hierarchically organized fashion. In a task like typing, where motor control processes will tune finger movements during typing, response conflict monitoring processes could provide signals that are useful for error detection, and higher level voluntary processes will compare planned outputs with expected outputs to detect errors. The contribution of our present findings is to show that the function of these error detection processes is not always to inspire adjustments and cause the performer to proceed with caution to prevent future errors. In tasks like typing, talking, and expert performance domains where performance is already highly optimized, the function of error detection is directed to cures. The cure could simply be to weather the storm and continue performing at a high level without making unnecessary adjustments or to immediately repair performance through corrective action.

## Conclusion

The distinction between prevention and cure raises questions about what performers should do following an error: to correct or not to correct, to adjust or not to adjust. Part of this decision is tied closely to task demands such as timing, deadline flexibility, repeatability, and deletion. Tasks that require temporal precision, that are low in deadline flexibility, and that do not allow repetition or deletion encourage prevention over cure. Tasks that are low in temporal precision, that are high in deadline flexibility, and that allow repetition and deletion can encourage cure over prevention. Part of the decision is tied to skill level. Novices making mistakes have more to learn and should make adjustments to prevent future errors. Experts may be better served by accepting their mistakes, correcting them if possible, and moving on without adjustment. Prevention and cure distinguish between two broad strategies shaping reactions to error that are widespread across performance domains. The distinction raises new direction for understanding the function and nature of error detection processes. We suggest that the error detection processes leading to correction and those leading to post-error adjustments in speed and accuracy may be distinct. There are different kinds of errors, some that can be cured and others that can only be prevented in the future; this suggests that there may be many different kinds of error detection, different styles of post-error responding, and many different causes of post-error slowing.

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