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Episodic Contributions to Sequential Control: Learning From a Typist's Touch

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Sequential control over routine action is widely assumed to be controlled by stable, highly practiced representations. Our findings demonstrate that the processes controlling routine actions in the domain of skilled typing can be flexibly manipulated by memory processes coding recent experience with typing particular words and letters. In two experiments, we extended Masson's (1986) procedure for measuring item-specific learning in the context of acquiring an unfamiliar skill to the highly skilled domain of typing. Skilled typists' performance improved during practice with typing words composed from a specific set of letters. In a transfer phase, performance was fastest for trained words, followed by new words composed of trained letters, and slowest for new words composed of untrained letters. The finding that recent episodic experience with typing particular words and letters influences skilled typing performance holds widespread implications for theories of typing, sequence learning, and motor control.

Keywords: episodic retrieval, serial ordering, typing, cognitive control

Sequential control of action supports a wide range of abilities from language production, everyday activities such as walking, making coffee, or driving a car, skilled performance domains like dance, music and sports, and performance in routine skilled tasks such as handwriting and typing (for reviews, see Houghton & Hartley, 1995; Rhodes, Bullock, Verwey, Averbeck, & Page, 2004). In domains such as skilled typing, the focus of our current investigations, successful task performance relies on a series of specific, well-practiced movement patterns for keystroke execution (Rieger, 2004). Models of typing (John, 1996; Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008) assume that reliable keystroke execution is controlled by stable schemas developed through years of practice. Our experiments test the notion that skilled typing could be controlled by episodic memory processes involved in coding the details of individual typing experiences. To this end, our experiments were designed to determine whether performance can be flexibly manipulated by recent experience with typing particular letters and words.

As with most skills, typing relies on multiple levels of component skills. Theories of typing and routine action (Cooper & Shallice, 2000, but see Botvinick & Plaut, 2004) assume that components are organized in a hierarchical fashion. In the microcosm of typing, actions are assumed to be hierarchically controlled by representations at the word, letter, and intermediate (bigram, trigram, etc.) levels. For example, typing rate slows as the structure of the letter string is modified from familiar words to random sequences (Hershman & Hillix, 1965), and typing rate is faster for frequent versus infrequent words (Inhoff, 1991). Furthermore, early in skill development keystroke execution relies on serial finger movements that give way to more overlapping parallel movements catered to the higher level structure of the to-be-typed sequence (Flanders & Soechting, 1992; Gentner, 1983).

The emergence of hierarchical processing is thought to rely on gradual chunking of elemental processes (Newell & Rosenbloom, 1981). In typing, perhaps the most elemental process is typing individual letters, followed by typing bigrams, trigrams, words, and finally sentences. With practice, lower level chunks like letters and bigrams are more frequently experienced than higher level chunks like trigrams and words (Newell & Rosenbloom, 1981). As a result, the underlying representations controlling typing for letters and bigrams should be more robust (i.e., further down the learning curve and less susceptible to change) than the representations controlling higher order combinations such as trigrams and words.

Although theories of skill acquisition and routine action accept the idea that complex routines are controlled hierarchically, theories offer different assumptions about how representations gain stability with practice. The representation of complex skills has been described in terms of schemas (Cooper & Shallice, 2001; Lashley, 1951; Norman & Shallice, 1986), distributed connectionist representations (Botvinick & Plaut, 2004), and memory instances (Logan, 1988). Chief among the differences between these views is whether the stability afforded by well-practiced representations is a property of encoding processes operating during the learning period, or a property of retrieval processes operating after the learning is over. Schema and connectionist accounts assume that stability is achieved during encoding, through processes responsible for tuning a summary representation of the intended action (either centralized in the case of schemas, or distributed in

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the case of connectionist accounts). With years of practice, the tuning process would gradually filter out irrelevant information, resulting in the formation a stable summary representation for the control of a particular action.

In contrast, instance accounts assume that stability can emerge during memory retrieval[1]. On this view, rather than filtering out irrelevant details during encoding, all of the details of specific performance episodes occurring over the course of practice are preserved in memory. In this way, depending on current task demands, retrieval processes can pool across a set of episodic traces, and this aggregate retrieval of many similar instances would provide stability to performance, as the average of the pooled instances would provide reliable directions for action. More important, instance based theories assume that all past experiences—remote and recent—are preserved in memory, and thereby allow the retrieval of recent experiences to shape performance, even in well practiced domains. In contrast, schema and connectionist theories would assume that recent experiences with performing a well-practiced routine would have minimal impact on the overlearned summary representations controlling performance.

The empirical goal for the present experiments was to discover whether the details of recent typing experiences can influence performance in skilled typists. A result of this nature would suggest that episodic representations coding recent experiences participate in the control of skilled typing. To this end we manipulated skilled typists' recent experience by having them type particular words and letters, and then tested their performance for typing trained and untrained letters and words.

Across two experiments we adapt a procedure developed by Masson (1986) demonstrating that the skill of reading mirror-reversed words depends on training with specific items. Masson created two groups of words constructed from different sets of letters. For example, one set of words was made from the letters a, b, d, g, i, j, l, n, q, s, u, v, and x, and another set was made from the remaining letters in the alphabet, z, w, e, c, r, f, t, y, h, m, k, o, p. The training phase involved reading aloud mirror-reversed words constructed from one letter set, and a transfer phase involved reading aloud old words from the training phase (old letters, old words: old/old), new words created from the trained set of letters (old letters, new words: old/new), and new words created from the untrained set of letters (new letters, new words: new/new). Transfer phase performance demonstrated faster reading times for practiced old/old than old/new items, and an advantage for old/new items over novel new/new items; furthermore, new/new items were not named faster than old items from the first training block. These findings demonstrated that the skill of reading mirror-reversed words was acquired in an item-specific fashion, and fit well with an instance-based framework for skill acquisition whereby encoding and retrieval of particular experiences with particular items facilitates performance for trained and untrained items as a function of similarity to the training set (Palmeri, 1997).

Experiment 1: Laser Keyboard

Masson's (1986) procedure investigated episodic contributions to performance in the context of acquiring an unfamiliar untrained skill. The novel aspect to our experiments was to investigate episodic influences in a highly skilled domain, typing, in which the underlying representations controlling performance have been developed over years of practice. Given that Masson found episodic influences in the context of acquiring an unfamiliar perceptual skill, our first step was to test for episodic influences in skilled typing in the context of acquiring an unfamiliar motor skill. To test the possibility that episodic influences may only be observed in unskilled domains we mimicked Masson's perceptual manipulation (e.g., mirror-reversing words) at the response level by requiring typists to respond on an unfamiliar laser-projection keyboard, which slows performance for skilled typists that are unfamiliar with the device (Crump & Logan, 2009; Roeber, Bacus, & Tomasi, 2003). Experiment 2 tested for episodic influences in the context of typing on a regular QWERTY keyboard.

Skilled typists were trained on regularly presented words composed from one set of letters and then were tested in a transfer phase with the same words (old/old), new words made from the same letter set (old/new), and new words made from the other letter set (new/new). There were two critical dependent measures: first-keypress reaction times (RTs), and interkeystroke intervals (IKSIs). First-keypress RTs[2] (hereafter referred to as RTs) and IKSIs provide different windows into processes mediating sequential control. RTs measure early perceptual processing and processes responsible for compiling the sequential responses prior to their execution. IKSI measures sequential control during online response execution. RTs were defined as the time between the presentation of the word and the first keypress. IKSIs were defined by the slope of a linear function relating the time at which each keystroke occurred, relative to the onset of the word, to the position of the keystroke in the word.

Our first goal was to discover whether RTs and IKSIs from the transfer phase would be influenced by recent typing experiences in the training phase. If recent episodic experience mediates typing performance, then we would expect measures of typing performance to be fastest for trained words (old/old), then untrained words from the trained letter set (old/new), and slowest for novel words from the untrained letter set (new/new). Furthermore, if episodic processes facilitate typing performance during the training phase, and if this facilitation is operating at the level of individual items, then we would expect that performance would not differ between new/new items at the beginning of the transfer phase and old items at the beginning of the training phase (Masson, 1986). Our second goal was to assess potential episodic influences at the level of letter, words, and bigrams. To this end we conducted post hoc analyses of IKSI performance for particular bigrams typed during the transfer phase.

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[1] In describing the notion of instance-based memory processes we are referring to processes involved in the automatic retrieval of prior episodes of performance. This kind of automatic retrieval is distinct from more conscious, recollection processes involved in retrieving the details of past experiences.

[2] We define *RT* in the standard cognitive psychology sense, as the interval between the onset of the stimulus and the first keypress. In the motor control literature, RT is often distinguished from movement time, so RT is the interval between the onset of the stimulus and the onset of the effectors movement, whereas movement time is the time from the onset of the effector's movement to the end of the movement. Thus, for us, RT is motor-control RT plus motor-control movement time to initiate the first keypress.

Method

Subjects. Subjects were 32 students from Vanderbilt University. Subjects were recruited for their self-reported ability to type at least 40 words per minute (WPM). Their skill was measured using a typing test from Logan & Zbrodoff (1998). Subjects were tested both on a regular keyboard (mean: 70 WPM; range: 42 to 105 WPM), and on the laser projection keyboard (mean: 33 WPM; range: 24 to 49 WPM). According to their self-report, subjects had been typing for an average of 12 years (range: 6 to 30). Eighty-four percent of subjects were self-reported touch typists. All subjects were compensated with course credit or were paid $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″ SVGA monitor running in-house software controlled by METACARD. Typing responses were issued on a laser projection keyboard (Bluetooth Virtual Keyboard, iTech Dynamic, Hong Kong), which projected a full-size image of a QWERTY keyboard onto a tabletop and registered keypresses made to the projected image.

To create different sets of words we divided letters on the keyboard according to a checkerboard pattern. Letter Set 1 was defined by the letters q, z, s, e, c, f, t, b, h, u, m, k, and o and Letter Set 2 was defined by the letters a, w, x, d, r, v, g, y, n, j, i, l, and p. Words were created from each letter set by filtering the University of South Florida word norms (Nelson, McEvoy, & Schreiber, 1998) for four- and five-letter words (see the Appendix). Letter Set 1 yielded 37 four-letter words and 21 five-letter words, and Letter Set 2 yielded 59 four-letter words and 35 five-letter words. The mean word frequency (Kucera & Francis, 1967) from Letter Set 1 was 78 per million with a range of 0 to 2,244. The mean word frequency for words from Letter Set 2 was 68 per million with a range of 0 to 1,013. Mean word frequency was not significantly different between Letter Sets 1 and 2, $t(79) = .22$, $p = .82$.

Procedure. The design involved a training and transfer phase. During the training phase subjects were presented with individual words generated from one of the letter sets (e.g., Letter Set 1). The training items were 10 four-letter words and 10 five-letter words. The words selected from the training set were chosen at random for each subject, and the letter set used to generate training items was counterbalanced across subjects. All 20 words were presented three times per block and order of words was randomized. There were eight training blocks, for a total of 480 trials.

There were two transfer blocks involving three kinds of items: old/old, old/new, and new/new. Each transfer block contained the 20 old words (old/old) from the training set (10 four-letter words, 10 five-letter words), 20 new words constructed from the trained letter set (old/new), and 20 new words constructed from the untrained letter set (new/new). All items were randomized within each block.

Subjects were seated approximately 57 cm from the computer monitor. At the beginning of each trial a fixation cross was presented in the centre of the screen for 500 ms, followed by a target word. Words were displayed in black on a white background. Letters were 8 mm in height and displayed in uppercase. Subjects were instructed to quickly and accurately type out each word, and then press the space bar to move on to the next trial. The target word was removed from the screen after subjects pressed the space bar. The next trial was initiated 500 ms later. Subjects were given online feedback regarding the letters that they were typing. The typed responses were presented at the bottom of each screen in lowercase. Subjects were instructed to ignore the case of the target and typed words. Subjects were further instructed that the backspace key would not function. In this way, all key press errors were recorded. A paragraph typing test providing an estimate of WPM (reported above) was administered at the end of the session.

Results and Discussion

Errors were counted whenever an erroneous keystroke appeared within a word. For each subject, RTs and IKSIs for each condition in each block were submitted to an outlier analysis (Van Selst & Jolicoeur, 1994), which trimmed approximately 3% of the observations from each dependent measure. Mean RTs and IKSIs for old/old, old/new, and new/new words, collapsed across word length, for all training and transfer blocks are displayed in Figure 1, and presented in numerical format in Table 1. Unless otherwise noted, an alpha criterion of .05 was adopted for all statistical tests. Results for the training session and transfer sessions are discussed separately.

Training phase. Mean RTs and IKSIs were submitted to separate one-way repeated-measures analyses of variances (ANOVAs) including Training Block 1, Training Block 8, and new/new words from the transfer phase. For RTs, the omnibus ANOVA was significant, $F(2, 62) = 11.72$, $MSE = 4{,}705.2$, $\eta_p^2 = .27$. RTs were longer in the first block (900 ms) than in the last block of training (819 ms), $F(1, 62) = 22.42$, $MSE = 4{,}705.20$, $\eta_p^2 = .27$. For IKSIs, the omnibus ANOVA was significant, $F(2, 62) = 5.90$, $MSE = 1{,}679.32$, $\eta_p^2 = .16$. IKSIs were longer in the first block (280 ms) than in the last block of training (245 ms), $F(1, 62) = 11.53$, $MSE = 1{,}679.32$, $\eta_p^2 = .16$. To derive a more complete picture of the learning trends, mean RTs and IKSIs for each block in the training phase were fit to separate power functions (Logan, 1988). Both RT and IKSI measures decreased monotonically across the training blocks. The power function yielded R^2 fits of .94 and .98 for the mean RTs and IKSIs, respectively. This finding demonstrates that skilled typists were able to improve their typing performance on the unfamiliar laser projection keyboard with limited practice.

To test generalized learning, we compared RTs and IKSIs in the first training session with RTs and IKSIs for new/new words in the transfer session (Masson, 1986). Training phase RTs (900 ms) were not significantly different from new/new RTs (874 ms), $F(1, 62) = 2.22$, $MSE = 4{,}705.2$, $p < .14$. Training phase IKSIs (280 ms) were not significantly different from new/new IKSIs (267 ms), $F(1, 62) = 1.58$, $MSE = 1{,}697.32$, $p < .21$. Both RTs and IKSIs for old/old items in the first block of training were not significantly different from new/new items in the transfer phase, indicating that training phase performance improvements were item-specific in nature (Masson, 1986). Apparently, performance did not improve in general for typing on the unfamiliar laser keyboard, but only improved for specific words, bigrams, and letters. To further support this claim, we note that in a separate submitted manuscript we found that 30 min of practice typing all unique words does not improve performance on the laser typing keyboard (Crump & Logan, 2009).

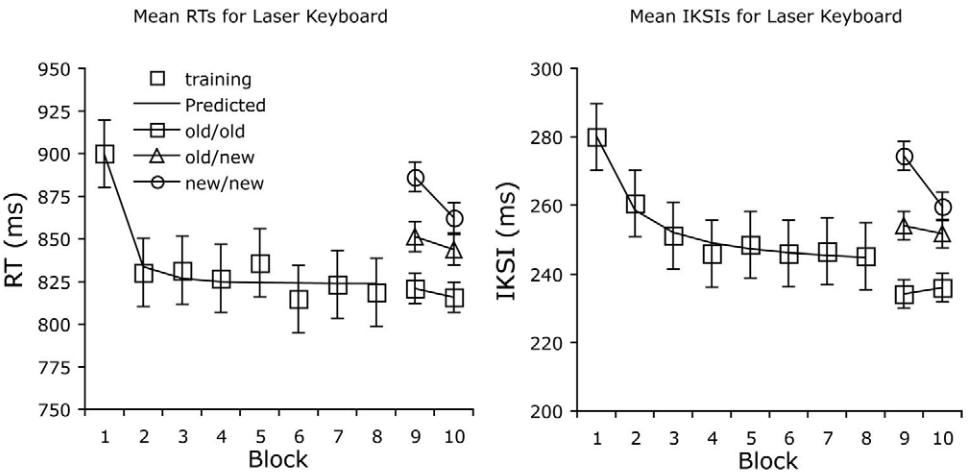

Figure 1. Depicts mean first-keypress reaction times (RTs) and interkeystroke intervals (IKSIs) for performance in the training and transfer sessions in Experiment 1 for the laser keyboard. The left and right figures depict mean RTs and IKSIs, respectively. Learning curves for each function were fit with a power function of the form RT (or IKSI) $= a + b \times N^{-c}$, where a is the asymptote, b is the maximum amount by which RT or IKSI can be reduced by practice, N is the number of practice trials, and c is the learning rate. For RTs, the best fitting equation was RTs $= 824 + 76N^{-2.92}$. For IKSIs, the best-fitting equation was IKSI $= 242 + 39N^{-1.19}$. Error bars represent 95% within-subject confidence intervals (Masson & Loftus, 2003).

Transfer phase. Results from the training phase suggested a role for item-specific learning processes, and these influences were further probed in the transfer phase with separate 2 (transfer block: first vs. second) × 2 (word length: four vs. five) × 3 (type: old/old, old/new, new/new) repeated-measures ANOVAs for RTs, IKSIs, and error rates.

For RTs, the only significant effect was the main effect of type, $F(2, 62) = 10.95$, $MSE = 9{,}142.66$, $\eta_p^2 = .26$. Old/old RTs (818 ms) were shorter than old/new RTs (847 ms), $F(1, 62) = 5.92$, $MSE = 9{,}142.66$, $\eta_p^2 = .09$, which were shorter than new/new RTs (874 ms), $F(1, 62) = 5.04$, $MSE = 9{,}142.66$, $\eta_p^2 = .08$. This pattern of RTs reproduces the pattern found by Masson (1986), and suggests that improvements to performance in the training session relied on item-specific learning processes.

A similar pattern of performance was found for IKSIs. The main effect of type was significant, $F(2, 62) = 13.99$, $MSE = 2{,}349.32$, $\eta_p^2 = .31$. Old/old IKSIs (235 ms) were shorter than old/new IKSIs (253 ms), $F(1, 62) = 8.58$, $MSE = 2{,}349.32$, $\eta_p^2 = .12$, which were shorter than new/new IKSIs (267 ms), $F(1, 62) = 5.52$, $MSE = 2{,}349.32$, $\eta_p^2 = .08$. The fact that IKSIs reproduced the pattern of RTs further implicates item-specific learning processes in mediating performance improvements across the training phase.

For error rates, there was a significant main effect of word length, $F(1, 31) = 19.33$, $MSE = 0.0145$, $\eta_p^2 = .38$. Error rates were higher for five letter words (.23) than four letter words (.18). No other main effects or higher order interactions were significant. Overall, the pattern of error rates was consistent with the pattern of RTs and IKSIs.

Table 1
Mean Reaction Times (RT), Interkeystroke Intervals (IKSI), and Error Rates (ER) for the Laser Keyboard Group During the Transfer Phase in Experiment 1

	Four			Five		
Variable	Old/old	Old/new	New/new	Old/old	Old/new	New/new
First transfer block						
RT	831	850	893	811	852	879
SE	23	22	33	22	23	20
IKSI	229	254	278	239	254	271
SE	8	11	15	10	13	14
ER	.14	.20	.19	.22	.27	.23
Second transfer block						
RT	808	834	860	823	853	865
SE	21	22	29	19	21	25
IKSI	237	256	260	235	248	259
SE	7	10	12	10	12	12
ER	.16	.19	.19	.21	.23	.24

The training phase led to performance improvements for both RTs and IKSIs. The transfer phase probed the item-specific nature of the practice induced performance improvements and demonstrated that trained words (old/old) were typed faster than untrained words composed of trained letters (old/new) and untrained letters (new/new). This general pattern was observed for both RTs and IKSIs, and provides a first demonstration that recent episodic experience can control skilled typing. A second goal of our analyses was to further determine the level (letter, bigram, word) at which episodic processes control performance. To this end we conducted a post hoc analyses of performance on typing bigrams in the transfer phase.

Analysis of bigrams. Mean IKSIs for all bigrams in the transfer phase were classified into four groups (see Figure 2). Figures 2a through 2d displays predictions for patterns of IKSI performance across bigram conditions assuming that episodic processes might separately influence performance at the level of letters, bigrams, and words. We analyzed IKSIs for four types of bigrams: Old/old trained bigrams from old/old words; old/new trained bigrams appeared as bigrams in old/old words but not as larger structures; old/new untrained bigrams, which never appeared in the training set although the letters did; and new/new untrained bigrams, which never appeared in the training set, nor did the letters. IKSIs for correctly typed bigrams were submitted to a one-way repeated-measures ANOVA including bigram type as the sole factor (old/old trained bigrams, old/new trained bigrams, old/new untrained bigrams, new/new untrained bigrams). Figure 2e displays mean IKSIs for each condition in the analysis.

The main effect of bigram type was significant, $F(3, 93) = 4.68$, $MSE = 899.89$, $\eta_p^2 = .13$. To test for the influence of episodic processing on performance at the level of letters, bigrams, and words, we conducted three linear contrasts corresponding to the predictions for performance displayed in Figures 2a through 2c. First, to test for episodic influences at the letter level we compared bigrams with trained letters against bigrams with untrained letters using the contrast weights 1, 1, 1, –3, $F(1, 93) = 9.61$, $MSE = 899.89$, $\eta_p^2 = .09$. Bigrams containing trained letters were typed significantly faster (18 ms) than bigrams containing untrained letters. Second, to test for episodic influences at the bigram level we compared trained bigrams against untrained bigrams using the contrast weights 1, 1, –1, –1, $F(1, 93) = 9.49$, $MSE = 899.89$, $\eta_p^2 = .09$. Trained bigrams were typed significantly faster (16 ms) than untrained bigrams. Third, to test for episodic influences at the word level we compared bigrams occurring in a trained word against bigrams not occurring in a trained word using the contrast weights 3, –1, –1, –1, $F(1, 93) = 8.48$, $MSE = 899.89$, $\eta_p^2 = .08$. Bigrams occurring in a trained word were typed significantly faster (18 ms) than bigrams not typed in a trained word. These linear contrasts suggest a role for episodic processes to influence performance at each of the letter, bigram, and word levels. Indeed, the overall pattern of IKSI performance closely matched the pattern predicted by the combination hypothesis (Figure 2d).

Finally, we determined whether the pattern of bigram performance observed in the group average was consistent across individual subjects. To this end, we correlated the pattern of each subject's IKSIs with the weights for each of the letter, bigram, word, and combination linear contrasts. Then, for each subject we determined which linear contrast was most highly correlated with IKSI performance. Figures 2a through 2d display the number of subjects whose pattern of performance was most correlated with each predicted linear contrast. This analysis suggests that episodic influences occurred at letter, bigram, and word level across subjects, and that the majority of subjects correlated most highly with the linear contrasts for letters and words.

Experiment 2: Regular Keyboard

Experiment 1 provided evidence that episodic influences at the letter, bigram, and word level can modulate typing performance in skilled typists. The main caveat to these findings was that typing performance was brought down from ceiling levels of performance as typists gave their responses on an unfamiliar laser projection keyboard. Experiment 2 determined whether episodic influences would also modulate performance when typing is at ceiling levels of performance. With this aim in mind, we repeated the experimental procedure introduced in Experiment 1, but instead of employing a laser projection keyboard, we used a regular QWERTY keyboard. Our aim was to investigate the influence of episodic processes in the context of performing a familiar, highly practiced skill.

Method

Subjects. Subjects were 32 students from Vanderbilt University. Subjects were recruited for their self-reported ability to type at least 40 WPM. Their skill was measured using a typing test from Logan & Zbrodoff (1998). For subjects in the regular keyboard condition mean scores were 78 WPM (range: 46 to 112 WPM). According to their self-report, subjects had been typing for an average of 12 years (range: 6 to 30). Eighty percent of subjects were self-reported touch typists. All subjects were compensated with course credit or were paid $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. Experiment 2 was the same as Experiment 1, with the exception that typists responded on a regular QWERTY keyboard.

Design and procedure. The experimental design and protocol was identical to Experiment 1.

Results and Discussion

For each subject, RTs and IKSIs for each condition in each block were submitted to an outlier analysis (Van Selst & Jolicoeur, 1994), which trimmed approximately 3% of the observations from each dependent measure. Mean RTs and IKSIs for old/old, old/new, and new/new words, collapsed across word length, for all training and transfer blocks are displayed in Figure 3, and presented in numerical format in Table 2.

Training phase. Mean RTs and IKSIs were submitted to separate one-way repeated-measures ANOVAs including Training Block 1, Training Block 8, and new/new words from the transfer phase. For RTs, the omnibus ANOVA was significant, $F(2, 62) = 21.32$, $MSE = 1{,}101.87$, $\eta_p^2 = .41$. RTs were longer in the first block (605 ms) than in the last block of training (569 ms), $F(1, 62) = 18.86$, $MSE = 1{,}101.87$, $\eta_p^2 = .23$. For IKSIs, the omnibus ANOVA was significant, $F(2, 62) = 527.45$, $MSE = 102.63$, $\eta_p^2 = .94$. IKSIs were longer in the first block (129 ms) than in the last

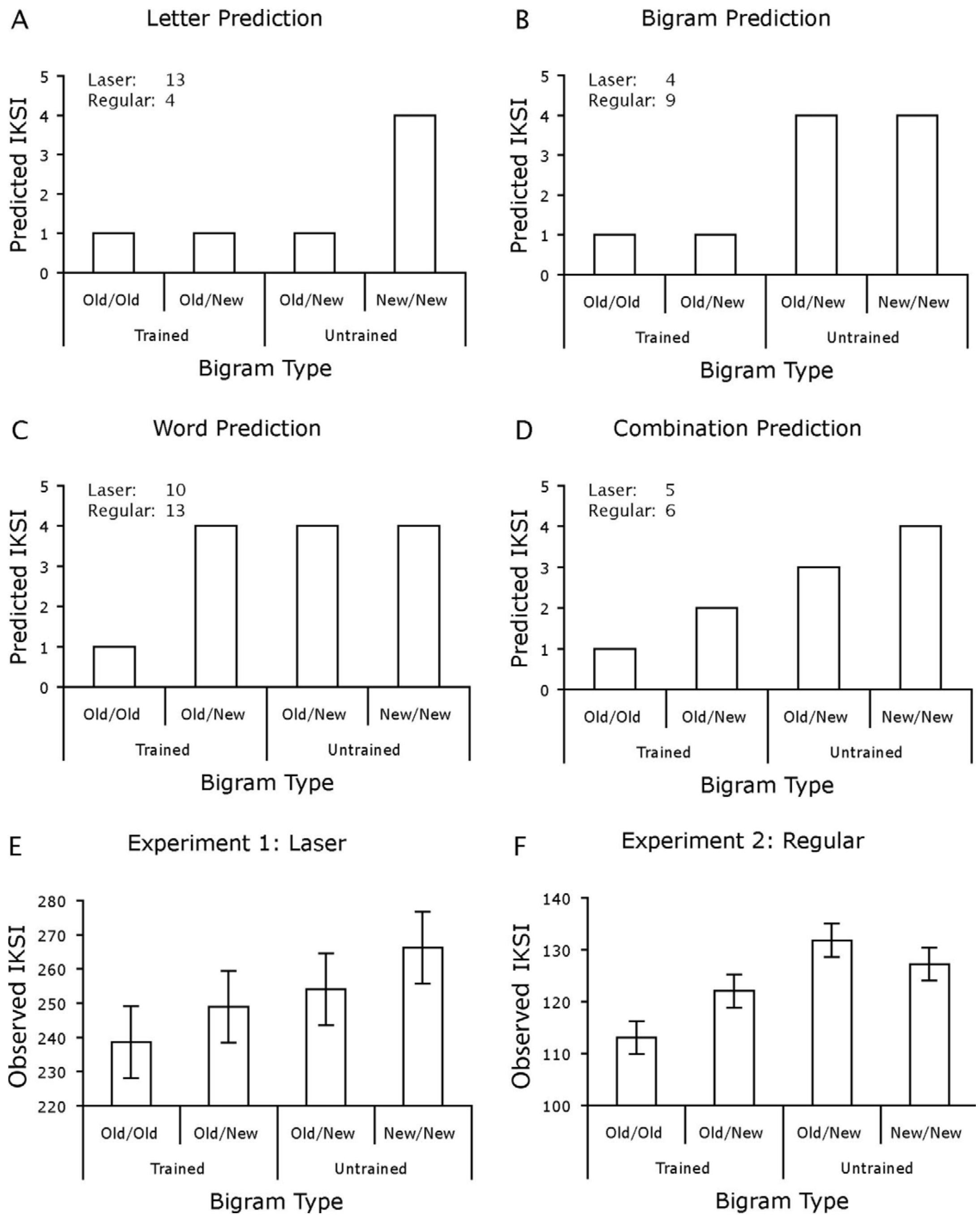

Figure 2. Displays predictions for the influence of episodic processes operating at the levels or letters (2a), bigrams (2b), words (2c), or a combination of levels (2d), on bigram performance. Smaller bars refer to shorter reaction times. Predictions for each level were generated by assuming that episodic processes would speed performance for all bigram conditions containing features from a particular level. Predictions were tested by forming linear contrasts comparing bigrams containing trained letters versus untrained letters (1, 1, 1, –3), trained bigrams versus untrained bigrams (1, 1, –1, –1), trained versus untrained words (3, –1, –1, –1), and a final contrast combining predictions from all three levels (–3, –1, 1, 3). In each figure the condition labels refer to the following bigram types: Trained old/old refers to bigrams from the training phase that occurred in the context of a trained word. Trained old/new refers to bigrams from the training phase that occurred in the context of an old/new word. Untrained old/new refers to novel bigrams composed from the trained letter set. Untrained new/new refers to novel bigrams composed from the untrained letter set. Figure 2e displays the mean IKSIs for bigram performance in Experiment 1 (laser keyboard), and Figure 2f displays mean IKSIs for bigram performance in Experiment 2 (regular keyboard). IKSI = interkeystroke interval.

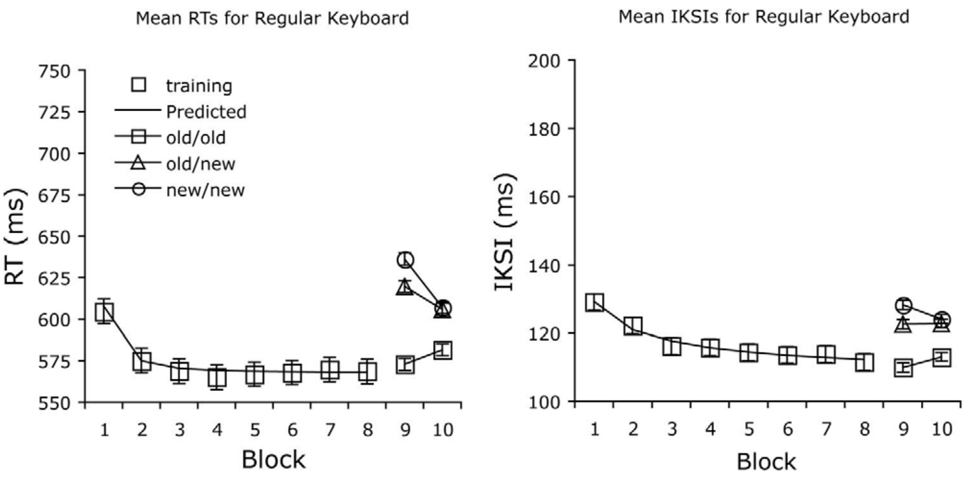

Figure 3. Depicts mean first-keypress reaction times (RTs) and interkeystroke intervals (IKSIs) for performance in the training and transfer sessions in Experiment 2 for the regular keyboard. The left and right figures depict mean RTs and IKSIs, respectively. Learning curves for each function were fit with a power function of the form RT (or IKSI) = $a + b \times N^{-c}$, where a is the asymptote, b is the maximum amount by which RT or IKSI can be reduced by practice, N is the number of practice trials, and c is the learning rate. For RTs, the best fitting equation was RT = $568 + 40N^{-2.53}$. For IKSIs, the best fitting equation was IKSI = $105 + 23N^{-0.62}$. Error bars represent 95% within-subject confidence intervals (Masson & Loftus, 2003).

block of training (112 ms), $F(1, 62) = 47.70$, $MSE = 102.63$, $\eta_p^2 = .43$. Following the ANOVA, mean RTs and IKSIs for each block were fit to separate power functions to test for learning (Logan, 1988). Both RT and IKSI measures decreased monotonically across the training blocks. The power function yielded R^2 fits of .98 and .98 for the mean RTs and IKSIs respectively (see Figure 3). In line with the results from Experiment 1, RTs and IKSIs improved after a short period of training on specific words for skilled typists, even when they responded on a regular QWERTY keyboard.

To test generalized learning we compared RTs and IKSIs in the first training session with RTs and IKSIs for new/new words in the transfer session. Training phase RTs (605 ms) were significantly shorter than new/new RTs (622 ms), $F(1, 62) = 4.21$, $MSE = 1{,}101.87$, $\eta_p^2 = .06$. Training phase IKSIs (129 ms) were not significantly different from new/new IKSIs (126 ms), $F(1, 62) = 1.27$, $MSE = 102.63$, $p < .26$. The fact that training RTs were shorter than new/new RTs suggests that the training experience may have interfered with performance on novel items during the transfer phase. At the same time, IKSI performance did not differ between the first training session and new/new words, providing further support for the notion that improvements to performance during the training phase were item specific in nature.

Transfer phase. To test for evidence of item-specific learning we conducted separate 2 (transfer block: first vs. second) × 2 (word length: four vs. five) × 3 (type: old/old, old/new, new/new) repeated measures ANOVAs for RTs, IKSIs, and error rates in the transfer phase.

For RTs, the main effect of type, $F(2, 62) = 18.47$, $MSE = 3{,}841.43$, $\eta_p^2 = .37$, and the Block × Type interaction was signif-

Table 2
Mean Reaction Times (RT), Interkeystroke Intervals (IKSI), and Error Rates (ER) for the Regular Keyboard Group During the Transfer Phase in Experiment 2

	Four			Five		
Variable	Old/old	Old/new	New/new	Old/old	Old/new	New/new
First transfer block						
RT	565	615	639	581	625	634
SE	12	18	20	15	19	16
IKSI	111	125	127	109	121	130
SE	4	4	6	4	4	6
ER	.05	.09	.11	.07	.14	.12
Second transfer block						
RT	575	586	602	588	626	612
SE	14	16	17	14	22	17
IKSI	114	122	122	112	124	126
SE	4	4	5	6	6	5
ER	.07	.08	.11	.07	.11	.12

icant, $F(2, 62) = 14.08$, $MSE = 821.79$, $\eta_p^2 = .31$. In the first transfer block, old/old RTs (573 ms) were shorter than old/new RTs (620 ms), $F(1, 62) = 85.33$, $MSE = 821.79$, $\eta_p^2 = .58$, which were shorter than new/new RTs (636 ms), $F(1, 62) = 10.71$, $MSE = 821.79$, $\eta_p^2 = .15$. These findings reproduced the same pattern of RTs as found in Experiment 1, and suggest that recent experience typing particular words can influence skilled typing performance. In the second transfer block, old/old RTs (582 ms) were again shorter than old/new RTs (606 ms), $F(1, 62) = 23.16$, $MSE = 821.79$, $\eta_p^2 = .27$, but, old/new RTs (606 ms) were not shorter than new/new RTs (607 ms; $F < 1$). Although the advantage for old/old items remained consistent across transfer blocks, the generalization effect for old/new items diminished as subjects gained experience with typing new/new items across the transfer blocks.

Of less theoretical importance was the main effect of block, $F(1, 31) = 8.67$, $MSE = 1{,}439.01$, $\eta_p^2 = .22$. RTs in the first block were shorter than RTs in the second block. Also, the main effect of word length was significant, $F(1, 31) = 10.57$, $MSE = 1{,}799.77$, $\eta_p^2 = .25$. No other higher order interactions were significant.

For IKSIs, the main effect of type, $F(2, 62) = 36.81$, $MSE = 205.58$, $\eta_p^2 = .54$, and the Block × Type interaction was significant, $F(2, 62) = 3.74$, $MSE = 115.78$, $\eta_p^2 = .11$. In the first transfer block, old/old IKSIs (110 ms) were shorter than old/new IKSIs (123 ms), $F(1, 62) = 44.57$, $MSE = 115.78$, $\eta_p^2 = .42$, which were shorter than new/new IKSIs (128 ms), $F(1, 62) = 8.93$, $MSE = 115.78$, $\eta_p^2 = .13$. This pattern of IKSIs matches the pattern of RTs in Experiment 2, and reproduces the pattern of IKSIs found in Experiment 1. In the second transfer block, old/old IKSIs (113 ms) were again shorter than old/new IKSIs (123 ms), $F(1, 62) = 26.10$, $MSE = 115.78$, $\eta_p^2 = .30$, but old/new IKSIs (123 ms) were not shorter than new/new IKSIs (124 ms; $F < 1$). No other main effects, or higher order interactions were significant. As with the RTs for Experiment 2, the generalization effect for old/new items disappeared across transfer blocks.

For error rates, there was a significant main effect of type, $F(2, 62) = 8.74$, $MSE = 0.00967$, $\eta_p^2 = .22$. Old/old items (.07) had smaller error rates than old/new items (.10), $F(1, 62) = 10.10$, $MSE = 0.00967$, $\eta_p^2 = .14$, which did not differ from new/new items (.11; $F < 1$).

In line with the findings for typing on the laser keyboard, the training experience modulated typing performance even when skilled typists responded on a regular keyboard. In the first transfer block, RTs and IKSIs were shorter for old/old items than old/new items, which in turn were shorter than RTs and IKSIs for new/new items. These results demonstrate for the first time that episodic processes can control highly skilled typing performance. In contrast with the results from Experiment 1, the advantage for old/new items over new/new items in both RT and IKSI was only significant in the first transfer block. The fact that transfer performance depended on transfer block suggests that item-specific influences may develop rapidly, and begin to speed performance as subjects gained experience with repeated instances of the old/new and new/new words appearing in the second transfer block.

Analysis of bigrams. Following Experiment 1, IKSIs for correctly typed bigrams were submitted to a one-way repeated-measures ANOVA including bigram type as the sole factor (old/old trained bigrams, old/new trained bigrams, old/new untrained bigrams, new/new untrained bigrams). Figure 2f displays mean IKSIs for each condition in the analysis.

The main effect of bigram type was significant, $F(3, 93) = 24.89$, $MSE = 83.22$, $\eta_p^2 = .45$. To test for the influence of episodic processing on performance at the level of letters, bigrams, and words, we conducted three linear contrasts corresponding to the predictions for performance displayed in Figures 2a through 2c. First, to test for episodic influences at the letter level we compared bigrams with trained letters against bigrams with untrained letters, $F(1, 93) = 6.97$, $MSE = 83.22$, $\eta_p^2 = .07$. Bigrams containing trained letters were typed significantly faster (5 ms) than bigrams containing untrained letters. Second, to test for episodic influences at the bigram level we compared trained bigrams against untrained bigrams, $F(1, 93) = 55.07$, $MSE = 83.22$, $\eta_p^2 = .37$. Trained bigrams were typed significantly faster (12 ms) than untrained bigrams. Third, to test for episodic influences at the word level we compared bigrams occurring in a trained word against bigrams not occurring in a trained word, $F(1, 93) = 56.32$, $MSE = 83.22$, $\eta_p^2 = .38$. Bigrams occurring in a trained word were typed significantly faster (14 ms) than bigrams not typed in a trained word. These linear contrasts suggest a role for episodic processes to influence performance at each of the letter, bigram, and word levels.

Finally, we were interested in determining whether the pattern of bigram performance observed in the group average was consistent across individual subjects. To this end, we correlated the pattern of each subject's IKSIs with each of the linear contrasts predicting performance at the letter, bigram, word, and combination levels. For each subject we determined which linear contrast was most highly correlated with IKSI performance. Figures 2a through 2d each display the number of subjects whose pattern of performance was most correlated with each predicted linear contrast. This analysis suggests that episodic influences occurred at each letter, bigram, and word level across subjects, and that the majority of subjects correlated most highly with the linear contrasts for bigrams and words.

General Discussion

Our experiments investigated whether recent experience typing specific letters, bigrams, and words can influence typing performance for highly skilled typists. We extended Masson's (1986) procedure for measuring item-specific learning in the context of acquiring an unfamiliar skill to the highly skilled domain of typing. We measured the role of item-specific learning at the level of words, bigrams, and letters in tasks requiring unfamiliar (Experiment 1) and familiar (Experiment 2) typing responses. Both experiments demonstrated that with relatively short amounts of practice, item-specific learning processes quickly influence performance, even in the context of performing a familiar, highly practiced skill in a normal fashion.

To summarize our results, we focus on RTs and IKSIs separately. In both experiments, RTs in the transfer phase were faster for old/old items than for old/new and new/new items. This finding demonstrates that processes involved in encoding and preparing a sequence depend on experience with specific items. In addition, the finding that old/new items were faster than new/new items demonstrates some generalization of knowledge to novel items that were constructed from the same letters experienced in training.

However, RT may not directly tap processes involved in sequential processing, and may instead reflect the operation of earlier perceptual processes involved in identification of the to-be-typed word.

A more direct measure of processes involved in sequential control is provided by IKSIs, which also depend on experience with specific items. For both keyboard groups, IKSIs were fastest for old/old items, followed by old/new items, which were in turn faster than new/new items. These findings reproduce the pattern of RTs, and provide stronger support for the notion that episodic processes influence sequential control during typing performance (Masson, 1986).

More impressive, we found episodic influences on RTs and IKSIs when skilled typists performed on both the unfamiliar laser keyboard, and the familiar regular keyboard. This finding indicates that episodic influences in skilled typing are robust enough to be detected even in well-practiced, familiar circumstances. At the same time, there were noteworthy differences in transfer performance between keyboard groups. In particular, the influence of the training experience on transfer performance was relatively short lived for the regular keyboard. Although RTs and IKSIs were significantly fastest for old/old items across the two transfer blocks, the advantage for old/new over new/new items was reduced across transfer blocks as subjects gained experience with the new items. In contrast, for the laser keyboard group, the RT and IKSI advantage for old/old over old/new, and old/new over new/new items remained significant across both transfer blocks.

To further understand the levels of representation influenced by recent experience with typing particular words and letters we carried out a post hoc analysis on performance for typing particular bigrams. With both keyboards, we found evidence of episodic effects at the word, bigram, and letter level. Taken together, our findings demonstrate that recent episodic experience typing specific words mediates speed of highly skilled typing movements. These findings conceptually replicate Masson (1986). They hold important implications for theories of typing specifically, but also sequence learning and motor control more generally.

Theories of typing typically assume an important role for schematic representations in the control of keystroke execution (John, 1996; Rumelhart & Norman, 1982; Salthouse, 1986; Wu & Liu, 2008). Schemas refer to node-like summary representation coding the details of motor effectors movements. A primary assumption of this view is that the details of individual typing experiences are filtered out in favor of an average summary representations of the intended action plan. In other words, memory traces for specific typing experiences are not represented, and previous research on typing has not provided any evidence for the view that multiple traces of typing experiences are stored. However, we note that Viviani & Laissard (1996) speculated that multiple traces may be laid down for small, highly frequent words (e.g., *the*), but suggested that multiple traces are unlikely to be stored for longer words. Crucially, our findings provide a first demonstration that individual memory traces of specific typing experiences are stored and can be retrieved to mediate typing performance, even for highly skilled typists.

More specifically, our evidence that recent item-specific learning processes participate in the control of skilled typing opens the door for an instance-based memory approach to understanding skilled typing (Logan, 1988). On this view, practice with typing specific words and letters would populate memory with specific examples of these task demands. In contrast to schematic views, where the details of individual experiences are averaged out during learning, the episodic view assumes that the details of each episode are stored, and that processes operating during retrieval play a role in selecting individual episodes, or pooling across instances, for the control of action. The notion that averaging could occur during retrieval affords stability to episodic representations, as the variance associated with individual instances would be constrained by the mean of the retrieved episodes. Assuming that memory retrieval could influence typing also implies that recent experiences might influence memory retrieval. Indeed, our results confirm that recent episodic experience can influence highly skilled typing performance.

Speaking more broadly, our proposal that skilled typing can be mediated by instance-based memory processes echoes similar proposals in the domains of motor control and sequence learning. In the context of motor control, Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, and Engelbrecht (1995) and Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) proposed that reaching movements are controlled by the retrieval of individually stored examples of movement patterns, termed *postures*. These stored postures reflect trace representations of previous experiences with a particular grasping movement, rather than a stored summary representation of the intended movement. We assume that the processing principles articulated by Rosenbaum et al. may be useful in further understanding the nature of processes controlling action in skilled typing.

In the sequence learning literature (for reviews in each literature, see artificial grammar learning, Pothos, 2007; serial reaction time, Clegg, DiGorolamo, & Keele, 1998), the representations employed by the processes controlling sequence learning has been a topic of considerable debate. Theories differ in the extent to which learning of sequence information is mediated by conscious application of rules about the grammatical structure of the sequence, by implicit processes involved in learning associations between elements in the sequence, or by exemplar-based memory retrieval processes. In particular, the role of exemplar-based memory processes in sequence learning has been thoroughly documented in the context of artificial grammar learning (for a review, see Neal & Hesketh, 1997), and has been suggested in the context of the serial reaction time (SRT) paradigm (Stadler, 1992, 1993, 1995). More recently, computational accounts of the exemplar approach have been proposed both in the domain of artificial grammar learning (Jamieson & Mewhort, 2009a), and in the SRT domain (Jamieson & Mewhort, 2009b). Our findings fall in line with this previous work, and we assume that the processing principles described to account for sequence learning in terms of exemplar-based memory processes would also apply to the domain of typing. At the same time, the task of typing is different from the kinds of tasks employed in the artificial grammar and SRT paradigms. Most notable is the fact that typists are well-practiced, and can execute highly familiar sequences very rapidly. Artificial grammar tasks usually involve decisions about the grammaticality of unfamiliar sequences, and SRT tasks involve responding to unfamiliar sequences usually defined by the spatial location of symbols presented on a computer monitor. In this light, what is novel about our current findings is the notion that exemplar-based memory processes also operate in the context of a highly skilled, familiar task domains, namely, typewriting.

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(*Appendix follows*)

Appendix

Letter set				
1				
Four-letter words	DAWN	DIAL	DILL	DRAG
	DRAW	DRIP	GANG	GIRL
	GLAD	GRAY	GRIP	JAIL
	LADY	LAVA	LAWN	LIAR
	LILY	NAIL	NAVY	PAIL
	PAIN	PAIR	PAWN	PILL
	PLAY	PRAY	VAIN	VARY
	WAND	WARN	WARY	WILD
	WILL	WIND	WRAP	YARN
	YAWN			
Five-letter words	ADVIL	AGAIN	ANGRY	AWARD
	DAILY	DAIRY	DIARY	DRAIN
	DRILL	GRAIN	GRAND	GRAVY
	GRILL	GRIND	JAPAN	PADDY
	PLAID	PLAIN	RAINY	RAPID
	VIVID			
2				
Four-letter words	BEEF	BEET	BEST	BOOM
	BOOT	BOSS	BUSH	BUTT
	BUZZ	CHEF	COKE	COMB
	COST	CUBE	CUFF	CUSS
	FEET	FOOT	FUSE	FUSS
	FUZZ	HOBO	HOME	HOOK
	HOOT	HOSE	HUSK	MEEK
	MEET	MESS	MOSS	MOTH
	MUCH	MUCK	MUSK	MUST
	MUTE	OBOE	SCUM	SEEK
	SEEM	SHOE	SHOT	SHUT
	SOCK	SOFT	SOOT	STEM
	STUB	SUCK	TEST	TOES
	TOMB	TOSS	TOTE	TUBE
	TUSK	TUTU	ZEST	
Five-letter words	BOOTH	BOOTS	BOOZE	CHEEK
	CHESS	CHEST	CHOKE	CHUCK
	COMET	COUCH	FOCUS	FUMES
	HOUSE	MOOSE	MOUSE	MOUTH
	QUEST	SCOUT	SHEET	SHOCK
	SHOES	SHOOT	SHOUT	SMOKE
	SOCKS	SOUTH	STOCK	STUCK
	STUFF	TEETH	THEFT	THEME
	THUMB	TOOTH	TOUCH	

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