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BRIEF REPORT

“Twisting fingers”: The case for interactivity in typed language production

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Abstract
Despite the obvious linguistic nature of typing, current psychological models of typing are, to a large extent, divorced from models of spoken language production. This gap has left unanswered many questions regarding the cognitive architecture of typing. In this article we advocate the use of a psycholinguistic framework for studying typing, by showing that such a framework could reveal important similarities and differences between spoken and typed production. Specifically, we investigated the interaction between the lexical and postlexical layers by using a phenomenon known in spoken production as the “repeated-phoneme effect.” Participants typed four-word sequences of “finger-twisters” (equivalent to tongue-twisters in spoken production), in which the vowel in the last two words was either repeated (e.g., “fog top”) or not (e.g., “fog tip”). We found reliably more migration errors between the consonants of the two typed words when the vowel was repeated, even after the effect of phonology was accounted for. This finding is compatible with an interactive typing system in which postlexical representations send feedback to lexical representations and reveals similar dynamics between spoken and typed production. Additional analyses showed further similarities to spoken production, such as distinct lexical and postlexical error categories, but also revealed that typing errors were much more likely than spoken errors to violate phonotactic constraints. These results provide the first demonstration of feedback between the postlexical and lexical layers in typing, and more generally demonstrate the utility of adopting a psycholinguistic framework tailored specifically to the study of typing.

Keywords Typing error · Interactivity · Segmental representation · Repeated phoneme effect

Most of us spend a good portion of the day typing our thoughts, either for professional assignments or to connect with others via texting, chatting, and social media. However, we rarely think about the challenges embedded in this seemingly simple activity: A message must be constructed, the right word(s) must be selected, the correct spelling must be retrieved, and the correct keys must be pressed in just the right order. Despite the increasing role of typing in everyday activities, research on typed language production remains scarce. In particular, the cognitive processes underlying typing and the degree of their similarity to spoken production are not fully understood. In this article, we examine the architecture of the typing system from the perspective of psycholinguistic models of spoken word production, with a special emphasis on the degree of interactivity between the layers in the system.

Architecture of the typing system

The most widely accepted model of typing is probably Logan and Crump’s (2011) hierarchical-processing model. Logan and Crump (2010) found that typists (implicitly) slowed down after a typing error, but no such slowing was observed when errors were artificially slipped into the visual feedback stream, despite the fact that the typists (explicitly) accepted the artificial errors as their own. This dissociation was implemented in Logan and Crump’s (2011) model by two informationally encapsulated loops. The outer loop is considered a central process responsible for organizing the plan to type, mapping the target text-to-word representations in copy-typing, and

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processing the visual feedback. The inner loop is thought to be responsible for mapping words onto letters and keystrokes, controlling the serial activation of keystrokes, navigating the fingers to the correct locations, and processing the proprioceptive feedback (Yamaguchi, Crump, & Logan, 2013). Although the model neatly explains the interaction between central and local (motor) control processes, it is not concerned with the details of the linguistic architecture behind typing.

A computational implementation of a typing model has also been proposed by Rumelhart and Norman (1982), consisting of "word schema," "keystroke schemata," and a "response system." The retrieved word schema activates the associated keystroke schemata, which are then mapped onto their target hand/finger positions on a keyboard in the response system. This model successfully simulates the performance of a skilled typist in terms of errors and timing. Although there are some differences between these two models, such as separate (Yamaguchi et al., 2013) versus combined (Rumelhart & Norman, 1982) letter and keystroke representations, both models agree that letters/keystrokes are postlexical *segmental* representations. In addition, in their current forms, both models view the flow of information as strictly feedforward, from the lexical to the segmental level(s), with no feedback (even though Rumelhart and Norman's model contains feedback connections between the response system and the keystroke schemata). This architecture is strikingly similar to the general backbone of a feedforward model of spoken production (e.g., Levelt, Roelofs, & Meyer, 1999).

In spoken production, however, there is now substantial evidence for feedback between the segmental and lexical layers. For example, semantic slips have a tendency to exhibit phonological similarity to the target word (cat → rat; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997), and phonological slips tend to create more lexical than nonlexical items (e.g., Nozari & Dell, 2009). Both patterns are most parsimoniously explained by feedback from the segmental to the lexical layer (see Dell, Nozari, & Oppenheim, 2014, for a review). If typing is similar to spoken production, then the assumption of feedforward connections between the lexical and segmental levels in typing is questionable. In this study, we tested for the presence of feedback from the segmental to the lexical layer in typing by using an experimental phenomenon that we refer to as "the repeated-letter effect."

The repeated letter effect

The "repeated-letter effect" in typing is akin to what Dell (1984, 1986) described as the "repeated-phoneme effect" in spoken production (see Fig. 1). The repeated-phoneme effect refers to the observation that the presence of a repeated phoneme increases the chance of the migration of nonrepeated phonemes between two words (Dell, 1984, 1986). For example, "fog top" is more likely to be produced as "tog fop" than "fig top" is to be produced as "tig fop." In his interactive two-step model of production, Dell (1986) explains this finding as follows: During the production of sequences such as "fog top/tip," both words are preactivated. The activation of the first word ("fog") activates its segments ("f," "o," "g") through feedforward connections. Feedback connections from the segmental to the lexical level then send activation back to the word nodes that contain those segments. This means that when the two words share a segment ("fog top"), the shared segment ("o") in one word (e.g., "fog") also feeds back to the other word ("top"), which in turn activates its own segments by forward propagation. This leads to competition between the unshared segments of the two words, increasing the chance of migration errors such as "fog" (top) → "tog." On the other hand, if the two words do not share any segments ("fog tip"), feedback connections only project to the originally activated word, without activating the other word and its segments, and no additional opportunities are created for migrations between the consonants of the two words. Thus the repeated-phoneme effect, which stems directly from feedback from the phonological to the lexical layer, predicts an increased probability of migration errors between two words when they share a phoneme as compared to when they do not. In a system with no feedback, on the other hand, phonological repetition should have no effect on the migration rate of nonrepeated phonemes.

In the present study, we propose that the similarity between representational layers in spoken and typed production should make it possible to probe the interaction between the lexical and postlexical layers in typing by using a conceptually similar effect that we call the "repeated-letter effect." The repeated-phoneme effect was originally elicited using the SLIP paradigm (Baars, Motley, & Mackay, 1975; Dell, 1984), in which participants silently read word pairs in quick succession and were occasionally prompted to produce out loud the last pair they had read. However, the effect does not depend on the specifics of the SLIP paradigm (MacKay, 1970); any paradigm that entails multiword production and elicits a reasonable number of errors should produce the same effect. We, thus, implemented the manipulation of the repeated letter in a four-word finger-twister task, adapted from oral versions of tongue-twister tasks that have previously been used to elicit between-word migrations (e.g., Nozari & Dell, 2012). Participants typed, under time pressure, four-word sequences of monosyllabic "finger-twisters" (equivalent to the tongue-twisters in spoken production) in which the last two words either did or did not share the vowel. If there is feedback from the postlexical to the lexical layer, we would expect higher migration rates in typing errors on the nonrepeated consonants in the pairs with a repeated vowel. Recall that for the

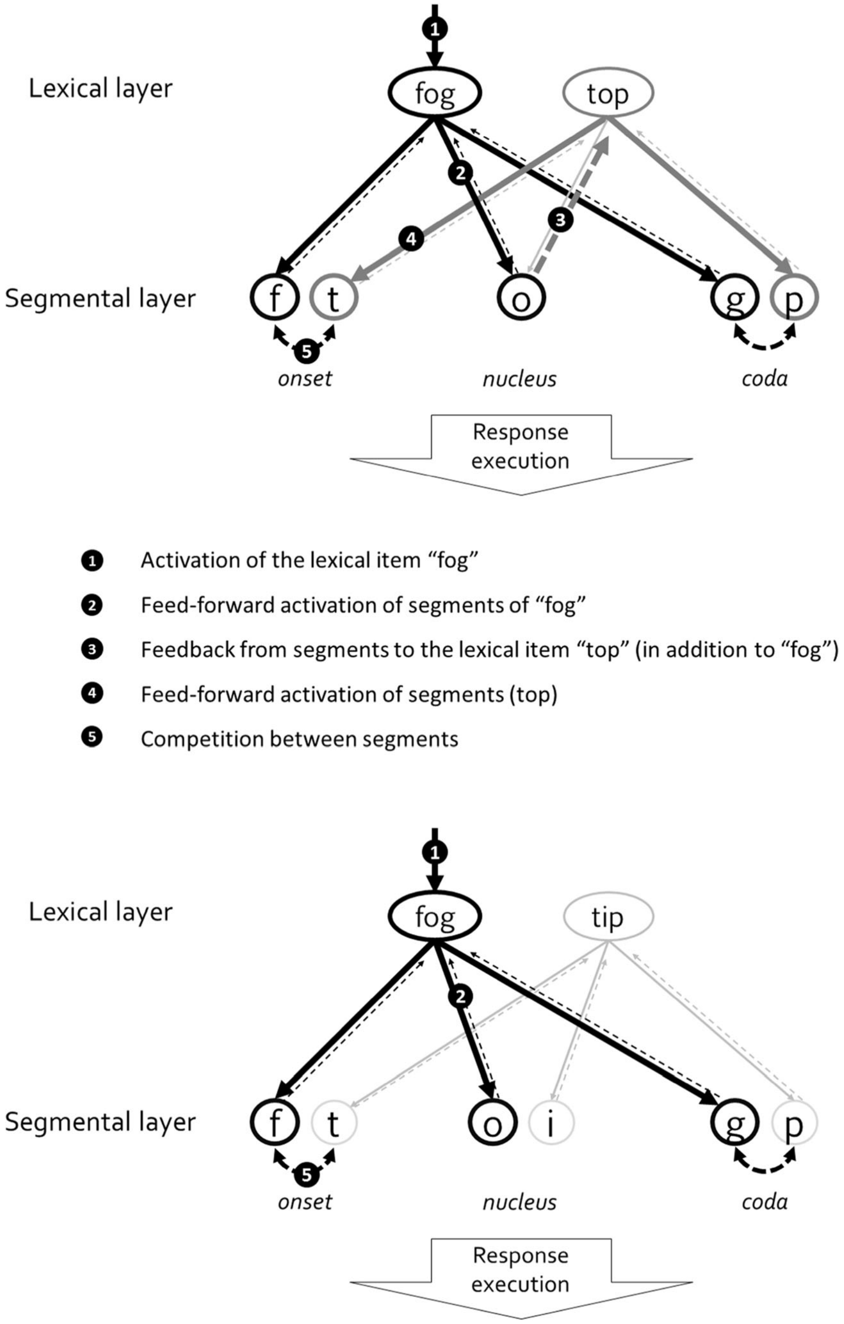

Fig. 1 Schematic of an interactive mapping between lexical and segmental representations in typing a two-word sequence. The target sequence is either "fog top" (upper panel) or "fog tip" (lower panel), and network activation is shown when the first word "fog" is to be produced. Numbers indicate the time course of spreading activation. Critically, Steps 3 and 4 are missing when the vowel is not repeated (lower panel). The onset consonants (F/T) are chosen as an example to demonstrate the mechanism, but similar processes apply to the codas (G/P).

repeated-phoneme effect, migration was due to feedback from phonemes to lexical items. In typing, this feedback would be from letters/keystroke schemata to lexical items. To control for the effect of phonology, participants also completed an oral version of the task. If the origin of the repeated-letter effect is purely phonological, covarying out the errors in speech should remove any potential effect of repeated letters in typing.

Method

Participants

Forty-two native English speakers (35 females, seven males; age: mean = 20.3 (± 2.95), range = 18–32) participated for payment. Consent was obtained under a protocol approved by the Institutional Review Board of Johns Hopkins School of

Medicine. Their mean typing speed was 83.3 (± 17.5) wpm (range = 50–118), as measured by a copy-typing task.

Materials

Forty-four "finger-twister" sequences were created with an ABBA pattern of onset consonants (e.g., "tank fed fog top"; see the Appendix). The last two words of the sequence had either a repeated vowel (e.g., fig/tip, fog/top) or a nonrepeated vowel (fig/top, fog/tip), resulting in 176 variations in total. The first two words of the sequence were the same for all four variations and did not share any segment with the final words other than the onset consonants.

We created four lists comprising equal numbers of sequences with repeated and nonrepeated vowels (44 trials in total). Only one variation from each sequence (i.e., one list) was presented to any individual participant. The lists contained equal numbers of three- and four-letter words and were balanced on the numbers of onset consonants typed by same/different hand(s), the numbers of uni-/bimanual intervals (between onset consonant and vowel), and the lexicality of the errors that would be produced by an onset consonant exchange.

Procedure

Participants were seated approximately 25 in. from a 15- by 12-in. Dell monitor, and typed their responses on a DirectIN PCB v2016 Empirisoft keyboard (millisecond accuracy), or spoke into a digital recorder (Sony ICD-PX333). The experiment comprised two 35- to 50-min sessions—typing and speaking—performed on different days in counterbalanced order. Each participant was presented with two to three practice trials followed by one of the four experimental lists (kept the same in both sessions) divided into three experimental blocks.

Materials were presented using MATLAB PsychToolBox (Kleiner, Brainard, & Pelli, 2007). The code for this experiment is available in the following GitHub repository: https://github.com/svetlanapinet/Finger-Twisters. Each trial in the typing session consisted of three phases: acquisition, rehearsal, and test. In the acquisition phase, participants copied a target sequence at their own pace. In the rehearsal phase, the target sequence was presented for 2 s, and upon its disappearance, participants typed it from memory at their own pace. Once ready, they entered the test phase where they had typed the sequence as fast and as accurately as possible four times in a row, each time within a 3.5-s window marked by two beeps, with 1 s between repetitions. Participants were free to correct their answer as they were typing. The spoken version was identical to the typed version, except that participants orally recited the sequence and the deadline for repetitions during the test phase was shortened to 1.5 s, to adjust for the difference in speed between typing and speaking. Only data from the test phase were analyzed, which resulted in 7,392 typed and 7,392 spoken trials. All data and analysis scripts are available at the following repository: osf.io/knby5 (Pinet & Nozari, 2018).

Results

Data were collected for each keystroke. Any difference between the typed responses and target sequences (addition, deletion, or substitution of a letter) was coded as an error, including the use of the backspace key. We report errors at the levels of both four-word sequences (7,392 opportunities) and individual words (29,568 opportunities). In the typing session, 2,427 sequences contained errors (33%), distributed over 3,373 erroneous words (11%). The spoken responses were double-transcribed offline by two independent raters, and discrepancies were resolved between the two. The spoken version yielded 692 erroneous sequences (9%) distributed over 931 erroneous words (3%).

General characteristics of typing errors

Given the scarcity of reports on the linguistic patterns of typing errors, we first present some general characteristics of the errors in our dataset, followed by a discussion of a few aspects of the data that helped us localize the source of the majority of the errors and assess the potential influence of spoken production on typed production.

Of the 2,427 incorrect trials, 1,112 (45%) contained at least one backspace, indicating an attempt at correction. The average typing rate was significantly slower for incorrect responses (149.7 ± 27.8 ms/keystroke)—with or without correction attempts—than for correct trials (125.7 ± 21.6 ms/keystroke; $z = -5.65$, $p < .001$; Fig. 2). Longer (four-letter) words were significantly more error-prone than shorter (three-letter) words (12% ± 7% vs. 11% ± 6%, $z = -2.22$, $p = .026$). The spaces between words were also subject to errors: 187 (6%) of the word errors involved a space error (e.g., intrusion in a word, doubling, or deletion).

Error types were coded according to the rules used in previous tongue-twister studies (e.g., Nozari & Dell, 2012; see Table 1). Any error (e.g., addition, deletion, substitution, or exchange) that resulted in a word was counted as a lexical error. Any letter addition, deletion, substitution, or exchange that did not result in a word was counted as a segmental error. We observed significantly more segmental (2,276; 68%) than lexical (1,097; 32%) errors ($z = -5.4$, $p < .001$), indicating that the majority of typing errors originated at the segmental level (or during later motor processes).[1]

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[1] Note that this is a conservative estimate, because some of the lexical errors might indeed be segmental errors—for example, mud rag → mug rag—caused by the migration of segments from other words in the sequence. In fact, 56% of lexical errors in this experiment were compatible with this mechanism, further increasing the proportion of segmental errors.

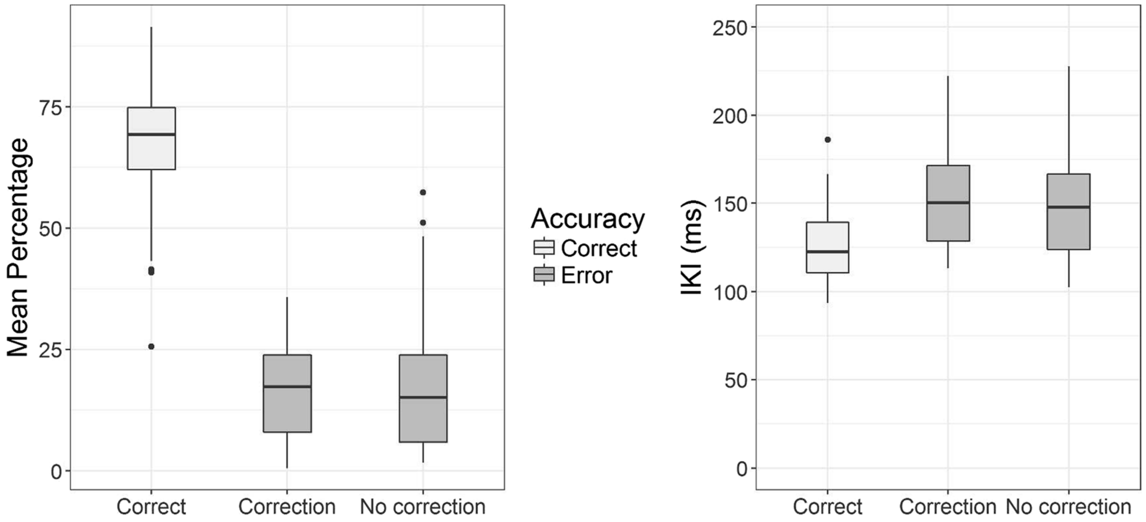

Fig. 2 Accuracy and typing speed for correct and error responses. (Left) Boxplot of percentages of correct trials and error trials with and without correction. (Right) Boxplot of interkeystroke intervals (IKI). The horizontal line within a box represents the median, the box extends from the first to the third quartile, and the vertical lines extend to 1.5 times the interquartile range.

To examine the influence of phonology on typing errors, we investigated phonotactic violations in the typing errors. In spoken production, these errors (e.g., erroneous production of /ŋ/ for an onset) are extremely rare (<1%; Warker & Dell, 2006). In our typing data, however, 677 (30%) of the segmental errors violated phonotactic constraints, a rate much higher than that reported for spoken production.

In summary, the predominance of segmental over lexical errors suggests that the majority of errors in this paradigm arise at the postlexical level, which makes the paradigm suitable for studying the interaction between the lexical and postlexical levels. Moreover, the much more frequent violation of phonotactic constraints in typing than in speech suggests that typing errors are not simply phonological errors that emerge during typing; they reflect the specific dynamics of a unique production system, which must be studied in its own right.

The repeated-letter effect

We tested for the repeated-letter effect on the third and fourth words of the sequence, comparing cases in which the vowel was repeated (*fog top*; $N = 185$) to those in which it was not (*fog tip*; $N = 142$; Fig. 3). Anticipations (e.g., *fog top* → *tog top*, *fop top*; 61%), perseverations (e.g., *fog top* → *fog fop*, *fog tog*; 27%), and exchanges (e.g., *fog top* → *tog fop*; 1%) were included in the analysis. Analyses were carried out using a logistic multilevel mixed model (MLM; lme4 package, Bates, Mächler, Bolker, & Walker, 2015, R version 3.3.2). The fixed effects included condition (repeated vs. nonrepeated), and speech errors in spoken production was included as a covariate to control for the effect of phonology. The random effects included random intercepts for subjects and items, as well as random slopes for condition by subjects. Table 2 shows the results of this analysis. When all trials were included in the model (i.e., contrasting migration errors to trials with correct or other error responses), there were significantly more migration errors in sequences with repeated segments, $z = 2.201$, $p = .027$. The pattern of speech errors did not reliably predict the pattern of errors in typing. We repeated this analysis, this time including only trials with errors (migrations of interest vs. other error types), to ensure that potential differences in the overall accuracy rate between conditions did not confound the results. The results were similar, $z = 1.979$, $p = .048$.[2] A direct comparison of the error rates in the repeated and nonrepeated conditions using the Wilcoxon signed-rank[3] test confirmed the findings of the MLM, $z = -2.16$, $p = .031$. The effect size phi (square root of chi-square divided by the number of observations) yielded .36, which constitutes a medium effect size. To summarize, we found a robust, medium-sized repeated-letter effect in our dataset that was not driven by phonology.

By a similar logic, one might expect that the interference created due to the feedback from the shared vowel would slow down the production of the consonants on correct trials, even though no overt errors have surfaced. Indeed, we observed a small but significant effect on the typing durations, such that the intervals leading up to the onset and coda consonants were slowed down in the repeated-letter condition ($M = 142$ ms ± 31.2) relative to the nonrepeated-

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[2] We have reported two-tailed p values for all tests, but since the hypothesis of the experiment was directional, technically a one-tailed p value (i.e., half the size of the reported p values) accurately represents the probability that the effect was due to chance.

[3] The pattern of results was similar whether speech errors were or were not subtracted from typing errors in this analysis.

Table 1 Subtypes of lexical and segmental errors and their frequencies in the typing data

Target	tank fed fog top	
Lexical errors		32% of all errors
Addition	tank ***tank/tan***[a] fed fog top	7%
Deletion	____ fed fog top	13%
Substitution	***fed/tan***[a] fed fog top	75%
Exchange	tank ***fog fed*** top	5%
Segmental errors		68% of all errors
Addition	tank***g***/tank***c*** fed fog top	32%
Deletion	_ank fed fog top	25%
Substitution	tank fed ***t***og/***y***og[a] top	36%
Exchange	tank fed ***g***o***f*** top/***t***og ***f***op/fo***p*** to***g***[b]	7%

[a] The two examples show errors originating from within versus outside the sequence

[b] Segments may be exchanged within a word or between two words

Table 2 Results of the repeated-segment analysis

Fixed Effects	Estimate	*SE*	*z* Value	Pr(>|*z*|)	(Sig.)
(*Intercept*)	– 4.155	0.136	– 30.5	<.001	***
Repeated letter	0.332	0.151	2.20	.0277	*
Speech errors	– 0.0764	0.441	– 0.173	.863	
Random Effects	Variance				
Subject intercept	0.200				
Repeated letter | subject	0.262				
Item intercept	0.376				

letter condition (M = 138 ms ± 26.8). An MLM analysis performed on the onset and coda intervals confirmed the pattern observed for migration errors, $\beta = 3.89$, $t = 2.87$, $p = .008$, similar structure than error analysis, with individual bigrams as random effects (Pinet, Ziegler, & Alario, 2016).

Discussion

We found a significant repeated-letter effect in our data: There were more migration errors between consonants and consonants were typed more slowly when sequences contained repeated vowels than when they did not. The effect on error rates persisted after accounting for errors made in speaking, which ensured that the effect was not solely of phonological origin. Moreover, errors had been recorded while sequences were being recalled from memory, in the absence of any visual representation of the words: this ensured that the effect was independent of visual processes. This finding can thus be taken as evidence for feedback from the postlexical to the lexical level in typing. To our knowledge, this is the first demonstration of interactivity within the typing system. However, several studies have probed a related issue, namely the modularity of response selection and execution—that is, whether execution starts before response selection is over (e.g., Damian & Freeman, 2008). One line of research that has tested the issue of modularity has reasoned that in a nonmodular system, the duration of response execution should be affected by factors influencing lexical selection. The majority of such studies

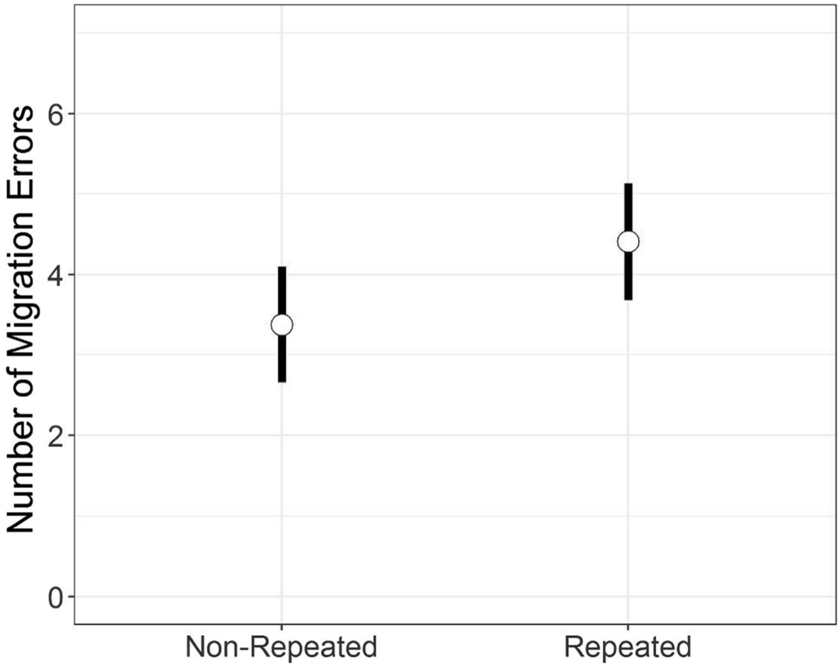

Fig. 3 Mean numbers of migration errors by condition. Error bars represent 95% confidence intervals corrected for within-subjects variability (Loftus & Masson, 1994).

have focused on the effect of word frequency on response latency or duration. It is not clear, however, whether word frequency is the appropriate variable. Drawing on findings from spoken production, there is little doubt that word frequency—and similarly age of acquisition—is reflected in the strength of lexical–phonological mappings (even though word frequency has an additional possible influence on lexical selection; Kittredge, Dell, Verkuilen, & Schwartz, 2008). Therefore, such variables do not necessarily—or exclusively—index lexical selection, but are expected to influence segmental encoding directly. Additionally, higher-frequency words are likely to be typed more frequently—that is, have more practiced motor plans. It is thus difficult to pin down the effect of frequency to a certain part of the system. Given these issues, it is not surprising that different studies have reached different conclusions regarding the effect of frequency on response execution times (Baus, Strijkers, & Costa, 2013; Pinet et al., 2016; Scaltritti, Arfé, Torrance, & Peressotti, 2016; Torrance et al., 2017).

A more careful test of the influence of lexical selection on response execution durations was carried out by Damian and Freeman (2008), who used a version of the Stroop task to manipulate the difficulty of lexical selection. They found longer response latencies, but not longer response durations, in the incongruent condition, in which lexical selection was more difficult. The absence of an effect on durations was taken as evidence for modular response selection and execution processes. Note, however, that this approach skips segmental encoding by directly linking lexical selection to response execution. An alternative interpretation is that there is interaction between lexical selection and segmental encoding, but not between segmental selection and response execution, at least not in a form that would affect the timing of individual key presses (O'Seaghdha & Marin, 2000). Viewed in this light, our present results would point specifically to feedback between segmental (either letter or keystroke) and lexical representations.

Finally, our results may also have implications for the encapsulation of the inner and outer loops in Logan and Crump's (2011) model. In this model, lexical representations constitute the interface between the two loops and are thus involved in processes related to both stages. If the claim is that lexical selection takes place as part of the processes in the outer loop, however, then the present results are incompatible with the two loops being informationally encapsulated. Previous results have also suggested that postlexical information that should be contained within the inner loop (kinesthetic feedback or motoric features) could actually be accessed by the outer loop and might influence response selection (Cerni, Velay, Alario, Vaugoyeau, & Longcamp, 2016; Kalfaoğlu & Stafford, 2014; Pinet et al., 2016; Topolinski, 2011).

Parallels between speaking and typing

It is not uncommon to dismiss the study of written/typed production as either irrelevant to spoken production (i.e., as a motor task that has little in common with speaking), or as superfluous to spoken production (i.e., as exactly the same as speaking but carried out by the hands). The present results argue against both of these extreme views by demonstrating that, although the general cognitive architecture of typing has many parallels with spoken production, it also has unique characteristics. Similarities between the two systems can be inferred from the presence of similar subtypes of lexical and segmental errors in typing and speaking, which suggests similar stages of semantic-to-lexical and lexical-to-segmental mapping. Moreover, as argued above, the presence of the repeated letter effect indicates that the system shows properties such as interactivity just like the spoken production system (Dell, 1986; Rapp & Goldrick, 2000). Quite remarkably, the repeated phoneme effect reported by Dell (1984) yielded effect sizes of .34 and .38 for the first and second experiments, respectively, comparable to our reported effect size of .36 for the repeated letter effect. These similarities suggest that a psycholinguistic model is quite appropriate for the investigation of the mechanisms underlying typing.

At the same time, however, there are clear differences between typing and spoken production, an example of which is the violation of phonotactic rules in typing errors demonstrated in the present study. Such differences necessitate the study of typing as an independent system that is related—but not identical—to spoken production (see Rapp & Fischer-Baum, 2014, for similar arguments about handwriting). In this vein, it will be important to elucidate the exact nature of postlexical representations in typing. As we alluded to in the introduction, the two currently dominant models of typing disagree on whether letter and keystroke representations are distinct or not (see also a discussion in Scaltritti, Longcamp, & Alario, 2017). The conclusion drawn from our findings does not critically depend on the number of postlexical layers of representation, but the question must be answered before a complete model of typing can be constructed, leaving room for further studies. A psycholinguistic framework might be helpful in shedding light on such matters (e.g., McCloskey, Macaruso, & Rapp, 2006; Pinet et al., 2016).

Conclusion

This was the first demonstration of feedback between the postlexical and lexical layers in typed production similar to that found in spoken production. More generally, the similarities in the error patterns in spoken and typed production motivate a psycholinguistic framework for studying the cognitive architecture of typing, complemented by research on specific aspects of typing not shared with spoken production.

Appendix

Table 3. Sequences used as materials for the present study

Sequence	Word 1	Word 2	Word 3	Word 4
1	cow	bill	bat/but	cap/cup
2	rib	mess	mad/mud	rag/rug
3	bond	sum	sat/sit	bag/big
4	pry	hem	hat/hit	pan/pin
5	few	bud	ban/bin	fat/fit
6	bun	way	wet/wit	bed/bid
7	him	rave	rob/rub	hot/hut
8	tank	fed	fig/fog	tip/top
9	ray	pull	pet/pot	red/rod
10	gas	pro	pen/pun	get/gut
11	ten	hill	ham/hum	tab/tub
12	bad	nip	net/nut	beg/bug
13	hold	tug	tan/tin	hap/hip
14	cut	milk	map/mop	cab/cob
15	cry	pug	pad/pod	cat/cot
16	dew	lap	lit/lot	dig/dog
17	fuzz	howl	has/his	fan/fin
18	let	curb	can/con	lag/log
19	week	fur	fall/fill	wash/wish
20	lid	men	math/moth	lack/lock
21	man	set	sick/suck	mill/mull
22	born	leg	last/lust	back/buck
23	ball	dorm	deck/duck	best/bust
24	rum	dock	dash/dish	rang/ring
25	fun	peg	pack/pick	fast/fist
26	day	meek	mist/must	dill/dull
27	fry	bang	beet/boot	feel/fool
28	pig	dawn	deem/doom	peel/pool
29	sip	fax	feed/food	seen/soon
30	lump	fawn	feet/foot	leek/look
31	may	rid	reef/roof	meet/moot
32	less	bye	bait/bout	laid/loud
33	lush	mitt	mean/moon	leap/loop
34	bird	tuck	teal/tool	beam/boom
35	pit	hung	head/hood	pear/poor
36	try	long	lake/like	tame/time
37	push	bot	bake/bike	pale/pile
38	mug	root	race/rice	make/mike
39	weep	surf	sale/sole	wake/woke
40	sub	toy	tale/tile	sane/sine
41	run	mat	mile/mole	rise/rose
42	low	rush	rate/rite	lace/lice
43	past	rung	ride/rode	pike/poke
44	bull	mix	made/mode	bane/bone

Four different variations of each sequence were created from the combination of Words 3 and 4

References

Baars, B. J., Motley, M. T., & Mackay, D. G. (1975). Output editing for lexical status in artificially elicited slips of the tongue. *Journal of Verbal Learning and Verbal Behavior*, *14*, 382–391.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48. doi:https://doi.org/10.18637/jss.v067.i01

Baus, C., Strijkers, K., & Costa, A. (2013). When does word frequency influence written production? *Frontiers in Psychology*, *4*, 963. doi: https://doi.org/10.3389/fpsyg.2015.00963

Cerni, T., Velay, J.-L., Alario, F. X., Vaugoyeau, M., & Longcamp, M. (2016). Motor expertise for typing impacts lexical decision performance. *Trends in Neuroscience and Education*, *5*, 130–138.

Damian, M. F., & Freeman, N. H. (2008). Flexible and inflexible response components: A Stroop study with typewritten output. *Acta Psychologica*, *128*, 91–101.

Dell, G. S. (1984). Representation of serial order in speech: Evidence from the repeated phoneme effect in speech errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*, 222–233.

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review*, *93*, 283–321. doi:https://doi.org/10.1037/0033-295X.93.3.283

Dell, G. S., Nozari, N., & Oppenheim, G. M. (2014). Word production: Behavioral and computational considerations. In M. A. Goldrick, V. S. Ferreira, & M. Miozzo (Eds.), The Oxford handbook of language production (pp. 88–104). Oxford: Oxford University Press.

Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. *Psychological Review*, *104*, 801–838.

Kalfaoğlu, Ç., & Stafford, T. (2014). Performance breakdown effects dissociate from error detection effects in typing. *Quarterly Journal of Experimental Psychology*, *67*, 508–524. doi:https://doi.org/10.1080/17470218.2013.820762

Kittredge, A. K., Dell, G. S., Verkuilen, J., & Schwartz, M. F. (2008). Where is the effect of frequency in word production? Insights from aphasic picture-naming errors. *Cognitive Neuropsychology*, *25*, 463–492.

Kleiner, M., Brainard, D. H., & Pelli, D. (2007). What's new in Psychtoolbox-3? In *Perception*, *36*(ECVP Abstract Suppl.), 14.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*, 1–38, disc. 38–75.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*, 476–490. doi:https://doi.org/10.3758/BF03210951

Logan, G. D., & Crump, M. J. C. (2010). Cognitive illusions of authorship reveal hierarchical error detection in skilled typists. *Science*, *330*, 683–686. doi:https://doi.org/10.1126/science.1190483

Logan, G. D., & Crump, M. J. C. (2011). Hierarchical control of cognitive processes: The case for skilled typewriting. In B. H. Ross (Ed.), The psychology of learning and motivation: Advances in research and theory (Vol. 54), pp. 1–27). San Diego: Academic Press.

MacKay, D. G. (1970). Spoonerisms: The structure of errors in the serial order of speech. *Neuropsychologia*, *8*, 323–350.

McCloskey, M., Macaruso, P., & Rapp, B. (2006). Grapheme-to-lexeme feedback in the spelling system: Evidence from a dysgraphic patient. *Cognitive Neuropsychology*, *23*, 278–307.

Nozari, N., & Dell, G. S. (2009). More on lexical bias: How efficient can a "lexical editor" be? *Journal of Memory and Language*, *60*, 291–307.

Nozari, N., & Dell, G. S. (2012). Feature migration in time: Reflection of selective attention on speech errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*, 1084–1090.

O’Seaghdha, P. G., & Marin, J. W. (2000). Phonological competition and cooperation in form-related priming: sequential and nonsequential processes in word production. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 57–73.

Pinet, S., & Nozari, N. (2018). “Twisting fingers”: the case for interactivity in typed language production. Retrieved from osf.io/knby5.

Pinet, S., Ziegler, J. C., & Alario, F.-X. (2016). Typing is writing: Linguistic properties modulate typing execution. *Psychonomic Bulletin & Review*, *23*, 1898–1906. doi:https://doi.org/10.3758/s13423-016-1044-3

Rapp, B., & Fischer-Baum, S. (2014). Representation of orthographic knowledge. In M. A. Goldrick, V. S. Ferreira, & M. Miozzo (Eds.), The Oxford handbook of language production (p. 338). New York: Oxford University Press.

Rapp, B., & Goldrick, M. (2000). Discreteness and interactivity in spoken word production. *Psychological Review*, *107*, 460–499.

Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive-motor performance. *Cognitive Science*, *6*, 1–36.

Scaltritti, M., Arfé, B., Torrance, M., & Peressotti, F. (2016). Typing pictures: Linguistic processing cascades into finger movements. *Cognition*, *156*, 16–29.

Scaltritti, M., Longcamp, M., & Alario, F.-X. (2017). The serial order of response units in word production: The case of typing. Journal of Experimental Psychology*: Learning, Memory, and Cognition*. Advance online publication. doi:https://doi.org/10.1037/xlm0000494

Topolinski, S. (2011). I 5683 You: Dialing phone numbers on cell phones activates key-concordant concepts. *Psychological Science*, *22*, 355–360.

Torrance, M., Nottbusch, G., Alves, R. A., Arfé, B., Chanquoy, L., Chukharev-Hudilainen, E., … Wengelin, Å. (2017). Timed written picture naming in 14 European languages. *Behavior Research Methods*. Advance online publication. doi:https://doi.org/10.3758/s13428-017-0902-x

Warker, J. A., & Dell, G. S. (2006). Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 387–398. doi:https://doi.org/10.1037/0278-7393.32.2.387

Yamaguchi, M., Crump, M. J. C., & Logan, G. D. (2013). Speed–accuracy trade-off in skilled typewriting: Decomposing the contributions of hierarchical control loops. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 678–699.