Typing is writing: Linguistic properties modulate typing execution

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Abstract

Typing is becoming our preferred way of writing. Perhaps because of the relative recency of this change, very few studies have investigated typing from a psycholinguistic perspective. In addition, and despite obvious similarities between typing and handwriting, typing research has remained rather disconnected from handwriting research. The current study aimed at bridging this gap by evaluating how typing is affected by a number of psycholinguistic variables defined at the word, syllable and letter levels. In a writing-to-dictation task, we assessed typing performance by measuring response accuracy, onset latencies —an index of response preparation and initiation —and interkeystroke intervals (IKIs) —an index of response execution processes. The lexical and sub-lexical factors revealed a composite pattern of effects. Lexical frequency improved response latencies and accuracy, while bigram frequency speeded up IKIs. Sound-spelling consistency improved latencies, but had an inhibitory effect on IKI. IKIs were also longer at syllable boundaries. Together, our findings can be fit within a framework for typed production that combines the previously developed theories of spelling and typing execution. At their interface, we highlight the need for an intermediate hierarchical stage, perhaps in the form of a graphemic buffer for typing.

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Introduction

With the development of new information technologies, we might be giving up pens for keyboards. The cognitive impact of this (r)evolution is unknown (Mikulak, 2014). On the one hand, it is reasonable to assume similar linguistic representations and brain substrates for written production, whether it is handwritten or typed (Purcell, Napoliello, & Eden, 2011). On the other hand, cognitive models of typing (Logan & Crump, 2011; Rumelhart & Norman, 1982) have remained somewhat disconnected from models of handwriting (e.g., Houghton & Zorzi, 2003; Rapp, Epstein, & Tainturier, 2002), with almost no attempts to make direct theoretical comparisons. Models of typing have been mainly concerned with the peripheral aspects of the typing process (i.e., response execution at the keystroke level) rather than its psycholinguistic components (i.e., response selection at the word level); the opposite is true for models of handwriting (Figure 1). Given the current interest in understanding motor planning (e.g. pre-motor, motor, monitoring, etc.) in the context of language production (for speech, see e.g., Bohland, Bullock, & Guenther, 2010; Hickok, 2014), such a separation seems no longer tenable.

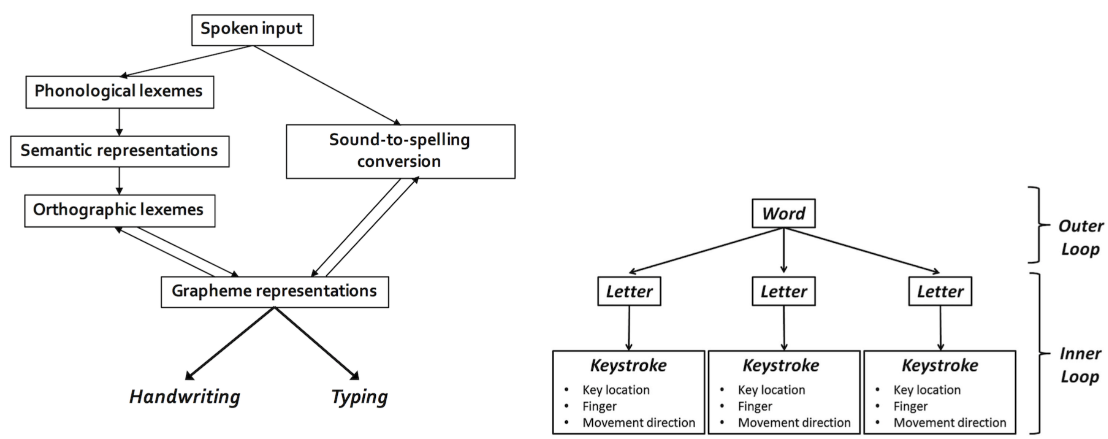

Figure 1: Prototypical models of spelling (adapted from Houghton & Zorzi, 2003; Rapp et al., 2002) and typing (Logan and Crump's (2011) hierarchical dual-loop model, figure from Yamaguchi & Logan, 2014).

Psychonomic research on typing has mainly focused on execution processes. Quite precise mechanisms have been proposed for the correct retrieval and ordering of keystrokes prior to execution (Rumelhart & Norman, 1982). Typically, these operate upon an already retrieved lexical representation. Logan and Crump's (2011) more recent model of typing (Figure 1) includes rather independent word and keystroke levels of processing: an "outer-loop" deals with language processing, while an encapsulated "inner-loop" produces a series of keystrokes from an input word. Consistent with this hypothesis, lexical frequency or Stroop-type interference do not appear to affect response durations or inter-keystroke intervals (IKIs) (Baus, Strijkers, & Costa, 2013; Damian & Freeman, 2008; Logan & Zbrodoff, 1998), whereas frequent letters, or bigram and trigram associations can speed up execution processes, depending on the typist's expertise (Behmer & Crump, n.d.).

Earlier seminal research on copy-typing also assessed the influence of lexical and sublexical properties and reported for example effects of word frequency on typing performance (e.g., Gentner, Larochelle, & Grudin, 1988; Inhoff, 1991; Viviani & Laissard, 1996; West & Sabban, 1982). However, copy-typing involves some specific perceptual and cognitive mechanisms (e.g., visual letter identification) that are not present in spontaneous typing or typing to dictation, which may reduce the generalizability of the previously reported effects (Bonin, Méot, Lagarrigue, & Roux, 2015; Nottbusch, Grimm, Weingarten, & Will, 2005; Will, Nottbusch, & Weingarten, 2006). Bonin et al. (2015) compared different handwriting tasks and suggested that dictation was more sensitive to sublexical variables than copying; in typing, very few studies explored other production tasks (Baus et al., 2013; Bertram, Tønnessen, Strömqvist, Hyönä, & Niemi, 2015; Will et al., 2006).

Concurrently, handwriting research has followed a different path. Since Van Galen's (1991) seminal psychomotor theory, handwriting research typically focused on psycholinguistic processing stages at the expense of motor components, perhaps because of the difficulty to precisely track execution processes in handwriting. Dual-route frameworks of spelling are well established (Houghton & Zorzi, 2003; Rapp et al., 2002). Data from neuropsychological cases favor the existence of both lexical and sublexical processing routes, their parallel activation and integration in a "graphemic buffer", as well as the existence of feedback connections from the grapheme level to both pathways (see Figure 1). Supporting the dual-route spelling framework are also numerous reports about the influence of lexical (e.g., word frequency) and sublexical (e.g., sound-spelling consistency) variables on handwriting latencies across multiple task settings (Bonin, Chalard, Méot, & Fayol, 2002; Bonin et al., 2015; Bonin, Peereman, & Fayol, 2001; Delattre, Bonin, & Barry, 2006; although see Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013). However, lexical and sublexical factors also affect whole word durations (lexicality in Roux et al., 2013, regularity in citealpDelattre2006) and finer measures of response execution (inter-letter intervals and stroke durations; e.g., bigram frequency in Afonso, Álvarez, & Kandel, 2015; Kandel, Peereman, Grosjacques, & Fayol, 2011; Roux et al., 2013. While spelling models are well suited to account for the effects on response selection, they are not sufficiently specified in order to account for the effects on response execution.

In the present study, an attempt was made to bridge the gap between models of typing and handwriting by investigating the effects of several linguistic properties on different levels of typing performance and to interpret the results at the cross-roads of both frameworks. We asked skilled typists to write words to dictation and measured response onsets, individual IKIs, and overall accuracy. Onset latency was considered an index of response preparation and movement initiation of the first keystroke (i.e. mostly "outer-loop"; Logan & Crump, 2011, whereas IKI was taken as an index for response execution processes ("inner-loop"). We manipulated lexical and sublexical properties at various psycholinguistic levels. At the word level, lexical frequency was manipulated. At the syllable level, we investigated the effects of sound-spelling consistency. Between syllables, we investigated whether pure orthographic syllable boundaries were processed differently from phono-graphic syllable boundaries. Finally, at the letter level, we manipulated the frequency with which two letters co-occur (bigram frequency) and the consistency of the onset. Following previous research on handwriting and typing, we hypothesized that word frequency should preferentially affect word retrieval processes, bigram frequency should preferentially affect execution processes, and sound-spelling consistency might affect different processing levels.

Method

Participants

Thirty-five skilled typists were recruited through campus advertisement on the basis of self-assessment criteria such as regular typed note-taking in classes. Five participants were excluded because they did not reach 70% accuracy in the task. Thus, we report data from 30 university students (7 males; mean age = 20.5 [18-35], all French native speakers). They had an average typing experience of 8.7 years and spent on average 3.5 hours a day typing. 75% of them took notes on their computer during classes.

Materials

Word frequency and consistency can only be manipulated between words. Because IKIs depend greatly on bigram layout on the keyboard (Gentner et al., 1988), we constructed material such that the same bigrams were associated with different word frequencies and consistencies. We restricted our search to 5 to 7 letter disyllabic nouns, with a frequency of at least 1 occurrence per million. From this set, we selected stimuli according to the bigrams they contained. Starting from a random seed of three words, we sampled the pool of words so that each new selected word had at least 80% of its bigrams in common with the already selected stimuli. We excluded emotionally loaded words and words containing written accents. The final stimuli set comprised 92 disyllabic words from the BRULEX database (Content, Mousty, & Radeau, 1990, see Table 1), with 126 different bigrams, each appearing between one to 23 times (mean = 4, SD = 3.7) across words (see Table 2). Word and bigram frequencies were log-transformed.

Variables	Mean	Median	SD	Min-Max	Q1-Q3
Word length	6.4	7	0.67	5-7	6-7
Word Frequency	1.9	1.7	1.48	0.03-5.9	0.5-3.0
Nb Phonemes	5.0	5	0.62	4-6	5-5
CR 1	0.8	0.96	0.30	0.003-1	0.74-1
CR 2	0.8	0.93	0.31	0.005-1	0.64-1
Initial ConsistencyP	0.9	0.99	0.25	0.03-1	0.77-1

Table 1: Stimuli characteristics provided by Lexique (New et al., 2004) and Planton (2014), and computed from BRULEX (Content et al., 1990).

Variables	Mean	Median	SD	Min-Max	Q1-Q3
Bigram Frequency	9.8	10.1	0.85	7.2-11.4	9.1-10.5
CR (syllable)	0.78	0.96	0.31	0.003-1	0.69-1
Position	3.45	4	1.70	1-6	2-5

Table 2: Bigram characteristics provided by Surface database (New et al., 2004) and computed from BRULEX (Content et al., 1990) (syllable boundaries excluded).

We computed consistency ratios (CRs) (Ziegler, Jacobs, & Stone, 1996) for each syllable by dividing the number of "friends" (words that share the same phonology and orthography for a given syllable) by the summed numbers of "friends" and "enemies" (words that share the same phonology for that syllable, regardless of their orthography), weighted by the frequency of each word (i.e. a token count). Initial Consistency was computed in the same way for the first phoneme-grapheme correspondence. Consistency cannot be defined at syllable boundaries. As a special test for the influence of phonological properties during typing of these segments, we compared IKIs within syllables to those at phono-orthographic ("s-t" in "jus-ti-ce"/"Zys-tis") and pure orthographic ("i-c" in "jus-ti-ce"/"Zys-tis") boundaries. Sound files were generated with Apple Macintosh's speech synthesizer (French voice: "Thomas"). The pronunciations were informally checked for appropriateness.

Experimental procedure

Participants were seated in front of a laptop computer (2013 Dell XPS). Responses were recorded via an external keyboard modified to provide millisecond accuracy (DirectIN High Speed Keyboard PCB v2010, Empirisoft). On every trial, a 200ms-beep was played to alert participants of the upcoming auditory target, presented between 500 and 800 ms later (lag randomly picked for every trial from a uniform distribution). Participants were given 2,500 ms from the onset of the stimulus to type the whole word. No visual feedback of what was typed was given; stimuli were delivered binaurally through standard headphones. As all relevant events were auditory, participants were instructed to look at the keyboard throughout the experiment.

The experiment consisted of three blocked repetitions of the same items, separated by a short break. All stimuli were presented in each block in different randomized orders with the constraint that two consecutive items never started with the same letter.

Statistical analysis

We performed analyses on accuracy rates, and on chronometric measures of correct trials only. A trial was considered correct if all letters of the word were correctly typed and no backspace occurred within the course of the trial. Responses that were not completed before the time out were excluded from the analysis. All analyses were performed using linear regression mixed-effects models (lme4 package in R software, Bates, Mächler, Bolker, and Walker (2015)). Latencies and IKIs were analyzed separately. Dependent variables were transformed to approximate a normal distribution according to the result of a Box-Cox test: RT were inverse-transformed and IKIs were log-transformed. Outliers were identified by visual inspection of a Q-Q plot and removed from the analysis. Accuracy rates were analyzed with the same model structures as latencies, but using logistic regression. We allowed intercept and slopes to vary by subject for all variables, by item for latencies and accuracy rates, and by bigram for IKIs. A comparison between a model fitted with random effects by bigram or by item confirmed that the bigram structure was preferable (smaller Akaike Information Criteria value). The consistency ratio variable did not have a homogeneous distribution because many values were close to 1. To avoid giving a higher weight to such extreme value, we performed the analyses on subsets of the data by randomly sampling items within this extreme population. Models run over the whole item set produced the same results than those reported here. In addition to the predictors of theoretical interest, the statistical models included control variables. For latencies and accuracy rates, we included block number, word length, stimulus acoustic duration, and typing speed (mean IKI computed by participants over all correct trials). For IKIs, we included block number, position within the word, and hand alternation (whether both letters of a bigram are typed with the same hand or not). As the generation of p-values for this kind of analysis is debated (Bates et al., 2015), we took t-values to approximate z-values, and considered significant any value above 1.96. Confidence intervals were computed by adding/subtracting [1.96 x standard error] to predictor parameter estimates.

Results

One item was excluded because its accuracy was less than 50% across all subjects ("harnais"). Trials with incomplete but otherwise correct responses were also excluded (7.8% of the data).

Latencies

Latency analyses showed significant facilitatory effects of word frequency ($\beta = -1.42E-05$; $t = -3.75$; $CI = [-2.16E-05; -6.74E-06]$) and of initial phoneme consistency ($\beta = -8.43E-05$; $t = -3.44$; $CI = [-1.32E-04; -3.63E-05]$). The more frequent a word and the more consistent the first phoneme, the shorter the onset latency. First or second syllable consistency ratios had no significant effects, and neither did bigram frequency ($\beta = 5,60E-05$; $t = -0,42$; $CI = [-3.20E-05; 2.08E-05]$; see Figure 2, upper row).

Block number and typing speed both showed significant negative effects, while stimulus acoustic durations had a significant positive effect (see Table 3).

	β	SE	t	95%CI		(sig)
(*Intercept*)	1.36E-03	2.02E-04	-6.74			
Word Frequency	-1.42E-05	3.78E-06	-3.75	-2.16E-05	-6.74E-06	*
Initial consistency	-8.43E-05	2.45E-05	-3.44	-1.32E-04	-3.63E-05	*
Bigram Frequency	-5.60E-06	1.35E-05	-0.42	-3.20E-05	2.08E-05	
Block number	-2.69E-05	3.26E-06	-8.26	-3.33E-05	-2.05E-05	*
Word Length	-4.94E-06	8.57E-06	-0.58	-2.17E-05	1.19E-05	
Typing Speed	2.03E-06	8.49E-07	-2.39	3.63E-07	3.69E-06	*
Acoustic Duration	2.65E-04	5.77E-05	4.60	1.52E-04	3.78E-04	*

Table 3: Results of the latencies analysis. β represent the magnitude of the effect (slope of the regression model); t-values above 1.96 are considered significant. RTs were inverse-transformed.

Accuracy rates

Correct responses occurred on 90.9% of the trials. Word frequency ($\beta = 0.23$; $z = 3.2$) had a significant positive effect and second syllable consistency ($\beta = 0.63$; $z = 1.9$) had a marginal positive effect. (Figure 2, middle row). Neither initial consistency ($\beta = 0.60$; $z = 1.5$), first syllable consistency ($\beta = 0.12$; $z = 0.39$), nor bigram frequency ($\beta = -0.20$; $z = -0.8$) had significant effects.

IKIs within syllables

Word frequency did not yield a significant effect ($\beta = 0.0028$; $t = 1.23$; $CI = [-0.035; -0.013]$). The consistency ratio of the syllable the IKI belonged to had a significant positive effect ($\beta = 0.062$; $t = 4.9$; $CI = [0.037; 0.087]$); the higher the syllable consistency, the longer the IKI (Figure 2, bottom). Bigram frequency had a significant facilitatory effect ($\beta = -0.055$; $t = -3.1$; $CI = [0.029; 0.083]$). Block number and position within the word also had significant effects (see Table 4).

The correlation of by-participant estimated effect sizes (i.e. random slopes) and typing speeds was significant for syllable consistency ($r = 0.69$, $p = 2.2E{-}5$) and bigram frequency

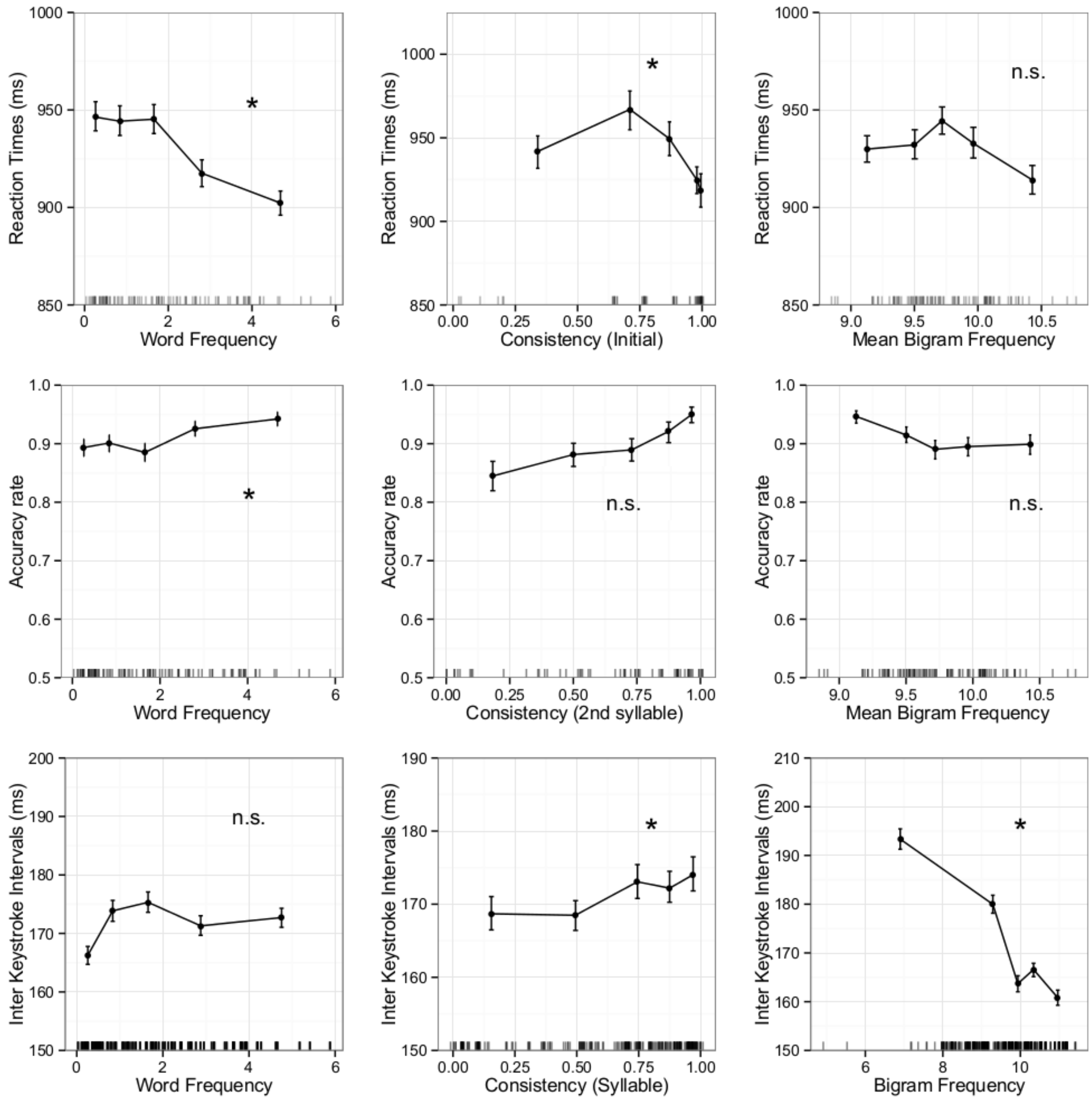

Figure 2: Dependent measures (in rows, respectively: reaction times, accuracy rates, and interkeystroke intervals (IKI)) by quintiles of predictors (in columns, respectively: word frequency, consistency and bigram frequency). Error bars correspond to mean standard error calculated by bootstrap. The distribution of each predictor is depicted along the x-axis.

	β	SE	t	95%CI		(sig)
(*Intercept*)	5.65	0.178	31.7			
Word Frequency	0.00282	0.00228	1.23	-0.0350	-0.0132	
Consistency	0.0563	0.0137	4.10	-0.0178	-0.000384	*
Bigram Frequency	-0.0552	0.0180	-3.07	0.0294	0.0832	*
Position	-0.0241	0.00558	-4.32	-0.0904	-0.0200	*
Block number	-0.009096	0.00444	-2.05	5.30	6.00	*
Hand alternation	0.0751	0.0388	1.93	-0.00166	0.00729	(*)

Table 4: Results of the IKI analysis. β represent the magnitude of the effect (slope of the regression model); t-values above 1.96 are considered significant. IKIs were log-transformed.

($r = 0.43$, $p = 0.02$), with effect sizes strongly consistent across participants (Figure 3). Word frequency random slopes did not correlate with typing speeds ($r = -0.25$, $p > 0.1$).

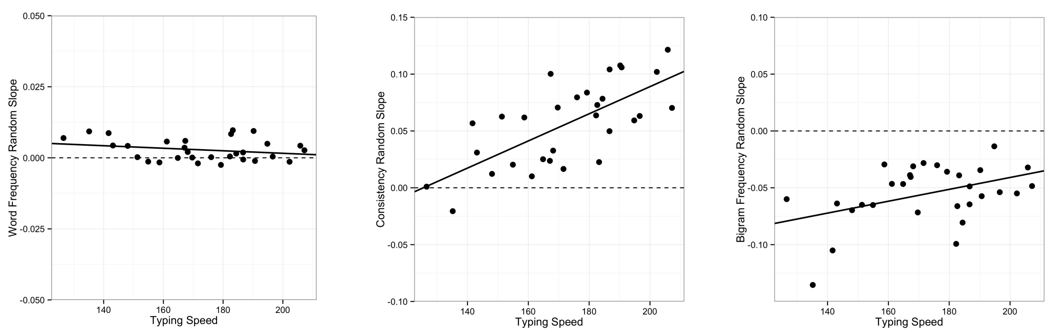

Figure 3: Correlations of by-participant random slopes (in IKI analysis) for word frequency, consistency and bigram frequency with participants' typing speed.

IKIs at syllable boundaries

The analysis of syllable-boundary IKIs revealed no effect of word frequency, while boundary type had a significant effect: IKI was longer at pure orthographic ($\beta = 0.064$; $t = 2.8$; $CI = [0.0182; 0.109]$) and at phono-orthographic boundaries ($\beta = 0.099$; $t = 4.6$; $CI = [0.0565; 0.142]$) than within a syllable; IKI at phono-orthographic boundaries tended to be longer than at pure orthographic boundaries (Figure 4). Bigram frequency also had a significant negative effect ($\beta = -0.043$; $t = -3.7$; $CI = [-0.0667; -0.0201]$). These effects were observed over and above the contributions of control variables: block number, hand alternation, and absolute position within the word (see Table 5).

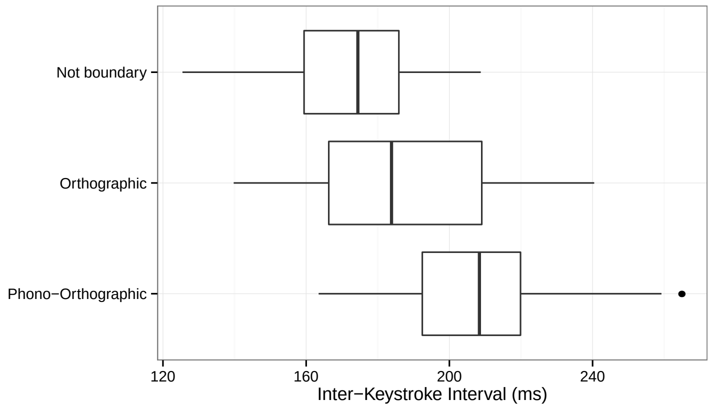

Figure 4: Boxplot of subjects mean IKI (in ms) at syllable boundaries.

	β	SE	t	95%CI		(sig)
(*Intercept*)	5.56	0.118	47.2			
Word Frequency	-0.00124	0.00134	-0.93	-0.00386	0.00138	
Boundary (O/NO)	0.0635	0.0231	2.75	0.0182	0.109	*
Boundary (PO/NO)	0.0992	0.0218	4.55	0.0565	0.142	
Bigram Frequency	-0.0434	0.0119	-3.66	-0.0667	-0.0201	*
Position	-0.0178	0.00526	-3.39	-0.0281	-0.00752	*
Block number	-0.00875	0.00399	-2.19	-0.0166	-0.000932	*
Hand alternation	0.0856	0.033	2.6	0.0209	0.1502	*

Table 5: Results of the syllable boundaries analysis. ß represent the magnitude of the effect (slope of the regression model); t-values above 1.96 are considered significant. IKIs were log-transformed. O: Orthographic boundaries. PO: Phono-orthographic boundaries. NO: Within syllable IKI.

Discussion

We assessed the effects of various psycholinguistic variables on different processing levels involved in word typing: lexical frequency (word level), sound-spelling consistency (syllable level), orthographic vs. phono-orthographic syllable boundaries (cross-syllabic positions), and bigram frequency and onset consistency (letter level).

Lexical frequency yielded a facilitatory effect on latencies and accuracy rates (word level), but not on IKIs (keystrokes). Bigram frequency had a facilitatory effect on IKIs, but had no effect on response latencies or accuracy rates. To the extent that latencies provide a measure of response selection, the lexical frequency effect points towards faster word retrieval with increasing word frequency. The bigram frequency effect on IKI points towards execution and inner-loop processes; hypothetically, frequent bigrams are typed more often, and the time between two keystrokes is reduced with practice and automaticity (Logan & Crump, 2011), as attested by the significant correlation of individual bigram frequency effects with typing speed (Behmer & Crump, n.d.; Gentner et al., 1988; West & Sabban, 1982).

The absence of word frequency effect on IKI contrasts with previous observations in spoken word production (Gahl, 2008), but is consistent with previous typing reports (Baus et al., 2013; Bertram et al., 2015; in handwriting, Delattre et al., 2006). It is also consistent with observations in graphemic buffer patients (Hillis & Caramazza, 1989), who showed sub-lexical errors in handwriting (e.g. letter substitutions, transpositions) that were insensitive to lexical factors (e.g. frequency). Together, all of the above observations support the central claim of previous typing models (e.g., Logan & Crump, 2011), which postulate distinct word and keystroke levels of processing.

Onset consistency does improve response latencies. This would be expected within dual-route models of spelling (Houghton & Zorzi, 2003; Rapp et al., 2002), where consistency results in a processing advantage because both the lexical and sublexical routes yield the same output. Dual-route models also naturally explain the effects of word frequency on response latencies because the lexical route is frequency-sensitive. Thus, it appears that a dual-route architecture is a well-suited addition to capture "outer-loop" word retrieval processes in typing (Logan & Crump, 2011).

Other aspects of our findings, however, might require additional assumptions. IKIs were longer at syllable boundaries than within syllables, replicating previous reports in typing (Gentner et al., 1988; Will et al., 2006) and handwriting (Kandel et al., 2011). Given that transitions between hierarchical levels take longer than transitions within the same level (Rosenbaum, Kenny, & Derr, 1983), we would argue that syllables constitute such a level of processing in typing between words and keystrokes and could perhaps be implemented in the context of a graphemic buffer (Hillis & Caramazza, 1989). This would be in line with theories of spelling (Kandel et al., 2011; Rapp et al., 2002), challenging Logan and Crump's (2011) two-level hierarchical organization.

Finally, syllable consistency had an inhibitory effect on IKIs —IKIs were longer for consistent than for inconsistent syllables —especially so in slower typists. This was unexpected, as dual-route models of spelling would always predict facilitatory effects of consistency (see above, onset consistency), inasmuch as they account for the effect at the outcome of word retrieval processes. Noticeably, opposite effects on latencies and IKIs have a precedent in both the typing and handwriting literatures. Snyder and Logan (2014) observed facilitation of latencies, along with lengthened durations with increasing prime-target orthographic overlap. Previously, Van Galen (1990) had reported shorter retrieval but increased handwriting durations for words with repeated syllables. He suggested that repeated syllables yield shorter retrieval at the word level but repeated strokes cause extra processing load at a lower level. These precedents suggest an explanation for the unexpected consistency effect because consistent syllables have greater orthographic overlap with their consistent neighbors ("friends" words with the same spelling) than inconsistent syllables. Thus taking a chaining account perspective (Snyder & Logan, 2014), one could argue that consistent syllables occur in different words and could therefore be associated with different motor programs, which might potentially create interference or uncertainty with respect to the motor program that would need to be executed.

One limitation of the current investigation is that language production was elicited through a dictation task. Dictation calls for specific auditory perceptual processes and might emphasize sublexical processes (Bonin et al., 2015). Thus, a general model of typing would need to be tested with different typed production tasks.

Overall, then, the present results call for a combination of the dual-route architecture for retrieval with a separated stage for execution ("inner loop"). They also suggest the need for a graphemic buffer involved in typing (Hillis & Caramazza, 1989; Van Galen, 1991). This buffer would constitute an additional level of hierarchical processing, complementing Logan and Crump's (2011) dual-loop model. Many details of this buffer remain to be established (see also Will et al., 2006, for considerations regarding the impact of linguistic properties on typing execution); our results highlight the role of orthographic and phonological boundaries, as well as the potential competition between sequences to be typed (motivated by the unexpected syllable consistency effect). The relationship between this putative buffer and the inner-loop, where letter sequences are processed for execution, remains as an important target for future work.

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