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What can typing tell us about language production?

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Abstract

Although research on typing has not exactly been sparse, studying typing within a psycholinguistic framework has not been a common approach. This paper argues in favor of this practice. By reviewing findings on patterns of typing errors and statistical learning in typed production, as well as influences of various factors on typing, including the similarity between the target word and its context, we show that typing has much in common with other modalities of language production and should be viewed as reflecting the general architecture of the language production system. We then discuss some of the contributions of typing research to the action monitoring literature due to the unique position that typing occupies at the interaction of phonological, orthographic, visual, and motor processes. We end by encouraging greater integration of typing research into psycholinguistic frameworks, not simply to confirm the predictions of such theories but to break new frontiers and push for new domains of inquiry.

Disclosure Statement

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1. Why study typing?

Research on language production, comprehension, and acquisition has undergone a major transformation in recent years in light of technological advances that have revolutionized communication. A tenet of such a transformation has been the rise of text-based, as opposed to speech-based, communication. Text is now used as the main input for training large language models (Chang et al. 2024) and many people share their thoughts by writing blog posts, interacting through text-based social media, and texting on their phones. Naturally, the ability to communicate thoughts by pressing buttons, once restricted to professional writers on their typewriters, has become a critical skill in modern society. Consequently, there has been a growing interest in understanding the cognitive and neural basis of this now-prevalent skill. This paper reviews the fruit of this research by focusing on what the findings can tell us about language production. The majority of studies reviewed here use typing on a keyboard, as research on typing on cell phones and other devices has been scant in comparison. However, basic principles such as the nature of representations and motor execution processes underlying typing on keyboards and cell phones appear to be largely similar, despite using different numbers of fingers on the two devices (Cerni et al. 2016).

The paper is organized as follows: first, we will briefly review some of the advantages of studying typing over other modalities of production to highlight its excellent potential as a research tool. Next, we present a brief overview of the architecture of the language production system and situate typing therein. The following four sections review the similarities and differences between typing and other modalities of language production (speaking and handwriting) from four angles: (a) factors affecting planning, (b) error patterns, (c) influences of contextual similarity on target production, and (d) statistical learning. These four are followed by a section discussing the mutual, but asymmetric, relationship between phonology and orthography. Finally, we will discuss typing in the broader framework of action monitoring, a framework that is gaining more and more popularity for studying language production as a self-regulating, goal-oriented system (Nozari 2025a).

The picture that emerges points strongly to typing as reflecting the general architecture of language production but adds unique angles to understanding its inner workings and interactions with other domains. We end by briefly reviewing a few areas of interest for future research.

2. Advantages of studying typed over spoken production

Studying speech production has been traditionally at a disadvantage compared to speech comprehension because of the methodological difficulties associated with researching the former.

Even with the advances in automated speech-to-text transcription technology, the output of automated transcriptions will often need to be manually checked and corrected for errors. Moreover, many aspects of language production, including error detection and repair, are not well-captured by automated transcriptions. Typing confers a big advantage here; production data are readily available and can be reliably coded without the manual labor required for processing spoken data. This, in turn, means much larger datasets, much greater statistical power, and more opportunities for replication (e.g., Pinet & Nozari 2022).

Aside from the sheer quantity of data, typing also allows for extracting more precise dependent measures. Word durations can be computed precisely in typing, whereas obtaining the same measurement in spoken production can be tricky, especially with fricatives such as /s/ and /z/ that have a gradual onset in the acoustic wave. Moreover, it is possible to register between-segment timings, called inter-key-intervals (IKIs), with high precision in typing, whereas doing so is nearly impossible in spoken production. Obtaining precise measures for onset latencies and durations, in addition to accuracy, with ease and over large quantities of data has two broader advantages: first, we can study speed-accuracy tradeoffs in production, which is critical for fully understanding the mechanisms underlying language production (Nozari & Hepner 2019a,b; see Pinet & Nozari 2021, for an example) Second, we can obtain fine-grained neural measures on segment-level production by time-locking neural data to individual units (e.g., Kalfaoğlu et al. 2018; Pinet & Nozari 2020). While electrophysiological studies of spoken production have come a long way, the precision is still at the lexical, rather than the segmental, level (Riès et al. 2021).

Some of these advantages stem from the unique characteristics of typing, including its discrete motor production, which is subject to much less coarticulation effects than spoken production. Such differences provide a good opportunity for studying processes that differ between typing and other production modalities. At the same time, they can be contrasted with what is common to all modalities of production. We review some of the shared and distinct processes across production modalities in the next sections after a brief overview of the general architecture of language production.

3. Architecture of the language production system in three modalities

Figure 1 shows a schematic of the language production system in three modalities, speaking, handwriting, and typing (e.g., Levelt et al. 1999; there is also another modality, sign language, which we leave out here). Some elements, such as semantic knowledge, are shared between all three modalities. From then onwards, two domains can be distinguished: phonological and orthographic. The phonological domain concerns sound representations produced through the articulatory system and perceived by the auditory system. The orthographic domain concerns text representations, usually generated by hands/fingers and perceived by the visual system. While related, the representations in these two domains do not necessarily have a one-to-one correspondence. For example, the word "more" (/ˈmɔɹ/) has four letters but three sounds.

Moreover, in languages with non-transparent orthography, such as English, orthography cannot always be predicted from phonology. For example, "for" (/ˈfɔɹ/) has three sounds, just like "more", but only three letters. These differences necessitate the existence of distinct, albeit related, phonological and orthographic representations.

A large body of research has shed light on the nature of representations involved in language production (e.g., Caramazza 1997; Dell 1986; Levelt et al. 1999). After a semantic concept is activated, its corresponding word is activated. In some theories, this representation is an abstract, modality-neutral, and syntactically rich representation called a "lemma" (e.g., Bock et al. 1994). A second word-level representation is assumed to be modality-specific (e.g., different between spoken and handwritten production) and to contain abstract segment-level information about the sequence of sounds/letters in the word. This is called a "lexeme" (e.g., Bock et al., 1994). In some theories, instead of two, a single modality-specific word-level representation is assumed with connections to syntax (Caramazza 1997; Dell 1986). Support for this view comes from studies demonstrating double dissociations between damage to spoken and handwritten production (e.g., 1997; Rapp et al. 2015).

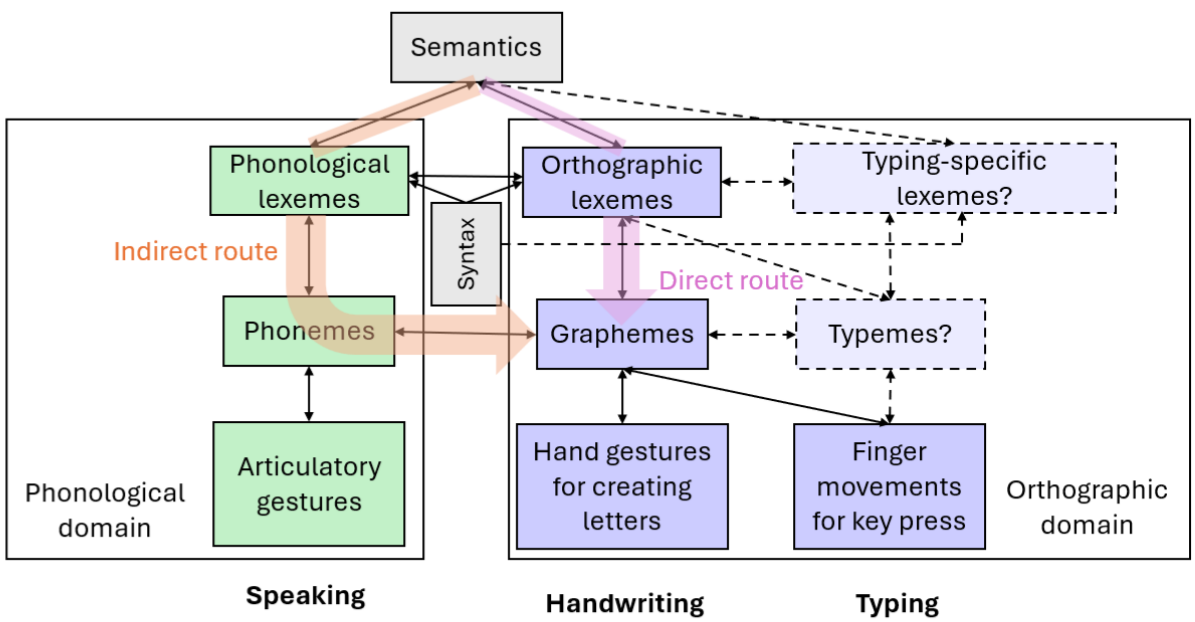

Figure 1. Architecture of the language production system for speaking, handwriting, and typing. Dashed lines show representations and connections in need of more empirical evidence.

Word-level representations then activate segments. In spoken production, these are called "phonemes", i.e., sound representations that do not yet contain information about motor movements. Phonemes, in turn, activate articulators, and a word is spoken (Dell 1986). In handwriting, the abstract segments are called "graphemes", or letters that are yet devoid of motor commands (Rapp & Caramazza 1997). Graphemes, in turn, activate motor effectors in arms and hands and a word is written. Past research has shown that spelling can be accomplished via two routes: a direct route (Fig. 1, pink arrow) mapping semantic knowledge onto letters directly via orthographic lexemes, and an indirect route (Fig. 1, orange arrow) mapping semantic knowledge to letters indirectly through phonological lexemes (Houghton & Zorzi 2003; Rapp et al. 2002). The contribution of the indirect route determines phonological influences on spelling.

Typing clearly falls within the orthographic domain but uses motor gestures different from those involved in handwriting. It is less clear whether typing uses the same lexeme and letter representations as handwriting or has its own unique equivalents (dashed boxes in Figure 1). While there is currently not enough data to answer this question conclusively, we can, nevertheless, examine how typing behaves in comparison to spoken and handwritten production and how it influences and is influenced by production in the phonological domain.

4. Planning in phonological and orthographic domains

Generally speaking, the same factors that affect linguistic retrieval in spoken production also affect handwriting and typing. For example, words with higher lexical frequency are retrieved faster in speaking (e.g., Kittredge et al. 2008), handwriting (e.g., Bonin & Fayol 2002), and typing (Pinet et al. 2016, 2022; Scaltritti et al. 2016; Torrance et al. 2018). Similarly, words learned earlier in life are retrieved more easily in all three modalities (speaking, Kittredge et al. 2008; handwriting, Weekes et al. 2003; and typing, Scaltritti et al. 2016). Moreover, greater name agreement facilitates retrieval in spoken (Alario et al. 2004), handwritten (Perret & Bonin 2019), and typed modalities (Scaltritti et al. 2016). Interestingly, inconsistent effects show the same inconsistency across modalities. For example, reports differ on whether longer words have longer latencies in spoken production (Bachoud-Lévi et al. 1998; Santiago et al. 2000; Snodgrass & Yuditsky 1996). Similarly, a study comparing typed picture naming across 14 languages found the effect of word length in only six languages (including Dutch, but excluding English, French, and Spanish), whereas the frequency effect was robustly uncovered in all 14 (Torrance et al. 2018).

In addition to these more general factors, factors specific to the orthographic domain affect handwriting and typing in the same way, including bigram and trigram frequency (e.g., handwriting, Zesiger et al. 1993; typing, Behmer & Crump 2016; Cerni & Job 2024), and phono-orthographic consistency (e.g., handwriting, Delattre et al. 2006; typing, Pinet et al. 2016; Pinet & Nozari 2022). Beyond these, typing efficiency is also affected by a set of typing-specific factors, including the number of fingers used for typing (Pinet et al. 2022; Scaltritti et al. 2016), consistent finger-to-key association (Logan et al. 2016), and daily typing time (Pinet et al., 2022). In contrast, looking at the keyboard negatively impacts typing speed (Logan et al. 2016).

In terms of linguistic access and planning, there are also clear parallels between speaking and typing. Several studies have shown that typing is sensitive to the word's morphological structure as well as the lexical properties of the constituents (e.g., Feldman et al. 2019; Gagné et al. 2023;

Weingarten & Nottbusch 2004; Will et al. 2006). For example, Gagné et al., (2023) showed that the typing of compound (e.g., carport) and pseudocompound (e.g., carpet) was sensitive to the lexical properties of each constituent, in line with the "decomposition" accounts of morphological processing in speaking (e.g., Lorenz et al. 2022, cf., Jacobs & Dell 2014). Parallels also exist at the level of sentence planning. For example, IKIs are longer at syllable boundaries (Pinet et al. 2016; Will et al. 2006) showing that planning in typing is subject to the same syllabification processes as spoken production. Also similar to spoken production, response latencies in typing are longer for conjoined noun phrases (e.g., "Peter and the cat") compared to simple nouns (e.g., "Peter"), suggesting similar scopes of planning across the two modalities (speaking, Martin et al. 2010; Wheeldon et al. 2013; typing, Roeser et al. 2019).

In short, there is ample evidence showing that typing is sensitive to linguistic structure and similar linguistic factors that affect other production modalities.

5. Error types in phonological and orthographic domains

Studies of speech errors have been instrumental in uncovering the processes underlying spoken production. Speech errors can arise at lexical (i.e., word) or sublexical (phonemes or articulatory features) levels and show distinct properties at these levels (Fromkin 1980; Garrett 1980). This distinction has given rise to two-step models of language production (Dell 1986 and later variations), in which the first stage of production includes the mapping of semantic features to word representations (lexemes) while the second stage maps the word representations onto its segments (phonemes, letters, etc.). Sublexical errors themselves can take multiple forms, including movement errors (anticipation; e.g., *fig **t**op → **t**ig* top; perseveration; e.g., ***f**ig top → fig **f**op*; or exchange, e.g., ***f**ig **t**op → **t**ig **f**op*), deletions (e.g., *fig **t**op → fig op*), additions (e.g., *fig top → fi**s**g op*), and substitutions (e.g., *fi**g** top → fi**s** op*), pointing to specific processes involved in sequencing and ordering of segments (e.g., Dell & Reich 1981). All of these error types are also observed in handwriting (Sgaramella et al. 1991) and typing (Grudin 1983; Logan 1999; Pinet & Nozari 2018), suggesting that typing follows an architecture and set of processes highly similar to those in spoken and handwritten production.

It is worth mentioning that beyond their mere taxonomy, certain properties of linguistic errors can be used to test certain characteristics of the system from which they arise. An example is the "repeated phoneme effect" (Dell 1986), which predicts a higher probability of a consonant movement between two words if they share a vowel (e.g., *p(fog **t**op → **t**og top) > p(fig **t**op → **t**ig top)*). The repeated phoneme effect is important because it suggests that the two stages of production, discussed above, are interactive: when the vowel is shared between two words, activation of one word can lead to the activation of the other word through that shared vowel, making the consonants of the second word more activated and thus prone to movement. Pinet and Nozari (2018) showed a similar repeated letter effect in typing. This demonstration is theoretically important because it falsifies strictly modular models, in which sublexical processes do not feedback to lexical representations (e.g., Logan & Crump 2011).

Aside from errors shared with the spoken modality, certain errors are unique to the orthographic domain and point to specific processes involved in sequencing letters. An example is gemination (double-letter) errors in English. Unlike some languages like Italian or Arabic, English has no gemination in the phonological domain, for example, speakers do not produce a stronger /t/ because it appears twice in "letter". An intriguing gemination error is the doubling of a different letter (e.g., letter → leeter). These errors are seen in both handwriting (Caramazza & Miceli 1990), and typing (Hepner et al. 2018) and are interesting because they point to a delicate balance between activation and suppression of letters during sequential letter production (see Hepner et al., 2018, for a proposed model).

There are also error types within the orthographic domain that are specific to typing. These primarily include motor slips. The most common type of motor slip is adjacent substitutions, where the error is produced by pressing the key adjacent to the target letter (e.g., *fig* → *fog*, where "o" is next to "i" on a QWERTY keyboard) (Grudin 1983). While a motor slip may appear uninteresting from a linguistic viewpoint, motoric errors can shed much light on how linguistic information is translated into motor actions in a bimanual (two-handed) system. For example, a special category of motoric errors is homologous errors, which are produced by using the correct finger of the wrong hand (e.g., *fig* → *feg*, where instead of using the middle finger of the right hand, the middle finger of the left hand was used). The prevalence of these errors (17% of expert and 62% of novice errors, compared to chance being 7%; Grudin 1983) points to a certain hierarchical structure in motor planning in which planning a finger may precede that of a hand. Finally, there are errors that are essentially sequencing errors but are strongly promoted by the ballistic nature of motor movements in typing. An example is alternating errors (e.g., *there* → *threr;* Rumelhart & Norman 1982). These errors, although clearly errors of binding letters to positions, are quite rare in handwriting, pointing to the influence of motor execution on orthographic sequencing.

To summarize, typing errors can fall into one of three categories: those arising from processes shared between all production modalities, those restricted to the orthographic domain and only shared with handwriting, and those arising from motor processes specific to typing. The first group suggests a similar architecture for typing and other production modalities, namely a two-stage interactive process, with similar sequencing operations in the second stage. The second group points to orthographic representations and sequencing operations that are common to both typing and handwriting. Therefore, studying typing errors can easily shed light on the general mechanisms of language production. Finally, the third group is specific to typing, but these too can be used to understand how motor commands are planned in linguistic contexts and how motor planning and execution interact with higher-level processes such as letter-position binding. Collectively, all three groups can advance theories of language production and their interaction with other systems.

6. Contextual similarity effects across domains

Similarity has been one of the greatest tools for understanding the nature of representations and operations involved in language production. Generally speaking, similarity in the linguistic domain can be defined in terms of meaning (semantic similarity, e.g., cat and dog) or form (phonological or orthographic similarity, e.g., cat (/kæt/) and mat (/mæt/)). In experimental settings, similarity can be manipulated through the local context. For example, participants may be asked to name a picture (e.g., "cat") in the context of other animals or unrelated items. A detailed review of the influence of semantic and formal similarity in production exists elsewhere (Nozari & Pinet 2020) and is beyond the scope of the current paper. Here, we focus on comparing some of the similarity effects that have been tested across domains.

Generally speaking, semantic similarity in the form of taxonomic cohorts (e.g., cat and dog) has been shown to interfere with spoken production. Such semantic interference was first demonstrated using the picture-word interference paradigm, where a picture must be named while ignoring a spoken or written distractor word (e.g., Schriefers et al. 1990; see Bürki et al., 2020, for a meta-analysis). Similar effects have been obtained in handwriting (Bonin & Fayol 2000) and typing (Upadhye & Futrell 2023). Semantic interference has also been shown in other paradigms, such as blocked cyclic naming, where a limited set of pictures are repeatedly named (e.g., Belke et al. 2005; Oppenheim & Nozari 2024), and continuous naming paradigms, where a series of pictures are named without repetition (e.g., Howard et al. 2006). There is evidence that similar interference exists in handwriting (e.g., Nozari et al. 2016) and typing (Stark et al. 2023).

The influence of form overlap is more mixed. For example, form-related distractors presented with or slightly after a target picture can speed up picture naming in spoken production (e.g., de Zubicaray et al. 2002; Schriefers et al. 1990). This effect has been replicated in handwriting (Zhang & Damian 2010) and typing (Muylle & Jarema 2024). Such facilitation is also present in second language (L2) production (speaking, Broos et al. 2018; typing, Muylle & Jarema, 2024). However, outside of the picture-word interference paradigm, the main effect of form overlap seems to be that of interference (Breining et al. 2016; Feng et al. 2021; Nozari et al. 2016). This interference also exists in handwriting (Breining et al., 2016; Nozari et al., 2016) and typing (Harrison et al. 2020), and in learning new vocabulary in the orthographic domain (Breining et al. 2019). It is worth noting that predictable onset overlap (e.g., learning that the majority of words in this experiment start with the phoneme /b/) can cause facilitation (e.g., O'Séaghdha & Frazer 2014) but this effect is strategic and can be abolished by making the form overlap unpredictable (Breining et al., 2016). For example, Nozari et al. (2016) showed onset-overlap facilitation and rhyme-overlap interference within the same participants in speaking and handwriting. Similarly, in typing, Scaltritti et al. (2018) showed onset-overlap facilitation in copy-typing French words like *roman-robot* but facilitation disappeared when overlap was at the end (e.g., *roman-bilan*).

Similarity effects can also exist across a bi- or multi-lingual speaker's different languages. For example, pictures of items that share both form and meaning, known as cognates (e.g., apple [English] – appel [Dutch]), are named more quickly than non-cognates (e.g., orange [English] – sinaasappel [Dutch]) in both spoken (e.g., Hoshino & Kroll 2008) and typed (Muylle et al. 2022) production in either first or second language, as well as in language switching (speaking, Li & Gollan 2018; typing, Roembke et al. 2024) and translation tasks (speaking, Kroll & Stewart 1994; typing, Muscalu & Smiley 2019; Zheng et al. 2024). Similar effects have been obtained in sentence production (speaking, Starreveld et al. 2014; typing, Woumans et al. 2021). But facilitation is not the only signature of cognates in production. Evidence of interference has also been reported (e.g., Martin & Nozari 2021). Also, faster response latencies for cognates are sometimes accompanied by interference in other production measures. For example, longer durations have been obtained during typed translation and picture naming for cognates with low orthographic overlap (e.g., hat [English] - hoed [Dutch]). Interestingly, this effect only exists in languages using the same script (Romanian-English: Muscalu & Smiley 2019; Dutch-English: Muylle et al. 2022) but not those with a different script (Chinese-English: Zheng et al. 2024).

To summarize, similarity can facilitate or interfere with language production. The interesting finding is that such facilitation and interference effects seem to be remarkably consistent across production modalities. This consistency adds to the evidence discussed in the previous sections in favor of a common architecture for speaking, handwriting, and typing. One account of similarity-induced interference and facilitation effects observed in language production is the incremental learning account (Breining et al. 2019; Oppenheim et al. 2010; Oppenheim & Nozari 2024; Qu et al. 2021). According to this account, each production attempt changes the production system in a way to facilitate the production of the encountered item in the future. This includes strengthening the connections of the encountered item and weakening the connections of similar items to the features they share with the encountered item. Such a rebalancing of connection weights happens implicitly and incrementally, making every act of production an act of learning. In the next section, we examine implicit learning more directly in phonological and orthographic domains.

7. Statistical learning in phonological and orthographic domains

Each language has a set of rules that determine how sounds and letters can be sequenced in that language. These are called phonotactic and orthotactic constraints, respectively. Importantly, phonotactic and orthotactic constraints are not always the same, especially in orthographically non-transparent languages. For example, in English, the sound /h/ can be at the beginning (onset) but not at the end (coda) of a word. But this phonotactic constraint does not translate directly into an orthotactic constraint; the letter "h" can be spelled at the end of words, e.g., "Noah". Conversely, the sound /v/ can appear as a coda, but there are few English words that end with the letter "v". These constraints are learned over the years with experience. One question is, does such learning stop after mastery, or does the system stay open to constant incremental changes?

This question was investigated in a series of studies by Dell and colleagues (e.g.,Warker & Dell 2006; Warker et al. 2008, 2009). Participants repeatedly produced sequences of four strings (e.g., *hes feng meg ken*). Unbeknownst to them, new phonotactic rules were embedded in the sequences, for example, "/f/ can only be an onset, and /s/ can only be a coda". Across several studies, the pattern of speech errors showed that participants had quickly learned the new constraints, almost to the level of language-wide constraints, like "/h/ can only be an onset". When the rules were made more complex (e.g., "/f/ can only be an onset if the vowel is /æ/ but a coda is the vowel is /ɪ/"), participants still learned them, albeit more slowly (Warker & Dell 2006). Exactly the same pattern was obtained in typing (Atilgan et al. 2022). In a follow-up experiment, Atilgan and Nozari (2025) tested whether orthotactic learning was distinguishable from phonotactic learning. They showed that the constraint "letter "s" is coda" could still be learned robustly, even if the sound /s/ generated from letter "c" could also be an onset. This finding shows that participants were able to learn the orthotactic rule even in the presence of an opposing phonotactic rule.

The parallel between phonotactic and orthotactic learning adds to the evidence discussed in earlier sections for the similarities between different modalities of language production. The parallel between statistical learning in phonotactic and orthotactic domains is particularly noteworthy in light of the very different motor demands across spoken and typed modalities. Phonotactic constraints of a language shape speakers' articulatory gestures over the years (the native accent). These gestures cannot be easily changed (hence the foreign accent), pointing to a key role for phonotactic learning in language development. No such constraint exists in typing. Attesting to this is the finding that language-wide phonotactic constraints (e.g., /h/ cannot be a coda) are almost never violated in speech errors but are frequently violated in typing (Pinet & Nozari 2018). The very different motor constraints of spoken and typed production, together with the very similar patterns of constraint learning across these modalities, show that the phonotactic/orthotactic constraint learning is not strongly modulated by the limitations of the motor apparatus responsible for ultimate production. Rather, the implicit and incremental learning of sequential patterns appears to be common to all modalities of production.

8. Phonological influences on typing

In the previous section, we discussed evidence showing that the learning of orthotactic and phonological rules can be dissociated. However, there is a close relationship between phonology and orthography in language production. In this section, we review some of the evidence for this interaction and argue that this relationship is asymmetric.

Past research has shown that phonological representations support and constrain the retrieval of orthographic representations during written production (e.g., Damian et al. 2011; Qu et al. 2011, 2016). For instance, producing a word through speaking facilitates its later production in writing (Damian et al. 2011). Similarly, orthographic representations can facilitate phonological retrieval during speaking (e.g., Damian & Bowers 2003; Wang et al. 2023). Wang et al. (2023) showed that shared orthography between items facilitated spoken picture naming in a blocked cyclic naming paradigm. However, the facilitatory effect of orthography on spoken word production has not been universally replicated (Alario et al. 2007; Chen et al. 2002; Roelofs 2006). Possibly, task, language status (first or second language), and language/writing system modulate this influence, whereas the influence of phonology over orthography is more robust.

Recently, Pinet and Martin (2025) investigated the influence of phonology vs. orthography on learning new vocabulary. Participants learned nonword labels for novel objects. All labels were presented both visually and auditorily, but participants practiced some of them by speaking and others by typing. The final picture naming test was carried out in both speaking and typing modalities. Not surprisingly, typing practice led to shorter durations in the typing test, but the key finding of the study was that typing practice led to better accuracy for *both* typing and speaking compared to speaking practice. This means that practicing phonology did not automatically activate orthography, but practicing orthography automatically strengthened phonological representations.

In summary, phonological and orthographic representations are distinct, but they interact. However, this interaction appears to be asymmetric, with a stronger influence of phonology on orthography than the other way around. Phonological influences on typing have interesting consequences. A prime example is homophone errors in typing. Many of us have experienced homophone errors such as mistyping “there/their/they’re”, where sound similarity between words elicits the wrong spelling. While previously attributed to poor spelling knowledge (e.g., Bonin et al. 2001), a recent study has shown that the probability of a homophone error is significantly higher than that of a control word with very similar properties (Muylle et al. 2024). Using a computational model, Muylle and colleagues showed that phonological similarity increases lexical competition, which in turn increases the probability of a homophone error (Muylle et al. 2025).

One finding that is particularly intriguing in the context of homophone orthographic errors is that they do not seem to respect syntactic categories in the same way speech errors do. In spoken production, lexical errors belong, overwhelmingly, to the same syntactic category as the target word. For example, “I’m buying a helmet for my daughter” could be misspoken as “I am buying a daughter for my helmet” (noun-noun exchange) but is much less likely to be misspoken as “I’m daughtering a helmet for my buy.” (noun-verb exchange)(Garrett 1975, 1976). This property of speech errors shows the constraining effect of syntax on lexical selection in spoken sentence production (e.g., Dell 1986; Ferreira & Slevc 2007). In contrast, handwriting errors have been reported to violate syntactic categories more often (Hotopf 1980; Romani et al. 2002). In typing, White et al. (2010) reported more homophone errors when the target and error belonged to the same vs. different syntactic categories in a sentence dictation task. However, that study did not use control words for homophones, so any differences observed between same vs. different category homophones may have stemmed from characteristics other than syntactic category. Moreover, while within the sentences used in the experiment, a target homophone (e.g., "poll") took on a single syntactic role (e.g., verb) and was thus deemed to be of a category different from the competing homophone ("pole", noun), some of the target homophones did also exist in the same-syntactic category as the competing homophone (e.g., "poll" can also be an noun), making the boundaries of same-/different-category hazy.

In contrast to White et al. (2010), Muylle et al. (2025) found comparable rates of homophone errors in the same and different syntactic categories as the target. The authors further replicated this finding in a question-answering task, which required participants to plan and type a new sentence from meaning. These findings, which fit well with the anecdotal evidence for "there/their/they're" errors, point to a much less prominent role of syntax in lexical selection in the orthographic domain, especially in typing. This weak influence is better understood as the overshadowing of syntactic influences by phonological influences which appear to strongly guide typing.

9. Typing and domain-general action monitoring

For years, the language production system was studied as a special system with its own rules and principles distinct from other domains of action and cognition. This trend has changed substantially in recent decades, as more similarities are unveiled between processing linguistic and non-linguistic information. For example, the same computational principles underlying working memory operations in visual processing also operate in speech perception and production (Black & Nozari 2023; Hepner & Nozari 2019; Nozari & Martin 2024). More generally, language production can be viewed as an example of a self-regulating goal-oriented system, subject to the same general principles of monitoring and control as any other system of action and cognition (Nozari 2018). Research on monitoring (i.e., collecting information about the current state of the system), control (using that information to regulate production), and repair (fixing problems when production is off-balance) has been at the forefront of situating the language production system within the broader framework of human cognition (Nozari 2025a,b), and typing has had important and even unique contributions to this endeavor. Below, we review some examples.

It has long been known that language can be monitored through external and internal channels (Levelt 1983, 1989). The external channel refers to the processing of sensory consequences of language production, and itself has multiple subchannels. For example, production of the word "mom" can be monitored through the proprioceptive subchannel (e.g., feeling that one's lips touch, part, and touch again), auditory subchannel (hearing the sound /mɒm/ when spoken outloud), or visual subchannel (seeing the word "mom" appear on the screen when typed). In contrast, the internal channel refers to processes that monitor production without reliance on overt sensory outcomes of performance. These processes are not just important for detecting errors but also for a continuous evaluation of the current state of the production system, which can then be used to adjust near-future states (Freund & Nozari 2018; Zhu et al. 2025; see Nozari, 2025a, b for more information and a review).

The existence of such a multi-channel monitoring system naturally raises questions about the contribution of each channel to monitoring. For example, in speech, evidence suggests that, compared to phonological errors, the detection of semantic errors is less reliant on auditory processing (Hartsuiker & Kolk 2001; Marshall et al. 1985). In a series of experiments, Pinet and Nozari (2020, 2021) tested the contribution of visual processing to error detection and repair in typing. For the most part, delaying visual feedback in typing left accuracy intact (cf., Snyder et al. 2015, in sentence copy-typing), whereas response latencies and/or durations increased, showing a role for visual processing in checking the behavior. When visual information was not available immediately, both error detection and repair performance suffered, but at very different rates; there was about a 20% decrease in detection of errors vs. a 70-80% decrease in repair attempts. In comparison, removal of auditory feedback plays a less serious role in speech error repairs (50% in Postma & Kolk 1992; 17% in Oomen et al. 2001; and no significant decrease in Nooteboom & Quené 2017). These results show that visual information plays a relatively minor role in monitoring typing but a much more critical role in fixing errors when they arise. Moreover, when it comes to initiating repairs, the most overt consequence of production (i.e., the produced sound vs. the visual form) is clearly less critical for repairing speech vs. typing errors. Pinet and Nozari (2021; Experiment 3) shed some light on this issue, by showing that the critical contribution of visual representations to repairs was, at least in part, due to the positional information they provided; when participants saw dots instead of the letters they typed (as in password typing), they were more willing to repair an error, compared to when no visual information was provided. This finding points to a stronger reliance of sequencing processes in language production on visual rather than auditory information when the modality permits the use of such information.

These behavioral results comparing the contribution of various types of information to monitoring across production modalities were complemented by neural data, showing similar signatures for monitoring in typing and more general action monitoring (Pinet & Nozari 2020). Two components are noteworthy here: the first is error-related negativity (ERN, Gehring et al. 1993), which marks the internal detection of errors and has been found in forced-choice button-press tasks and spoken picture naming tasks alike (Riès et al. 2011). The second is Pe, which has been taken as a marker of conscious awareness over errors (Nieuwenhuis et al. 2001). A similar component has also been reported in verbal tasks, although not always labeled as Pe (Ganushchak & Schiller 2008; Masaki et al. 2001). Compatible with the past literature, Pinet and Nozari (2020) found a stronger ERN when immediate visual feedback was removed, suggesting a switch away from the external toward the internal channel. Similarly, they uncovered a Pe in the delayed-feedback condition only when participants were aware of an error. These similarities show that typing fits quite well within the general framework of action monitoring applied to spoken production, as well as non-speech tasks.

Finally, the neural data from Pinet and Nozari (2020) shed new light on the integration of internal monitoring and external feedback. This study reported, for the first time, a feedback-related negativity (Miltner et al. 1997) in language production when participants finally saw the visual word they had typed after the delay period. For ~ 400 ms after feedback, there was no difference between errors that had and had not been detected internally in the FRN they generated, but both were distinct from correct responses. In contrast, a later phase revealed a frontocentral positivity (FCP; Butterfield & Mangels 2003), which clearly distinguished between detected and undetected errors and categorized the latter with false alarms (correct productions that were incorrectly labeled as errors). In other words, the temporal change in the pattern suggests that the system shifts its categorization from correct/incorrect *response status* to correct/incorrect *monitoring of the response status*, a shift that is a hallmark of a self-regulating system.

Relative to monitoring, much less research has investigated the processes underlying repairs in language production. Consequently, little is known about the properties that a repair system must possess. A key question with regard to the repair process is whether or not it depends on conscious awareness. Not surprisingly, this question is extremely difficult to answer in spoken production because neurotypical individuals rarely make errors in single-word production, and stopping people mid-sentence to ask them whether they were or were not aware of a repair interferes too much with the original task to obtain useful data. In multiple experiments, Pinet and Nozari (2020, 2022) asked participants to announce whether they had or had not made an error, and whether they had or had not repaired it, in a single-word typing-to-dictation task. Across three experiments, they replicated the finding that in 10-20% of repairs, participants had no awareness of an error or a repair. This finding persisted despite using explicit instructions on what to count as a repair ("if you used the backspace"), having participants type their answers ("yes", "no") instead of pressing buttons, and ruling out memory errors as confounding factors. It appears that, at least in the typed modality of production, conscious awareness of errors is not critical for initiating a repair. This is particularly intriguing, because of the need for using backspace in typing to erase the error first. Although extrapolating this claim to spoken production requires a direct replication in the spoken modality, the absence of an intermediate corrective step like using backspace makes it even more likely that repairing speech errors could be carried out without conscious deliberation (see Burgess & Nozari 2022; Nozari 2025a, for a computational model of repairs that accommodates this property).

To summarize, typing research has added to the body of evidence in favor of language production being subject to the same domain-general action-monitoring principles as other actions. In addition, it has provided unique opportunities for better understanding the nature of such processes.

10. Conclusions and future directions

Throughout this paper, we showed that typing not only has much in common with other production modalities but can make unique contributions to understanding both language production and, more broadly, human cognition. For example, error types, contextual similarity effects, and incremental learning mechanisms all point to common principles across language modalities. The prevalence of typing errors and the possibility of obtaining much more precise measurements of such errors is an important asset here. Moreover, individual differences in typing proficiency for L1 are much greater than spoken proficiency, allowing researchers to study the influence of expertise on various aspects of language production.

In addition, typing is an excellent medium for studying the interaction between phonological and orthographic domains. We have discussed some evidence for an intriguing and asymmetric interaction between phonological and orthographic representations, but much is yet to be learned about how such influences are modulated by task, language, and writing script. Finally, we have reviewed the utility of typing for studying monitoring, control, and repair in language production. We discussed evidence pointing to a common neural basis for monitoring in typing and general action monitoring, which makes typing a good testbed for uncovering general principles of monitoring and control. Sitting at the junction of the language processing system, motor system, and visual processing system, typing is a powerful tool for studying the interaction between these three systems at the service of goal-oriented behavior in a self-regulating system.

We go further here by arguing that typing may be one of the gold standard tools for studying domain-general operations such as self-regulation of behavior, as the pattern of typing errors provides a much more nuanced data set than those of button-press responses in forced-choice tasks. Sadly, much of the research on typing has made little contact with theories of language production. We hope this review inspires a greater integration of typing research into those theories, not merely to confirm their predictions but rather to push their boundaries and open up new directions.

We end this paper with a brief discussion of some of the open questions worth investigating. From the perspective of classic psycholinguistic models, such as the schematic in Figure 1, research on typing can speak to the nature of representations involved in production through a new modality. This is particularly interesting because handwriting and typing share orthographic representations but diverge at the level of motor movements. The question is how early in the system does this divergence occur? Does typing use the same lexemes and abstract letter representations as handwriting, or are these also distinct?

Another area concerns the interaction between the processes unique to typing, including ballistic motor movements, and higher-level processes such as segment sequencing. Studying error patterns unique to typing (e.g., alternating errors, there → threr) can shed light on such influences, which will in turn speak to issues of modularity —or lack thereof— in language processing. Aging and bilingualism are also domains in which typing research has been sparse but may reveal interesting interactions between age-related changes in the processing of linguistic knowledge and rapid fine motor movements. Finally, a new and largely understudied area is AI-assisted typing.

Autocompletion and autocorrect tools are widely available in typing apps on cellphones, but also more generally on emails, etc., which can be accessed through keyboards. Autocorrect apps are interesting from a monitoring point of view as they provide a constant source of external feedback that can override internal monitoring. The immediate and long-term consequences of such overriding for typing proficiency and learning can be of interest to both basic science researchers and those with pedagogical interests.

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