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Typing /s/—morphology between the keys?

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Abstract

Morphological structure exerts an influence on acoustic duration. But does it also influence typing duration? The present article reports an experimental study that tests for the influence of morphological structure on typing timing. It is also a first of its kind comparison between spoken and written language production within the same paradigm, which explores the extent to which a pattern that has been found for speech production may have an analogue in written language production. In an online typing study using the experimental design of Schmitz et al. (Phonetica 78:571–616, 2021a), we test their results from the spoken domain for transferability to the written domain. Specifically, our study investigates whether language users type word-final <s> in English pseudowords at different word-internal boundaries—non-morphemic, plural, auxiliary *has*-clitic and *is*-clitic—with differing speeds and how our results compare to those found by Schmitz et al. (Phonetica 78:571–616, 2021a) for articulation. We find that the influence of morphological structure on articulation and typing timing does not follow an identical principle. While durational differences are found for the different morphological categories in articulation, participants in our experiment type non-morphemic <s> and plural <s> at almost identical speed. A significant difference emerges, however, for the typing of auxiliary clitics. Our results suggest that processing units other than morphemes might be dominant in written language production.

Keywords Cross-modal comparison · Written language production · Typing · Orthographic processing articulation · Morphology

Introduction

In our daily lives, typing is a ubiquitous activity that plays a significant role in communicating privately but also professionally. Despite its frequent use, the complexities of typing are often overlooked. The process involves constructing a message, selecting the right words, retrieving the correct spelling, and pressing the right keys

in the right order. From a linguistic point of view, typing itself can be described as a peripheral motor process, while the initial stages of constructing a written message would be classified as central cognitive processes (Purcell et al., 2011). As linguists, our knowledge about the processing architecture involved in language production and the interaction between central and peripheral production stages predominantly stems from studies on spoken language; for one, because generations of linguists have been taught about the primacy of spoken language and its relevance in researching language processing (Pinet et al., 2016:p. 1898) but also due to technical difficulties in recording and analyzing handwriting and typing in the same way as we are able to record and analyze the speech signal (Will et al., 2006:p. 154). Since technical developments have long caught up, there has been an ever-increasing interest in written language production from a psycholinguistic point of view (e.g., Frisson & Sandra, 2002; Gagné & Spalding, 2016; Kandel et al., 2013; Kandel & Perret, 2015; Pinet et al., 2016; Roux et al., 2013; Sandra, 2010; Treiman et al., 2021; Treiman et al., 2015; Treiman & Wolter, 2018; Will et al., 2006). And although much of this research draws on a comparison to spoken language production, findings have mostly been discussed independent of each other.

There are two main arguments as to why a more mutually informing approach could be useful to further our understanding of the cognitive architecture that supports language processing in general. For one, theories of written and spoken production have largely converged on similar processing architectures. Central cognitive processing stages, such as lexical access and retrieval, are followed by peripheral motor stages, such as the planning and execution of movement of hands or articulators (Kandel, 2023; Logan & Crump, 2011 for (hand) writing and e.g., Levelt et al., 1999 for speech production). Yet, no convincing argument has been made thus far as to why these architectures should not, at least partially, overlap (Caselli & Cohen-Goldberg, 2014; Chen & Mirman, 2012; Cohen-Goldberg, 2017). Secondly, the very argument that has been held against researching written language production from a (psycho)linguistic viewpoint in the first place can be seen in favor of doing exactly this: since writing and typing are learned much later in life, compared to speaking, it is conceivable that the acquisition of the latter will also influence the former. Researching both modalities in direct comparison might tell us more about how our cognitive processing architecture is built and maintained throughout our life (Rapp & Fischer-Baum, 2014:p. 339; Ravid, 2012:p. 3). Given the parallels between the spoken and the written domain, we argue that typing as a peripheral process might be as suitable a source of evidence for psycholinguistic questions as articulation, including the processing of complex words (Gahl & Plag, 2019:p. 2; Libben, 2020:p. 114).

The present study reports an experiment that transfers an existing experimental setup from the spoken domain, developed by (Schmitz et al., 2021a), to the written domain. We examine whether execution timing in typing reflects the presence and strength of morphological boundaries, with an additional focus on how our results compare to what is known from the spoken domain.

The paper is structured as follows: in the next section, we will take a closer look at both morphological effects on written and on spoken word production to set the stage for the present study. Sect. "Method" details our methodology, followed

by a presentation of our analysis in Sect. "Analysis". We present our results in Sect. "Results" and discuss them and their implications in Sect. "Discussion". The paper concludes with a stocktaking, a discussion of limitations and a brief outlook.

Background

In their 2021 paper, Schmitz et al. investigated whether the acoustic duration of word-final /s/¹ in English varies depending on the morphological category of the /s/ in question. With their setup, the authors set out to seek further evidence that morphological information is present in the phonetic signal, particularly in word-final /s/, a finding which poses a challenge to current theories of morpho-phonology and speech production (Schmitz et al., 2021a: p. 572). The study examined four categories of word-final /s/ in English, namely non-morphemic, plural, *is*-, and *has*-clitic /s/, among native speakers of Southern British English. The authors found that, all else being equal, non-morphemic /s/ had a significantly longer duration than plural /s/, which was in turn longer than clitic /s/. Additionally, there was no difference in duration between the two clitic types. These findings support previous corpus studies (Plag et al., 2017; Tomaschek et al., 2021) and suggest that the morphological category of a word-final /s/ is a strong predictor of its phonetic realization in speech production, leading to systematic subphonemic differences originating from central levels of language production. These durational differences would be unexpected if we assume that articulation—as a peripheral production stage—remains unaffected by sublexical information, such as morphological structure. As a result, the study highlights the need for updating current models of speech production that do not consider morphology in later production stages (Schmitz et al., 2021a: p. 604).

Now, what about written language production? In general, the assumptions for written language production, as derived from existing models, would be strikingly similar. There is a consensus that written language production involves both central-cognitive and peripheral-motor processes. According to such a view, typing would be a peripheral-motor process and keyboard keys could be conceptualized as postlexical segmental representations (Pinet & Nozari, 2018:p. 1450). Consequently, the questions targeted by research also largely overlap: How exactly do central and peripheral processes interact? And what are the operant linguistic units in the production process? It has been argued that typing is a motor process unimpeded by central cognitive processing (e.g., Damian, 2003), while the opposing view is that linguistic properties do affect the execution (e.g., Gagné & Spalding, 2016). Research on typing as a language production process is still relatively scarce and existing results have not been discussed in relation to what is known from spoken language production. Another important question that remains unanswered so far is whether the peripheral processes of written language production, such as typing (and by implication also handwriting) are comparable to articulation as a peripheral

¹ In the following, we will use /s/ whenever we refer to the spoken segment, <s> whenever we refer to the written segment and S as an umbrella expression for both modalities.

production process that reflects central processing stages. One way of testing this would be to look at the influence of morphological structure on written language production and compare findings to what has been found for spoken language production.

In the following, we give a brief overview of existing results on the influence of morphological structure first on written and then on spoken word production and discuss their accommodation by existing theories, pointing to relevant gaps for the present study.

Morphology and writing

Our study builds on growing evidence that error performance, response latencies and execution timing in written language production are all influenced by a range of lexical and sublexical variables. In other words, the quality and quantity of errors and the duration it takes to initiate the writing or typing of a word as well as the overall time that elapses between the writing of letters or pressing of keys is not determined solely by random variation or by non-linguistic factors (Ostry, 1983). Instead, existing evidence suggests a rather complex interaction of writing and the linguistic properties of words, which appears to be somewhat comparable to what we find in speech. This has been shown repeatedly for both handwriting and typing. Typing, specifically, appears to be susceptible to manipulations of, for example, different frequency measures (e.g., Baus et al., 2013; Bertram et al., 2015), semantic transparency (e.g., Gagné & Spalding, 2016; Libben & Weber, 2014), prosodic boundaries (e.g., Fuchs & Krivokapić, 2016) and syllable structure (e.g., Nottbusch et al., 2005; Weingarten et al., 2004; Will et al., 2006). Studies that focus explicitly on the influence of morphological structure in the writing process in both children and adults, on the other hand, are still rather scarce (Hess et al., 2022:p. 900).

For handwriting, it has been repeatedly demonstrated that morphological structure has an impact on writing onset times and overall writing durations for both adults and children. The effects found, however, vary in their magnitude and their directionality. Some studies report delayed writing onset times for monomorphemic compared to complex words and bases for children (Breadmore & Deacon, 2019 for English-speaking children age 6 to 11; Suárez-Coalla et al., 2017 for Spanish-speaking children age 7 to 12). Other studies find corroborating effects for adults but null effects in the corresponding child population (cf. Quémart & Lambert 2019). Contrary evidence is provided, for instance, by Kandel et al. (2008) for French adults and Afonso and Álvarez (2019) for Spanish adults, who both report an inhibitory effect of morphological complexity on writing onset times. All studies, however, report comparable inhibitory effects on trajectory formation for complex words compared to monomorphemic words (Hess et al., 2022:p. 902). In a copy-task with German children from Grade 3 and 4, Hess et al. (2022) find an effect of visual disruption on writing onset times and letter durations, which hints at a complex interaction of syllabic and morphemic processing during written word production. The authors measure writing onset times and letter durations in three conditions, visually highlighting either morphemic (e.g., ‘Golfer’, German ‘golfer’) or syllabic structure

(e.g., ‘G**ol**fer’) or neither (e.g., ‘G**o**lfer’). Their results point to longer writing onset latencies only where the visual disruption was morpheme-congruent (‘G**ol**fer’). Additionally, latencies at the morpheme boundary decreased in the syllable-congruent condition, while latencies at the syllable boundary were increased. These findings generally corroborate existing results on morphological effects on handwriting but also highlight the potentially interfering effects of syllable structure, which have been discussed by a range of studies (Gagné et al., 2023:p. 101).

For typing, effects of morphological structure are less documented but seem to be generally in line with what is found for handwriting. In a picture-naming experiment, Bertram et al. (2015) find an effect of syllabic and/or morphemic structure causing inflation of inter-keystroke intervals (IKIs) at both syllabic and morpho-syllabic boundaries (Bertram et al., 2015:p. 6). Comparable effects of an interplay of morphological and syllabic structure are documented by Will et al. (2006). In a typing task using both visual and oral stimuli, the authors find that IKIs across words will be the longest where syllable and morpheme boundaries coincide (Will et al., 2006:p. 164). Additionally, their results suggest that effects of morphemic structure interact with both frequency and lexicality of target words (Will et al., 2006:p. 165). Furthermore, it has also been suggested that for compounds, morphological structure interacts with semantic transparency in influencing typing speed. Gagné and Spalding (2016) compared typing of compounds, pseudo-compounds and monomorphemic words and found that, while all three categories of targets were initiated with a similar latency by participants, monomorphemic words were typed overall faster across the entire word. Increased semantic transparency of the first constituent in compounds additionally inflates the IKIs at the morpheme boundary (Gagné & Spalding, 2016:p. 1491). However, the authors do not address potentially overlapping effects of syllable structure.

The effect of semantic transparency and morphological structure has been discussed similarly by Libben and Weber (2014) and Libben (2020), who investigate the typing of ambiguous novel compounds and find elevated IKIs at all potential constituent boundaries. Libben (2020:p. 112) argues that these latency spikes are reflexes of morphological chunking and can be seen as evidence for a *Fuzzy Forward Lexical Activation*, i.e., a parallel parsing and activation of several potential sub-word constituents during the processing of complex words. Crucially, neither Libben (2020) nor any of the other above studies focuses on the effects of inflectional morphology. Instead, so far, the main focus is put on lexical substrings and typing timing is seen as evidence of morphological decomposition and morphological parsing (Libben, 2020:p. 109). Studies, however, do not address the fact that a putative morphological boundary between two free morphemes (e.g., in a compound or pseudo-compound) is likely also a (phonological and/or orthographic) syllable boundary and, in some cases, even closely resembles a word boundary. Consequently, the generalizations arrived at do not factor in the presumably complex interactions of multiple sub-word constituents.

Taken together, the existing results suggest a twofold effect dynamic: systematically varying onset latencies hint at an influence of morphological processing *before* the initiation of the writing or typing process. This evidence would support a hierarchical processing architecture, in which the information about morphological

structure is not reflected in peripheral processing stages. A smaller number of results simultaneously suggest morphological effects that occur *during* motor execution, which in turn provide evidence for a direct influence of morphological structure on motor processes (e.g., Feldman et al., 2019; Libben, 2020; Will et al., 2006). While the latter evidence is currently less substantial and less conclusive, it is primarily this evidence that would challenge models of written language production which assume an independence of central and peripheral processes (e.g., Logan, 2018; Logan & Crump, 2011; Yamaguchi et al., 2017). Effects of morphological structure across the course of typing would suggest a more dynamic and cascading processing architecture, where central processes remain active and morphological information remains available during motor execution (e.g., Afonso et al. 2009; Quémart & Lambert 2019; Scaltritti et al., 2016; Will et al., 2006).

The inconsistency of the found effects regarding both their locus and their directionality as well as their magnitude presents a critical challenge: it has not yet been sufficiently tested to which extent some of the most influential variables in written language production – syllable structure, semantic transparency, frequency, and morphological structure – are collinear, confounded or whether suppression/elevation-dynamics play a role. Gagné et al., (2023:p. 101) argue that there is an intricate network of influential linguistic properties in written language production, with morphological structure as one source of influence. To be able to gain insight into such an intricate network and probe the individual units of written language processing, candidate units should be probed independently (cf. the brief discussion of “separate modifiability” as coined by Sternberg (2001) in Rapp & Fischer-Baum, 2014:p. 341).

Now, how do theories of written language production account for such diverse evidence of how linguistic information might affect the motor execution? And how do models of writing and typing accommodate the existing findings? According to a most recent model of written language production (Kandel, 2023), word writing is a dynamic process best depicted with a complex hierarchy that allows several different processing levels to be active at the same time, where information is anticipated top-down and passed on from higher-level to lower-level processing stages (Kandel, 2023:p. 220). Kandel proposes that writing involves both a lexical and a sub-lexical route that will feed information to the system to generate output. In Kandel’s model, lexical processing involves the processing of morphemes, syllables and graphemes that are translated into letter chunks, which the motor system will then produce either through handwriting or typing. Sub-lexical processing, on the other hand, contributes syllable and graphemic chunks to the output generation (Kandel, 2023:p. 225). The model has the main advantage that it will allow for morphological structure to influence peripheral processing. The model also predicts a complex interaction between a range of putative sub-word units, such as syllables, morphemes and graphemes (Kandel, 2023:p. 219). It does not, however, make clear predictions as to when and how this influence manifests in the output, nor does the model offer a satisfying explanation of the chronology of the processes involved. Kandel acknowledges these shortcomings, as she posits that word writing “involves the extremely complex processing of orthography and movement control, so more specific information is definitely needed” (Kandel, 2023:p. 226).

The primary objective of the present study is to offer such specific information. To achieve this, we center our investigation on the impact of morphological structure on typing timing. By doing so, we simultaneously address several of the above-mentioned issues. Most importantly, our approach allows us to examine a single purported unit of processing, namely morphological constituents. Finally, the unique design of this study, adapted from the spoken domain, provides an opportunity to gain insight into how our findings relate to prior research in the spoken domain.

Below, we will first give a short overview of the relevant findings from the spoken domain, before we connect theoretical approaches and existing empirical results from both domains to arrive at our own set of predictions for the present study.

Morphology and articulation

In recent years, several corpus and experimental studies have taken a close look at putative homophonous linguistic units at varying levels—the word level (e.g. Drager, 2011; Gahl, 2008; Lohmann, 2018), the stem level (Kemps et al., 2005a, 2005b) and the affix level (Ben Hedia & Plag, 2017; Schmitz et al., 2021a; Seyfarth et al., 2018) –and found robust evidence that these seemingly homophonous units differ significantly in phonetic details such as vowel quality or length. Taken together, there is growing evidence that homophones and homophonous elements are in fact not identical but differ in their acoustic realization depending on their morphological status. While the exact nature of the differences and explanatory variables vary across studies, the effects remain robust. At the same time, these findings cannot be readily accommodated by most existing theoretical approaches to speech production.

In the spoken domain, too, there is an ongoing debate about a possible interplay of the central morphological and the peripheral articulatory system. The following overview details the main theoretical approaches with an increasing concession of possible information exchange between these levels with time. Much like theoretical approaches to written word production, earlier approaches postulate a clear divide and no possible links between the two levels, while more recent research suggests that traces of the morphological structure leak into the periphery.

Formal theories of morphology such as Lexical Phonology (Kiparsky, 1982; Mohanan, 1986) follow a feed-forward strategy and do not allow for interaction between the morphological level and the articulatory level. For spoken language production, this means that as soon as a unit has been handled by the morphological level, it is fed into the next one, i.e., the phonological level. The same applies to the form which is fed into the peripheral level. No mechanism allows for a feedback-loop. Moreover, morphological information may be cleared by means of a mechanism called *bracket erasure* before entering the next stage (Kiparsky, 1982) and consequently morphological information is not available on the post-lexical level.

A similarly strict separation of the lexical and the post-lexical level is conceptualized in psycholinguistic models for speech production such as Levelt's (1993). Additionally, more recent neuroanatomically grounded approaches argue for morphology and articulatory processes to be represented in two distinct modules that do

not interact (Roelofs & Ferreira, 2019; Sahin et al., 2009). In these models, morphological encoding is followed by phonological encoding, which in turn is followed by phonetic encoding. To illustrate this, let us consider the case of the production of a plural noun such as *pots*. First, during morphological encoding, the lemma and its plural specification are mapped onto a stem and plural suffix. Then in phonological encoding, phonemes are selected. After the process of syllabification, the representation of the phonological word is passed to the next level, phonetic encoding, where the respective syllable motor programs are activated. Crucially, the morphological information is not passed onto the next levels, i.e., the representation of the phonological form is /pots/, regardless of its underlying morphological function. As was described above, this is not what is observed in the data.

Within the framework of Prosodic Phonology (Booij, 1983; Nespor & Vogel, 2007), it is conceived that morphological information is leaking into later processing levels. Stems and affixes are assigned to specific prosodic structures, which in turn can feed into the realization of word forms. As a result, homophones with different underlying morphological structures – such as /pots/ for *pots* (plural), *pot*'s (genitive singular), *pots*' (genitive plural), *pot*'s (*has*-clitic) or *pot*'s (*is*-clitic) – have different representations with respect to their prosodic structure. Depending on their morphological function, the different /s/ instantiations are assigned to different levels in the prosodic hierarchy (Plag et al., 2017; Schmitz et al., 2021a). These would lead to differing realizations, e.g., in terms of duration. The overarching idea is that a more peripheral element in the representation is different from a more central element in the representation. It is unclear, however, how these differences would play out, that is, whether to expect a lengthening or a shortening effect on individual segments. A likely possibility would be that the presence of phrase boundaries may evoke an effect of phrase-final lengthening (Klatt, 1975; Wightman et al., 1992), i.e., a lengthening of sounds in phrase-final position. The described architecture, however, would predict relatively long durations in clitic constructions as compared to non-morphemic forms or suffixed forms, but this is also not what is observed in the data.

Theoretical approaches that do allow for traces of morphological information at the periphery are exemplar-based models (e.g., Bybee, 2001) or models that directly associate forms with meanings, such as discriminative learning (Baayen et al., 2011, 2019). According to these approaches, accumulating linguistic experience is shaping the representations and, consequently, interplays of different levels are generally allowed. Schmitz et al. (2021b), for instance, successfully modeled the above-mentioned durational differences as emerging from the mental lexicon using linear discriminative learning (Baayen et al., 2019) but see also Tomaschek et al. (2021) for a successful implementation of naive discriminative learning (Baayen et al., 2011).

To summarize, while most theories of speech production would not predict this, it has been shown repeatedly that word-final /s/ in English differs in duration depending on its morphological status. It has been consistently found that non-morphemic /s/ is longest (*bus*), followed by plural suffix /s/ (*two pots*) and clitic /s/ is the shortest (*the pot's been put...*). These systematic durational differences have been found in corpus data (Plag et al., 2017; Tomaschek et al., 2021) as well as the experimental data we used as a case of comparison for the present study (Schmitz et al., 2021a) and have recently also been replicated for German (Schmitz & Baer-Henney, 2024).

Typing and articulation: same same... but different?

Before we lay out the predictions for our experiment, we first need to address two additional caveats of comparing typing and articulation. While we have already argued that much of the research on spoken and written language production deals with similar questions and theoretical approaches in both domains map out similar processing architectures, it is equally valid to argue that there are some important and potentially divisive differences. For one, speech is mostly evanescent, while writing leads to a permanent product. This may influence the linearity of the production process. As a result, feedback and repair mechanisms might work differently and affect the temporal structure of the production process (Conijn et al., 2019). Consequently, we also cannot assume a direct correspondence between disfluencies, trajectory forming, and durational measures in both modalities. For the present purpose, we focus on word-final S and its properties in realization, looking at two different measurements: acoustic duration for articulation and inter-keystroke intervals (IKIs) for typing. Although they cannot be fully equated, both measurements relate to properties of the word-final segment and have previously been shown to be sensitive to morphological structure (e.g., Libben, 2020; Schmitz et al., 2021a).

Furthermore, the exact mapping of production units onto cognitive processes does not come without problems. What exactly is the cognitive correlate of a key-press – and is the interval between two keypresses even a distinct unit or is it a mere approximation? This “problem of alignment” has been discussed in the context of typing, for example, by Galbraith and Baaijen (2019). It is noteworthy, however, that comparable fundamental discussions cannot be found for speech production. The same question arguably might arise as to whether the articulation of a specific segment is truly reflective of the underlying processing of that exact segment or rather reflective of more global processing units. Considering the robust findings discussed above, we argue that if everything else is held constant in an experimental setup² and participants still produce a statistically significantly longer /s/ in “bus” /bʌs/ (non-morphemic, singular) compared to “pots” /pɒts/ (morphemic, plural) and “pot’s” /pɒt’s/ (both is- or has-clitic), this can be seen as strong evidence in favor of an effect of morphological structure precisely on the realization of the /s/. Similarly, we would assume that any purported latency spikes or dips in IKIs in a controlled experimental setup like the present one provide evidence for or against an influence of morphological structure.

At present, however, what exactly drives these durational differences remains unclear. Especially because theories of speech production that do allow for a direct influence of morphological structure on articulation would predict a reversed durational pattern, with clitics as the longest and monomorphemic /s/ as shortest realization (see Sect. “Morphology and articulation” for a more detailed discussion). The most promising explanations in this context could be derived from exemplar-based models (e.g., Bybee, 2001) or models that directly associate forms with meanings,

² see Plag et al. (2017) and Schmitz et. al. (2021a, 2021b) for a detailed discussion of all variables and covariates that were controlled for.

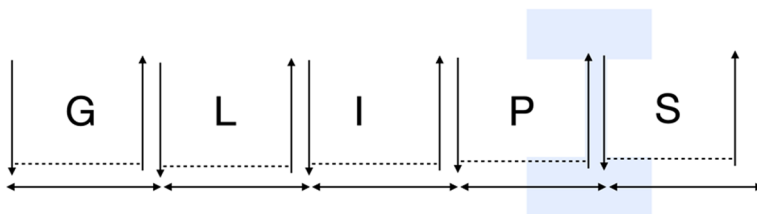


Fig. 1 Interkey intervals for the pseudoword glips. Vertical arrows indicate the downstroke and release of keys, horizontal arrows indicate the intervals delimited by each downstroke (Conijn et al., 2019 p. 2355)

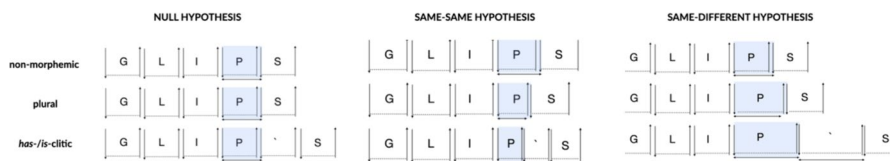


Fig. 2 A schematic visual summary of the prediction for IKIs across all categories according to our three hypotheses

such as discriminative learning (Baayen et al., 2011, 2019). Both frameworks would conceptualize durational differences as arising from usage, i.e. as a function of relations between words.

For typing, it is commonly held that increased or decreased latencies at linguistic boundaries, can be seen as indirect evidence of an activation of the respective units during processing. If the execution of two consecutive keypresses spans a linguistic boundary, the interval between these keypresses will be inflated as a reflection of the surplus of time needed to activate and process the respective linguistic units (syllables, morphemes) in parallel. This line of argumentation has been proposed, for example, by Hess et al. (2022), Libben (2020) or Kandel (2008).

Present study

For the present study, participants had to type word-final <s> in English pseudowords at different word-internal boundaries: non-morphemic, plural, auxiliary *has*-clitic and *is*-clitic. We measure the duration of the interkey intervals for the transition onto <s>. This interval is delimited by the downstroke of the preceding key and the downstroke of the <s>-key, as illustrated in Fig. 1 below.

Drawing on the theories and existing results discussed above, we can now formulate three different hypotheses for our experiment. We will illustrate each prediction with an example and briefly summarize its theoretical implications. Figure 2 below provides an overview and a simplified visual summary of the three predictions and the associated patterning of IKIs, again using the example of *glips*.

Any theory of language production, be it written or spoken, that assumes a strict divide between higher-level or central processing and peripheral or motor processing, without cascading, would not expect structural properties of

words—such as morphological status—to directly modulate the linguistic output signal. For a word like *glips* the typewritten output would be expected to no longer reflect whether it is singular, monomorphemic *glips* with a word-final non-morphemic <s> or whether it is plural *glips*, which is composed of a stem *glip* + *s*_{plural}. Similarly, for the typing of *glip*'s, it would be expected that any disfluency or variation in the trajectory forming around the apostrophe should be explicable by motor planning and execution alone and no longer contain traces of its underlying structure *glip* + *has*_{cliticized}. The absence of any durational differences between IKIs across all categories of our experiment constitutes our null hypothesis:

(1) Null hypothesis

There are no durational differences between the different types of word-final <s>.

If we do not find any meaningful fluctuation in the output, i.e. the time between keys is evenly distributed and not disrupted, we can assume that the IKIs around <s> are primarily determined by motoric factors and typing ability. In other words, we would have to assume that any processing other than motor coding and execution must be complete by the downstroke of the key preceding <s>. Such fluent typing has previously been indicated to be characterized by IKIs of around 150 ms on average (Roeser et al., 2024).

Theories that map out more cascading and parallel processing, where morphological processing remains active through motor planning and execution, would predict durational differences between the different types of word-final <s>. These differences, however, could pattern in various ways. As was described above, the directionality of such an effect is inconclusive in the literature. Previous research found both inhibitory and facilitating effects of morphological structure (Hess et al., 2022:p. 910).

One possibility would be that the durational pattern of IKIs echoes what was found for acoustic duration. To use our example again: for *glips*, the maximum IKI in the transition from *p* to *s* is expected to occur for singular *glips* with a word-final non-morphemic S. The transition from <*p*> to <*s*> would be slightly faster for plural *glips*, and the fastest for *glip*'s, with no difference between *has*- or *is*-clitic. If we assume that the IKI in singular *glips* is determined by motor planning and execution alone and both plural <*s*> and clitic <*s*> display a decreased IKI, this pattern could be seen as evidence of a facilitating effect of morphological structure. A presumably comparable effect of morphological structure on error performance has been described by, for example, Caramazza and Hillis (1989) and Badecker et al. (1990) for dysgraphic patients. In their study, multi-morphemic words elicited fewer errors among their patients compared to mono-morphemic words that were matched in characteristics. This was taken to suggest that the cognitive load on working memory might be reduced when individual morphemes can be processed separately (Rapp & Fischer-Baum, 2014:p. 345).

In the context of the present study, we have called this the *Same-same Hypothesis* to emphasize that it predicts the same pattern of durational differences for IKIs that was previously described for acoustic duration by Schmitz et al. (2021a).

(2) Same-same hypothesis

There are durational differences between the different types of word-final <s> that pattern out in the same way as for acoustic duration: non-morphemic <s> will be longer than plural <s>, which will be longer than clitic <s>. There will be no difference between the auxiliary clitics.

In contrast, if we assume an inhibitory effect of morphological processing, the presence of a morphological and an underlying word boundary, would still be reflected in the IKIs, however, the pattern would be the mirror image of the above-described differences. This pattern would corroborate existing findings on IKIs at linguistic boundaries by, for example, Bertram et al. (2015), Gagné and Spalding (2016), Libben (2020) or Will et al. (2006). This means that the typing of non-morphemic <s> in *glips* (singular) would elicit the shortest IKI because it involves a mere key transition <p> to <s> with no underlying linguistic boundary. In comparison, we would expect an increased IKI for the typing of plural <s> in *glips*, where the transition from <p> to <s> spans the morphological boundary that separates the stem *glip* from plural affix <s>. Lastly, in this scenario, the transition to the auxiliary clitics will elicit the longest transition because it involves an underlying word boundary, and hence processing of a parallel word unit, which should be visible in the interval left and right to the apostrophe key.

Alluding to the fact that both hypotheses (2) and (3) predict durational differences, but suggest reversed patterns, we have called this the *Same-different hypothesis*.

(3) Same-different hypothesis

There are durational differences between the different categories of word-final <s> that reflect the strength of the underlying linguistic boundary: non-morphemic <s> will be shorter than plural <s>, which will be shorter than clitic <s> and there will be no difference between the auxiliary clitics.

Method

We used sentence copying task with pseudowords in real language context. In the original experiment, Schmitz et al. (2021a) used a form of reading-and-retelling paradigm, i.e. the context slowly faded while participants were producing their response. We transformed this into an immediate copying paradigm, where the stimulus was visible the entire time, while the participants typed their response. The exact procedure will be detailed below. All relevant code and data for the analysis and results discussed in the following section can be found at <https://osf.io/f79pt/>.

Table 1 Orthographic representation of complete stimulus set (taken from Schmitz et al., 2021a:p. 583)

	i	i:	u:	ʌ	aʊ	eɪ
items for morphemic S elicitation	glip	pleep	cloop	prup	bloup	glaip
	glit	pleet	cloot	prut	blout	glait
	glik	pleek	clook	pruk	blouk	glaik
	glif	pleef	cloof	pruf	plouf	glaiif
items for non-morphemic S elicitation	glips	pleeps	cloops	prups	bloups	glaiips
	glits	pleets	cloots	pruts	blouts	glaits
	gliks	pleeks	clooks	pruks	blouks	glaiiks
	glifs	pleefs	cloofs	prufs	bloufs	glaiifs

Participants

136 participants were recruited via *Prolific* and participated for payment. Participant age had a mean of 35 years and a median of 32 years with a standard deviation of 13 years. The youngest participant was 18 years old; the oldest participant was 75 years old. Consent was obtained in accordance with a protocol sanctioned by the ethics board at our home institution. The participants were pre-screened through *Prolific* as North American native speakers of English, using a physical QWERTY keyboard with a desktop PC or laptop.

Materials

The materials were adopted from Schmitz et al. (2021a). The authors employed Berko-Gleason's (1958) pseudoword paradigm for the creation of 48 pseudowords that followed the phonotactic constraints of English (Clements & Keyser, 1983).

The items contain complex onsets, consisting of a plosive and an approximant (/pl/, /bl/, /kl/, /gl/, /pr/) plus a short vowel, a long vowel or a diphthong as nucleus, followed by either simple or a complex coda consisting of a plosive or a plosive plus affricate respectively (/p/, /t/, /k/, /f/ or /ps/, /ts/, /ks/, /fs/). All items were either four- or five-letter pseudowords. An overview of all stimuli can be found in Table 1.

The items were constructed in a way that allows to keep phonotactic and spelling interference to a minimum. For the vowels, those orthographic representations with the highest phoneme-grapheme probability were chosen (Gontijo et al., 2003). For the word-final consonants, those representations were chosen that allow for a linear mapping of phonemes onto graphemic representations (see, e.g., Muschalik & Kunter, 2023 for a detailed discussion of the influence of orthographic complexity on pronunciation). Additionally, the carrier sentences were constructed in a way that reduces potential coarticulatory effects, which do not come into play in the same way for written word production (see Schmitz et al.: 583 for a detailed description).

To reduce potential priming effects, Schmitz et al. (2021a) divided the resulting pseudowords into two sets, each containing 24 pseudowords. Within each set, 12 pseudowords were designated for morphemic /s/ elicitation and the remaining 12 for non-morphemic /s/ elicitation. This approach ensured that no participant encountered phonologically identical pseudowords as both a simplex and complex form. Participants were evenly distributed across the two groups and each participant was tasked with producing 12 tokens for each of the four /s/ types (non-morphemic, plural, *is*-clitic, *has*-clitic), resulting in a total of 48 tokens. To guarantee that each pseudoword was elicited within every context and with each verb for every /s/ type, the authors created 12 pseudorandomized lists. These lists were consistent across both groups for comparability and the order of /s/ types was alternated to prevent consecutive elicitation of the same type and minimize priming effects (Schmitz et al., 2021a:p. 584). We adopted this procedure in its entirety.

For our present purpose, the stimulus design had a number of additional advantages. First, monosyllabic items reduce the previously discussed potential interference from syllabic boundaries in written word production. This way, it is possible to test for an influence of morphological structure in isolation. Furthermore, the pseudoword stimuli presumably have a comparable semantic transparency. Each pseudoword is introduced during the experiment as the name of an alien creature and either ending in a consonant (for morphemic S elicitation) or a consonant + S-cluster (for non-morphemic S elicitation; see Table 1). In other words, the stimuli are proper names and are either uninflected or constitute the base for both plural S-affixation and auxiliary cliticization. Consequently, their meanings are considered highly transparent, which presumably minimizes interference by varying semantic transparency. Thirdly, the spelling was kept constant with the most probable spelling-to-sound mapping. This allows for a greater between-item comparability and reduces potential noise resulting from orthographic (in) consistency (e.g., Cassar & Treiman, 1997). Lastly, the construction of the stimuli also leads to two similar targeted transitions from the word-final consonants to the <s> key on the keyboard, one more proximal (<f> and <t> to <s>) and the other more distal (<k> and <p> to <s>).

Procedure

The technical side of the experimental design was adapted from Pinet et al. (2016), using jsPsych (de Leeuw et al., 2023) to record for the target responses both all individual keypresses and the associated interkey intervals. After being recruited via *Prolific*, participants were directed to the landing page of our experiment, which informed them about the experiment structure (see Fig. 2). Participants were led to believe that they were serving as a control group in an experiment that assesses typing speed in younger children. By clicking enter, participants consented to participate in two consecutive experiment parts. The first was designated as a warm-up task, where participants had to copy five pangrams, containing all alphabetic letters as well as the target transitions in various environments. Following that, participants were asked to copy 48 bold-print sentences in total, each containing a stimulus as described above. Figure 3 is an illustrative example of a stimulus slide.



Aliens in Action: Online Typing Experiment

Why ?

The purpose of this study is to assess typing abilities in younger children. You are part of the control group, so don't be puzzled by the simplicity of the task.

How ?

This experiment will measure your typing speed in different contexts. The data collected is completely **anonymous**. You can decide to leave the experiment at any point. The data is only collected at the very end of the experiment. For the reliability of our data, we would ask you to **only participate once**.

Who are we ?

This study was developed and carried out by members of a research unit at

Any questions ?
Curious to see the results ?
Contact us !

START



Additional Information

Introduction

Dear participant,

Recently, some strange creatures have been found on a far away planet. These aliens, even though bizarre in appearance, exhibit some human features and engage in activities known to us. As these creatures were only discovered a short time ago, their names will sound strange to you. Do not worry about any unfamiliar words in the following experiment – you do not have to remember them!

During the experiment, you will read words and sentences and will be asked to copy them on your keyboard.

The slides of the following experiment will contain the following elements:

- pictures and/or names of alien creatures
- a short explanation of the situation
- a prompt to copy a sentence into an allocated box
- the answer box.

You may look at each slide as long as you think is needed. **Then please type the answer into the allocated box.**

Once you have finished the experiment, you will be awarded a small compensation. (Do we do that?)

Again, do not be confused by the simplicity of the task. The experiment was designed for children and you are part of the control group.

By clicking the «start» button below you acknowledge having read, understood and accepted the conditions described above.

START

Open the experiment

For more information (anonymity, legal notice...), click [here](#).

Fig. 3 Landing page and introduction to the experiment

Each trial followed a consistent pattern, as illustrated in Fig. 3. Initially, relevant pseudowords were introduced as alien creatures with one pseudoword in its plural form for plural trials and two different pseudowords for the other three conditions. Two images of alien creatures (van de Vijver & Baer-Henney, 2014) representing the pseudowords were shown with the same creature twice for plurals and two different creatures for the remaining three contexts. Pseudowords and images were randomly paired across lists to eliminate potential appearance-related confounding effects (e.g., Fort et al., 2014; Köhler, 1929; Schmitz et al., 2023). A context was introduced, and participants were prompted with a question to copy the bold-print sentence containing the target (Fig. 4).



This creature is a glip.



And this is another one.

Last week, the glips played a game.

What happened last week?

Fig. 4 Item display during the experiment

Each trial contains one of the stimuli in one of the following four contexts, which we adopted from Schmitz et al., (2021a:p. 586):

- (1) non-morphemic context
 Introduction: This is a clooks. # And this is a glifs.
 Target: **Every day, the clooks plays with the glifs.**
 Target prompt: What happens every day?
- (2) plural context
 Introduction: This is a clook. # And this is another one.
 Target: **Two days ago, the clooks ate their lunch together.**
 Target prompt: What happened two days ago?
- (3) is-clitic context
 Introduction: This is a clook. # And this is a glif.
 Target: **The clook's meeting the glif for a drink.**
 Target prompt: What's happening tonight?
- (4) has-clitic context
 Introduction: This is a clook. # And this is a glif.
 Target: **The clook's written a love letter to the glif.**
 Target prompt: What's happened?

The stimulus was visible on screen the whole time while participants were typing. The experiment was self-paced, and participants were asked to type as fast as they could but with as few errors as possible (see Fig. 3 for the instructions).

Labels and measurements

In a first step, we aligned the individual keypresses with the respective time stamps to derive a durational measure for each of the targeted interkey intervals (IKI). For both the non-morphemic and the plural condition, we measured the transition from the preceding consonant onto the word-final <s> as the target IKI. For the two auxiliary clitics, we measured two IKIs, namely the transition from the preceding consonant onto

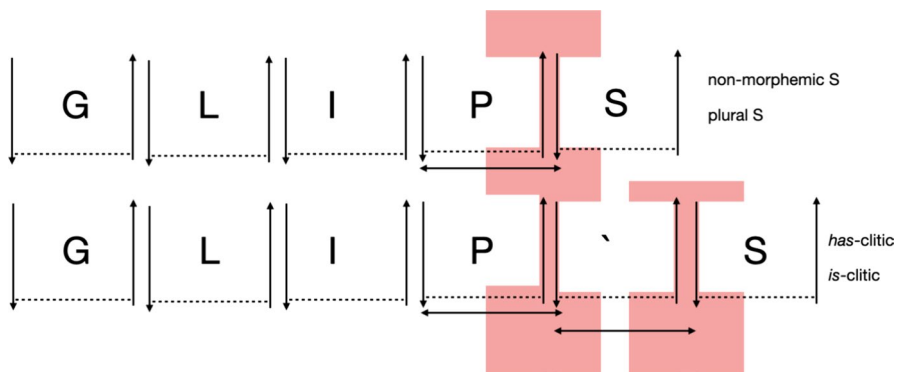


Fig. 5 Target IKI measuring points for all four conditions

Table 2 Overview of target frequencies across all four conditions

non-morphemic	plural	<i>is</i> -clitic	<i>has</i> -clitic
1272	1290	1183	1132

the apostrophe, as well as the transition from the apostrophe onto the word-final S (Fig. 5).

While the latter was what we were primarily interested in, we collected the second measurement to increase comparability with the non-morphemic and the plural condition, as this is the transition following the fourth or fifth letter respectively. At this point it seems relevant to emphasize that, since all participants were pre-screened as using a QWERTY keyboard, the apostrophe key was on the surface key, no shift key pressing was necessary.

The two data sets were further processed and analyzed as data set A (preceding consonant to apostrophe) and data set B (apostrophe to word-final S).

Pre-processing

At the outset, the data were pre-processed to include only those responses where the target was produced without any error, no matter whether these errors were corrected or not. Our 136 participants produced 6528 target words in total, of which we had to exclude approximately 25% ($n = 1651$). This rather high degree of data loss is one of the reasons we decided for an immediate copying paradigm because we assumed that memorized pseudowords would lead to an even higher degree of wrongly spelled targets. For the analysis, we were able to retain 4877 data points, reasonably evenly distributed across all four conditions (see Table 2).

Analysis

Variables

The set of covariates used in the present study is similar to that of previous studies on morpho-phonetic effects (Plag et al., 2017; Schmitz et al., 2021b). Additionally, a range of variables related to typing itself are included. In the following, variables for which potential effects are known are described first. Then, variables with assumed random effects are introduced.

TYPEOfS. This categorical variable encodes the type of <s> of a pertinent trial and its related data. As four types of <s> were under investigation, this variable can take four values: nm for non-morphemic, pl for plural, is for *is*-clitic and has for *has*-clitic <s>.

HAND_WATCH. Watching one's hands while typing might significantly influence the typing process itself and can be seen as a proxy for motor practice (Pinet et al., 2016). Participants were asked whether they always, often, rarely or never watch their hands during typing.

TRAINING. As professional training or personal training attempts for faster typing might influence typing speed and behavior, participants were asked whether they took part in such training efforts. This was a binary variable with yes and no as levels.

MEANIKI. Analogously to talking speed and segment durations in spoken language, an overall higher typing speed should come with generally shorter IKIs. In **MEANIKI**, the mean of all IKIs of a trial is given. The lower this value, the faster the typing speed. Values were log-transformed due to skewness.

KEYDISTANCE. As the distance between two keys might play a role in how fast these keys are typed in sequence (Fitts, 1954), the Euclidean distance between two pertinent keys was incorporated as the variable **KEYDISTANCE**.³

TRIALNUMBER. To account for potential effects of learning and/or exhaustion during the experiment, the number of trials is incorporated as a variable.

AGE. Since aging is discussed as affecting general cognitive and motor skills, this variable was introduced to control for potential effects of age differences in our participants (e.g., Spirduso & MacRae, 1990).

BIGRAPHFREQUENCYLOG. A potential factor influencing the IKI of two keys is the frequency of the pertinent key combination within the language. The more frequent a key combination is, the shorter the pertinent IKI potentially should be. A measure of bigraph frequency based on COCA (Davies 2008–) was incorporated to account for such an influence. The measure was log-transformed due to being skewed.

PARTICIPANT. To account for potential further inter-participant differences, a variable participant with participant IDs as levels was used.

³ The code for calculating keyDistance is available in the OSF repository.

PSEUDOWORD_LENGTH. To account for potential effects of target word length in keys, this information was contained within the variable PSEUDOWORD_LENGTH. The value was either 5, 6 or 7.

PSEUDOWORD. To rule out any effects of individual pseudowords, this variable was included.

LEFTHAND / RIGHTHAND. Depending on how many and which fingers a person typically uses to type, different keys should be more easily accessible than others (Hyman, 1953). This information is accounted for in the variables LEFTHAND and RIGHTHAND for the fingers of the left and the right hand, respectively. Either variable consisted of the combination of used fingers on the respective hand. For instance, if a participant used their right thumb and index finger to type, their righthand value was ti, i.e., t for thumb, i for index finger. Further abbreviations were m for middle finger, r for ring finger, and l for little finger.

Finally, the log-transformed interkey intervals are given as a variable called IKILOG. Log-transformation was necessary as non-transformed IKI values are standardly highly skewed (Roeser et al., 2024:p. 373). This variable is the variable of interest and will thus be the dependent variable in the following analysis.

Statistical analysis

For the statistical analysis, the log-transformed IKI data entered generalized additive models (GAMs) as a dependent variable. GAMs were used as they allow for non-linear effects. Due to the exploratory nature of our study and the complex distributional properties of our response variable, we cannot a priori assume linearity of effects but need to account for effects of any type. As there are two IKIs of interest in the case of *is-* and *has-clitic* <s> (see Sect. "Labels and measurements"), models were fitted to two separate data sets: One with the IKIs between the preceding consonant and the apostrophe (data set A) and one with the IKIs between the apostrophe and the word-final <s> (data set B).

GAMs were fitted in R (R Core Team, 2023) using the mgcv package (Wood, 2017). Using the SfL package (Schmitz & Esser, 2021) before model creation, all independent variables were checked for high correlation coefficients, i.e., $\rho \geq 0.5$, to avoid potential issues of collinearity in the fitted models. Collinearity is an issue often arising with strongly correlated independent variables within the same model, leading to unreliable model estimates (Tomaschek et al., 2018).

For data set A, problematic correlation coefficients for the following variable pairings were identified: TYPEOfS vs. BIGRAPHFREQUENCYLOG ($\rho = -0.78$), TYPEOfS vs. KEYDISTANCE ($\rho = 0.70$), KEYDISTANCE vs. BIGRAPHFREQUENCYLOG ($\rho = -0.53$), and RIGHTHAND vs. LEFTHAND ($\rho = 0.7$). Taking a closer look at the interrelation of TYPEOfS, KEYDISTANCE and BIGRAPHFREQUENCYLOG, it became apparent that the values of KEYDISTANCE and BIGRAPHFREQUENCYLOG are clearly divided between non-morphemic and plural <s> on the one hand and *is-* and *has-clitic* <s> on the other hand. More specifically, the lower half of BIGRAPHFREQUENCYLOG values and the majority of the higher half of KEYDISTANCE values is only found for clitic <s>, while the upper half of BIGRAPHFREQUENCYLOG values and the lower half of KEYDISTANCE

Table 3 Overview of both data sets: summary of the dependent variable, numerical and categorical predictors for data sets A and B

Dependent variable	Mean	St. Dev	Min	Max
IKI_LOG (DATA SET A)	5.346	0.673	1.946	9.652
IKI_LOG (DATA SET B)	5.552	0.746	0.693	9.652
NUMERICAL PREDICTORS	Mean	St. Dev	Min	Max
MEANIKI	211.310	110.706	82.060	1733.940
KEYDISTANCE (DATA SET B)	123.35	48.21	38.10	163.04
AGE	35.770	12.999	18.000	75.000
BIGRAPHFREQUENCYLOG (DATA SET B)	15.140	1.421	11.900	16.120
TRIALNUMBER	24.130	13.585	1.000	48.000
PSEUDOWORDLENGTH	6.138	0.685	5.000	7.000
CATEGORICAL PREDICTORS	Levels			
TYPEOfS	nm: 1272	pl: 1290	is: 1183	has: 1132
HAND_WATCH	always: 47	often: 1041	rarely: 2816	never: 930
TRAINING	yes: 3149	no: 1692		
FINGERS	32 levels			
PARTICIPANT	136 levels			
PSEUDOWORD	24 levels			

values is only found for non-morphemic and plural $\langle s \rangle$. This is a direct result of the stimulus design and the transfer to the written domain: Non-morphemic and plural $\langle s \rangle$ IKIs are captured as the IKIs between a consonant and the $\langle s \rangle$, while the clitic IKIs are the IKIs between a consonant and the apostrophe. We decided to drop KEYDISTANCE and BIGRAPHFREQUENCYLOG as measures for the analysis of data set A. The underlying effects of KEYDISTANCE and BIGRAPHFREQUENCYLOG, however, are nonetheless represented by TYPEOfS due to the clear distribution of properties across non-clitic and clitic $\langle s \rangle$.

For RIGHTHAND vs. LEFTHAND, no such clear picture was found. Apparently, the use of fingers on both hands is nowhere near symmetrical (at least within our participants it is not). Thus, dropping one of the two variables as for the previous pair of correlated variables was not an option. Instead, we opted to create a new variable FINGERS, combining the values of RIGHTHAND and LEFTHAND into one. This procedure does not drop any information on finger usage and was thus preferred over other potential solutions such as, for example, principal component analysis.

For data set B, only one problematic correlation was found: RIGHTHAND vs. LEFTHAND ($\rho = 0.7$). As these variables are independent of which IKIs are part of the data set, we adopted the same procedure as for data set A. That is, a combined variable FINGERS was created and retained for the analysis. The newly created FINGERS variable showed no strong correlation coefficients with any of the other variables for both data sets.

Gaussian GAMs were then fitted for both data sets using nearly identical model specifications. An overview of both data sets is given in Table 3. Log-transformed IKI values were used as dependent variables. The variable of interest, TYPEOfS,

Table 4 Overview of the GAM fitted to data set A

	β estimate	SE	t-value	p-value
(Intercept)	5.247	0.397	13.323	0.000
TYPEOfSPL	0.008	0.021	0.378	0.706
TYPEOfSis	0.117	0.021	5.557	0.000
TYPEOfSHAS	0.109	0.021	5.123	0.000
HAND_WATCHNA	−0.069	0.295	−0.234	0.815
HAND_WATCHNEVER	−0.218	0.177	−1.233	0.217
HAND_WATCHOFTEN	−0.155	0.174	−0.888	0.375
HAND_WATCHRARELY	−0.165	0.171	−0.964	0.335
TRAININGNO	0.190	0.361	0.528	0.597
TRAININGYES	0.212	0.360	0.589	0.556
	edf	Ref. df	F-value	p-value
MEANIKI	4.386	5.303	52.291	0.000
TRIALNUMBER	6.894	7.980	2.169	0.029
AGE	1.916	2.003	2.726	0.066
FINGERS:HANDEDNESSAMBI	0.000	2.000	0.000	0.825
FINGERS:HANDEDNESSLEFT	0.000	11.000	0.000	0.951
FINGERS:HANDEDNESSNA	0.000	1.000	0.000	0.206
FINGERS:HANDEDNESSRIGHT	18.750	26.000	30.199	0.044
PARTICIPANT	84.200	125.000	4.411	0.011
PSEUDOWORDLENGTH	0.000	1.000	0.000	0.858
PSEUDOWORD	21.960	23.000	22.933	0.000

entered the analysis as a parametric term, as did HAND_WATCH and TRAINING. MEANIKI, KEYDISTANCE (for data set B), BIGRAPHFREQUENCYLOG (for data set B), TRIALNUMBER, and AGE entered the model as smooth terms. FINGERS and HANDEDNESS were included in interaction. PARTICIPANT, PSEUDOWORDLENGTH, and PSEUDOWORD were given as random smooth terms.

Results

Data set A

Effects of the following variables were found: TYPEOfS, MEANIKI, TRIALNUMBER as well as for the random effects of PARTICIPANT and PSEUDOWORD. The interaction of FINGERS and HANDEDNESS just reached significance for right-handedness ($p = 0.044$). An overview of the model is given in Table 4. For the parametric terms, we provide the β estimates and the corresponding standard errors (SE), t -values and p -values. For the smooth terms, the estimated degrees of freedom, the reference degrees of freedom, the F -values and the p -values are given.

Using Bonferroni-corrected pairwise comparisons for the levels of TYPEOfS, it is found that the effects of non-morphemic and plural <s> as well as the effects of *is*- and *has*-clitic <s> are not significantly different ($p = 1$). A clearly significant

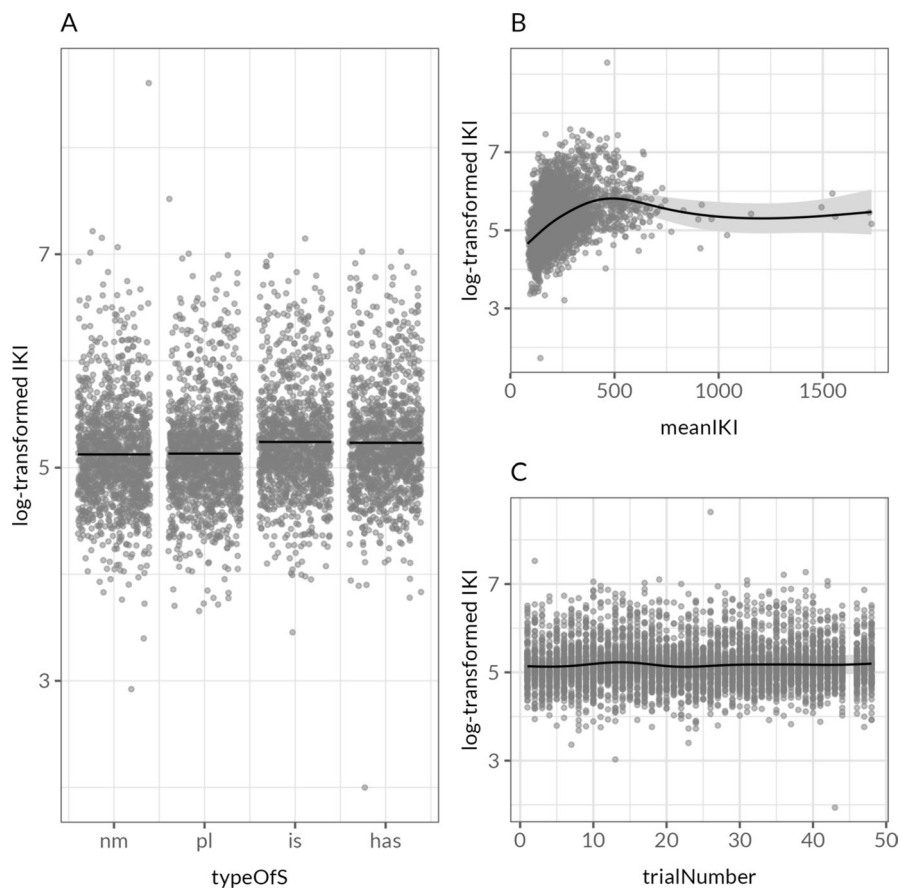


Fig. 6 Significant effects found in the GAM fitted to data set A for *typeOfS* (Panel A), *meanIKI* (Panel B) and *trialNumber* (Panel C). Abbreviations: nm=non-morphemic; pl=plural; is=is-clitic; has=has-clitic

difference, however, is found when comparing the effects of non-morphemic and plural <s> to those of *is*- and *has*-clitic <s> ($p < 0.0001$).

Panel A of Fig. 6 shows the nature of the effects found for *typeOfS*. Non-morphemic and plural <s> come with significantly lower IKI values as compared to *is*- and *has*-clitic <s>. The effect of *meanIKI* is shown in Panel B: Faster overall typing speed comes with lower IKI values. Panel C displays the effect of *trialNumber*. While there is a slight increase in IKI values between trials 10 to 20, this increase is lost after trial 20.

Data set B

Effects of the following variables were found: *typeOfS*, *meanIKI*, *keyDistance*, *age* as well as for the random effects of *participant* and *pseudoword*. The interaction

Table 5 Overview of the GAM fitted to data set B

	β estimate	SE	t-value	p-value
(Intercept)	5.034	0.358	14.066	0.000
TYPEOfSPL	0.009	0.021	0.449	0.654
TYPEOfSis	1.440	0.106	13.629	0.000
TYPEOfSHAS	1.420	0.106	13.404	0.000
HAND_WATCHNA	−0.167	0.335	−0.498	0.619
HAND_WATCHNEVER	−0.394	0.207	−1.908	0.057
HAND_WATCHOFTEN	−0.344	0.204	−1.691	0.091
HAND_WATCHRARELY	−0.353	0.200	−1.763	0.078
TRAININGNO	0.138	0.294	0.470	0.638
TRAININGYES	0.220	0.293	0.750	0.453
	edf	Ref. df	F-value	p-value
MEANIKI	4.799	5.797	42.858	0.000
KEYDISTANCE	3.000	3.000	34.076	0.000
TRIALNUMBER	7.820	8.638	1.126	0.295
AGE	1.720	1.776	4.229	0.014
FINGERS:HANDEDNESSAMBI	0.000	2.000	0.000	0.838
FINGERS:HANDEDNESSLEFT	0.000	11.000	0.000	0.828
FINGERS:HANDEDNESSNA	0.000	1.000	0.000	0.218
FINGERS:HANDEDNESSRIGHT	9.408	26.000	9.831	0.586
PARTICIPANT	97.340	125.000	6.782	0.000
PSEUDOWORLENGTH	0.000	1.000	0.000	0.881
PSEUDOWORD	22.370	23.000	15.100	0.000

of FINGERS and HANDEDNESS did not reach significance. An overview of the model is given in Table 5. For the parametric terms, we provide the β estimates and the corresponding standard errors (SE), z -values and p -values. For the smooth terms, the estimated degrees of freedom, the reference degrees of freedom, the F -values and the p -values are given.

The effect of TYPEOfS is given in Panel A of Fig. 7. The IKI values of non-morphemic and plural <s> are higher than those of the two clitics, while there is no significant difference found between non-morphemic and plural <s> and between *is*- and *has*-clitic <s>. Bonferroni-corrected pairwise comparisons for TYPEOfS yielded similar results as for data set A. For MEANIKI higher values come with longer IKIs as shown in Panel B. In Panel C, the effect of KEYDISTANCE is illustrated. Greater distances come with lower IKI values. The effect of AGE is given in Panel D. Older participants show higher IKI values.

Summary of findings

In sum, our variable of interest, TYPEOfS, shows a significant effect in both data sets. In both cases, clitic <s> comes with higher IKI values than non-morphemic and plural <s>. This difference is more pronounced when considering the IKI between

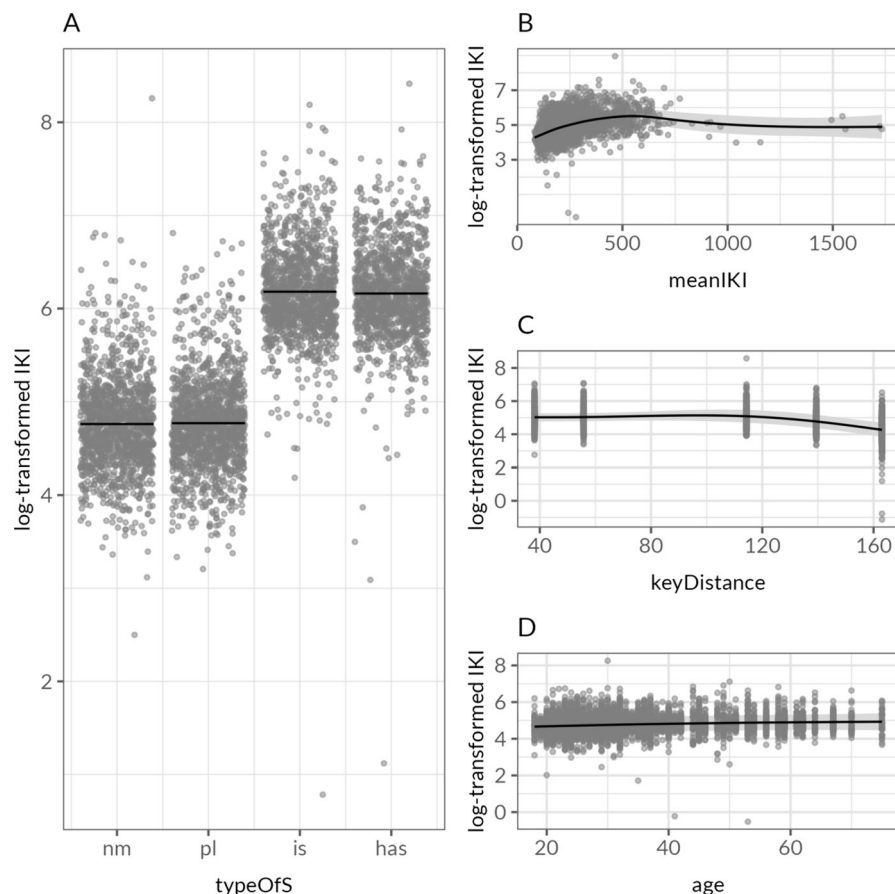


Fig. 7 Significant effects found in the GAM fitted to data set B for TYPEOfS (Panel A), MEANIKI (Panel B), KEYDISTANCE (Panel C) and AGE (Panel D). Abbreviations: nm = non-morphemic; pl = plural; is = is-clitic; has = has-clitic

apostrophe and <s> (data set B) but highly significant nonetheless when looking at the IKI between coda consonant and apostrophe. The differences between both clitics and non-clitics are not significant.

Additionally, higher mean speed comes with lower IKI values (data sets A and B), while greater distances between keys (data set B) and higher age (data set B) come with higher IKI values.

Discussion

In the present study, we tested whether the morphological status of word-final S in English influences its typing duration. To ensure a maximal degree of comparability with existing results on the influence of morphological structure on acoustic

duration, we adapted a production experiment developed by Schmitz et al. (2021a), investigating a well-researched phenomenon, namely the acoustics of word-final /s/ in English. Choosing this phenomenon and this specific study design had the additional advantage of a highly controlled environment, monosyllabic stimuli with unvarying semantic transparency, consistent spelling and minimized confounding lexical effects.

We find no significant durational difference between non-morphemic and plural <s>, i.e., no heightened transitional duration at the suffix boundary. We do, however, find significantly inflated IKIs for *is*-clitic and *has*-clitic at both the transition from the coda consonant to the apostrophe and the transition from the apostrophe to the word-final <s>, with the latter being much more pronounced.

Our null hypothesis assumed no durational differences for the target transition across all categories of our experiment. We argued that IKIs would be determined by motor planning and execution alone. We can reject our null hypothesis based on our controlled evidence indicating varying typing durations for the different categories.

Our Same-same hypothesis predicted durational differences that echo the pattern found for acoustic duration, specifically by Schmitz et al. (2021a). The hypothesis predicted maximum IKIs for non-morphemic <s> compared to plural <s>, and the shortest IKIs for both *has*- and *is*-clitic. Based on our findings, the Same-same hypothesis must also be rejected.

Lastly, our Same-different hypothesis predicted durational differences between different types of word-final <s>, with non-morphemic <s> being shorter than plural <s> and plural <s> being shorter than both auxiliary clitics. Confirming this hypothesis would corroborate findings on typing durations at varying linguistic boundaries, as presented by, for example, Libben (2020), Bertram et al. (2015), Gagné and Spalding (2016) or Will et al. (2006). According to the literature, the activation of linguistic units parallel to motor execution will cause an inflation of IKIs at the corresponding linguistic boundaries compared to a control condition. Our results confirm the Same-different hypothesis in positing that auxiliary clitics would exhibit the longest IKIs and show no difference in duration themselves. The hypothesis fails, however, to correctly predict the lack of contrast for the realization of plural <s> and non-morphemic <s>. Both categories display IKIs of around 150 ms on average, which is exactly what would be predicted for fluent typing without any disfluencies caused by higher-level processing (cf. Roeser et al., 2024).

In other words, while the typing of plural <s> did not exhibit any traces of parallel activation of the plural morpheme in the form of inflated IKIs at the affix boundary, the typing of the cliticized auxiliaries exhibits an inhibitory effect at the underlying word boundary. This effect is already visible in the transition from the coda consonant to the apostrophe, with IKIs averaging at around 200 ms, but becomes much more pronounced in the transition from the apostrophe to the cliticized <s>, with IKIs of around 300 ms on average for both clitics. To prevent potential misunderstandings, it is important to reiterate that our participants underwent pre-screening and were required to use a QWERTY keyboard for input. In this specific keyboard layout, the apostrophe is situated on the surface and does not require activation through the Shift key. The delay we see at the transition to the apostrophe and to the word-final <s> in clitics can thus not stem from the pressing of any additional

key. In terms of motoric routine, the transition to <s> should also be much more routinized for our participants, as it is a much more frequent key combination in English compared to each individual consonant transition to the apostrophe (cf. Jones & Mewhort, 2004). It is thus more expected and should be easier to anticipate within the motor program.

This suggests that the enhanced IKIs we see at the clitic-transitions are not determined by motor processing alone but reveal some kind of disrupted cascading. Processing of the apostrophe and the cliticized <s> seem to be incomplete at the time of execution, which delays the trajectory forming. The fact that the transition from the apostrophe to the clitic <s> is more pronounced could either be an indicator of the enhanced complexity of the underlying cognitive operation necessary for cliticization or it could be interpreted as evidence of the underlying word boundary and parallel activation of the next word unit (Torrance & Conijn, 2024:p. 241).

Conclusion

Before we conclude, there are several limitations we would like to address, specifically regarding the lack of contrast between non-morphemic and plural <s>, which also serve as pointers to future research.

First, we would like to highlight that all the effects of morphological structure on typing timing previously described in the literature surface at boundaries of lexical substrings, either in compounds or derived words. To the best of our knowledge, no previous study has systematically distinguished between effects of derivational and inflectional morphology on typing timing. There is accumulating evidence, however, specifically for the influence of inflectional morphology on spelling performance (Badecker, 1996; Badecker et al., 1990; Berg et al., 2023; Rapp et al., 2015; Sandra, 2010; Sandra et al., 1999; Schmitz et al., 2018). Additionally, morphological boundary strength has been discussed as a potential source of influence on written language production, specifically on spelling performance (Gahl & Plag, 2019). In line with work by Hay and Baayen (2002, 2005), morphological boundary strength can be understood as a continuum, encompassing factors like morphological productivity, semantic transparency and base and derivative frequency (Hay & Baayen 2002; Vannest et al., 2011), all of which are also known to influence written language production, and which would differ for plural <s> compared to some of the derivational affixes previously investigated. Consequently, we would tentatively conclude that we do not see an effect of *inflectional* morphology, rather than assuming there is no effect of morphology at all (Libben et al., 2016 for a discussion of the special psychological status of derivational morphemes).

Further, it might be argued that the choice of pseudowords as stimuli generally promotes less semantic processing. The debate around the semantics of pseudowords and their processing has persisted for a long time (see, e.g., Cassani et al., 2020 for a detailed discussion and thorough literature review). Ultimately, this claim remains to be tested by future studies that include a comparison with real word items in this context. At this point, however, we would refer to recent computational modeling approaches that were able to demonstrate that pseudowords are in fact semantically

processed, even if their semantics cannot be put on the same level with the semantics of existing words in terms of richness (cf. Chuang et al., 2021; Schmitz et al., 2021b). While this was previously often seen as a disadvantage, it could contrarily also prove particularly advantageous for experimental investigations into the reciprocal relation between perception and production in language processing (Chuang et al., 2021:p. 969).

Shallow processing could be additionally fostered by the immediate copying-paradigm, with the stimulus visible for the entire production phase. It could be argued that copying would only necessitate the initiation of the respective motor-programming without any lexical processing involved (see, e.g., Purcell et al., 2011 for a discussion of the different pathways involved in written language processing). This, too, appears to be a valid concern that can only be fully probed by future studies. Based on existing findings on task-dependency effects in written language production, however, we maintain that an immediate copying paradigm has no disadvantage over other paradigms in the present context (e.g., Bonin et al., 2015; Feldman et al., 2019).

The last factor potentially influencing our findings is the infrequent occurrence of orthographic word-final single <s> in English simplex words.⁴ The fact that an orthographic C<s>-structure is almost exclusively aligned with plural-realization in English, presumably results in a special status as a *morphographic* spelling (Aronoff et al., 2016; Muschalik & Kunter, 2023). It is conceivable that participants, upon not thoroughly reading through the descriptions, thus did not parse a difference between, for example, *glips* in a singular and a plural meaning, as the latter is much more probable. This would also be in line with results from a computational analysis of German word-final consonant clusters (Calderone et al., 2014). The authors argue that *morphonotactic* clusters – consonant clusters that are strongly associated with morphologically complex words – are represented differently and can emerge as morphological boundary signals (Calderone et al., 2014:p. 66).

In sum, it seems that typing and articulation are not the same – yet not entirely different in that both do not appear to be accurately captured by strictly feed-forward models, which assume independence of peripheral processes (e.g., Logan, 2018; Logan & Crump, 2011; Yamaguchi et al., 2017 for typing). More refined models of written language production, such as Kandel (2023), would allow for linguistic information to be available and used during the motor output process. According to Kandel's model (2023:p. 218), writers continuously activate different processing units in real time during written word production. The activation of word-sized units triggers the activation of syllable-, morpheme- and grapheme-sized units, which should have an inhibitory effect on the movement execution at the respective boundaries in trajectory forming (also Hess et al., 2022:p. 900 for a discussion of handwriting). However, in its present state, the model can neither explain the lack

⁴ An exploratory search on <http://cubedictionary.org/>, which allows simultaneously searching for sounds and corresponding spellings in a particular environment, yields only 19 matches for monosyllabic English words ending in /s/, spelled with a single <s>. Of these 19 matches, only eight have a complex coda, i.e. a word-final C-<s>-structure.

of effect for the suffix-boundary in the present results, nor specifically locate the temporal structure of emergence or origin of the effects found. This calls for further investigation of the complex interplay between morphology and language production and for a more thorough exploration of the potential overlap but also the presumed differences between the spoken and the written processing domain.

Overall, the present results highlight the need for a more systematic investigation of written language production as a window into processing architecture. The results also bring up several questions that will have to be addressed by follow-up studies. First, as was mentioned, there is the question of how real words would compare to pseudowords in this context. Similarly, we have mentioned that a reading-and-retyping paradigm might be employed in future studies instead of immediate copying, presumably increasing semantic processing. Further, it is conceivable that morphological effects might arise at an earlier point in production as suggested by, for example, Hess et al. (2022) or Quémart and Lambert (2019). To gain more insight into the exact locus of potential effects, it might thus be fruitful to investigate the temporal structure of typing across several measuring points, including the typing onset. And lastly, we might need a more fine-grained approach to morphological boundaries to allow for the possibility that derivational processes affect written language production differently compared to inflectional processes.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Afonso, O., Álvarez, C. J. (2019). Spelling and Writing Words: Theoretical and Methodological Advances. In: C. Perret, T. Olive (Eds.), *Spelling and Writing Words. Theoretical and Methodological Advances* (pp. 151–162). Brill <https://doi.org/10.1163/9789004394988>
- Álvarez, C. J., Cottrell, D., & Afonso, O. (2009). Writing dictated words and picture names: Syllabic boundaries affect execution in Spanish. *Applied Psycholinguistics*, 30(2), 205–223. <https://doi.org/10.1017/S0142716409090092>
- Aronoff, M., Berg, K., & Heyer, V. (2016). Some implications of english spelling for morphological processing. *The Mental Lexicon*. <https://doi.org/10.1075/ml.11.2.01aro>
- Baayen, R. H., & Hay, J. (2002). *Affix Productivity and Base Productivity*. In Communication Présentée Au Morphological Productivity Seminar, ESSE (Vol. 6). Citeseer
- Baayen, H., Chuang, Y.-Y., Shafaei-Bajestan, E., & Blevins, J. (2019). The discriminative lexicon: A unified computational model for the lexicon and lexical processing in comprehension and production grounded NOT in (De)composition but in linear discriminative learning. *Complexity*, 2019, 1–39. <https://doi.org/10.1155/2019/4895891>
- Baayen, R. H., Milin, P., Đurđević, D. F., Hendrix, P., & Marelli, M. (2011). An amorphous model for morphological processing in visual comprehension based on naive discriminative learning. *Psychological Review*, 118(3), 438–481. <https://doi.org/10.1037/a0023851>
- Badecker, W. (1996). Lexical morphology and the two orthographic routes. *Cognitive Neuropsychology*, 13(2), 161–176. <https://doi.org/10.1080/026432996381980>
- Badecker, W., Hillis, A., & Caramazza, A. (1990). Lexical morphology and its role in the writing process: Evidence from a case of acquired dysgraphia. *Cognition*, 35(3), 205–243. [https://doi.org/10.1016/0010-0277\(90\)90023-D](https://doi.org/10.1016/0010-0277(90)90023-D)
- Baus, C., Strijkers, K., & Costa, A. (2013). When does word frequency influence written production? *Frontiers in Psychology*. <https://doi.org/10.3389/fpsyg.2013.00963>
- Ben Hedia, S., & Plag, I. (2017). Gemination and degemination in english prefixation: Phonetic evidence for morphological organization. *Journal of Phonetics*, 62, 34–49. <https://doi.org/10.1016/j.wocn.2017.02.002>
- Berg, K., Hartmann, S., & Claeser, D. (2023). Are some morphological units more prone to spelling variation than others? A case study using spontaneous handwritten data. *Morphology*, 34(2), 173–188. <https://doi.org/10.1007/s11525-023-09417-4>
- Berko-Gleason, J. (1958). The child's learning of english morphology. *Word*, 14, 150–177.
- Bertram, R., Tonnessen, F., Strömqvist, S., Hyönä, J., & Niemi, P. (2015). Cascaded processing in written compound word production. *Frontiers in Human Neuroscience*, 9, 207. <https://doi.org/10.3389/fnhum.2015.00207>
- Bonin, P., Méot, A., Lagarrigue, A., & Roux, S. (2015). Written object naming, spelling to dictation, and immediate copying: Different tasks, different pathways? *Quarterly Journal of Experimental Psychology*, 68(7), 1268–1294. <https://doi.org/10.1080/17470218.2014.978877>
- Booij, G. E. (1983). Principles and parameters in prosodic phonology. *Linguistics*, 21(1), 249–280. <https://doi.org/10.1515/ling.1983.21.1.249>
- Breadmore, H. L., & Deacon, S. H. (2019). Morphological processing before and during children's spelling. *Scientific Studies of Reading*, 23(2), 178–191. <https://doi.org/10.1080/10888438.2018.1499745>
- Bybee, J. (2001). *Phonology and language use*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511612886>
- Calderone, B., Celata, C., Korecky-Kröll, K., & Dressler, W. U. (2014). A computational approach to morphonotactics: Evidence from German. *Language Sciences*, 46, 59–70. <https://doi.org/10.1016/j.langsci.2014.06.007>
- Caramazza, A., & Hillis, A. E. (1989). The disruption of sentence production: Some dissociations. *Brain and Language*, 36(4), 625–650. [https://doi.org/10.1016/0093-934X\(89\)90091-6](https://doi.org/10.1016/0093-934X(89)90091-6)
- Caselli, N. K., & Cohen-Goldberg, A. M. (2014). Lexical access in sign language: A computational model. *Frontiers in Psychology*. <https://doi.org/10.3389/fpsyg.2014.00428>
- Cassani, G., Chuang, Y.-Y., & Baayen, R. H. (2020). On the semantics of nonwords and their lexical category. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 46(4), 621–637. <https://doi.org/10.1037/xlm0000747>

- Cassar, M., & Treiman, R. (1997). The beginnings of orthographic knowledge: Children's knowledge of double letters in words. *Journal of Educational Psychology*, 89(4), 631–644. <https://doi.org/10.1037/0022-0663.89.4.631>
- Chen, Q., & Mirman, D. (2012). Competition and cooperation among similar representations: Toward a unified account of facilitative and inhibitory effects of lexical neighbors. *Psychological Review*, 119(2), 417–430. <https://doi.org/10.1037/a0027175>
- Chuang, Y.-Y., Vollmer, M. L., Shafaei-Bajestan, E., Gahl, S., Hendrix, P., & Baayen, R. H. (2021). The processing of pseudoword form and meaning in production and comprehension: A computational modeling approach using linear discriminative learning. *Behavior Research Methods*, 53(3), 945–976. <https://doi.org/10.3758/s13428-020-01356-w>
- Clements, G. N., & Keyser, S. J. (1983). *CV phonology: A generative theory of the syllable*. MIT Press.
- Cohen-Goldberg, A. M. (2017). Informative differences: An Argument for a comparative approach to written, spoken, and signed language research. In S. Plane, B. Charles, F. Rondelli, C. Donahue, A. N. Applebee, & C. Boré (Eds.), *Research on writing: multiple perspectives* (pp. 457–476). The WAC Clearinghouse; CREM. <https://doi.org/10.37514/INT-B.2017.0919.2.25>
- Conijn, R., Roeser, J., & van Zaanen, M. (2019). Understanding the keystroke log: The effect of writing task on keystroke features. *Reading and Writing*, 32(9), 2353–2374. <https://doi.org/10.1007/s11145-019-09953-8>
- Damian, M. F. (2003). Articulatory duration in single-word speech production. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29(3), 416–431. <https://doi.org/10.1037/0278-7393.29.3.416>
- Davies, M. (2008–). *The corpus of contemporary American English (COCA): 560 million words, 1990-present*. Available at: <https://www.english-corpora.org/coca/>
- de Leeuw, J. R., Gilbert, R. A., & Luchterhandt, B. (2023). jsPsych: Enabling an open-source collaborative ecosystem of behavioral experiments. *Journal of Open Source Software*, 8(85), 5351. <https://doi.org/10.21105/joss.05351>
- Drager, K. K. (2011). Sociophonetic variation and the lemma. *Journal of Phonetics*, 39(4), 694–707. <https://doi.org/10.1016/j.wocn.2011.08.005>
- Feldman, L. B., Dale, R., & van Rij, J. (2019). Lexical and Frequency effects on keystroke timing: Challenges to a lexical search account from a type-to-copy task. *Frontiers in Communication*. <https://doi.org/10.3389/fcomm.2019.00017>
- Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47(6), 381–391. <https://doi.org/10.1037/h0055392>
- Fort, M., Martin, A., & Peperkamp, S. (2014). Consonants are more important than vowels in the Bouba-Kiki effect. *Language and Speech*, 58(2), 247–266. <https://doi.org/10.1177/0023830914534951>
- Frisson, S., & Sandra, D. (2002). Homophonic forms of regularly inflected verbs have their own orthographic representations: A developmental perspective on spelling errors. *Brain and Language*, 81(1), 545–554. <https://doi.org/10.1006/brln.2001.2546>
- Fuchs, S., & Krivokapić, J. (2016). Prosodic boundaries in writing: Evidence from a keystroke analysis. *Frontiers in Psychology*. <https://doi.org/10.3389/fpsyg.2016.01678>
- Gagné, C. L., & Spalding, T. L. (2016). Written production of english compounds: Effects of morphology and semantic transparency. *Morphology*, 26(2), 133–155. <https://doi.org/10.1007/s11525-015-9265-0>
- Gagné, C., Spalding, T. L., & Taikh, A. (2023). Impact of morphology on written word production: An overview of empirical evidence and theoretical implications. In D. Crepaldi (Ed.), *Linguistic Morphology in the Mind and Brain* (pp. 96–107). London: Routledge. <https://doi.org/10.4324/9781003159759>
- Gahl, S. (2008). Time and thyme are not homophones: The effect of lemma frequency on word durations in spontaneous speech. *Language*, 84(3), 474–496. <https://doi.org/10.1353/lan.0.0035>
- Gahl, S., & Plag, I. (2019). Spelling errors in english derivational suffixes reflect morphological boundary strength. *The Mental Lexicon*, 14(1), 1–36. <https://doi.org/10.1075/ml.19002.gah>
- Galbraith, D., & Baaijen, V. M. (2019). Aligning keystrokes with cognitive processes in writing. In E. Lindgren & K. Sullivan (Eds.), *Observing writing: Insights from keystroke logging and handwriting* (pp. 306–325). Leiden, The Netherlands: Brill. https://doi.org/10.1163/9789004392526_015
- Gontijo, P. F. D., Gontijo, I., & Shillcock, R. (2003). Grapheme—phoneme probabilities in British English. *Behavior Research Methods, Instruments, & Computers*, 35(1), 136–157. <https://doi.org/10.3758/BF03195506>

- Hay, J. B., & Baayen, R. H. (2005). Shifting paradigms: Gradient structure in morphology. *Trends in Cognitive Sciences*, 9(7), 342–348. <https://doi.org/10.1016/j.tics.2005.04.002>
- Hess, S., Mousikou, P., & Schroeder, S. (2022). Morphological processing in developmental handwriting production: Evidence from kinematics. *Reading and Writing*, 35(4), 899–917. <https://doi.org/10.1007/s11145-021-10204-y>
- Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, 45(3), 188–196. <https://doi.org/10.1037/h0056940>
- Jones, M. N., & Mewhort, D. J. K. (2004). Case-sensitive letter and bigram frequency counts from large-scale english corpora. *Behavior Research Methods, Instruments, & Computers*, 36(3), 388–396. <https://doi.org/10.3758/BF03195586>
- Kandel, S. (2023). Written production: The APOMI model of word writing: Anticipatory processing of orthographic and motor information. In R. J. Hartsuiker & K. Strijkers (Eds.), *Language Production* (pp. 209–232). Routledge. <https://doi.org/10.4324/9781003145790-9>
- Kandel, S., Alvarez, C. J., & Vallée, N. (2008). Morphemes also serve as processing units in handwriting production. In M. Baciú (Ed.), *Neuropsychology and cognition of language: Behavioural, Neuropsychological and neuroimaging studies of spoken and written language* (pp. 87–100). Research Signpost.
- Kandel, S., Peereman, R., & Ghimenton, A. (2013). Further evidence for the interaction of central and peripheral processes: The impact of double letters in writing english words. *Frontiers in Psychology*, 4, 729. <https://doi.org/10.3389/fpsyg.2013.00729>
- Kandel, S., & Perret, C. (2015). How does the interaction between spelling and motor processes build up during writing acquisition? *Cognition*, 136, 325–336. <https://doi.org/10.1016/j.cognition.2014.11.014>
- Kemps, R. J. J. K., Ernestus, M., Schreuder, R., & Baayen, R. H. (2005a). Prosodic cues for morphological complexity: The case of dutch plural nouns. *Memory & Cognition*, 33(3), 430–446. <https://doi.org/10.3758/BF03193061>
- Kemps, R. J. J. K., Wurm, L. H., Ernestus, M., Schreuder, R., & Baayen, H. (2005b). Prosodic cues for morphological complexity in dutch and english. *Language and Cognitive Processes*, 20(1–2), 43–73. <https://doi.org/10.1080/01690960444000223>
- Kiparsky, P. (1982). Lexical morphology and phonology. In I.-S. Yang (Ed.), *Linguistics in the morning calm: selected papers from SICOL* (pp. 3–91). Seoul: Hanshin.
- Klatt, D. H. (1975). Vowel lengthening is syntactically determined in a connected discourse. *Journal of Phonetics*, 3(3), 129–140. [https://doi.org/10.1016/S0095-4470\(19\)31360-9](https://doi.org/10.1016/S0095-4470(19)31360-9)
- Köhler, W. (1929). *Gestalt psychology*. New York, NY: Liveright.
- Lambert, E., & Quémart, P. (2019). *Introduction to the special issue on the dynamics of written word production: Methods. Models and Processing Units: Reading and Writing*. <https://doi.org/10.1007/s11145-018-9929-3>
- Levelt, W. J. M. (1993). Speaking: From intention to articulation. *The MIT Press*. <https://doi.org/10.7551/mitpress/6393.001.0001>
- Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, 22(1), 1–38. <https://doi.org/10.1017/S0140525X99001776>
- Libben, G. (2020). What can we learn from novel compounds? In S. S. Walde & E. Smolka (Eds.), *The role of constituents in multiword expressions: An interdisciplinary, cross-lingual perspective* (pp. 107–127). Berlin: Language Science Press.
- Libben, G., Jarema, G., Derwing, B., Riccardi, A., & Perlak, D. (2016). Seeking the -ational in derivational morphology. *Aphasiology*, 30(11), 1304–1324. <https://doi.org/10.1080/02687038.2016.1165179>
- Libben, G., & Weber, S. (2014). Semantic transparency, compounding, and the nature of independent variables. In F. Rainer, W. U. Dressler, F. Gardani, & H. C. Luschützky (Eds.), *Morphology and meaning* (pp. 205–222). Benjamins.
- Logan, G. D., & Crump, M. J. C. (2011). Hierarchical Control of Cognitive Processes. The Case for Skilled Typewriting. *Psychology of Learning and Motivation - Advances in Research and Theory*, 54, 1–27. Elsevier Inc <https://doi.org/10.1016/B978-0-12-385527-5.00001-2>
- Logan, G. D. (2018). Automatic control: How experts act without thinking. *Psychological Review*, 125(4), 453–485. <https://doi.org/10.1037/rev0000100>
- Lohmann, A. (2018). Time and thyme Are NOT homophones: A closer look at Gahl's work on the lemma frequency effect including a reanalysis. *Language*. <https://doi.org/10.1353/lan.2018.0032>

- Mohanan, K. P. (1986). Lexical phonology and psychological reality. In K. P. Mohanan (Ed.), *The theory of lexical phonology* (pp. 182–204). Dordrecht: Springer, Netherlands.
- Muschalik, J., & Kunter, G. (2023). Do letters matter? The influence of spelling on acoustic duration. *Phonetica*, 81(2), 221–264. <https://doi.org/10.1515/phon-2023-0012>
- Nespor, M., & Vogel, I. (2007). *Prosodic phonology. With a new foreword*. Berlin, Boston: De Gruyter Mouton. <https://doi.org/10.1515/9783110977790>
- Nottbusch, G., Grimm, A., Weingarten, R., & Will, U. (2005). Syllabic structures in typing: Evidence from deaf writers. *Reading and Writing*, 18(6), 497–526. <https://doi.org/10.1007/s11145-005-3178-y>
- Ostry, D. J. (1983). Determinants of interkey times in typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 225–246). New York, NY: Springer, New York.
- Pinet, S., & Nozari, N. (2018). ‘Twisting fingers’: The case for interactivity in typed language production. *Psychonomic Bulletin & Review*, 25(4), 1449–1457. <https://doi.org/10.3758/s13423-018-1452-7>
- Pinet, S., Ziegler, J. C., & Alario, F.-X. (2016). typing is writing: Linguistic properties modulate typing execution. *Psychonomic Bulletin & Review*, 23(6), 1898–1906. <https://doi.org/10.3758/s13423-016-1044-3>
- Plag, I., Homann, J., & Kunter, G. (2017). Homophony and morphology: The acoustics of word-final S in english. *Journal of Linguistics*, 53(1), 181–216. <https://doi.org/10.1017/S002226715000183>
- Purcell, J., Turkeltaub, P., Eden, G., & Rapp, B. (2011). Examining the central and peripheral processes of written word production through meta-analysis. *Frontiers in Psychology*, 2, 239. <https://doi.org/10.3389/fpsyg.2011.00239>
- R Core Team. (2023). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Rapp, B., & Fischer-Baum, S. (2014). Representation of orthographic knowledge. In M. Goldrick, V. S. Ferreira, & M. Miozzo (Eds.), *The oxford handbook of language production* (pp. 338–357). Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780199735471.013.026>
- Rapp, B., Fischer-Baum, S., & Miozzo, M. (2015). Modality and morphology: What we write may not be what we say. *Psychological Science*, 26(6), 892–902. <https://doi.org/10.1177/0956797615573520>
- Ravid, D. D. (2012). The psycholinguistics of spelling: Phonology and beyond. In D. D. Ravid (Ed.), *Spelling morphology: The psycholinguistics of hebrew spelling* (pp. 21–39). Boston, MA: Springer, US.
- Roelofs, A. P., & Ferreira, V. (2019). The Architecture of speaking. In P. Hagoort (Ed.), *Human language: From genes and brains to behavior* (pp. 35–50). MIT Press.
- Roeser, J., De Maeyer, S., Leijten, M., & Van Waes, L. (2024). Modelling typing disfluencies as finite mixture process. *Reading and Writing*, 37(2), 359–384. <https://doi.org/10.1007/s11145-021-10203-z>
- Roux, S., McKeeff, T. J., Grosjacques, G., Afonso, O., & Kandel, S. (2013). The interaction between central and peripheral processes in handwriting production. *Cognition*, 127(2), 235–241. <https://doi.org/10.1016/j.cognition.2012.12.009>
- Sahin, N. T., Pinker, S., Cash, S. S., Schomer, D., & Halgren, E. (2009). sequential processing of lexical, grammatical, and phonological information within Broca’s area. *Science*, 326(5951), 445–449. <https://doi.org/10.1126/science.1174481>
- Sandra, D. (2010). Homophone dominance at the whole-word and sub-word levels: Spelling errors suggest full-form storage of regularly inflected verb forms. *Language and Speech*, 53(3), 405–444. <https://doi.org/10.1177/0023830910371459>
- Sandra, D., Frisson, S., & Daems, F. (1999). Why simple verb forms can be so difficult to spell: The influence of homophone frequency and distance in dutch. *Brain and Language*, 68(1–2), 277–283. <https://doi.org/10.1006/brln.1999.2108>
- Scaltritti, M., Arfé, B., Torrance, M., & Peressotti, F. (2016). Typing pictures: Linguistic processing cascades into finger movements. *Cognition*, 156, 16–29. <https://doi.org/10.1016/j.cognition.2016.07.006>
- Schmitz, D., & Esser, J. (2021). *SfL: Statistics for Linguistics*. R package version 0.4.2. URL: <https://github.com/dosc91/SfL>
- Schmitz, D., & Baer-Henney, D. (2024). Morphology renders homophonous segments phonetically different: Word-final /s/ in German. In: *Proceedings of Speech Prosody*
- Schmitz, D., Baer-Henney, D., & Plag, I. (2021a). The duration of word-final /s/ differs across morphological categories in english: Evidence from pseudowords. *Phonetica*, 78(5–6), 571–616. <https://doi.org/10.1515/phon-2021-2013>

- Schmitz, D., Cicek, D., Nguyen, A. K., & Rottleb, D. (2023). Cuteness modulates size sound symbolism at its extremes. *Open Linguistics*. <https://doi.org/10.1515/opli-2022-0257>
- Schmitz, D., Plag, I., Baer-Henney, D., & Stein, S. D. (2021b). Durational differences of word-final /s/ emerge from the lexicon: Modelling morpho-phonetic effects in pseudowords with linear discriminative learning. *Frontiers in Psychology*. <https://doi.org/10.3389/fpsyg.2021.680889>
- Schmitz, T., Chamalaun, R., & Ernestus, M. (2018). The Dutch verb-spelling paradox in social media. *Linguistics in the Netherlands*, 35(1), 111–124. <https://doi.org/10.1075/avt.00008.sch>
- Seyfarth, S., Garellek, M., Gillingham, G., Ackerman, F., & Malouf, R. (2018). Acoustic differences in morphologically-distinct homophones. *Language, Cognition and Neuroscience*, 33(1), 32–49. <https://doi.org/10.1080/23273798.2017.1359634>
- Spiro, W. W., & MacRae, P. G. (1990). Motor performance and aging. *Handbook of the psychology of aging* (3rd ed., pp. 183–200). San Diego, CA, US: Academic Press.
- Sternberg, S. (2001). Separate modifiability, mental modules, and the use of pure and composite measures to reveal them. *Acta Psychologica*, 106(1), 147–246. [https://doi.org/10.1016/S0001-6918\(00\)00045-7](https://doi.org/10.1016/S0001-6918(00)00045-7)
- Suárez-Coalla, P., Martínez-García, C., & Cuetos, F. (2017). Morpheme-based reading and writing in Spanish children with dyslexia. *Frontiers in Psychology*, 8, 1952. <https://doi.org/10.3389/fpsyg.2017.01952>
- Tomaschek, F., Hendrix, P., & Baayen, R. H. (2018). Strategies for addressing collinearity in multivariate linguistic data. *Journal of Phonetics*, 71, 249–267. <https://doi.org/10.1016/j.wocn.2018.09.004>
- Tomaschek, F., Plag, I., Ernestus, M., & Baayen, R. H. (2021). Phonetic effects of morphology and context: Modeling the duration of word-final S in english with naïve discriminative learning. *Journal of Linguistics*, 57(1), 123–161. <https://doi.org/10.1017/S0022226719000203>
- Torrance, M., & Conijn, R. (2024). Methods for studying the writing time-course. *Reading and Writing*, 37(2), 239–251. <https://doi.org/10.1007/s11145-023-10490-8>
- Treiman, R., Decker, K., Kessler, B., & Pollo, T. C. (2015). Variation and repetition in the spelling of young children. *Journal of Experimental Child Psychology*, 132, 99–110. <https://doi.org/10.1016/j.jecp.2014.12.008>
- Treiman, R., Wolter, S., & Kessler, B. (2018). Phonological and graphotactic influences on spellers' decisions about consonant doubling. *Memory & Cognition*, 46(4), 614–624. <https://doi.org/10.3758/s13421-018-0793-9>
- Treiman, R., Wolter, S., & Kessler, B. (2021). How sensitive are adults to the role of morphology in spelling? *Morphology*, 31(3), 261–271. <https://doi.org/10.1007/s11525-020-09356-4>
- van de Vijver, R., & Baer-Henney, D. (2014). Developing biases. *Frontiers in Psychology*. <https://doi.org/10.3389/fpsyg.2014.00634>
- Vannest, J., Newport, E. L., Newman, A. J., & Bavelier, D. (2011). Interplay between morphology and frequency in lexical access: The case of the base frequency effect. *Brain Research*, 1373, 144–159. <https://doi.org/10.1016/j.brainres.2010.12.022>
- Weingarten, R., Nottbusch, G., & Will, U. (2004). Morphemes, syllables and graphemes in written word production. In T. Pechmann & C. Habel (Eds.), *Multidisciplinary approaches to language production* (pp. 529–572). Berlin, New York: De Gruyter Mouton. <https://doi.org/10.1515/9783110894028.529>
- Wightman, C. W., Shattuck-Hufnagel, S., Ostendorf, M., & Price, P. J. (1992). Segmental durations in the vicinity of prosodic phrase boundaries. *The Journal of the Acoustical Society of America*, 91(3), 1707–1717. <https://doi.org/10.1121/1.402450>
- Will, U., Nottbusch, G., & Weingarten, R. (2006). Linguistic units in word typing. *Written Language & Literacy*, 9(1), 153–176. <https://doi.org/10.1075/wll.9.1.10wil>
- Wood, S. N. (2017). *Generalized additive models: An introduction with R, second edition* (2nd ed.). Boca Raton: Chapman and Hall/CRC. <https://doi.org/10.1201/9781315370279>
- Yamaguchi, M., Randle, J. M., Wilson, T. L., & Logan, G. D. (2017). Pushing typists back on the learning curve: Memory chunking improves retrieval of prior typing episodes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43(9), 1432–1447. <https://doi.org/10.1037/xlm0000385>

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