Flow in mind, flow in fingers: Parallelism in written language production

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Abstract

Language production is known to operate on different levels of representation. "Flow" in writing results from parallelism in the coordination of subsequent planning units. In this article we discuss three points arising from Roeser, Conijn et al. (2025): (1) parallel processing results in non-additive effects, (2) study of the production of multisentence texts permits testing of questions around how language production is coordinated in real time, and, more generally, (3) statistical models must closely align with what we know about the cognitive process of what is being studied.

Keywords: Language production; writing; parallel planning; mixture models

In "Typing in tandem: Language planning in multisentence text production is fundamentally parallel" published in the *Journal of Experimental Psychology: General* (Roeser, Conijn et al., 2025) we propose that the mental preparation of language in the unconstrained production of multisentence texts unfolds in parallel to production. We suggest that the common experience of "flow" in competent writers, where ideas seem to emerge relatively effortlessly while typing, results from a fundamental parallelism in these mental processes. This work is the first robust empirical evidence for parallelism in written composition and aligns with theories of spoken language production.

More specifically we challenged the traditional understanding of planning in written language production as a serial process, and argue for a fundamentally parallel model. Our hypothesis was that planning of upcoming text in writing does not unfold as a series of writing pauses, during which next-text is prepared, and bursts of production, during which planned text is output (Flower & Hayes, 1980; Hayes, 2012). Instead by default our mind prepares the message and language of what to say next in parallel with previous output.

Using keystroke logging data from six datasets—from children, adults, L1 and L2 writers, in various languages, and with various writing tasks—we analysed the time between consecutive keystrokes (interkey intervals) in a series of Bayesian models. Under the serial account, planning is a sequential process, occurring only during hesitations in execution. Therefore, the duration of interkey intervals is directly explained by the time needed to generate the next piece of information before output can resume. This is consistent with observations that interkey intervals are typically longer before larger linguistic units, such as sentences, compared to words or mid-word keypresses, as more planning (message and syntax) is assumed to be required for these larger units (Torrance et al., 2016; Wengelin, 2002). In contrast, the parallel account suggests that planning for the next text segment occurs concurrently with the execution of the preceding text. As a consequence of this parallelism, interkey intervals arise from two distinct processes: fluent motor execution and upstream cognitive

planning that occasionally causes hesitations. Under this view, pauses are more *likely* to occur at larger linguistic edges, but this will not necessarily be the case. Separating out these two accounts requires going beyond methods that simply estimate mean differences in inter-keystroke intervals.

We therefore compared two general statistical models: a single-distribution model consistent with serial processing, and a two-distribution mixture model representing parallel processing. Across all datasets the mixture model consistently outperformed single-distributions models in predictive performance. Importantly, interkey intervals at sentence and word boundaries were frequently too short to reflect extensive advance planning of upcoming linguistic information suggesting that planning often occurs in parallel with ongoing execution. Interestingly, even young writers and L2 learners showed patterns consistent with parallel processing.

There are three lessons to be learned from this paper that we present in the remainder of this review.

Parallel processing leads to non-additive effects

The idea of parallelism in language production—that the mind plans the next text unit simultaneously with the execution of the preceding text—aligns with the "just-in-time" principle long established for speech production (Christiansen & Chater, 2016). For writing, Van Galen (1991) proposed a modular model of handwriting in which processing at different representational levels (semantic, syntactic, motor) is buffered and initiated as soon as upstream input becomes available. Olive (2014) extended this to typing, arguing that planning and execution are coordinated in a parallel fashion with transient storage allowing asynchronous flow between levels. Importantly, what influences the time course of the language output is the coordination between processing levels, not an additive relationship between them.

How does parallelism work in writing? Writing is typically understood as involving a sequence of mental operations moving from higher-level conceptual planning to lower-level motor execution. These levels are hierarchically organised, with conceptual (idea generation), linguistic (syntactic structuring, lexical retrieval), and motor (handwriting or typing) processes. Each of these levels has a planning unit with a minimal required scope that is likely to depend on the level of processing. Language can in principle be prepared for full sentences. However the minimal unit that is required to onset a sentence is smaller and might be a clause / proposition on the meaning level, the first phrase on a syntactic level, the first content word on the lexical level, and the first word on the phonological level (Bock & Ferreira, 2014; Wheeldon & Konopka, 2023). The coordination of planning stages for subsequent planning units can either be thought of as serial or parallel.

In a parallel system, information flows continuously from central (higher) to peripheral (lower) processes. This information flow can be "cascading", meaning that information flows to the next processing stage immediately, or "stacked", meaning that the system waits until planning is complete at the current level before it is available to the next. Different levels of processing can operate simultaneously on different segments of text. For example, lexical planning for upcoming words typically happens simultaneously with output. Writers only hesitate if upcoming lexical information cannot be planned in parallel (Roeser, Aros Muñoz & Torrance, 2025; Rønneberg et al., 2022). In speaking, there is additional pressure to plan in parallel (Griffin, 2003) because hesitation affects communication. Transient storage ("buffers") temporarily holds information from upstream

processes until downstream processes are ready for input. As different modules operate at varying speeds, these buffers are necessary to allow for unsynchronised output ("time friction") without a complete interruption of the overall process.

An important implication of parallel processing in language production is that, in the context of a sequence of actions, effects on interkey intervals are non-additive. In a serial model, cognitive processes—message generation, lexical retrieval, syntactic planning, orthographic encoding, motor execution—can only start once the previous processing unit is completed. Consequently, the duration of an observable behavior (e.g. an interkey interval) is the sum of the time taken by each process. For example, at a sentence boundary, the interkey interval would reflect the additive time required to plan the message, retrieve the first word, encode its spelling, and prepare the motor action.

By contrast, in a parallel model, planning of the next unit of text begins while the previous unit is still being executed. As a result, the duration of an interkey interval is not a simple sum of upstream and downstream processes. If higher-level planning processes produce information at a rate equal to, or faster than, motor execution can use it, then interkey intervals are determined just by the time needed for finger movements (motor execution). However, with some caveats, if there is a delay in the upstream planning processes the interkey interval will be determined just by the time needed to finish the higher-level processing and is independent of time for motor execution. Given this, interkey intervals come from two independent—non-additive—data-generating processes: one associated with fluent motor execution (short intervals) and another associated with delays caused by higher-level processing ("hesitant" intervals). This distinction is captured in the two-component mixture model used by Roeser, Conijn et al. (2025).

The presence of a large proportion of very short interkey intervals even at sentence boundaries—where content and syntactic planning planning would be expected—reported in Roeser, Conijn et al. (2025) is strong evidence against additivity (see also Rønneberg et al., 2022). These intervals are too brief to plausibly include all necessary planning steps and can only be explained if planning operates in parallel with prior execution.

Language theories need to accommodate planning in continuous production

Theories of cognitive mechanisms in language production—and how they are coordinated—must be constrained by what actually happens during continuous production moving beyond the traditional focus on how single-word or single-sentence utterances are planned before production onset (Roeser, Torrance & Baguley, 2025; Roeser et al., 2019; Torrance & Nottbusch, 2012; Torrance et al., 2018).

How language planning is coordinated in real time has received attention in research on spoken conversation (see Brown-Schmidt & Konopka, 2011; Pickering & Garrod, 2007, 2013). A central insight from this research has a notable parallel to our findings on multisentence text production. In spoken conversation, listeners actively start preparing their utterance while the interlocutor is still speaking. This overlap of comprehension and production processes is essential for the remarkable speed of turn-taking, where gaps between turns average around 200 milliseconds. Such rapid responses would be impossible if a speaker had to wait for the interlocutor to finish, fully comprehend the utterance, and then plan their response.

As we have argued, a similar parallelism can be found for multisentence text production. In Roeser, Conijn et al. (2025) we report that many—around 50%—interkey intervals at word and sentence boundaries, are too brief—around 150 milliseconds (see also Conijn et al., 2019)—to reflect advance planning of lexical and syntactic information[1] suggesting that planning is occurring "just-in-time". So in multisentence text production writers often produce language fluently and with minimal hesitation, even at points where traditional theories of language production (Wheeldon & Konopka, 2023) would predict significant planning effort if produced in isolation (e.g. before sentences or at word boundaries). In Roeser, Conijn et al. (2025) we show that planning is distributed across time, overlapping with execution, and not confined to discrete pauses. This is a "just-in-time" principle similar to what has been established in speech production (Christiansen & Chater, 2016).

This perspective on writing highlights the contrast with traditional experimental work. Specifically psycholinguistic research investigating language production has often focused on planning prior to utterance onset in experimental tasks that elicit single words, phrases or utterances in response to pictorial stimuli (Wheeldon & Konopka, 2023). Tasks that focus on utterance-initial planning create conditions that appear to support a serial view by limiting the opportunities for parallel processing. For example, it is frequently assumed that processing of the first syntactic phrase (Martin et al., 2010) and some lexical information (Wheeldon et al., 2013) must be completed before output onset. In Roeser et al. (2019) we suggest that syntactic planning of the initial phrase is obligatory and modality-independent but lexical retrieval for non-initial nouns within that phrase can be delayed until after production onset (for an alternative view of sentence-initial planning of syntax see Roeser, Torrance et al., 2024).

We are, of course, not arguing against the value of experimental study of the written production of words or phrases. Our point is just that the parallelism that occurs during unconstrained, multi-sentence production means that restricting study just to very constrained tasks misses important, fundamental features of how the cognitive mechanisms responsible for text production are arranged and interact. Keystroke logging allows insights into how cognitive processes unfold across time moment-by-moment. This is important because contemporary models of written word production (Kandel, 2023) acknowledge that orthographic representations for words are incomplete at writing onset (see Roeser, Aros Muñoz & Torrance, 2024, for empirical evidence). Happily, keystroke logging is a particularly easy way to collect real-time language production data and can inform questions about language production that cannot easily be addressed in speech (Pinet, 2025). This is because timecourse information about the unfolding production process are not easily available for spoken language production (Konopka, 2019; Roeser et al., 2019).

Hypothesis testing needs to go beyond differences in means

Theory testing in the context of language production requires thinking about effects on distributions, not just changes in means. In cognitive psychology—and particularly in language production research—hypothesis testing has traditionally focused on differences in means between conditions.

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[1]For context, neural oscillations associated with keystrokes occur approximately every 153 milliseconds (Duprez et al., 2021); in contrast, the time from stimulus to typing onset is distributed around roughly 1 second for single-noun responses (Torrance et al., 2018) and simple sentences (Roeser et al., 2019).

This approach can obscure the underlying cognitive mechanisms when those mechanisms affect not the central tendency of a distribution, but its shape, spread, or frequency of extreme values. In Roeser, Conijn et al. (2025)—and also Chukharev et al. (2025), Roeser, De Maeyer et al. (2024), Roeser, Torrance et al. (2024), Van Waes et al. (2021)—we highlighted the importance of a close mapping between the theoretically assumed cognitive mechanisms that generate responses and the assumptions implemented in the statistical models used for inference.

Research on language production, including the analysis of keystroke data in writing, has often used single-distribution statistical models (ANOVA, linear mixed-effects models) that assume a single underlying data-generating process and typically report a single mean and a measure of dispersion to represent the central tendency of response latencies within a specific experimental condition. There are three fundamental problems with this approach:

First, summary statistics can result in a loss of crucial information about timecourse variations, such as disfluencies. For example keystroke data are not normally distributed; they are typically heavily right-tailed because typing speed is restricted by motor planning time but pauses can, in principle, have no upper bound. A single mean in such a distribution represents the average, but fails to capture where the majority of data points are located, leading to biased estimates and potentially incorrect inferences about the writing process. Second, pause frequencies and writing bursts—sometimes used to assess writing performance—rely on arbitrary pause criterion thresholds (often set at 2 seconds) to distinguish fluent from hesitant periods (Wengelin, 2001, 2006). These fixed thresholds fail to account for individual differences in typing skill, task, or the specific location of the keystroke transition, leading to potential misclassifications. Third, the reliance on mean differences in single-distribution models implicitly supports a serial account of language production. Under this view, longer mean interkey intervals before larger linguistic units (words, sentences) are seen as direct evidence of additive planning time for message, syntax, and lexical retrieval. A single-distribution model will obscure data when averaging across hesitant and non-hesitant responses or interkey intervals.

The same general principle applies in any case where an experimental manipulation may or may not affect performance for a particular participant on a particular trial. More often than not the expected effect will not be that response time will increase by a small amount for all participants, but rather that a higher proportion of participants will take substantially longer to respond than would be expected in a control condition (for a similar argument see Bolger et al., 2019). In other words, data is a mixture of distributions for when participants were and were not affected by manipulation, and test of hypothesis is not an average across these, but the relative size of each distribution.

Bayesian mixture models (Roeser, Conijn et al., 2025; Roeser, De Maeyer et al., 2024) are a principled approach to address these issues and better align statistical analysis with cognitive theory. The main point in Roeser, Conijn et al. (2025) is that parallel processing in multisentence text production leads to a mixture of two underlying data-generating processes: one associated with fluent, uninhibited activation flow into motor programs (short intervals) and another capturing interruptions or delays from higher-level cognitive processes (longer, hesitant intervals). The cognitive coordination between planning units is reflected in the frequency of hesitant intervals, not the mean interkey interval. Also, we demonstrated that mixture models can capture and control for individual difference in writing speed and pausing behaviour ("typing style"; see Roeser, De Maeyer et al., 2024). Across different types of data from language production, we consistently found that

two-distribution mixture models outperformed single-distribution models, after controlling for over-fitting through cross-validation (Roeser, Conijn et al., 2025; Roeser, De Maeyer et al., 2024; Roeser, Torrance et al., 2024; Van Waes et al., 2021). Similar approaches have been used to test for the non-additivity of effects in reading comprehension (Lissón et al., 2023; Vasishth, Chopin et al., 2017; Vasishth, Jäger & Nicenboim, 2017; Vasishth et al., 2019). For examples of other domains of cognition see for example Spivey et al. (2005), and Fischer and Weber (1993, cited in Farrell & Lewandowsky, 2018, p. 113–114).

Conclusion

In this review we made three main points: First, the non-additive nature of parallel processing challenges the assumption that pauses or latencies directly reflect planning effort. Instead, fluency emerges from overlapping processes that are dynamically aligned. This is true in written production, but also across any other situation where the next action is planned inline with current output. Second, looking beyond the production onset in natural multisentence contexts provides interesting avenues to study the coordination of language production in real time (similar to conversation Pickering & Garrod, 2013). Third, theory tests must move beyond simple comparisons of means in single-distribution models. Statistical techniques like Bayesian mixture models allow the implementation of cognitively plausible statistical models of real-time dynamics of language production.

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