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### **The scope of planning serial actions during typing**

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### Abstract

Human activities consisting of multiple component actions require the generation of ordered sequences. This article investigates the scope of response planning in highly serial task, typing, by means of event-related potentials indexing motor response preparation. Specifically, we compared motor-related ERPs yielded by words typed using a single hand, against words that had all keystrokes typed with a single hand except for a deviant one, typed with the opposite hand. The deviant keystroke occurred either early in the typed sequence, corresponding to the second or third letters, or late, corresponding to the penultimate or last letter. Motor-related ERPs detected before response onset were affected only by deviant keystrokes located at the beginning of the sequence, whereas deviant keystrokes located at the end yielded ERPs that were undistinguishable from uni-manual responses. These results impose some constraints on the notion of parallel processing of component actions.

## Introduction

Many human activities consist of multiple component actions assembled into ordered sequences. Many of these can be performed with remarkable speed and efficiency (Cooper & Schallice, 2006; Botvinick & Plaut, 2004). Parallel processing of these multiple components has been considered important in achieving skilled performance (Lashley, 1951). The parallel, i.e. simultaneous, processing of multiple component actions considerably reduces the overall processing time. It is thus considered that parallel processing represents a key feature for complex, skilled behaviors.

Typewriting is a complex activity involving multiple component actions, the keystrokes, governed by corresponding motor-programs (motor schemata, Rumelhart & Norman, 1982) and assembled in ordered sequences. The prevalence of typing, particularly in the younger population, and its exploitability in laboratory settings make it a valuable resource to address issues related to skilled performance (Logan & Crump, 2011). In an effort to clarify the scope of parallel activation for motor programs in skilled performance, in this article we exploit electroencephalographic event-related potentials (ERPs) indexing motor-response preparation and examine the planning of the sequence of keystrokes in typing.

Extant literature provides some evidence that typing relies on the parallel processing of its constituent actions, i.e. keystrokes. Crump and Logan (2010) presented participants with a prime-word followed by a single letter target, and asked them to read the prime-word and to type the target letter. Participants were faster in typing the target letter when it was part of the word-prime, compared to when it was not, suggesting that, despite not being typed, the prime word pre-activated its constituent keystrokes. Importantly, this priming effect was reliable and similar irrespective of whether the target-letter corresponded to an initial, middle, or final letter of the prime word. This indicated that all the letters in the prime pre-activated the corresponding keystrokes to similar extents, irrespective of their serial position.

Evidence from EEG indexes of motor-response preparation is also consistent with parallel processing of keystrokes in typing. The lateralized readiness potential (LRP; e.g., Coles, 1989) is an event-related potential (ERP) recorded above the motor cortices and that captures motor-related activations. The LRP is usually computed in tasks requiring left vs. right hand responses by subtracting ERP's ipsilateral and contralateral to the effector, thus capturing the lateralization of electrophysiological activity generated by the activation of a specific response hand (Kutas & Donchin, 1980; Masaki, Wild-Wall, Sangals, Sommers, 2004). Logan, Miller, and Strayer (2011) measured the amplitude of the LRP time-locked to the first keystroke of typed responses. The amplitude was largest when all the keystrokes of a given word were typed with the same hand, and it decreased as a function of the total number of keystrokes within the word that were typed with the opposite hand (i.e. *deviant keystrokes*). This suggested that motor programming occurring before response onset encompasses all the keystrokes within a word. It is important to note that such LRP modulations, however, do not clarify whether their origin lies in motor cortices ipsi- or contralateral to the effector, or in both. As we will point out below, this distinction can be important to elucidate the functional interpretation of these effects.

Parallel activation, moreover, is not sufficient to drive typing. Typists need to retrieve programs for multiple keystrokes but also to combine them in ordered sequences. For example, in the seminal model of typing (Rumelhart & Norman, 1982), serial order is achieved via inhibition between the different keystrokes, with earlier keystrokes inhibiting

the following ones. After being typed, the keystroke is deactivated, and the next one, released from inhibition, becomes the most active. Serial order is thus established in the form of graded activation within a competitive queuing framework (Behmer & Crump, 2017).

In the present article, we investigate the balance between these postulated activation and inhibition of component actions that drive serial ordering during typing. If all keystrokes are programmed in parallel and inhibited as a function of their order in the sequence, then, during response preparation, earlier keystrokes should be more active than later ones. This prediction regarding the scope of parallel processing is operationalized in a test where we investigated if, prior to the onset of the first keystroke, the activation for subsequent keystrokes differs as a function of whether they occur earlier vs. later in the sequence. The answer to this question will come from a thorough analysis of ERPs elicited during a typing task where, instead of manipulating the number of keystrokes typed with either hand (Logan et al., 2011), we manipulated their position within the word.

As in Logan et al (2011), the LRP time locked to the first keystroke should be largest for uni-manual responses, compared to those including a deviant keystroke, that is, a keystroke typed with the opposite hand compared to the one used to type all the other keystrokes. If the EEG asymmetry captured by the LRP reflects the difference in activation between the two hands (Logan et al., 2011), the critical point is whether this difference will decline with the distance at which deviant keystrokes are located within the sequence. A simple parallel account, where all the keystrokes are equally activated before response onset, predicts that the LRP amplitude would be smaller compared to uni-manual responses irrespective of the location of the deviant keystroke. In contrast, an account where keystrokes are activated in parallel but gradually as a function of their position (Rumelhart and Norman, 1982; Behmer and Crump, 2017) predicts that the LRP will be smaller for responses with deviant keystrokes at the beginning, rather than at the end, both being smaller than in uni-manual responses. Finally, if the scope of planning is shorter than a word then deviant keystrokes at the end of the sequence should not modulate LRP amplitudes time-locked to the first keystroke, and thus uni-manual and late-deviant conditions should not differ.

Our analysis went beyond the simple computation of LRPs. We also explored the underlying pattern of motor-related ERPs given that, prior to the onset of a manual response, a negative potential surfaces over the motor cortex contralateral to the effector, and a positive potential unfolds over the ipsilateral one. Previous evidence suggests that the former reflects activation of the contralateral motor cortex triggering the response, whereas the latter indexes the inhibition of the ipsilateral motor cortex, instantiated to prevent erroneous response with the inappropriate hand (e.g. Burle, van den Wildenberg, Spieser, & Ridderinkhoff, 2016; Burle, Vidal, Tandonnet, & Hasbroucq, 2004; Meckler, Allain, Carbonnel, Hasbroucq, Burle, & Vidal, 2010; Tandonnet, Burle, Vidal, & Hasbroucq, 2003; Taniguchi, Burle, Vidal, & Bonnet, 2001; Vidal, Grapperon, Bonnet, & Hasbroucq, 2003).<sup>1</sup> These potentials can thus shed light on how the results observed at the level of the LRP are related to the activation and inhibition of the motor cortices.

## Experiment

The study received approval from the local Ethic Committee, filed under “ID RCB: 2011-A00562-39” at “Comite de Protection des Personnes Sud Méditerranée I” in Marseille, France.

## Method

**Participants.** Eighteen French native speakers were recruited. Sample size was estimated on the basis of previous evidence with a very similar paradigm (Logan et al.,

2011). Data from one participant were excluded, due to the low proportion of accurate responses (.46), leaving 17 participants in the final sample (12 females;  $M_{age} = 23.65$ ;  $SD_{age} = 3.18$ ). Their mean score at the Edinburgh Handedness Inventory (Oldfield, 1971) was 84.47 ( $SD = 18.21$ ), therefore they could be classified as right-handed. Before the experimental session, participants received detailed information and provided written informed consent. Typing skills were assessed using a typing test (Pinet, Hamamé, Longcamp, Vidal, & Alario, 2015), usually taking place in a separate session a few days before the experiment. Participants were admitted to the experimental phase only if they were touch-typists, that is only if they could type fluently, using all their fingers with a consistent and predictable finger-to-keystroke mapping, and without looking at their hands. Only one participant reported having attended a formal training in typing. Participation was compensated with 10€ per hour.

**Stimuli.** Three sets of 60 (for a total of 180) French words, all 7 letter long, served as experimental stimuli. They were selected based on the distribution of their keystrokes between the left and the right hand on a French standard AZERTY keyboard. The first set consisted of words requiring all the keystrokes to be typed with the left hand (Control condition, e.g., cascade). For the second set, words consisted of keystrokes typed with the left hand, except for one *deviant keystroke* typed with the right hand and corresponding either to the second or the third letter of the word (Early-deviant condition, e.g., cHarade). The third set included words for which all keystrokes had to be typed with the left hand, except for one deviant keystroke typed with the right hand, and corresponding either to the sixth or the seventh letter of the word (Late-deviant condition, e.g., cerveau). These three-set of items were matched for a series of relevant psycholinguistic variables, summarized in Table 1.

It was not possible to find enough 7-letter words exclusively typed with the right hand alongside the corresponding early- and late-deviant words (i.e. right hand for all letters but one). Still, it was important that within the experiment both hands were used in roughly similar proportions. For this reason, items typed (mostly) with the right hand were included as fillers. Specifically, a set of 111 6-, 7-, and 8-letter words were selected which included a maximum of 3 left-hand keystrokes. Fillers were excluded from the analyses.

There were no diacritical marks (“accents”) in the experimental nor in the filler items. In French, diacritical marks are typically not represented when writing in upper-case (as our participants did), and these words were excluded to prevent any potentially conflicting activation of multiple keystrokes for single characters (marked vs. unmarked) while typing. Additionally, words never included the letter *b* because previous research suggested that participants tended to type it inconsistently with the left and the right hands.

### **Apparatus and procedure.**

**Typing test.** Participants were seated in an armchair in front of a computer keyboard and a computer screen located at about 60 cm from them, in the same set-up later used for the experimental phase. Before the test began, participants were given time to familiarize with the keyboard and the setting. Typed responses were collected via a DirectIN PCB v2010 keyboard (Empirisoft) granting millisecond accuracy in keystroke timing data. The typing test consisted in copy-typing three texts of 611, 662, and 696 characters, spaces included. Each text was first presented on the screen in written format, and participants were invited to read it mentally. Afterwards, each text was divided in three separate parts, presented sequentially on the screen. Participants had to copy-type each part in turn. The text being typed was displayed online on the screen below the text to copy, as would happen during normal typing. Editing and self-corrections were allowed. Within each text, typing speed was calculated by dividing the number of words (normalized to 5 characters, Crump & Logan,

2010) correctly typed by the time elapsing between the first and the last keystroke. Accuracy was defined as the percentage of words with no errors or corrections. On average, participants typed 53 words per minute (SD = 12), with an average accuracy of .87 (SD = .04).

**Experiment.** Participants were installed as above, and were again given time to familiarize with the keyboard. The presentation of the stimuli and response acquisition were controlled using the software Presentation (NeuroBehavioral Systems). During the experiment, each trial started with a fixation cross with a duration of either 600, 700, 800, or 900 ms. The target word was then presented in lowercase at the center of the screen. Responses were displayed in uppercase on the screen as they were typed, slightly below the target stimulus. After 4000 ms from stimulus onset, the stimulus and the responses disappeared from the screen, and a blank screen lasting 1000 ms was presented before the next trial. All the stimuli appeared in black (RGB 0, 0, 0) on a light grey background (RGB 210, 210, 210) and were displayed in Times New Roman font (20 point size).

Participants were instructed to copy-type the single words appearing in written format on the computer screen. Speed and accuracy were equally emphasized. They were instructed to blink, if they felt the need, during the blank screen. These instructions were followed by 10 practice trials. Words presented in the practice phase were not part of the experimental or filler sets described before. The experimental phase consisted of 4 blocks of 58 trials, and a fifth one of 59. Stimuli were presented in pseudo-randomized lists where no more than 4 experimental items could be presented in a row. Across participants, lists were presented with trials in the reverse order.

**EEG recording and processing.** EEG was acquired from 64 Ag/AgCl active electrodes (BioSemi Active Two system) placed in the standard 10-20 positions, referenced to the CMS-DRL ground, with a sampling rate of 512 Hz (filters: DC to 104 Hz, 3 db/octave slope). Vertical and horizontal electro-oculograms were obtained with surface electrodes placed one below the left eye and two next to the two outer canthi. Signal processing was performed using MATLAB toolboxes EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon & Luck, 2014).

EEG data were re-referenced to the average of both mastoids, filtered (Order 6 Butterworth 0.1– 100 Hz cut-offs), and then segmented into epochs going from 300 ms before stimulus onset to 4000 ms after stimulus onset. Noisy electrodes were interpolated via spherical interpolation and a first artifact rejection was performed. ICA was then computed (algorithm: AMICA; Palmer, Makeig, Kreutz-Delgado, & Rao, 2008). Components corresponding to blinks were removed and a second artifact rejection was performed to exclude remaining noisy epochs. A baseline correction from -200 to 0 ms preceding the onset of the word stimulus was applied. Shorter epochs were finally extracted, both stimulus locked (-200 to 1000 ms, with 0 being the time of the target stimulus appearance) and response-locked (-600 to 200 ms, with 0 being the time of the first keystroke). Following previous works investigating typing with EEG (Pinet et al., 2015; Pinet, Dubarry, & Alario, 2016; Scaltritti, Pinet, Longcamp, & Alario, 2017) and choice reaction times tasks (e.g., Burle et al., 2004; Vidal et al., 2015), analyses were conducted on Laplacian-transformed epochs, to increase spatial resolution for scalp potentials (Babiloni et al., 2001), as well as the temporal and spatial differentiations of ERPs (Vidal et al., 2015). This was done with the spline interpolation method (Perrin, Pernier, Bertrand, & Echallier, 1989) as implemented by Cohen (2014; order of splines = 4; maximal degree of Legendre polynomial = 10; lambda parameter =  $10^{-5}$ ).

Stimulus- and response-locked LRPs were computed by subtracting the ERPs recorded above the motor cortex ipsilateral to the responding hand (C3, as the first keystroke of experimental items was always typed using the left-hand) from the one recorded over the contralateral one (C4).

**Statistical analysis.** Only trials featuring correct responses for experimental stimuli were considered in the analyses. Epochs corresponding to these trials were averaged within conditions and within participants, and the resulting averages were submitted to cluster-based permutation analyses (Maris & Oostenveld, 2007) with an alpha level of .05 implemented via the MATLAB toolbox MASS UNIVARIATE ERP (Groppe, Urbach, & Kutas, 2011). This method was selected to control for family-wise error rate when testing differences between conditions at each time-point and within each electrode. At each time-point, a paired t-test is performed between the two conditions under examination. Values of  $t$  above a pre-determined threshold ( $p < .05$ ) are then grouped into clusters based on spatial and temporal adjacency.<sup>2</sup> For each cluster, the sum of all the  $t$  statistics is used to determine the cluster-level statistics. Cluster  $p$ -values are calculated under a null distribution of the test statistics generated via permutations by randomly re-assigning samples across conditions (2500 permutations in the present analyses). Specifically, the  $p$ -values for the cluster is determined by the proportion of permutations that yields a larger test statistics compared to the observed one (Groppe et al., 2011; Maris & Oostenveld, 2007).

## Results

**Behavioral data.** There was no significant effect of condition on the accuracy ( $F [2, 32] = 1.53, p > .23$ ). The effect was instead significant on response times ( $F [2, 32] = 3.48, p = .04$ ), the time elapsing from the onset of the stimulus until the first keystroke. Pairwise comparisons suggest that words in the Early-deviant condition yielded slower reaction times compared to the Late-deviant condition ( $t [16] = 2.67, p = .02$ ) and to the Control condition, albeit this latter comparison just approached conventional significance ( $t [16] = 1.78, p = .09$ ). There was no difference between the Late-deviant and the Control conditions ( $t < 1$ ).

**Stimulus-locked EEG data.** The LRP for the Early-deviant condition was significantly smaller than in the Control (one negative cluster,  $p = .001$ ) or in the Late-deviant conditions (one negative cluster,  $p < .001$ ), whereas no difference surfaces between the latter two (all clusters'  $p$ 's  $> .74$ ; Figure 1, upper half).

Moving to the analysis of the whole set of electrodes, the contrast between the Control and the Early-deviant condition reveals a significant positive cluster over the left hemisphere ( $p < .001$ ), and a negative one ( $p = .02$ ) over the right hemisphere, both involving central recording sites. Similarly, the contrast between the Late-deviant and the Early-deviant conditions reveals a significant positive cluster over the left hemisphere ( $p = .002$ ) and a negative one over the right hemisphere ( $p = .030$ ), involving again central electrodes (Figure 2, panel A). In contrast, no significant difference surfaces from the contrast between the Late-deviant and the Early-deviant conditions (all clusters'  $p$ 's  $> 1$ ). In summary, the Early-deviant condition triggers a reduction in contralateral negativity and ipsilateral positivity, both with respect to the Control and the Late-deviant conditions, whereas these two latter conditions reveal remarkably similar results (Figure 3, panel A).

**Response-locked EEG data.** In terms of LRPs, the contrast between the Control and the Early-deviant conditions revealed a significant difference, surfacing around 200 ms before response onset (1 significant negative cluster,  $p < .001$ ; Figure 2, panel B). The amplitude of the LRP was significantly reduced in the Early-deviant condition. In contrast, no difference surfaced when comparing the Control and the Late-deviant condition (all clusters'



$p > .37$ ). Finally, the contrast between the Late-deviant and the Early-deviant conditions revealed a significant negative cluster ( $p < .001$ ), as the amplitude of the LRP was significantly smaller in the Early-deviant condition (Figure 1, lower half).

In the analysis encompassing the whole set of electrodes, the comparison between the Control and the Early-deviant condition yielded a significant positive cluster over the left hemisphere ( $p = .002$ ), and a significant negative one ( $p = .046$ )<sup>3</sup> over the right-hemisphere. Both clusters involved lateralised, central electrodes (Figure 2, panel B). The begin condition thus yields a reduction in terms of both the negativity over the contralateral motor cortex and the positivity over the ipsilateral motor cortex (Figure 3, panel B). In contrast, the comparison between Control and Late-deviant conditions did not reveal any significant difference (for all clusters,  $p > .4$ ). Finally, the contrast between Late-deviant and Early-deviant only highlights a positive cluster ( $p = .005$ ) over the central electrodes of the left hemisphere (Figure 2, panel B). This suggests that the bulk of the difference between the two conditions comes from a reduction of ipsilateral positivity in the Early-deviant condition compared to the Control one. Yet, visual examination of the ERPs suggests that a similar reduction is taking place also for the contralateral negative-going potentials (Figure 3, panel B), even though negative clusters fail to reach significance (all  $ps > .33$ ).

### General Discussion

We explored the scope of keystrokes planning during typing, by comparing words typed only with the left hand (uni-manual Control condition), with words typed only with the left hand, except for one deviant keystroke typed with the right hand, occurring either early (Early-deviant condition) or late (Late-deviant condition) in the sequence. The Early-deviant condition yielded slower reaction times compared to other conditions, in line with previous evidence suggesting that hand-alternation at the beginning of the typed sequence delays the onset of the response (Ostry, 1983). In terms of the EEG indexes of motor-response preparation, stimulus-locked analyses revealed a reduction of the LRP for the Early-deviant condition compared to the other two (uni-manual Control and Late-deviant), which did not differ from one another. The difference surfaced around 400 ms after stimulus onset, suggesting that the next few keystrokes are being processed at the level of the motor cortex relatively early after stimulus onset (around 400 ms). This time-window, moreover, is compatible with estimated latencies for the selection of keystroke schemata (Pinet et al., 2016).

Critically, the same pattern was detected also at the level of response-locked LRPs. The temporal alignment of the EEG signal with the onset of the response, rather than the stimulus, allows to more closely investigate dynamics of motor-response planning. Response-locked LRPs showed a reduction in amplitude selectively for the Early-deviant condition, compared to both the Control and the Late-deviant one, which yielded undistinguishable activities.

In sum, consistent with previous research (Logan et al., 2011), we observed that the LRPs were reduced when, further down in the sequence, the typed response included a deviant keystroke, that is a keystroke typed with the hand not used for the first keystroke. However, this was true only when the deviant keystroke was located towards the beginning of the sequence, in second or third position. In contrast, when the deviant keystroke occurred at the end of the sequence, the LRP recorded at response onset was undistinguishable from the one surfacing for unimanual responses.

One possible interpretation is that, at the time of response onset, no information has been processed about the movements needed to perform the final keystrokes. If this is the case, we would need to revise the hypothesis that the scope of planning encompasses the whole word and the all its keystrokes are programmed in parallel before response onset. Alternatively, we may see our results as consistent with an activation that is still parallel, but graded. In this scenario, the final keystrokes are less active compared to the first ones (Rumelhart & Norman, 1982). The activation of the final keystrokes might be so small to prevent any influence at response onset. If we consider competitive queuing models (Rumelhart & Norman, 1982; see also Behmer & Crump, 2017), all component actions are activated in parallel, but each unit inhibits the following ones, allowing the system to output a correctly ordered sequence of keystrokes. In this scenario, the last keystroke would be strongly inhibited and thus irrelevant in terms of response programming at the time of response onset.

These interpretations converge with that of recent results by Behmer and colleagues (in press). The authors asked participants to copy-type 5-letter words and nonwords. The stimuli had a single letter typed with the right index, and the position of this letter varied across serial positions 1 to 5, or were typed uni-manually with the left hand. A single-pulse TMS was applied over the (left) motor cortex at the time of the first keystroke, in order to estimate motor readiness from the measure of motor evoked potentials (MEP) at the right index finger. Behmer and colleagues report that for responses where the right index keystroke corresponded to the fifth (and final) serial position, the amplitude of the MEP was minimal, and actually undistinguishable from the one recorded in uni-manual responses involving only left-hand keystrokes. This pattern is in line with the indistinguishable motor-related ERPs elicited by the Control and Late-deviant conditions reported here. Both results point towards a limited scope for parallel keystroke activation. Importantly, Behmer et al (in press) also tracked MEPs amplitude across other intermediate serial positions. MEPs were maximal when the right index keystroke corresponded to the second keystroke (i.e., the immediate next keystroke), and decreased monotonically across the following positions. This detailed pattern is clearly in line with competitive queuing models where serial order is reflected in graded activation of component actions as a function of their positions.

Interestingly, competitive queuing models posit that graded activation is obtained via the inhibition exerted by each component action on the following ones. In our analysis of each of the two motor potentials underlying the LRP, we were able to distinguish activation and inhibition dynamics in the motor cortices that were, respectively, contralateral and ipsilateral to the response hand performing the first (left) keystroke. Neither of these potentials was affected by the presence of a deviant keystroke in the last part of the response: If we tentatively identify the concept of inhibition hypothesized in competitive queuing models (e.g., Rumelhart & Norman, 1982; see also Behmer & Crump, 2017) with the inhibition of the motor cortex ipsilateral to the effectors (Pinet et al., 2015, General Discussion), our results speak against the notion of graded parallel activation determined via mutual inhibition of component actions. This is because inhibition was not increased for late vs. early deviant keystrokes. It is worth pointing out, however, that, for all we know, the inhibition we traced at the EEG level merely affects the alternative response hand, whereas the inhibition postulated in the model affects subsequent keystrokes irrespective of their lateralization or keyboard position more generally. Such postulated inhibition would apply even in the case of two consecutive keystrokes typed with the same hand. It is thus possible that lateralized motor-ERPs do not index the full range of activation- and inhibition-dynamics postulated by computational models. Further research is needed to explore this issue, which will require signal with increased spatial resolution, to distinguish activities within

hemispheres, and increased “cognitive resolution”, to specify further the level of processing at which the dynamics of activation and inhibition are operative.

Despite the link with computational models not being fully established yet, our findings suggest that, during motor programming occurring before response onset, information about response side is available just for a limited set of keystrokes, those located towards the beginning of the response. The scope of parallel processing thus seems limited to the first keystrokes. This interpretation would in turn suggest that words are not systematically the chunking units driving motor programming in typing, in contrast with the currently accepted view (e.g., Yamaguchi & Logan, 2014a; 2014b). At least for longer words (we used 7-letter words, where Behmer et al. used 5-letter words), smaller representations might represent the unit of response programming (e.g., syllables, morphemes). There is evidence that the syllabic structure influences behavioral measures of response execution (Pinet, Ziegler, & Alario, 2016; Will, Nottbusch, & Weingarten, 2006; for a theory based on multi-tier representation of orthographic knowledge, see Rapp & Fischer Baum, 2014). We can only speculate that syllables may represent chunking units for typing, at least for longer, multisyllabic words, because in our experiment the position of the deviant keystroke (early vs late) is confounded with syllabic structure. All deviant keystrokes in the initial condition belong to the first syllable, whereas deviant keystrokes in the end condition belong to the second one.

In summary, by tracking the influence of keystrokes typed with a different hand compared to the one used to initiate the response, this experiment revealed that, at the time of response onset, information seems to be available about the laterality of the first few (3rd position) keystrokes, whereas no trace of extra activation nor inhibition were detected for the final keystrokes (6th to 7th positions). These findings question the notion that words are the sole planning units of movement in typing. At least for longer words, smaller units may drive movement preparation. While this result may not seem counterintuitive, it suggests an important constraint on the scope of keystroke planning during typing.

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### Footnotes

1. The argument for a neurophysiological inhibition comes from a combination of Hoffman reflex, transcranial magnetic stimulation (TMS) and electroencephalography in a choice task (Burle et al., 2004), recently extended to typing using TMS by Behmer et al. (in press).
2. For LRPs, the clustering involved just temporal adjacency, as a single ERP was analyzed.
3. In replicating our analyses, we noted that this negative cluster was not consistently significant. Due to the random re-assignment during permutations, in fact, different runs of the same analyses can produce slightly different results when performing cluster based permutation tests. Importantly, this negative cluster must be considered with caution, due to its limited consistency in terms of significance across multiple instantiations of the same analysis.

Table 1

*Summary of the variables controlled across the three experimental conditions (Control, Begin, End).*

Variable	Control	Early-deviant	Late-deviant	Control vs Early-deviant	Control vs Late-deviant	Late- vs Early-deviant
Frequency	2.22	2.62	3.56	-0.43	-1.03	0.71
N. of homographs	1.18	1.11	1.22	0.96	-0.41	1.26
Orth. N.	1.95	1.85	1.72	0.37	0.88	-0.55
N. of Syllable	2.32	2.15	2.17	1.56	1.50	0.17
Mean Bigr. Freq.	9005	9444	9131	-0.83	-0.21	-0.54

*Note.* N. of homograph = number of homograph; Orth. N. = number of orthographic neighbors; Mean Bigr. Freq. = mean bigram frequency. All variables retrieved from the LEXIQUE database (New, Pallier, Brysbaert, & Ferrand, 2004). The first three columns report mean values of variables as a function of experimental condition (Control, Early-deviant, Late-deviant). The last three columns report *t*-values determined with independent-sample *t*-tests between pairs of conditions, as expressed in the corresponding heading. All *ps* > .12



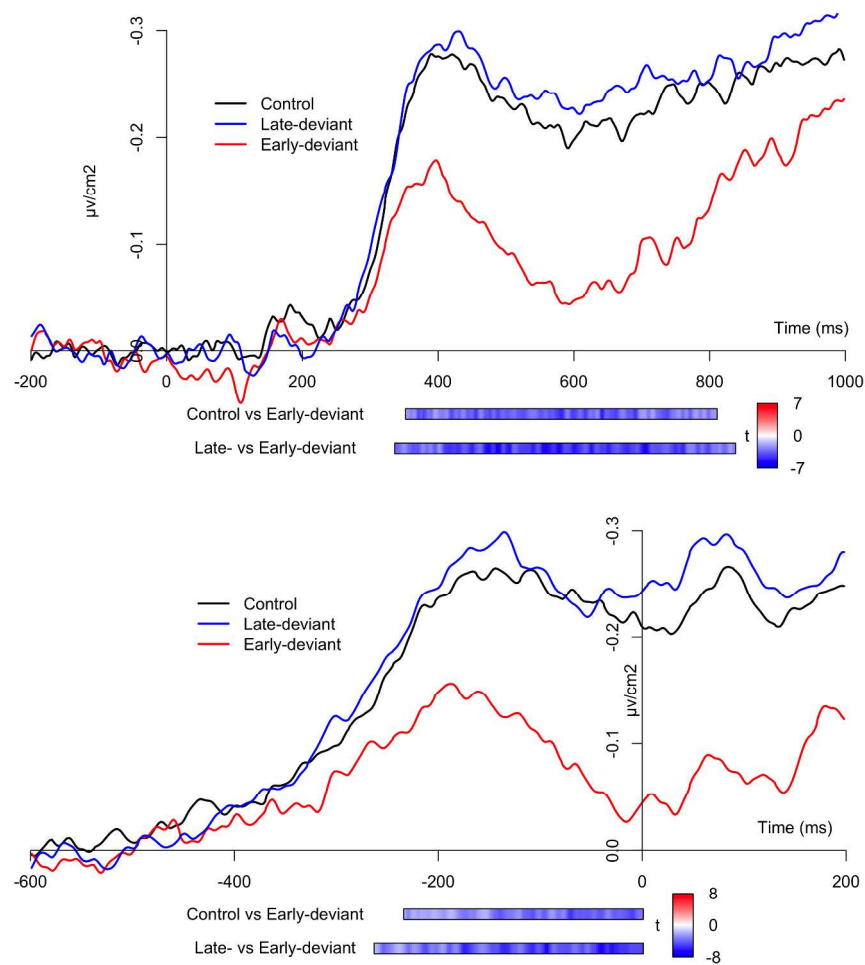


Figure 1. Stimulus- (upper half) and response-locked (lowerhalf panel) LRPs for the three experimental conditions (Control, Late-deviant, Early-deviant). The horizontal bars below the plot represent the results for the significant clusters surfacing from the comparisons between the conditions (Control vs. Early-deviant; Late-deviant vs. Early-deviant), temporally aligned to the timecourse of the ERP plot. The color within the bars codes for the value of  $t$  at each time step.

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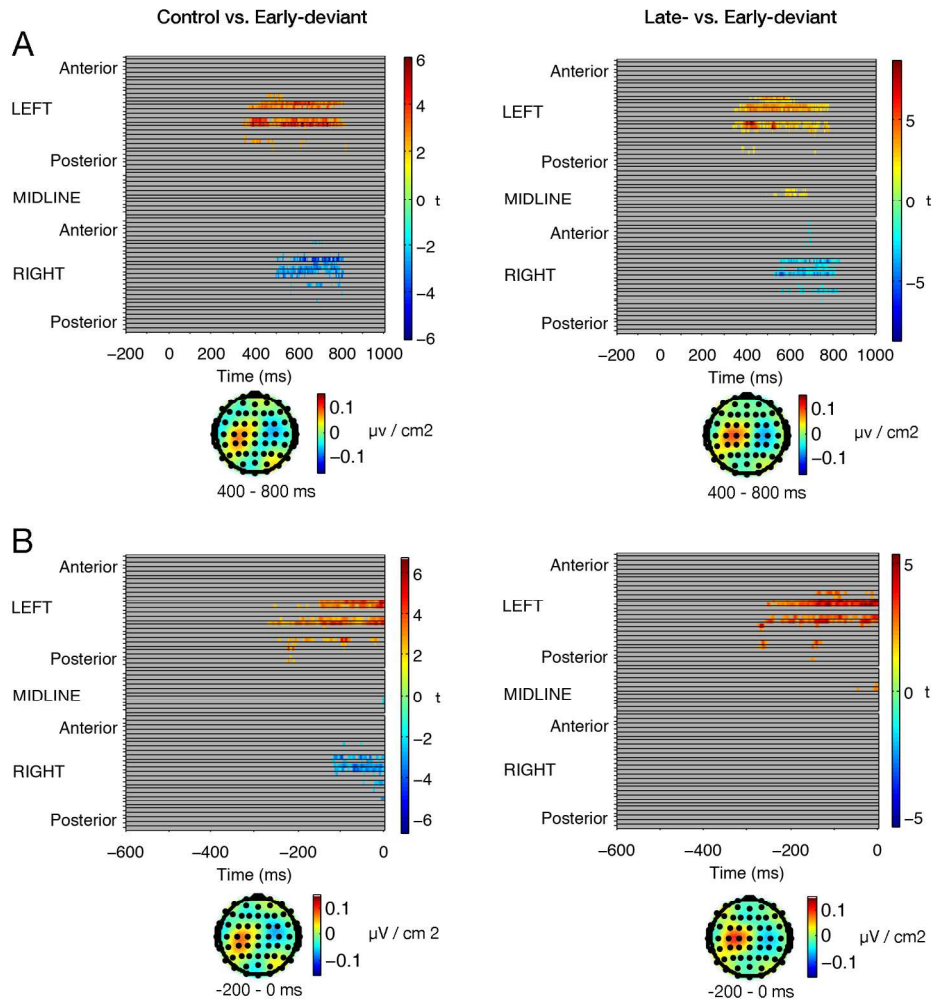


Figure 2. Raster plots of the significant t-values for Stimulus- (Panel A) and response-locked epochs, and corresponding topographies for the contrast between the Control and the Early-deviant condition (left column) and between the Late-deviant and the Early-deviant conditions (right column).

189x189mm (300 x 300 DPI)

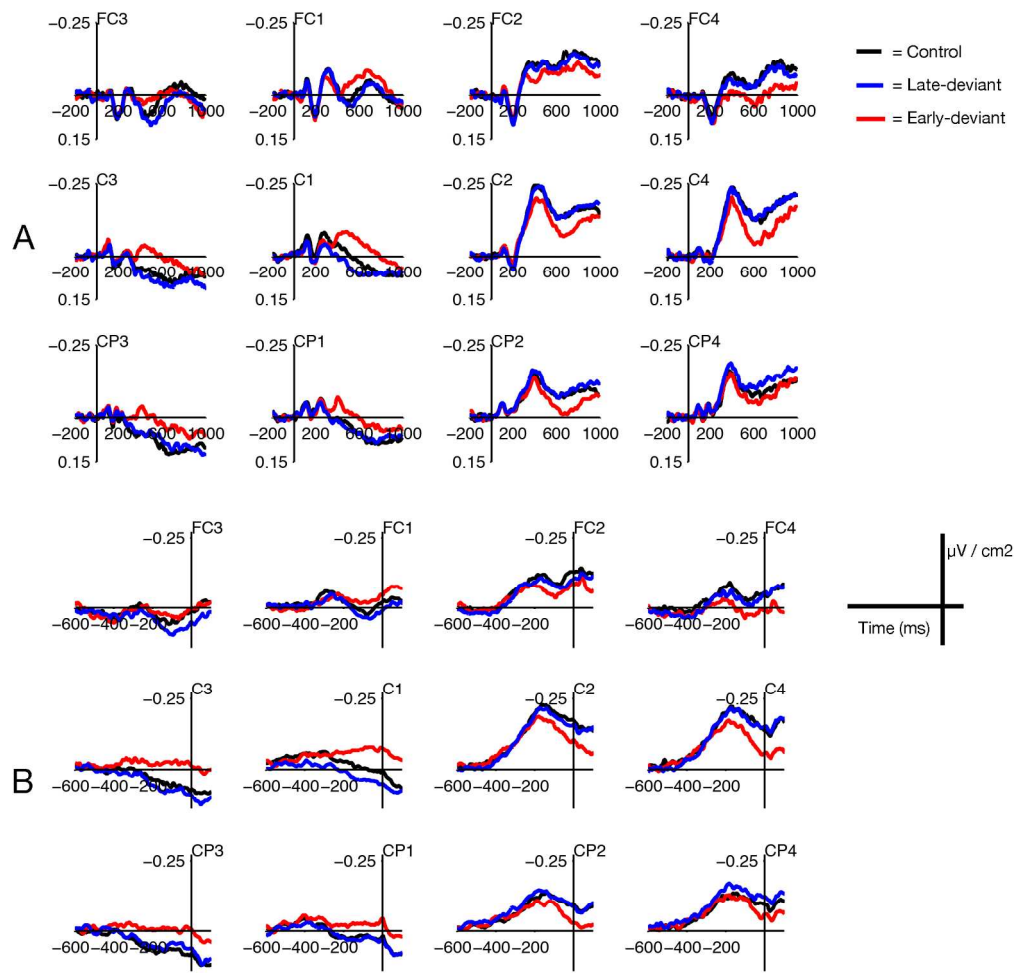


Figure 3. Stimulus- (panel A) and response-locked (Panel B) ERPs for the 3 experimental conditions over central electrodes. The first 2 columns (odd-numbered electrodes) report electrodes on the left hemisphere, whereas the last 2 columns report homologous electrodes on the right hemisphere.

189x199mm (300 x 300 DPI)