On the functional relationship between language and motor processing in typewriting: an EEG study

Michele Scaltritti, Svetlana Pinet, Marieke Longcamp, F-Xavier Alario

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On the functional relationship between language and motor processing in typewriting: an EEG study

Michele Scaltritti[a], Svetlana Pinet[a,†], Marieke Longcamp[b] and F.-Xavier Alario[a]

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ABSTRACT

The functional relationship between language and motor processing was investigated to elucidate whether it is better described in terms of a discrete or a continuous account of information flow. To this end, we recorded event-related potentials during a typewriting task that combined a semantic priming paradigm with a manipulation of response side (response initiated with right vs. left hand), and focused on the lateralised potentials indexing motor-response activation and inhibition. The critical issue was to assess whether, in the semantically related condition, the increased evidence for the target representation at the conceptual-lexical levels percolates into motor-response preparation, thus triggering an enhanced activation of the corresponding response hand, or whether lexical-semantic and motor-preparation processes unfold independently. Despite effective priming on response times, no selective influence of semantic relatedness was observed on motor-preparation potentials. These results are more compatible with a discrete account.

Language production requires that linguistic representations are not only retrieved but also implemented as motor programmes which generate spoken, written, or signed outputs. These two aspects of language production, that is, "language" and "production", have been mostly investigated in separation (Hickok, 2012; Hickok, 2014; Kandel & Perret, 2015; Mousikou & Rastle, 2015; Weingarten, Nottbusch, & Will, 2004). A common assumption has been that motor implementation can begin only after linguistic processing has terminated (e.g. Levelt, Roelofs, & Meyer, 1999; Meyer & Levelt, 2000), an assumption of staged processing also made in models that postulate continuous information flow across other representational levels (e.g. Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland, 1979).

More recently, the functional relationship between language and motor processes has started to be explicitly explored. One rationale hinges on assessing the effects of linguistic variables (e.g. consistency between phonology and orthography) on behavioural measures of response execution (e.g. response durations). Evidence of the former influencing the latter is taken against a staged model, and in favour of continuous accounts. Mixed results have been reported, both for spoken (e.g. Balota, Boland, & Shields, 1989; Damian, 2003; Gahl, 2008; Gahl, Yao, & Johnson, 2012;

Kawamoto, Kello, Higareda, & Vu, 1999; Kello, Plaut, & MacWhinney, 2000; Munson & Solomon, 2004; Rìes, Legou, Burle, Alario, & Malfait, 2012, 2015; for reviews, see Gahl et al., 2012; Mousikou & Rastle, 2015) and handwritten production (e.g. Damian & Stadthagen-Gonzalez, 2009; Delattre, Bonin, & Barry, 2006; Kandel & Perret, 2015; Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013).

Within this context, typewriting has received relatively less attention. Yet, typewriting would seem to provide a very appropriate context to address the issue, for various reasons. Typing represents an ever-increasing modality of language production, and strong typing expertise is widespread, particularly among "digital-native" young adults. Secondly, typing makes measures related to motor execution readily available, such as millisecond timed inter-keystroke intervals (IKIs; Pinet, Zielinski, et al., 2016) and response durations. Finally, typing involves lateralised manual responses and such responses are associated with clear electrophysiological signatures of motor preparation (e.g. the lateralised readiness potential or LRP: Coles, 1989; Vidal, Grapperon, Bonnet, & Hasbroucq, 2003; for the equivalent in typing see Pinet, Hamamé, Longcamp, Vidal, & Alario, 2015, and further details below). In sum, typing offers the possibility to directly study the potential effects of language-related processes on the neurophysiological

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dynamics of motor-response preparation, as well as the unfolding of the behavioural response. This is precisely the aim of the current study.

A recent theoretical perspective describes typing in terms of two nested hierarchical loops: an *outer* and an *inner* loop (Logan & Crump, 2011; Rumelhart & Norman, 1982; Yamaguchi, Logan, & Li, 2013). The outer loop controls language processing, by comprehending and/or generating the words to be typed. The inner loop receives these words as input, and translates them into the corresponding sequence of keystrokes. The details of the functional relationship between cognitive and motor processes in typing, that is, how information flows across the two loops, remains to be described in detail.

In one view, it is only after word selection has been terminated in the outer loop that the corresponding representation might be passed to the inner loop to be transformed into a series of keystrokes. Consistent with this view, the two loops appear to rely on different and dissociable feedbacks to monitor their performance (Logan & Crump, 2010), and there is evidence that the inner loop is informationally encapsulated, as it relies on implicit knowledge about which typists have very little explicit insight (e.g. Liu, Crump, & Logan, 2010; Logan & Crump, 2009, 2011). Additionally, task-irrelevant information (e.g. the response conveyed by the word stimulus in a Stroop paradigm) does not seem to affect response execution but only response latency (Logan & Zbrodoff, 1998), suggesting that response selection is fully accomplished before the onset of the motor-response.

In an alternative view, a more continuous passage of information may occur, in which word-level lexical representations still serve as interface between the two loops, but where word identification needs not be finished for keystroke activation or programming to start. Then, aspects of word processing (e.g. fast efficient retrieval *vs.* slow uncertain decision) could have a direct impact on motor programing and execution. Consistent with this view, a number of linguistic variables thought to primarily affect word retrieval and encoding have been shown to also affect measures related to typed response execution (Scaltritti, Arfé, Torrance, & Peressotti, 2016), albeit with some empirical discrepancies (e.g. the lexical frequency of occurrence of the words: Gentner, Larochelle, & Grudin, 1988; Scaltritti et al., 2016; but see Baus, Strijkers, & Costa, 2013; Pinet, Ziegler, & Alario, 2016; syllabic boundaries: Weingarten et al., 2004, Pinet, Ziegler, et al., 2016). Such effects would suggest that language processing modulates response production in typing.

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Here, we resorted to electroencephalography (EEG) to investigate whether the transition from language to motor processing can be better described in terms of a discrete or a continuous account. We devised an experiment to assess the impact of a language-related manipulation on electrophysiological markers of motor-response preparation in typing.

It is indeed possible to track the electrophysiological signatures of motor-response preparation during typing. In the context of two-alternatives forced choice tasks (e.g. the flanker or the Simon tasks), the response preparation of a manual keypress yields a specific pattern of lateralised event-related potentials (ERPs), with differential activity in the motor cortices contralateral and ipsilateral to the responding hand. Computing the difference between potentials recorded over the two motor cortices reveals the LRP, a reliable index of motor-response activation (De Jong, Liang, & Lauber, 1994). When the contralateral and ipsilateral activities have been considered separately, additional functional attributions have been made. Particularly after Current Source Density estimation (CSD, or Laplacian Transform; e.g. Babiloni, Cincotti, Carducci, Rossini, & Babiloni, 2001; Vidal et al., 2015), a negative-going potential can be tracked over contralateral motor cortex, while a positive-going deflection is sizeable over ipsilateral motor cortex. The former is linked with activation of the contralateral primary motor cortex triggering the response, while the latter has been related to inhibitory processes of the ipsilateral motor cortex to avoid an erroneous response with the inappropriate hand (e.g. Burle, van den Wildenberg, Spieser, & Ridderinkhoff, 2016; Burle, Vidal, Tandonnet, & Hasbroucq, 2004; Meckler et al., 2010; Tandonnet, Burle, Vidal, & Hasbroucq, 2003; Taniguchi, Burle, Vidal, & Bonnet, 2001; Vidal et al., 2003). Notably, similar electrophysiological dynamics have been recently reported during typewriting. Logan, Miller, and Strayer (2011) demonstrated the possibility to track the LRP component locked to the first keystroke in a typing task. Furthermore, by manipulating the hand needed to type the first two keystrokes, Pinet and colleagues (Pinet et al., 2015; Pinet, Dubarry, & Alario, 2016) observed in a picture typing task the electrophysiological pattern previously described in the context of single manual responses, and interpreted it as the activation and inhibition of, respectively, the motor cortices contralateral and ipsilateral to the responding hand. Following these recent findings, in our experiment we thus manipulated across responses the hand needed to perform the first two keystrokes, in order to track the unfolding of the lateralised potentials reflecting processes of motor-response preparation, arguably occurring at the level of the inner loop.

For the manipulation intended to affect linguistic stages in the outer loop, we focused on the semantic priming effect, whereby word processing performance is improved by semantically related words (e.g. "doctor" – "NURSE") compared to unrelated words (e.g. "carpet" – "NURSE"; reviewed in Neely, 1991). This choice was driven by two motivations. First, the semantic priming effect holds a well-known electrophysiological correlate, the N400 effect, whereby a negative-going component detected around 400 ms after stimulus presentation is attenuated in the related *vs.* unrelated condition (reviewed in Kutas & Federmeier, 2011). This provides a reliable marker of the effectiveness of our manipulation in influencing the EEG signal. Second, and most importantly, the semantic priming effect has been convincingly ascribed to central cognitive stages of conceptual processing (e.g. Neely, 1991; McKoon & Ratcliff, 1992), for example, where related representations processed close in time spread activation to one another. Such central locus was essential for our rationale, as our intention was to track the influence of word recognition processes occurring at the level of the outer loop on the dynamics related to motor implementation within the inner loop. The unambiguous localisation of the semantic priming within the outer loop is thus an important feature that other traditional psycholinguistic manipulations may not share, as their functional locus in the terms of cognitive vs. motor stages may be less clear and selective (Abrams & Balota, 1991; Crump & Logan, 2010a).

While the effects of semantic priming on behavioural performance have been ascribed to linguistic processing, the critical issue here is to track its possible effect on motor-response preparation. Do faster responses detected in the related condition merely reflect faster conceptual processing and target recognition, or do they reflect a modulation of how the motor response is implemented? If we endorse a continuous account to envisage the transition from language to motor processing during typing, we would predict that the semantic manipulations exert a distinctive influence on motor potentials as well. Indeed, previous research has tested whether experimental manipulations targeting central cognitive processes modulate as well the electrophysiological dynamics related to motor-response preparation. In this context, it has been shown that both the negative- and the positive-going potentials related to activation and inhibition of the motor cortices can be selectively affected by different experimental factors, such as response conflict in the Simon paradigm (Burle et al., 2016) or foreperiod duration in reaction time paradigms (Tandonnet et al., 2003). With respect to our experiment, spreading of activation is deemed as the foundation of semantic priming effects (e.g. Neely, 1991). During processing of the prime, activation would spread to other related representations. When one of these representations is later presented (in short temporal proximity) as the target, its processing would benefit from the activation received by the prime. If this boost of activation produced by the prime on the target cascades onto the motor-processing level, we may expect to detect a selective enhancement of the motor-preparation component related to activation of the correct response hand. In other words, the critical issue is to track whether spreading activation percolates into motor-response preparation, and whether increased evidence for the target at the lexical-conceptual level is reflected in corresponding response-preparation dynamics.

In summary, within the current experiment we manipulated the semantic relatedness between words in a classic semantic priming paradigm with typewritten responses. In parallel, we also manipulated the hand used to initiate the responses (i.e. to type the first two keystrokes), thus making it possible to observe the unfolding of lateralised potentials indexing activation and inhibition of the motor cortices for the forthcoming motor response. The goal was to track whether spreading activation at the conceptual-semantic level of processing percolates into the phase motor-response preparation, thus prompting enhanced activation for the correct response hand. To provide a concrete example, for an electrode located over the left-side of the scalp, we expected to detect a negative-going potential in case of a right-hand response, unfolding before response onset and signalling activation of the motor cortex contralateral with respect to response hand. Furthermore, we expected to observe a positive-going deflection for left-hand responses, indexing inhibition of the ipsilateral motor cortex. If semantic relatedness modulates motor-response activation by enhancing the activation component, we would thus predict that here (i.e. left-electrode) the related condition selectively modulates the motor potential triggered by a right-hand response, effectively resulting in an interaction between the semantic relatedness and response-hand manipulations. Of course, the reverse reasoning applies for electrodes located over the right part of the scalp, in which we would expect an effect of semantic relatedness solely for the activation component triggered by left-hand responses. This pattern of results would strongly support the notion that activation at the lexical-semantic level of processing correspondingly affects activation at the levels of motor-response preparation, thus providing evidence in favour of a continuous account of the transition from cognitive to motor processing. Differently, an independent unfolding of

motor potentials with respect to activation dynamics at the lexical-semantic stages would be more coherent with a description of the flow of information between the two loops in the terms of a staged processing account.

Method

The study received appropriate ethical approval, filed under "ID RCB: 2011-A00562-39" at "Comite de Protection des Personnes Sud Méditerranée I" in Marseille, France.

Participants

Twenty-five right-handed, French native-speakers were recruited. Two participants were excluded from the analyses due to poor signal quality, leaving 23 participants in the final sample (13 females, $M_{age} = 23.13$, $SD_{age} = 3.18$). Before the experimental session, participants were given details about the experimental procedure and they were asked to provide their informed consent. Typing skills were evaluated using a typing test (described below; see also Pinet et al., 2015). The typing test took place a few days before the actual experiment. Participants were admitted to the experimental phase proper if they proved to be touch-typists by typing fluently, without looking at their hands, and using all their fingers with consistent and predictable finger-to-keystroke mapping. All participants received monetary compensation (10€ per hour) for their participation. Only one participant reported having received formal training in typing. On average, they reported typing 4.37 (SD = 2.43) hours a day. Their mean score at the Edinburgh Handedness Inventory (Oldfield, 1971) was 76.52 (SD = 30.26), revealing that participants could be classified as right-handed.

Stimuli

One hundred and twenty semantically associated prime-target pairs were selected, mainly from French association norms (Bonin, Méot, Ferrand, & Bugaïska, 2013; Ferrand, 2001; Ferrand & Alario, 1998). Twenty-one pairs were created ad-hoc and 8 were taken from the Nelson, McEvoy, and Schreiber (1998) norms. As the latter were collected in the American population, care was taken to select pairs for which the semantic association was valid even in French (e.g. right–left; airport–plane).

The hand needed to type the first two letters of the target words on AZERTY keyboards defined Response Side. Half of the pairs (60) included a target for which

the first 2 letters have to be typed using the left hand (left targets), while for the other half the first two letters are to be typed with the right hand (right targets). For both left and right targets, prime words (which were not to be typed) evenly represented each of the four possible combination of Response Side as defined by the first two letters (i.e. left–left, right–right; left–right, and right–left). Unrelated pairs were created by randomly reassigning primes and targets. Care was taken to avoid that randomly generated unrelated pairs resulted in a semantic relationship of any kind and, in such case, the items were re-paired. Additional 34 pairs of semantically related words were retrieved or created to serve as practice and buffer trials (see description of the procedure), while another set of 36 pairs was selected to serve as filler trials. Filler trials were selected in order to have targets that required hand alternation in terms of Response Side (left–right or right–left targets). Audio files for the targets were recorded from a native French speaker (one of the authors, F.-X. A.) in a sound-attenuated room and normalised off-line for acoustic amplitude using the software Audacity (version 2.0.5).

Right and left targets and corresponding primes were comparable along a number of relevant psycholinguistic variables (Table 1). Following previous work on N400-related semantic effects (Blackford, Holcomb, Grainger, & Kuperberg, 2012), Latent Semantic Analysis (LSA; Landauer & Dumais, 1997) was used as a measure of semantic relatedness between primes and target words. We

Table 1. Summary of the variables controlled across prime-target pairs.

Variables	Primes			Targets		
	LL	RR	t	LL	RR	t
Frequency	48.11	53.09	0.20	89.11	130.28	0.59
Number of homographs	1.42	1.25	1.40	1.45	1.55	0.78
Number of letters	6.12	6.23	0.41	5.58	5.35	0.89
Orthographic neighbourhood	3.47	2.68	1.09	4.18	4.00	0.24
Number of homophones	–	–		3.55	3.73	0.47
Number of phonemes	–	–		4.22	3.97	1.06
Phonological neighbourhood	–	–		10.77	9.72	0.66
Phonological uniqueness point	–	–		4.08	3.83	1.16
Number of syllables	–	–		1.68	1.52	1.40
LSA	–	–		0.21	0.26	1.03
Duration	–	–		499	476	1.42
Number of opposite keystrokes	–	–		1.63	1.90	1.42

Note: LL = target/primes with the first two keystrokes performed with the left hand. RR = target/primes with the first two keystrokes performed with the right hand. *t* values (columns *t*) were determined with independent-sample *t*-tests between LL and RR items. LSA = latent semantic analysis score; all variables retrieved from the LEXIQUE database (New, Pallier, Brysbaert, & Ferrand, 2004), except for LSA scores (retrieved from http://lsa.colorado.edu/), duration (the duration of the auditory targets in ms) and number of opposite keystrokes (reflecting the number of keystrokes typed with the opposite hand with respect to the first two). For all the reported *t*-values (*t*) all *p*s > .15 (degrees of freedom = 118).

retrieved pairwise comparison values for primes and targets (from Français-Monde-Extent database, available at http://lsa.colorado.edu/). Furthermore, left- and right-targets were comparable in terms of the number of keystrokes that had to be performed with the opposite hand with respect to the one involved in the first two. Finally, audio files for left- and right-targets were comparable in terms of duration. The experiment implemented a 2×2 factorial design, with the factors of Semantic Relatedness (Related vs. Unrelated) and Response Side (left targets vs. right targets) both manipulated within participants. Semantic Relatedness was manipulated within items, while Response Side was manipulated between items.

Apparatus and procedure

Typing test

Participants were seated in an armchair in front of a computer screen and a computer keyboard. They had to copy three texts (consisting, respectively of 611, 662, and 696 characters, spaces included). Each text was first presented written on the screen, and participants were instructed to read it in order to familiarise with its contents. Next, each text was presented again divided in three separate parts, presented consecutively on the screen. For each part, participants had to copy-type it. The typed text was displayed on the screen below the text to copy and corrections were allowed. Typing speed was calculated by dividing the number of words (5 character-words; Crump & Logan, 2010b) correctly typed by the time elapsing between the first and the last keystroke of each text. Accuracy was defined as the percentage of words containing no error (i.e. backspace or typographical error). On average, participants typed 53 words per minute (SD = 12), with an average accuracy of.87 (SD = .04).

Experiment

Participants were comfortably seated in an armchair placed in a Faraday cage. Primes were presented in written format on a computer screen placed at a distance of ∼60 cm from the participants. Targets were presented in auditory format via earphones. Responses were collected from a highspeed DirectIN Keyboard PCB v2010 manufactured by Empirisoft to get keystroke timing data with at least 1 ms accuracy. The keyboard and the screen were placed on the same table in order to resemble the usual typing context for the participants.

Before the beginning of the experimental procedure, participants filled a questionnaire collecting demographic information, as well as information regarding typing habits, and the Edinburgh Handedness Inventory (Oldfield, 1971). They were then given as much time as they needed to familiarise with the keyboard. After installation of the EEG cap, the experimental procedure began. Participants were instructed to pay attention and mentally read the written words (primes) and to type the auditory words that shortly followed each prime. Written instructions were presented on the screen at the beginning of the experimental procedure, followed by 10 practice trials. The experimental phase consisted of 4 blocks with 75 trials each. Participants took self-terminated breaks between blocks. Each experimental block started with 6 buffer trials.

Each trial started with a fixation cross (+) displayed at the centre of the screen. The duration of the fixation cross was randomly selected in each trial (1000, 1100, 1200, 1300, or 1400 ms). Written prime words were displayed immediately after the fixation cross, at the centre of the screen, for 100 ms. After a 100 ms interval, auditory targets were presented through the earphones, and participants were instructed to type them as fast and as accurately as possible. Participants' responses were displayed as they were typed in the centre of the screen in uppercase. Participants were explicitly reminded not to type diacritical marks, as is commonly done in French when typing in uppercase. Trials were separated by an interval of 2000 ms, in which a blank screen was displayed. All the visual 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 (32 point size). Stimuli presentation and response acquisition were controlled using the software Presentation (NeuroBehavioral Systems).

Experimental stimuli were presented twice (once in the Related condition, once in the Unrelated condition), for a total of 240 experimental trials. Stimuli were presented in pseudo-randomised lists, which followed 3 criteria: (a) the presentations of the same primes or targets were separated by at least 30 trials in which different stimuli were presented, (b) the same experimental condition, both in terms of Semantic Relatedness and in terms of Response Side, could not be repeated more than 5 times in a row, and (c) no more than 9 experimental trials could be presented in a row without the presentation of a filler trial. Across participants, lists were presented with trials on the reverse order as well.

EEG recording and processing

EEG was acquired from 64 scalp locations using Ag/AgCl active electrodes (BioSemi Active Two system), referenced to the CMS-DRL ground and placed accordingly the standard 10–20 positions. The sampling rate was 512 Hz (filters: DC to 104 Hz, 3 db/octave slope). Vertical and horizontal electro-oculograms were recorded with

three surface electrodes placed one below the left eye and the other two next to the two outer canthi. Analyses were performed using the MATLAB toolboxes EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon & Luck, 2014), and MASS UNIVARIATE ERP (Groppe, Urbach, & Kutas, 2011), along with custom routines. Data were re-referenced to the average of both mastoids. Continuous data were filtered (Order 6 Butterworth 0.1–100 Hz cut-offs), and then segmented into large epochs going from 500 ms before stimulus onset to 3500 ms after stimulus onset. Noisy electrodes were interpolated by means of spherical interpolation. A first artefact rejection was performed on these epochs. Afterwards, ICA was computed (algorithm: AMICA; Palmer, Makeig, Kreutz-Delgado, & Rao, 2008). Components corresponding to blinks were removed and a second artefact rejection was then performed to exclude remaining noisy epochs from the analyses.[1]

Shorter epochs were finally extracted, both stimulus-locked (–400 to 1200 ms) and response-locked (–600 to 200 ms). A –400 to –200 ms pre-stimulus baseline was applied by subtraction on stimulus-locked epochs, while a –600 to –400 pre-response baseline was applied for response-locked epochs. In line with previous electrophysiological investigations on typing (e.g. Pinet et al., 2015) and choice reaction times tasks (Burle et al., 2004; Vidal et al., 2015), analyses were conducted on Laplacian-transformed epochs, in order to increase the spatial resolution for scalp potentials (Babiloni et al., 2001), as well as the temporal and spatial differentiations of ERP components (Vidal et al., 2015). For both stimulus- and response-locked epochs, we (separately) computed surface Laplacian using 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}).

Only correct responses to experimental trials were considered in the analyses. Epochs were averaged within conditions and within participants. The resulting averages were submitted to cluster-based permutation analyses (Maris & Oostenveld, 2007) using a family-wise alpha level of.05, thus pursuing a data-driven comparison considering all time points and all channels, while providing appropriate control for multiple comparisons. This method consists in performing, for each sample, comparisons between experimental conditions via paired t-tests. Values of t above a pre-determined threshold ($p < .05$) are clustered on the basis of spatial and temporal adjacency, and cluster level statistics are calculated by summation of each cluster's t-values. Cluster p-values are calculated under a permutation distribution in which samples are randomly re-assigned across conditions to generate a null distribution of the test statistics (1000 permutations in the present analyses). The p-value for the cluster is defined by the proportion of random permutations that result in a larger test statistic than the observed one (Groppe et al., 2011; Maris & Oostenveld, 2007).

Results

Behavioural data

For responses in experimental trials to be considered correct, they had to fulfil three conditions. Specifically, (a) the first two letters were typed correctly, (b) the backspace was never pressed during the execution of the typed response, and (c) the final response did not include more than one typographical error (deletion, substitution, transposition). If any of these conditions was violated, the response was considered as an error (18.99% out of the total sample of responses for experimental trials). Mean proportion of accurate responses was significantly lower in the experimental task (M = .81, SD = .12), compared to the pre-test (M = .87, SD = .04), t (22) = 2.77, $p < .05$, possibly due to the more constraining conditions imposed by the recording of the EEG (e.g. the requirements to limit the movements of head and arms and to minimise occasions in which the gaze was diverted from the monitor to the keyboard). There was however a significant correlation between accuracy during the pre-test and the proper experimental phase, r (21) = .43, $p < .05$, suggesting that specificities related participants typing skill was not obscured by task constraints.

This analysis of behavioural performance concerned response onset latency (RTs) and accuracy rate, as well as mean IKIs and the first IKI. Mean IKIs were calculated by averaging the intervals of time elapsing between keystrokes within each response, and can be considered as a measure of typing rate. The first IKI represent the time elapsing from the first and the second keystroke. This measure was included as it has been suggested that cascaded effects from language processing on motor execution might be stronger in the initial phases of the response (Kawamoto et al., 1999). For all the dependent variables, analyses were performed by-participants and by items, thus yielding respectively $F1/t1$ and $F2/t2$ statistics. For RTs and IKIs, we analysed only the trials with correct responses. Results are summarised in Table 2.

For RTs, the main effect of Semantic Relatedness was significant, F_1 (1, 22) = 47.49, MSE = 900.07, $p < .001$, F_2 (1, 118) = 47.08, MSE = 2,420.69, $p < .001$, with faster latencies in the Related condition. Neither the effect of Response Side. $F_1 < 1$, F_2 (1, 118) = 2.10, MSE =

Table 2. Summary of the behavioural results.

Variables	LL		RR	
	Unrelated	Related	Unrelated	Related
RT	880 (28)	844 (30)	873 (42)	823 (37)
IKI	194 (9)	195 (10)	207 (10)	202 (9)
First IKI	201 (14)	197 (14)	231 (13)	223 (12)
Accuracy	0.80 (0.03)	0.83 (0.03)	0.80 (.02)	0.81 (0.02)

Note: Mean reaction times (RT; in ms), inter-keystroke interval (IKI; in ms), and accuracy (proportion) as a function of Response Side (left targets vs. right targets) and Semantic Relatedness (Related vs. Unrelated). Standard errors of the means across participants are reported within parentheses. LL = targets with the first two keypresses performed by the left hand; RR = targets with the first two keypresses performed by the right hand.

21,370.39, nor the interaction between Response Side and Semantic Relatedness, F_1 (1, 22) = 2.05, MSE = 587.97, $F_2 < 1$, were significant. With respect to mean IKIs, the main effect of Response Side was significant, F_1 (1, 22) = 11.89, MSE = 174.57, $p < .01$, F_2 (1, 118) = 5.76, MSE = 1241.61, $p < .05$, with faster IKI for left targets, while the main effect of Semantic Relatedness, F_1 (1, 22) = 1.56, MSE = 74.00, $F_2 < 1$, and the interaction between Response Side and Semantic Relatedness, F_1 (1, 22) = 2.00, MSE = 130.64, F_2 (1, 118) = 2.42, MSE = 118.00, were not. With respect to the first IKI, we detected significant effects of Semantic Relatedness, F_1 (1, 22) = 5.19, MSE = 313.86, $p < .05$, F_2 (1, 118) = 6.56, MSE = 548.20, $p < .05$,[2] and Response Side F_1 (1, 22) = 11.23, MSE = 1,643.06, $p < .01$, F_2 (1, 118) = 13.36, MSE = 4,992.36, $p < .001$, but no interaction between the two, $F_1 < 1$, F_2 (1, 118) = 1.03, MSE = 548.20. Finally, the analysis of accuracy revealed no effect of Response Side, both $F_s < 1$, an effect of Semantic Relatedness that was just approaching conventional levels of statistical significance, F_1 (1, 22) = 3.49, MSE = .002, $p = .07$. F_2 (1, 118) = 2.85, MSE = .006, $p = .09$, and no reliable interaction of the two factors, $F_s < 1$.[3]

EEG data

For the present analyses, cluster-based permutation tests considered as spatially adjacent electrodes that lied within a distance of ~4.2 cm (i.e. average number of neighbours per electrode = 4.2, SD = 1.2). One thousand within-participant random permutations of the data were computed. For the analyses of the interaction between Semantic Relatedness and Response Side, average differences between the Unrelated and the Related conditions were computed separately for left- and right-targets, and submitted to the same cluster-based permutation test described above.

N400 effect

A rich literature has linked the effect of semantic priming in single words paradigm to the N400 effect at the EEG level (e.g. Anderson & Holcomb, 1995; Deacon, Hewitt, Yang, & Nagata, 2000; Franklin, Dien, Neely, Huber, & Waterson, 2007; Holcomb & Anderson, 1993; Holcomb & Neville, 1990; Rugg, 1985; see also Holcomb, 1993). To offer a term of comparison with this literature, first we present an analysis of the stimulus-locked epochs, without Laplacian transformation, to inspect the features of our (expected) N400 effect. Statistical analyses revealed the presence of a significant difference (2 negative clusters, $p < .05$) between Related and Unrelated Condition (Figure 1, column A). The difference between the Unrelated and the Related conditions is broadly distributed (Figure 1, column B). ERPs reveal a pattern that is quite consistent with the traditional N400 effects, with Related pairs yielding an attenuation of the negative component compared to Unrelated ones (Figure 1, column C) and the difference surfacing around 350 ms after stimulus onset and remaining visible thereafter.

Surface Laplacian

The remainder of the analyses will present results obtained on Laplacian-transformed epochs. We decided to focus on these to capitalise for the temporal and spatial separation they can offer with respect to ERP components. Surface Laplacian can be in fact considered as a spatial filter in which activity is weighted on the basis of the distance between electrodes, thus filtering out spatially broad activity and increasing topographical selectivity (Cohen, 2014). Analyses are separately presented for stimulus- and response-locked epochs. Within both, we examined the main effects of Semantic Relatedness and Response Side and, critically, the presence of a potential interaction.

Stimulus-locked analyses. Statistical analyses revealed a significant effect of Semantic Relatedness (1 negative cluster, $p < .05$; Figure 2(a), left column). Maximal differences between Unrelated and Related pairs were mostly focused in left parietal electrodes (Figure 2(b), left column), in the latency range between 350 and 800 ms. Compared to untransformed epochs, the topography of the semantic effect thus appears much more focused. Inspection of the corresponding ERPs revealed an attenuated positive deflection for Unrelated trials compared to Related one in this time window (Figure 2 (c), left column). With respect to Response Side, the contrast between left- and right-targets displayed significant difference going in opposite directions across the two hemispheres (1 positive and 1 negative cluster, with ps < .05; Figure 3(a), left column). The difference was maximal over frontocentral, central, and centroparietal electrodes (Figure 3(b), left column). Examination of the ERPs (Figure 3(c), left column) reveals the clear presence of a negative-going wave over electrodes contralateral
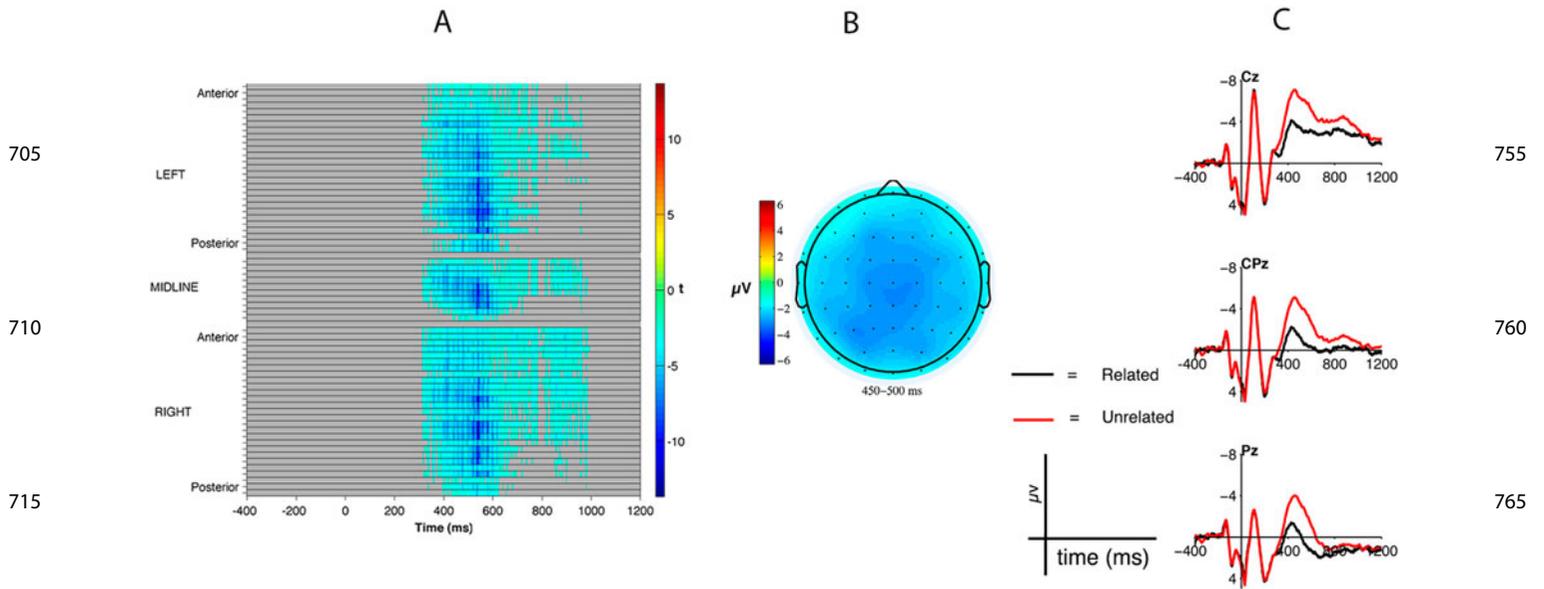
Figure 1. Results for the Related vs. Unrelated contrast in stimulus-locked epochs. Column A: raster-plot for the significant *t*-values in the Unrelated vs. Related contrast. Column B: topography of the difference between the Unrelated and the Related conditions in the 450–500 ms time window. Column C: ERPs for the Related (black) and Unrelated (red) conditions as detected on centroparietal electrodes along the midline.

with respect to response hand (i.e. left electrodes for right targets, right electrodes for left targets), and more positive-going deflections on ipsilateral electrodes (i.e. left electrodes for left targets, and right electrodes for right targets) The two seem to clearly differentiate around 400 ms after stimulus onset, and to remain different throughout the reminder of the epoch. Finally, we found no statistically reliable interaction (Figure 4, top panel; for all clusters, *p* > .24). The two effects are indeed detected over different and non-overlapping electrodes in stimulus-locked epochs.

Response-locked analyses. Statistical analyses revealed a significant effect of Semantic Relatedness in response-locked epochs (1 negative cluster, *p* < .05; Figure 2(a), right column). The spatial features of the difference between Unrelated and Related trials before response onset (Figure 2(b), right column) were different compared to those observed in stimulus-locked epochs. In particular, maximal differences across the two conditions were detected at more anterior (central) electrodes, in both the right and the left hemisphere, as well as on the midline (Figure 2(a), right column). Examination of the ERPs revealed attenuated negativity for the Related condition over different sites (Figure 2(c), right column). The effect of Response Side was significant, with differences of opposite signs in the two hemispheres (1 positive and 1 negative cluster with *p*s < .05; Figure 3(a), right column). The difference was maximal over frontocentral, central, and centroparietal electrodes (Figure 3(b), right column). ERPs revealed the clear

presence of a negative-going potential in electrodes contralateral with respect to response hand (Figure 3 (c), right column). The positive-going potentials in ipsilateral electrodes appeared rather attenuated compared to tasks with single manual responses (Burle et al., 2004).

Finally, we found no interaction between Semantic Relatedness and Response Side (for all clusters, *p* > .58). In line with the hypothesis of a clear separation between language and motor processes, examination of ERPs indeed suggests that the two factors yield independent additive effects (Figure 4, lower panel).

General discussion

We examined the functional relationship between language and motor processing in typing with a crossed factorial manipulation of the semantic relationships between words, and of the hand used to begin each typed response. Our central interest was on the electrophysiological correlates of manual motor-response preparation triggered by the response-hand manipulation, and in particular on the potential effects of the semantic manipulation on the negative-going component related to the activation of the correct response hand. Both manipulations yielded reliable expected effects. At the electrophysiological level, however, the two effects unfolded in clearly independent ways.

Examination of stimulus-locked EEG activity revealed that the two manipulations affected different and non-
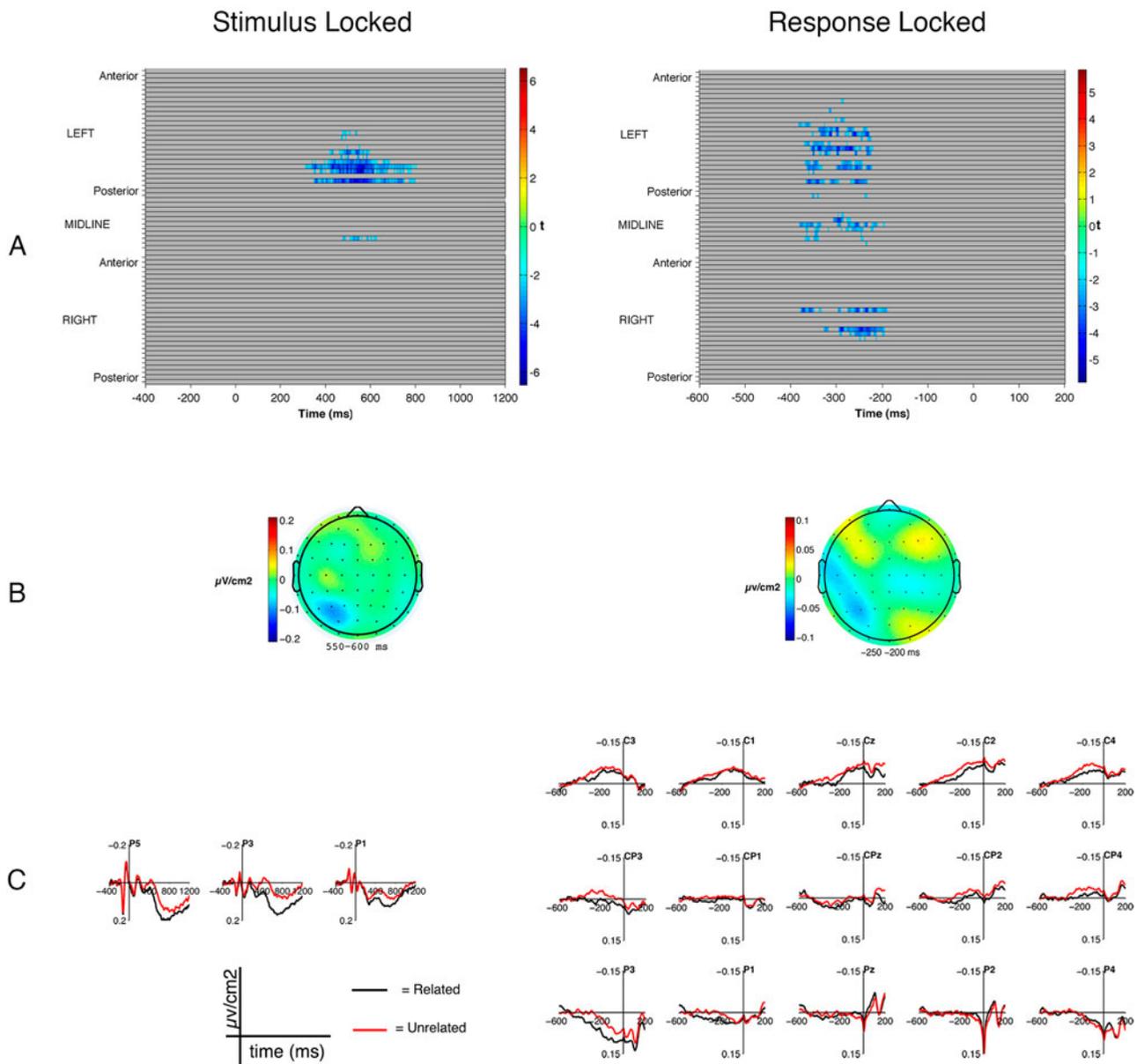
Figure 2. Results for the Related vs. Unrelated contrast in stimulus- (left column) and response-locked (right column) epochs, surface Laplacian. Row A: raster-plots for the significant *t*-values in the Unrelated vs. Related contrast. Row B: topographies of the difference between the Unrelated and the Related conditions. Row C: ERPs for the Related (black) and Unrelated (red) conditions.

overlapping recording sites. Thus, the influence of the semantic manipulation on lateralised motor potentials was virtually non-existent in stimulus-locked epochs. In the context of the present research, however, the most informative examination focuses on response-locked activity. Interestingly, we detected a significant effect of semantic relatedness even at this level. The response-locked signature of the semantic effect, moreover, involved spatio-temporal coordinates that were at least partially overlapping with the lateralised motor-preparation potentials, as the semantic effect was detected over central electrodes on both hemispheres which are clearly involved in motor programming (as shown by

the effect of response side). Yet, the semantic effect and the lateralised motor-preparation potentials combined in a purely additive fashion, a result that we deem more coherent with a staged architecture.

It is important to note that, by themselves, spatio-temporal overlaps for different EEG effects are not indicative of a functional overlap in the underlying processes. In fact, the temporal resolution of ERPs is limited by how the temporal jitter across trials and participants impacts averaging (e.g. Poli, Cinel, Citi, & Sepulveda, 2010). Concerning the spatial distribution of the effects, an electrode shown to reflect motor programming need not exclusively reflect motor-related processes. The N400
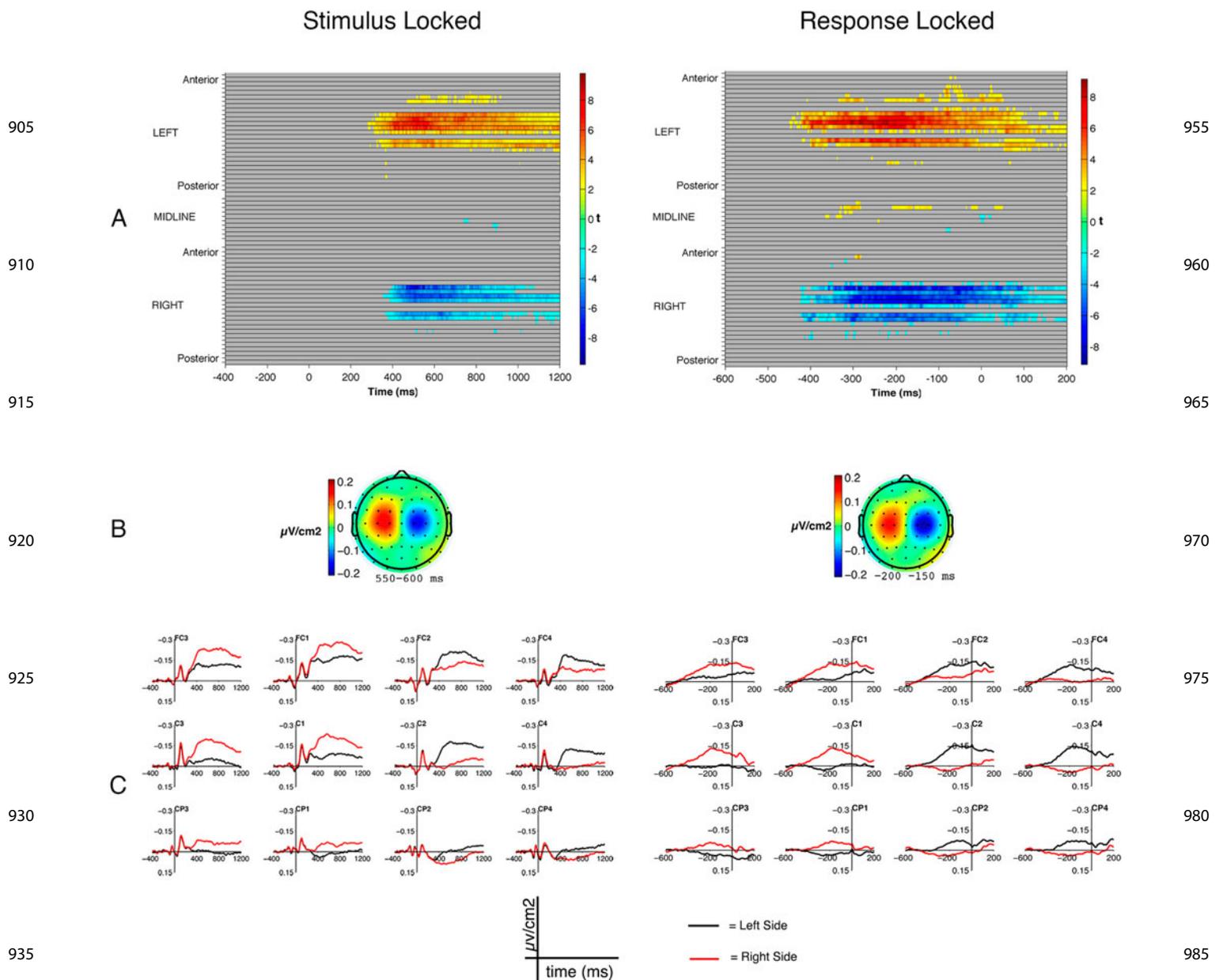
Stimulus Locked   Response Locked

Figure 3. Results for the Left vs. Right response side contrast in stimulus- (left column) and response-locked (right column) epochs, surface Laplacian. Row A: raster-plots for the significant *t*-values for the Left vs. Right response side contrast. Row B: topographies of the difference between the Left and Right response sides. Row C: ERPs for the Left (black) and Right (red) response side conditions.

effect has multiple neural generators (Lau, Phillips, & Poeppel, 2008). These may surface differentially on the topographies as a function of the point in time and of the reference on which the ERPs are aligned. Thus, the spatial overlap might be merely detecting in an additive fashion activities occurring elsewhere and for different functions. This again does not favour the notion that the enhanced activation generated by a semantically related prime at the conceptual-semantic level extends into motor-response preparation, correspondingly modulating the activation of the motor response from the correct response hand.

As a further test of the additive pattern of semantic and motor-related effects in response-locked epochs, we performed post-hoc Bayesian analyses. In this framework, it becomes possible to evaluate the amount of evidence in favour of the null hypothesis, that is, in favour of the lack of an interaction between semantic priming and the unfolding of motor-preparation potentials. As signalled by the effect of response side (Figure 3, right column), the lateralised motor-preparation potentials unfolded over a specific set of electrodes (FC1, FC3, C1, C3, CP1, CP3, and the homologous set of electrodes on the right) within a time-window unfolding from –
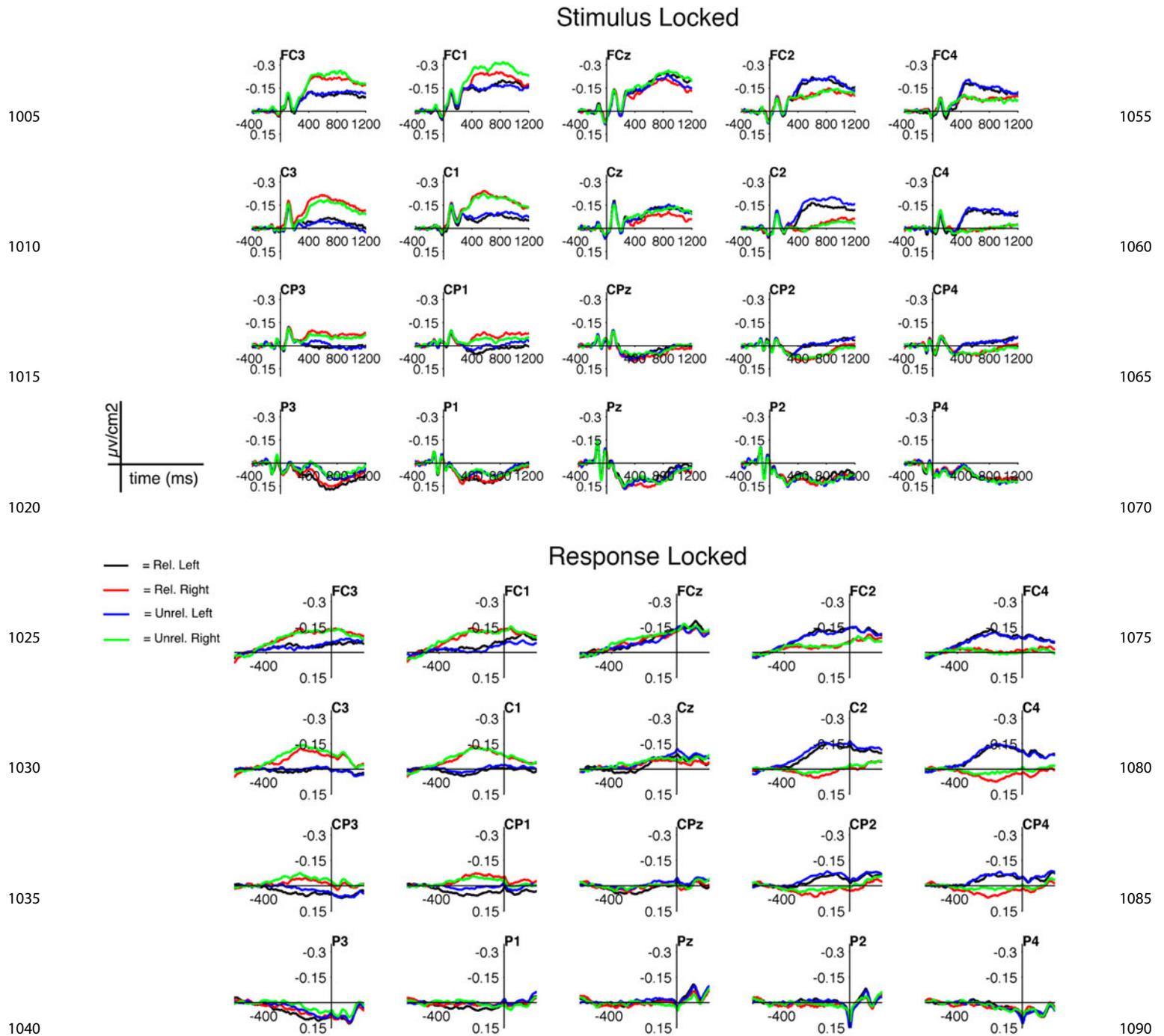
Figure 4. Stimulus- (top panel) and response-locked epochs (lower panel), Surface Laplacian. ERPs for the 4 experimental conditions (black = Related Left-Response; red = Related Right Response; blue = Unrelated Left-Response; green = Unrelated Right Response). No raster-plot and no topographies are reported, as there was no significant interaction.

400 ms until response onset. When considering the average amplitudes of the lateralised motor-related potentials separately measured within each electrode over this temporal window, the models considering semantic relatedness and response side as additive terms always yielded higher Bayes factors compared to the alternative models in which the two terms were considered in an interactive relationship. On average, Bayes factors for the additive models were 2.74 larger than those for the models encompassing the interaction (SD = 0.86, range = 0.43–3.58). As such, our data do seem more likely under the hypothesis that semantic and motor EEG effect combine in a pure additive fashion, rather than in an interactive way. Finally, we further tested the interaction performing a cluster-based permutation analysis limited to this same subset of electrodes,

in order to focus on spatial coordinates in which a potential effect was expected to occur. Again, no significant clusters were found (for all clusters, all *ps* > .36).

A potential interpretative difficulty might arise when we consider that the priming effect at the EEG level may also capture post-lexical aspects of semantic integration between prime and target. Under this perspective, such conceptual integration of the prime and target representations may still be on-going during motor-response preparation, without directly influencing it. Semantic integration and motor-response preparation would thus merely represent two post-lexical processing stages occurring independently and in parallel, thereby combining additively at the level of the EEG signal. Yet, leaving aside its electrophysiological correlate, it is worth noting that priming had a behavioural effect, as it reduced response latency, thus proving a direct influence in the time of initiation of the motor-response. Possibly, such influence would merely reflect faster processing within central language processing stages, for example faster lexical access (e.g. Neely, 1991) or better quality of the information available for the target word (McKoon & Ratcliff, 1992), without a further modulation of the neurophysiological dynamics underlying the preparation of the corresponding motor-response. This scenario would essentially represent a staged account of the transition from language to motor processing.

Our rationale had identified the component related to the activation of the motor cortex contralateral to the response hand as the most suitable candidate to reflect semantic priming effects, as it might have captured at the motor-level the boost in activation produced by the prime at the conceptual processing stage. While semantic priming indeed modulated the onset of motor behavioural responses, the contralateral electrophysiological motor component was not specifically affected by the semantic relatedness factor, suggesting that increased activation or increased evidence for the semantic-lexical representations of the target are not reflected into an enhancement of the activation for the corresponding motor-response. Even if we do not commit to our specific hypothesis on motor-response activation, it is clear that also the positive-going component reflecting inhibition of the contralateral motor cortex did not exhibit any selective involvement in the semantic priming effect. Importantly, we would like to note again that similar components (i.e. positivity and negativity over ipsi- and contral-lateral cortices, respectively) have been shown to be selectively sensitive to other cognitive manipulations (Burle et al., 2016; Tandonnet et al., 2003).

Our results can be interpreted in the framework of the hierarchical two loops model of typing (Logan & Crump, 2011). Assuming that semantic priming targets the outer loop, and that the manipulation of response side reflects the inner loop, the independence of the corresponding electrophysiological correlates suggests that the two loops would be functionally organised in a staged-fashion. Lexical-semantic and motor processing would then be envisaged, at least in typing, as substantially independent perhaps even sequential phenomena. This discrete architecture could rely, in the transition from language to motor processing, on an equivalent of the graphemic buffer that has been postulated for handwriting (e.g. Caramazza & Miceli, 1990; Caramazza, Miceli, Villa, & Romani, 1987; Rapp & Fischer-Baum, 2014), here postulated for typing (Pinet, Ziegler, et al., 2016).

It is worth noting that a minor feature of the behavioural data may be interpreted in line with a non-staged functional architecture. Semantic priming failed to show any significant effect in terms of average IKIs, suggesting that related and unrelated targets are typed at a similar pace. Yet, we found a significant semantic priming effect when selectively considering the first IKI only (i.e. the interval between the first and the second keystrokes). Assuming that effects cascading from language to motor processing are more visible during the initial phase of the response (e.g. Kawamoto et al., 1999), our result may be coherent with the idea that language processing has an impact on motor-response execution. We note that this effect was not very robust (see footnote 3), and that some previous behavioural observations did not lend support to cascading between language and motor processes. For example, there is behavioural evidence that processes related to word-level response selection have no impact on processes of the inner loop. Indeed, a phenomenon such as the Stroop interference has been shown to affect the time needed to begin a typed response, but not the execution of typed response itself (Logan & Zbrodoff, 1998), suggesting that a manipulation at the level of word encoding does not affect processes of motor-response execution handled within the inner loop. On the other hand, there is some evidence that seems to contradict this view. For example, different linguistic aspects such as the lexical frequency of occurrence of the words (Gentner et al., 1988; Scaltritti et al., 2016; but see Baus et al., 2013; Pinet, Ziegler, et al., 2016), or syllabic boundaries (Pinet, Ziegler, et al., 2016; Weingarten et al., 2004) have been shown to affect motor-response execution in typing.

It should be noted that the two-loop theory represents a model of skilled performance. Although data available in the extant literature provide important information, we would argue that typewriting remains still

relatively under investigated from a strictly psycholinguistic perspective. This lack of explicit psycholinguistic models for typing warrants some caution in drawing links across modalities of language production and, in particular, in extending present findings to other modalities. The interplay between language and motor processing in typing and, more generally, in language production thus needs to be further elucidated.

In summary, the present experiment assessed the effect of semantic priming on EEG dynamics underlying motor-response preparation, in an effort to determine whether the enhanced activation of the target produced by the prime at the lexical-conceptual level can be tracked as well at the level of motor preparation, in line with a continuous account for the transition from linguistic processing to response execution in typewritten word-production. The two manipulations yielded essentially independent modulations of the examined electrophysiological correlates, with clear additive effects in response-locked EEG activity, singling the absence of any selective influence of semantic relatedness on either one of the two potentials related to motor-response preparation. The overall pattern of results thus appears to be more coherent with a staged account of the functional relationship between cognitive and motor processes in typewritten language production.

Notes

1. Examination of the resulting ERPs identified a positive burst of voltage, time-locked to the first keystroke and focused in right-parietal electrodes (mostly P2). Albeit this pattern was particularly evident for a subset of (6) participants, grand-averages computed after their exclusion still revealed the presence of this feature, suggesting a more widespread presence. When examined within single participants, the positive burst appeared to surface irrespective of experimental conditions, with no differential impact as a function of semantic relatedness or response hand. Additionally, no major difference emerged when comparing overall results with and without interpolation of the interested electrodes within a single participant clearly exhibiting the presence of the positive burst. Despite being aware of its potential artifactual nature, we could not identify the precise nature of this burst, nor we found evidence for a detrimental impact on the key results.
2. When we limited the analyses of behavioural results to those trials that were actually considered in the EEG analyses (i.e., those trials with correct responses that survived artefact rejection), the effect of Semantic Relatedness on the first IKI was no longer reliable, F_1 (1, 22) = 1.87, MSE = 744.22, F_2 (1, 118) = 1.87, MSE = 429.61, somewhat mitigating its reliability.
3. It is important to underlie that the Semantic Relatedness by Response Side interaction, that we deemed crucial for

electrophysiological data, was explored in terms of behavioural results just for the sake of completeness, as it does not offer any insight about the issue at stake. Response Side, indeed, was manipulated just to yield the pattern of ERP components associated with activation and inhibition of the contralateral and ipsilateral motor cortices with respect to the hand performing the response. An interaction at the electrophysiological level could then be interpreted in functional terms as reflecting selective modulation of components related to motor-response preparation. This is not the case when we examine the very same interaction at the behavioural level, where Response Side simply reflects whether the first two letters of the target were typed with the left or the right hand. At this level, the presence/absence of an interaction is theoretically irrelevant.

Disclosure statement

No potential conflict of interest was reported by the authors. **AQ8**

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