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Negation markers inhibit motor routines during typing of manual action verbs

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ABSTRACT

We explored whether negation markers recruit inhibitory mechanisms during keyboard-based action-verb typing. In each trial, participants read two sentences: the first featured a context (*There is a contract*) and the second ended with a relevant verb which had to be immediately typed. Crucially, the verb could describe manual actions, non-manual actions or non-motor processes, with either affirmative (*You do sign it*) or negative (*You don't sign it*) polarity. We assessed the impact of verb type and polarity on two typing dimensions: motor programming (lapse between target onset and first keystroke) and motor execution (lapse between first and last keystroke). Negation yielded no effect on motor planning, but it selectively delayed typing execution for manual-action verbs, irrespective of the subjects' typing skills. This suggests that processing negations during comprehension of manual-action sentences recruits inhibitory mechanisms acting on same-effector movements. Our novel finding extends embodied models of language and effector-specific motor-language integration.

1. Introduction

Research on language embodiment has variously shown that words pointing to external referents are grounded in sensorimotor brain networks (Bedny & Caramazza, 2011; Pulvermüller, 2005, 2013; Willems, Hagoort & Casasanto, 2010; Zwaan, 2014). For instance, nouns evoking particular smells, adjectives related to color, and verbs denoting bodily actions are differentially grounded in networks supporting olfaction (Gonzalez et al., 2006), chromatic perception (Simmons et al., 2007), and motor activity (e.g., Birba et al., 2017; Buccino et al., 2005; Raposo, Moss, Stamatakis & Tyler, 2009), respectively. However, little attention has been paid to the embodied foundations of other crucial linguistic elements, such as negation markers, let alone in a daily life task. To address this issue, we conducted the first investigation on the grounding of linguistic negation during word typing.

Negative markers are associated with several cognitive effects, such as reducing mnesic accessibility of the negated concept (Kaup, 2001; Kaup & Zwaan, 2003; Kaup, Ludtke, & Zwaan, 2005; MacDonald & Just, 1989), prompting it (Kaup, Yaxley, Madden, Zwaan & Lüdtke, 2007), evoking a complementary scenario (Kaup et al., 2005; Orenes, Beltrán & Santamaría, 2014; Orenes & Santamaría, 2014), and increasing overall cognitive effort (Carpenter & Just, 1975; Clark & Chase, 1972; Kaup, 2006). Also, negation seems to reduce motor cortex involvement during processing of action sentences (Aravena et al., 2012; Bartoli et al., 2013; Foroni & Semin 2013; Liuzza, Candidi, & Aglioti, 2011). More particularly, recent evidence indicates that negation may be neurocognitively rooted in mechanisms specialized for response inhibition (Beltrán, Muñetón-Ayala & de Vega, 2018; de Vega et al., 2016; García et al., 2016; Papeo, Hochmann, & Battelli, 2016).

For instance, relative to their affirmative counterparts, negative action sentences (e.g., *Now you will not cut the bread*) involve reduced fronto-central theta power –a robust index of brain motor inhibition (de

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Vega et al., 2016)–, larger amplitude of the inhibition-related N1 component (Beltrán et al., 2018), greater and delayed event-related desynchronization of the mu rhythm –another classical marker of motor simulation (Alemanno et al., 2012)–, and hypoactivation of putative motor hubs (Tettamanti et al., 2008). Compatibly, single-pulse transcranial magnetic stimulation over the left precentral gyrus increases the amplitude of motor-evoked potentials for action relative to state verbs in affirmative sentences, but no such modulation occurs in negative contexts (Papeo et al., 2016). By contrast, as compared to affirmative sentences, negative sentences increase the cortical silent period, a proposed marker of GABAergic system activity (Papeo et al. 2016). More indirectly, patients with atrophy of regions implicated in inhibitory processes, such as frontostriatal networks (Jahanshahi, Obeso, Rothwell, & Obeso, 2015; Jahanshahi & Rothwell, 2017), are characterized by atypical production of negative markers in spontaneous discourse (García et al., 2016). Taken together, these findings suggest that a key mechanism underlying sentential negation processing consists in recycling neural networks which are (non-exclusively) involved in response inhibition (Mirabella, 2014; for a critical view on this point see Aron, Robbins & Poldrack, 2014), such as the suppression of preplanned reaching arm movements (e.g., Mirabella, Pani & Ferraina, 2011; Mattia et al., 2012) or voluntary prevention of a prepared action (Coxon, Stinear & Byblow, 2006).

However, no study has explored the relationship between negation and inhibitory processes via dynamic written production measures. Note, in this sense, that most tasks in the field involve physical and/or verbal behavior patterns that rarely, if ever, occur beyond laboratory settings –e.g., placing the hand's index finger and thumb in a pinch position and separating them to respond to specific stimuli, while striving to maintain a constant distance between them throughout the experimental session (Dalla Volta, 2009)–, and they typically involve linguistic and motor processes that are only arbitrarily related –e.g., holding a pressure-sensitive cylinder while listening to words (Aravena et al., 2012)–, which may create unnatural executive or dual-task demands. Conversely, writing offers an elegant alternative to partially circumvent these limitations. In particular, keyboard typing is an activity in which linguistic and motor processes are consubstantiated, given that (effector-specific) motoric activity is indispensable for the completion of ongoing verbal processes. Moreover, since subjects can perform this task without restrictions on their bodily position or indications as to which fingers or hands to use for each trial, keyboard-typing paradigms may better reflect some of the conditions of daily physical activity. Of note, this approach has proven sensitive to tap into fine-grained motor-language coupling effects, showing that action verbs, in general, and manual action verbs (MaVs), in particular, can differentially interfere with motor programming and execution processes during typing (García & Ibáñez, 2016a).

Therefore, building on previous findings about the embodied basis of negation (Alemanno et al., 2012; Beltrán et al. 2018; de Vega et al., 2016; García et al., 2016; Papeo et al., 2016; Tettamanti et al., 2008), and considering that MaVs yield systematic effector-specific effects over manual movements (García & Ibáñez, 2016b), we advanced three interrelated hypotheses considering measures of motor planning and execution during typing. First, we predicted that typing of action verbs, relative to non-action verbs (nAVs), would yield (i) coarse-grained and (ii) effector-specific interference effects on non-manual action verbs (nMaVs) and MaVs, respectively. More crucially, we expected (iii) such interference to be greater in negative than affirmative sentences and to evince effector-specificity, as MaVs would be further delayed due to added inhibitory effects triggered by negation markers. In short, with this study, we aim to shed new light on the neurocognitive mechanisms engaged during processing of linguistic negation.

2. Methods

2.1. Participants

Sixty-four healthy adults carried out the experimental task and then completed a questionnaire including demographic questions and various items on computer and keyboard-typing skills. One of the participants was dismissed due to poor task performance. The final sample consisted of 63 (44 female) adults, with means of 21.2 years of age (*SD* = 4.8) and 16.3 years of education (*SD* = 1.8). All the participants fulfilled the study's inclusion criteria: they were highly educated, neurologically healthy native Spanish speakers with normal or corrected-to-normal vision, good overall computer and keyboard operation abilities, and a preference for QWERTY keyboards. Also, they were all right-handed, as determined by a Spanish translation of the Edinburgh Handedness Inventory (Oldfield, 1971).

Participants self-rated their abilities in the use of hardware and software on a five-point scale (1 = very low, 2 = low, 3 = intermediate, 4 = advanced, 5 = expert). The sample's operational knowledge of hardware (e.g., connecting devices) (*M* = 3.17, *SD* = .74) and software (e.g., handling documents) (*M* = 3.15, *SD* = .64) fell between intermediate and advanced. All subjects were frequent Windows users and rated their overall keyboard-typing skills between intermediate and advanced (*M* = 3.6, SD = .82), using a mean of 7.4 (*SD* = 2.5) fingers for such a task. As regards gaze habits during typing, 28 subjects claimed that they mainly focus on the screen, five were mostly keyboard lookers, and 30 reported similarly distributing their gaze between screen and keyboard.

The study was approved by the institutional ethics committee and carried out in accordance with the ethical standards of the Declaration of Helsinki. All participants gave informed consent and received course credit for their participation.

2.2. Materials

The stimuli comprised 72 two-sentence Spanish texts and four practice trials. The first sentence typically involved (impersonal) existential constructions, pointing to the presence of an object (*Ahí está la puerta* [*There is a door*]), person (*Ahí hay una mujer* [*There is a woman*]) or event (*He ahí una mentira* [*Here is a lie*]). The second sentence described an interaction between an implicit second-person subject (*you*) and the complement of the first sentence. Crucially, such an interaction could be presented with an affirmative (*Ahora sí la vas a abrir* [*Now you are going to open it*]) or a negative (*Ahora no la vas a abrir* [*Now you are not going to sign it*]) polarity marker (see Table 1). Note that, in Spanish, the presence of the particle *sí* [yes] and *no* [no] at the beginning of the verb phrase is quite frequent and natural, explicitly indexing the occurrence or non-occurrence of the process denoted by the verb.

In all cases, the second sentence ended with the infinitive form of the target verb. The stimulus set comprised 24 MaVs, denoting

Table 1
Examples of the materials. Illustrative sentences are shown for the six experimental conditions, resulting from crossing Polarity (affirmative, negative) and Verb Type (MaV, nMaV, nAV).

Example sentence	Verb type
Ahí está la puerta. Hoy [sí/no] la vas a **abrir** *There is the door. Today you are [not] going to* ***open*** *it*	MaV
Ahí está la mujer. Hoy [sí/no] le vas a **hablar** *There is the woman. Today you are [not] going to* ***talk*** *to her*	nMaV
He ahí una mentira. Ahora [sí/no] la vas a **creer** *Here is a lie. Now you will [not]* ***believe*** *it*	nAV

All examples are provided in Spanish (as appearing in the experiment), followed by their approximate English translations (in italics). MaV: manual action verb; nMaV: non-manual action verb; nAV: non-action verb.

movements of the hand (e.g., *abrir* [*to open*]); 24 nMaVs, denoting movements performed with body parts other than the hands (e.g., *hablar* [*to talk*]); and 24 nAVs, denoting mental or perceptual processes implying no physical action (e.g., *creer* [*to believe*]). Importantly, we conducted a rating study to statistically verify the adequacy of the stimuli selected for each category. To this end, we recruited a new sample of participants ($n = 20$), presented them with short versions of the stimuli –including just the verb and the complement (e.g., Trial 2: "Open the door")–, and asked them to indicate whether they believed each process was: (1) mainly performed with the arms/hands, (2) mainly performed with other parts of the body (feet, legs, mouth), or (3) done with no need to perform any bodily movement. Results showed that participants consistently associated each verb to its corresponding category (MaVs = 99.79%, nMaVs = 92.92%, nAVs = 96.04%). Raw scores and additional details for each stimulus are presented in Supplementary Data, Tables A1-A2. For additional stimulus details, see Supplementary Data A (Tables A3-A7). Also, to ensure that all three conditions were comparable in terms of their cognitive and typing demands, we implemented a four-step control procedure.

First, the three verb sets constructed were psycholinguistically comparable. ANOVA tests, based on normative data from the EsPal database (Duchon, Perea, Sebastián-Gallés, Martí & Carreiras, 2013), showed that they were similar in length [$F(2,69) = .07$, $p = .932$], log frequency [$F(2,69) = .364$, $p = .690$], familiarity [$F(2,69) = .554$, $p = .578$], number of orthographic neighbors [$F(2,69) = .581$, $p = .560$], Levenstein distance [$F(2,69) = .519$, $p = .597$], bigram frequency [$F(2,69) = .555$, $p = .577$], syllabic length [$F(2,69) = .936$, $p = .397$], and age of acquisition [$F(2,69) = .901$, $p = .411$]. Also, all target verbs ranged between four and eight letters, which guarantees that they could be read in a single ocular fixation (Lavidor & Ellis, 2002; Weekes, 1997).

Second, the three sets were also similar in terms of their (motoric) typing demands. Considering that, in QWERTY keyboards, left-side keys (up to 't', 'g', and 'v') are mostly typed with the left hand, whereas the remaining letters are typically typed with the right hand (Marklin & Simoneau, 2004), we calculated the number of keystrokes per hand required by each Verb Type. On average, our verbs involved more left-sided ($M = 4.5$; $SD = 1.21$) than right-sided ($M = 1.97$; $SD = 1.13$) keystrokes [$t(71) = 10.50$, $p < .001$], but no differences were observed among the verb categories either in left keys [$F(2,69) = .533$, $p = .59$] or right keys [$F(2,69) = .975$, $p = .38$]. Moreover, the number of first-, second-, and third-row keys requiring left and right-hand actions was similar across categories –first row, left hand [$F(2,69) = .275$, $p = .760$]; second row, left hand [$F(2,69) = .846$, $p = .433$]; third row, left hand [$F(2,69) = .487$, $p = .617$]; first row, right hand [$F(2,69) = .687$, $p = .507$]; second row, right hand [$F(2,69) = .74$, $p = .481$]; third row, right hand [$F(2,69) = .774$, $p = .465$]. Therefore, the traveling distance of hands and fingers can be presumed similar for all Verb Types. Finally, none of the words included characters requiring more than a single key press; thus, letters with diacritics, such as 'ü' and 'á', as well as the Spanish 'ñ', were avoided during stimulus selection.

Third, we ran a normative study with 61 volunteers to establish the level of association between the target verbs in each set and the complement they governed in each sentence. Rankings based on 7-point Likert scales showed that all verb-complement pairs had an association score of 4 or higher. Crucially, there were no differences between MaVs ($M = 5.76$; $SD = .86$), nMaVs ($M = 5.72$; $SD = 1.04$), and nAVs ($M = 5.29$; $SD = 1.03$) [$F(2,66) = 1.492$, $p = .232$].

Finally, to control for the effect of other sentence constituents, we compared the frequency of all nouns across sentences in each category. ANOVA tests, based on normative data from the EsPal database (Duchon et al., 2013), showed that there were no significant differences [$F(2, 46) = 1.1$, $p = .350$] in the lexical frequency of nouns in MaV sentences ($M = 56.6$; $SD = 53.7$), nMaV sentences ($M = 80.5$; $SD = 90.7$), and nAV sentences ($M = 90$; $SD = 75.4$) –for details, see Supplementary Data A (Table A8).

2.3. Design and procedure

We implemented a factorial design with two factors, namely Verb Type (MaV, nMaV, nAV) and Polarity (affirmative, negative). All participants were administered the full set of 72 two-sentence-long texts, such that 36 were presented with affirmative Polarity and 36 with negative Polarity. Sentences were completely randomized. The Polarity of the sentences was counterbalanced among subjects.

After completing the questionnaire described in Section 2.1, participants were tested individually in a dimly illuminated room. They sat comfortably at a desk, facing a laptop and a screen. Participants carried out the experiment on a computer on a QWERTY keyboard for Latin script including Spanish characters.

Instructions were first provided orally and then recapped on screen. Participants were asked to read a passage composed of two sentences. Stimulus presentation and response collection was conducted on E-Prime (Schneider, Eschman, & Zuccolotto, 2002). Each passage started with a 500-ms central fixation cross at the center of the screen, followed by the first sentence, which remained on the screen for 2000 ms. Next, after a 190-ms black screen, the second sentence was automatically presented word-by-word with a fixed delay (blank screen) between words of 190 ms –except for the screen preceding the target verb, which remained on screen for a random period between 250 and 350 ms. The fixation cross, as well as the first and the second sentences, were presented in the middle of a black panel occupying the upper half of the screen (font: Courier New; color: white; background: black; size: 48). When the last word (target verb) appeared, participants were prompted to type it as fast and accurately as possible. The paradigm made it unambiguously clear that this was the only word to be typed in each sentence, as it was the only item accompanied by an empty line (underscore sign), and it was always preceded by the deterministic construction "*Ahora sí [no] la vas a* ___ (*Now you are [not] going to* ___)", which was systematically present in all stimuli. Also, instructions were explicit about this point and, prior to the task, participants completed four practice trials in the presence of a researcher –importantly, although they had the opportunity to repeat this practice phase if they made mistakes, this was not necessary for any of the participants. It was emphasized that the target word should be written in a single, uninterrupted typing gesture. The 'delete' key was deactivated and no time restrictions were applied. The participants' keyboard actions appeared on the empty line located at the bottom of the screen, indicated by an underscore that moved forward with every typed character (simulating text entry in classic computer programs), with the same font features as those of the upper panel (Fig. 1). Participants were further instructed to press the spacebar upon completion of typing –this action triggered the following trial or the verification task described below.

To assess comprehension, in 30% of the trials (8 per condition, 24 in total), we included a sentence-picture verification task (Fig. 1). A single picture was shown depicting the described action or event. In half of the cases, the picture was masked with a light-red 'X', symbolically indicating that the action/event did not occur. All the pictures depicted the process denoted by the target verb, so that responses in this verification task required focusing on the sentence's polarity. For instance, after reading "*Ahí está la pelota. Ahora sí [no] la vas a patear* (*There is the ball. Now you are [not] going to kick it*)", participants saw a picture of a person kicking a ball, and this picture could be masked by a red cross or not. Subjects were instructed to respond "Yes" when the sentence was affirmative and the picture unmasked, or when the sentence was negative and the picture was masked; otherwise, they should press "No". The keys "2" and "9" in the top row of the keyboard were assigned for the yes-no responses. Half of the images were congruent with their corresponding two-sentence text.

Participants were randomly assigned to one of the two lists in which the two conditions of Polarity were counterbalanced. The yes-no

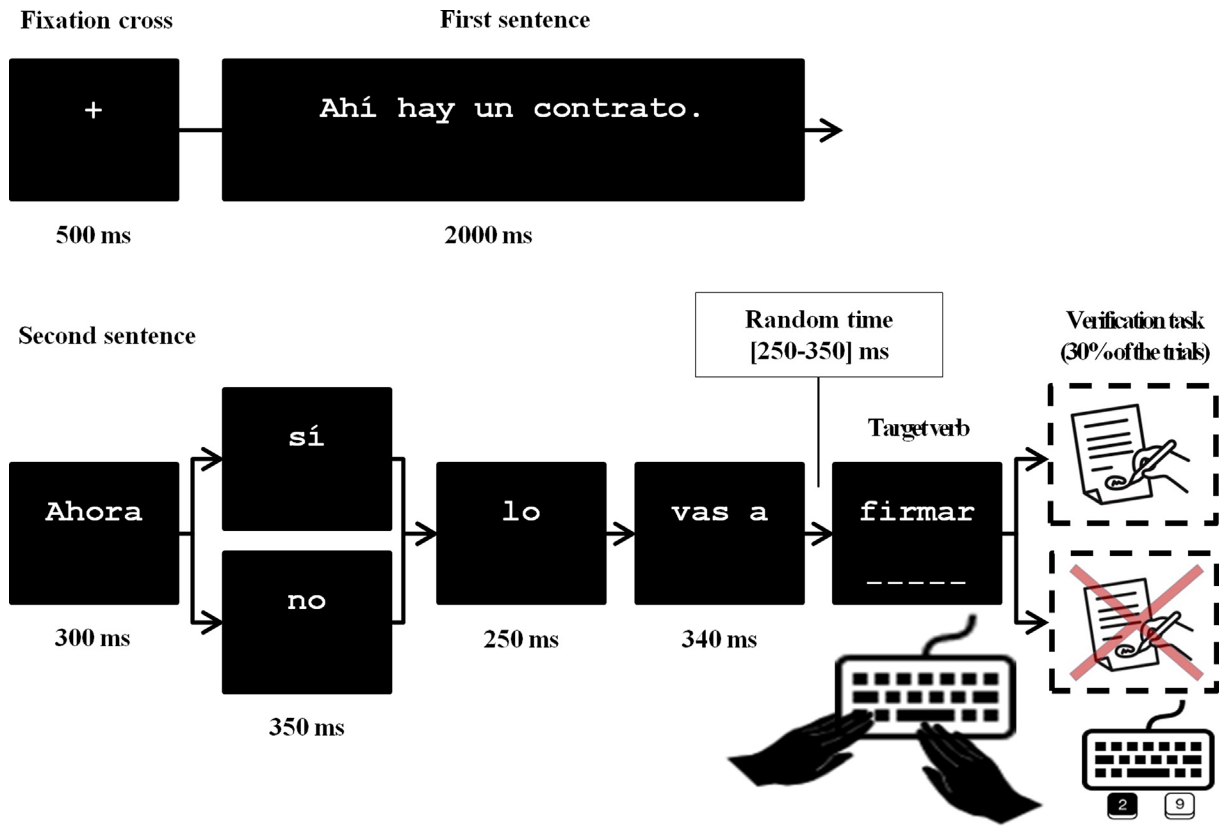

Fig. 1. Trial structure. The diagram illustrates a trial in the MaV condition, translatable as *There is a contract. Now you [are / are not] going to sign it*. The first sentence (shown all at once) set a semantic context and the second (presented one word at a time) finished with the target verb. Each item in the latter was preceded by a 190-ms black screen –except for the target verb, whose preceding black screen had a random duration between 250 and 350 ms. In a third of the trials, the subjects' typing response was followed by a sentence-picture verification task; in all cases, the process portrayed in this task matched the one denoted by the target verb, but only half of the trials matched the Polarity of the sentence (with the values 'affirmative' and 'negative' indicated by the presence or the absence of an 'X', respectively).

response for the verification task was counterbalanced among subjects and between the two lists, in such a way that all items appeared once in each list, but with a different Polarity. Before the experimental task, four additional practice trials were presented with stimuli not included in the experimental blocks. The complete session for each participant lasted roughly 20 min.

2.4. Statistical tests

As in a previous keylogging study (García & Ibáñez, 2016a), the main measures of interest were first-letter lag (FLL), indexed by the time-lapse between target presentation and the first keystroke made thereon; and whole-word lag (WWL), assessed considering the time-lapse between the first and last keystroke on a trial, prior to a spacebar press. FLL was taken as a proxy of motor programming. Instead, WWL indexed mechanisms at play during the unfolding of typing execution.

The E-Prime script calculated FLL and WWL for each trial. Any trial in which the target verb was not perfectly typed was automatically encoded as a miss and rejected as a failed response –i.e., responses in which the target verb was written with a typo, or with missing or added characters, were excluded from the analysis. Within each condition, no prior response restrictions were applied; on the analyses, response times that exceeded more than 2.5 *SD*s from the participant's mean (FLL or WWL) were also excluded. Finally, the remaining data were analyzed to obtain the FLL and WWL means for each condition and participant. We also calculated accuracy (percentage of errors) in the sentence-picture verification task.

A Polarity (affirmative, negative) by Verb Type (MaV, nMaV, nAV) repeated measures ANOVA was performed for the following dependent measures: verification task accuracy, failed typing responses, FLL, and WWL (with alpha levels set at $p < .05$). Tukey's post-hoc tests were used to examine pairwise comparisons for significant ANOVA results. Effect sizes for main effects and interactions were calculated based on partial eta squared, η_p^2. Depending on the value of this index, effect sizes can be considered small (> .02), medium (> .13), or large (> .26) (Cohen, 1988). All analyses included a Greenhouse-Geisser correction for departure from sphericity. Also, in order to further explore the role of Polarity and Verb Type in interaction effects, we performed separate ANOVAs to individually test each of these variables. Effect sizes for pair-wise comparisons were calculated via Cohen's d (Cohen, 1988). Depending on the value of d, effect sizes can be considered very small (0–0.20), small (0.20–0.50), medium (0.50–0.80), or large (> 0.80) (Cohen, 1988). All analyses were performed using the SPSS (v 24.0) statistical package (IBM corporation). The full dataset can be accessed online (García-Marco, 2018).

3. Results

3.1. Verification task accuracy

The mean of correct responses in the verification task was 81.15%. We observed a main effect of Polarity [$F(1, 62) = 31.75$, $p < .001$, $\eta_p^2 = .339$], with higher accuracy for affirmative ($M = 92.2\%$, $SD = 1.5\%$) than negative ($M = 70.1\%$, $SD = 3.9\%$) sentences. The main effect of Verb Type was also significant [$F(2, 124) = 7.08$, $p = .001$, $\eta_p^2 = .102$], there being fewer correct responses for images related to nAVs ($M = 76.8\%$, $SD = 2.4\%$) than for both MaVs ($M = 83.3\%$, $SD = 2.8\%$; $p < .01$) and nMaVs ($M = 83.3\%$, $SD = 2.4\%$; $p < .01$). The two variables interacted, under a Greenhouse-Geisser correction for sphericity [$F(2, 124) = 3.35$,

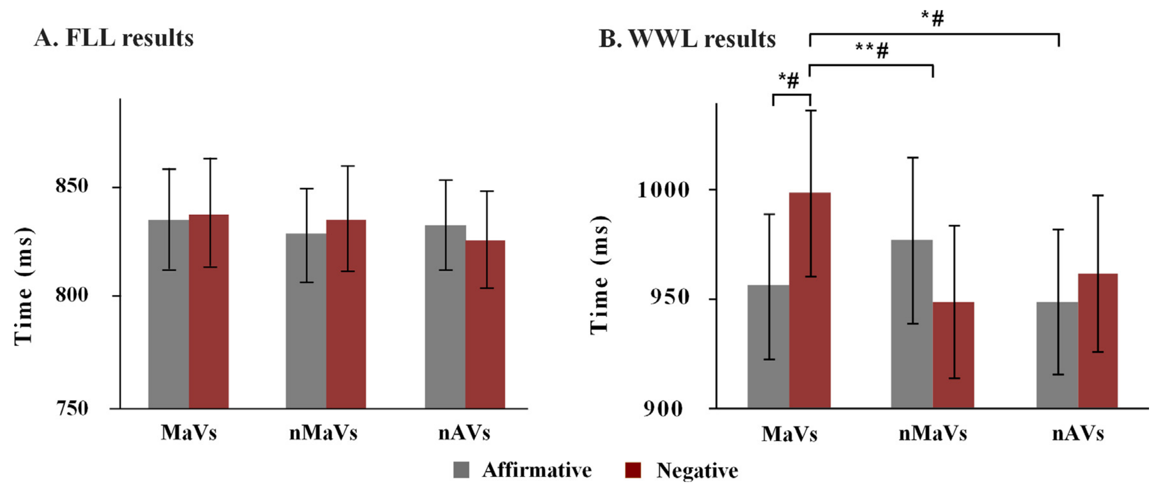

Fig. 2. Results. (A) First-letter lag (FLL). Negation had no significant effect on any verb type. (B) Whole-word lag (WWL). Negation of MaVs yielded selective delays in this measure, relative to affirmative MaVs as well as negative nMaVs and NAVs. Error bars represent standard errors. A single asterisk (*) indicates significant effects at $p < .05$; a double asterisk (**) denotes significant effects at $p < .01$; the hash (#) indicates significant effects surviving statistical correction for typing skills. MaVs: manual action verbs; nMaVs: non-manual action verbs; nAV: non-action verbs.

$p = .045$, $\eta_p^2 = .051$]. For additional details, see Supplementary Data B (Tables B1-B3).

3.2. Failed typing responses

The average number of failed typing responses was 10.03%, ranging from 8.99% to 11.24% across conditions. No significant effects of Verb Type [$F(2, 124) = .793$, $p = .455$, $\eta_p^2 = .013$] or Polarity [$F(1, 62) = 1.198$, $p = .278$, $\eta_p^2 = .019$] were observed, and the interaction between these factors was also non-significant [$F(2, 124) = .164$, $p = .849$, $\eta_p^2 = .003$]. For additional details, see Supplementary Data C (Tables C1-C3).

3.3. FLL results

FLL analyses revealed no main effects of Verb Type [$F(2, 124) = .515$, $p = .599$, $\eta_p^2 = .008$] or Polarity [$F(1, 62) = .126$, $p = .723$, $\eta_p^2 = .002$]. Neither did we observe a significant interaction between those factors [$F(2, 124) = .701$, $p = .498$, $\eta_p^2 = .011$]. For additional details, see Supplementary Data D (Tables D1-D3) and Fig. 2A.

3.4. WWL results

WLL analyses revealed a significant main effect of Verb Type [$F(2, 124) = 3.18$, $p = .0448$, $\eta_p^2 = .049$]. A post hoc test (Tukey's HSD) showed that MaVs ($M = 977$ ms, $SD = 281$) were typed significantly more slowly than nAVs ($M = 955$ ms, $SD = 274$; $p = .035$), there being no significant differences between MaVs and nMaVs ($M = 962$ ms, $SD = 288$; $p = .22$) or between nMaVs and nAVs ($p = .68$).

No main effect of Polarity was observed [$F(1, 62) = .68$, $p = .412$, $\eta_p^2 = .011$]. Nevertheless, the main effect of Verb Type was qualified by an interaction with Polarity, under a Greenhouse-Geisser correction for sphericity [$F(2, 124) = 3.607$, $p = .038$, $\eta_p^2 = .055$]. Pairwise comparisons ($MS = 10963$, $df = 124$) under the Hochberg method for three tests showed that WWL was longer for negative MaVs ($M = 998$ ms, $SD = 298$) than for affirmative MaVs ($M = 956$ ms, $SD = 263$, $p = .011$, $d = .149$). Also, negative MaVs yielded significantly longer WWLs than negative nMaVs ($M = 948$ ms, $SD = 279$, $p = .008$, $d = .173$] and negative nAVs ($M = 961$, $SD = 288$, $p < .049$, $d = .126$]. No other effects emerged. For additional details, see Supplementary Data E (Tables E1-E3) and Fig. 2B

Finally, to examine whether the above WWL results were linked to the participants' typing skills, we ran an ANCOVA with a relevant covariable based on the combination of the two self-reported measures: keyboard ability (very poor, poor, acceptable, good, very good) and gaze distribution during typing (keyboard looker, screen looker, keyboard-and-screen looker). This covariable had a significant effect on WWL [$F(1, 61) = 9.61$, $p < .003$]. The main effect of Verb Type disappeared after covariation [$F(2, 120) = .165$, $p = .848$, $\eta_p^2 = .003$]. Crucially, however, the interaction between Polarity and Verb Type remained significant after controlling for the effect of typing skills, upon application of a Greenhouse-Geisser correction [$F(2, 120) = 3.55$, $p = .040$, $\eta_p^2 = .055$]. Pairwise comparisons ($MS = 10803$, $df = 120$) under Hochberg's method for three tests showed that WWL was longer for negative MaVs than for affirmative MaVs ($p = .011$). Also, negative MaVs yielded significantly longer WWLs than negative nMaVs ($p < .008$) and negative nAVs ($p < .049$).

4. Discussion

This is the first study exploring whether and how the inhibitory properties of sentential negation affect motor processes during keyboard writing. As shown by FLL results, neither Verb Type nor Polarity affected the motor planning stage of typing. By contrast, WWL results evinced that negation selectively delayed typing execution for effector-congruent verbs (MaVs), and that this effect emerged independently of the subjects' self-reported typing skills. Therefore, the inhibitory effects of sentential negation seem to differentially affect the planning and execution stages of written production, yielding a selective effector-specific impact on the latter. Below we discuss our findings, highlighting their theoretical implications for the language embodiment framework.

The principal finding of our study concerned motor execution dynamics. The WWL measure yielded robust and highly specific results, typified by a selective delay for typing of MaVs in negative sentences –relative to every other condition, including affirmative MaVs (Fig. 2B). This finding aligns with previous research underscoring the inhibitory character of sentential negation. Relative to affirmative sentences, negative sentences reduce motor and premotor cortical activity (Tettamanti et al., 2008; Tomasino, Weiss, & Fink, 2010) and corticospinal excitability (Liuzza et al., 2011; Papeo et al., 2016), while also augmenting motor mu rhythm desynchronization (Alemanno et al., 2012), modulating inhibitory frontal theta rhythms (de Vega et al., 2016), and increasing the amplitude of the N1 component, a marker of proactive inhibition (Beltrán et al., 2018). In light of this empirical background, we propose that the specific delay observed for MaVs could reflect the direct recruitment of inhibitory mechanisms by linguistic negation.

The most notable aspect of the above finding is its effector-specificity, as negation selectively delayed the typing of verbs denoting the very body part used for typing. Previous studies comparing MaVs with abstract (mainly including 'mental') verbs have shown that, when negated, only the former interfere with arm kinematics (Bartoli et al., 2013) and increase the silent period induced by transcranial magnetic stimulation –indexing modulation of GABAergic activity in the inhibition process, according to Papeo et al.'s (2016) interpretation of their results. Importantly, despite its valuable contributions, this evidence fails to reveal whether the observed effects were specific to effector-compatible verbs or general to any type of action verb. In this sense, our finding that the Polarity effects observed for MaVs did not emerge for either nAVs or, more crucially, nMaVs, refines extant evidence by revealing that the inhibitory effects of negation on action execution can manifest in an effector-selective fashion –a feature that characterizes other forms of motor-language interaction (García & Ibáñez, 2016b).

Furthermore, the selective effect of negation on WWL for MaVs remained even when correcting for the subjects' typing skills. This is a non-trivial result, given that motor training can modulate action-language processing (Trevisan, Sedeño, Birba, Ibáñez & García, 2017), even at an effector-specific level (Glenberg, Sato & Cattaneo, 2008). Therefore, our main finding seems potentially generalizable across multiple levels of task-specific dexterity.

On the other hand, the FLL measure yielded null effects of Polarity and Verb Type (Fig. 2A). While this may seem unexpected, the dynamics of action-language embodiment seem to entail a tradeoff between execution and planning processes. As shown elsewhere, effector-specific effects on motor execution (e.g., kinematic) measures are systematically accompanied by the *absence* of initial-movement effects (Boulenger et al., 2006, 2008; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Nazir et al., 2008). Moreover, this pattern aligns with the two-step hypothesis of sentential negation (Kaup, Yaxley, Madden, Zwaan & Lüdtke, 2007), which posits that comprehenders first simulate the negated state of the event and then simulate the actual events. Under this assumption, motor-planning processes would not be affected by the semantics of the negation because they would fall within the first simulation step, while motor-execution processes would manifest interference as the full event is construed in the second step. On the other hand, motor-planning effects are typically significant only when effector compatibility yields null (Mirabella, Iaconelli, Spadacenta, Federico, & Gallese, 2012) or opposite (Dalla Volta et al., 2009) effects on action unfolding. In fact, motor-planning effects during context-free verb typing become variously attenuated during motor execution (García & Ibáñez, 2016a), further demonstrating the uneven dynamics of pre- and post-execution stages.

More particularly, the lack of FLL effects in our study might reflect the impact of contextual factors. Unlike the isolated verbs used by García & Ibáñez (2016a), target words in our design were preceded by highly constraining texts. Added sentential integration costs across conditions –e.g., anaphoric referent resolution (Streb, Hennighausen, & Rösler, 2004; Nieuwland & Van Berkum, 2008)– may have overridden fine-grained embodied effects on FLL. Also, contextual constraints may have induced gross predictions of the incoming verb's features, further reducing motor planning effects –note that target verbs in our study were strongly associated to a preceding complement (see Section 2.2 and Supplementary Data A). As suggested by cloze probability principles, the noun in *There is the door* is likely to prime verbs such *open* or *close*, pre-activating manual motor plans, whereas the context *This is a lie* may prompt the activation of mental verbs like *believe* or *ignore* (Tremblay, Sato & Small, 2012; Boulenger et al., 2008). Given that contextual variables can modulate early embodied dynamics (García & Ibáñez, 2016b), including the elimination of gross-motor and effector-specific action-language grounding effects (Gianelli & Dalla Volta, 2015), the differences between present and previous keylogging results likely reflect the impact of task-related factors.

While the above issue requires further research, our overall findings have noteworthy theoretical implications. In particular, they allow extending the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model (García & Ibáñez, 2016b), a fine-grained account of motor-language coupling effects. HANDLE posits that, in the absence of polarity markers, processing of MaVs can delay immediate manual actions via *interference*: as two processes (one semantic, one motoric) are recruiting *(partially) shared* circuits, the second one does not have full access to its putative resources and is thus delayed (Mirabella et al., 2012, 2017; Spadacenta, Gallese, Fragola & Mirabella, 2014). Yet, in a complementary fashion, our experiment indicates that effector-specific delays can also occur via *inhibition*: negation markers would activate action-suppression mechanisms which *act on* hand-specific motor circuits. This second operation is well supported by previously cited studies showing that negative action sentences directly modulate general brain signatures of motor inhibition (Beltrán et al., 2018; de Vega et al., 2016; Papeo et al. 2016). Additional research on these two mechanisms could yield important constraints for HANDLE and other language embodiment models.

Finally, unlike all previous research on sentential negation, this study was based on an everyday keyboard typing task, which partially circumvents the dual-task demands characterizing several tasks in the field of embodied semantics (García & Ibáñez, 2016b). Our results thus offer unprecedented evidence that the recruitment of inhibitory mechanisms by sentential negation also holds in tasks which seamlessly integrate motoric and linguistic processes. In this sense, the present approach could be further adapted to partially reduce the artificiality of embodied paradigms, a pressing requisite in the field (Desai, Choi, Lai & Henderson, 2016; García et al., 2016, 2018; Ibáñez & García, 2018; Kurby & Zacks, 2013; Trevisan et al., 2017).

5. Limitations and avenues for further research

The present study features a number of limitations, which pave the way for additional research. First, our protocol did not include baseline measures of the participants' inhibitory and comprehension skills. Although our within-subject design and experimental controls circumvented potential confounds related to these factors, their inclusion as predictors could prove greatly informative in future replications. Second, concerning the verification task, it could be possible that participants responded based on peripheral characteristics of the stimuli –e.g., using ad hoc strategies, such that if the sentence featured the word 'no' and the picture had an 'X', then the response should be 'yes'. However, this does not seem to be the case, given that negation only affected the verification of MaVs, discarding the possibility of superficial content-independent processing. Notwithstanding, eventual replications of our study could directly assess this issue via specific experimental manipulations.

Third, our protocol made no provision for obtaining neural markers of inhibitory dynamics. Even though robust behavioral paradigms are self-sufficient to reveal fine-grained aspects of embodied mechanisms (García & Ibáñez, 2016b), complementary insights could be gained through measures of time-frequency (de Vega et al., 2016), ERP (Beltrán et al., 2018), and stimulation-induced (Papeo et al. 2016) markers of motor inhibition. Fourth, all stimuli in our task had the same structure. Whereas this typical practice (for a review, see García & Ibáñez, 2016b) allowed for a strict control of lexical and grammatical variables across conditions, it also diminished the study's ecological validity, calling for more naturalistic adaptations of our protocol in the future. In particular, ecological validity could be increased if the writing task allowed for freer linguistic production, as opposed to being confined to copying a single sentence-final verb. Finally, note that, in line with previous works (e.g., Aravena et al, 2010; Klatzky, Pellegrino, McCloskey, & Doherty, 1989; Borghi & Scorolli, 2009; Santana & de

Vega, 2013; Ibáñez et al., 2013), our evidence of effector specificity stems from the detection of differential effects between one verb category and one specific body part. However, a fuller demonstration of effector-specific phenomena could be pursued in future research testing for similar (and, ideally, dissociative) effects between (affirmative and negative) leg-related verbs and foot actions, relative to (affirmative and negative) MaVs and hand actions (see, for example, Buccino et al., 2005).

At the same time, our study motivates new questions for the field. For example, what is the functional impact of negation on nAVs and other types of abstract content words? Also, more generally, are there specific embodied mechanisms underlying the processing of other syntactic elements, like subordinators, disjunctions or counterfactual markers? Further investigation along these lines will allow developing the embodied language framework beyond its usual focus on concrete, factual expressions alluding to external entities.

6. Conclusion

This is the first study on the embodied basis of sentential negation using a keyboard-based writing task. Despite yielding null effects on motor-planning processes, negation selectively delayed typing execution for MaVs (namely, the verbs coinciding with the active body part), irrespective of the participants' typing skills. Such a finding constitutes the first demonstration of a robust, effector-specific inhibitory effect of negation during language production. Promising avenues are thus opened to explore novel aspects of negation-related inhibitory dynamics and, more generally, of the grounding of highly abstract linguistic expressions.

Conflict of interest

None to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2018.10.020.

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