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How words ripple through bilingual hands: Motor-language coupling during L1 and L2 writing

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ABSTRACT

The speed of our hand movements can be affected by concurrent processing of manual action verbs (MaVs). Whereas this phenomenon is well established for native languages (L1s), it remains underexplored in late foreign languages (L2s), especially during highly automatized tasks. Here we timed keystroke activity while Spanish-English bilinguals copied MaVs, non-manual action verbs, and non-action verbs in their L1 and L2. Motor planning and execution dynamics were indexed by first-letter lag (the time-lapse between word presentation and first keystroke) and whole-word lag (the time-lapse between first and last keystroke), respectively. Despite yielding no effects on motor planning, MaVs facilitated typing execution in L1 but delayed it in L2, irrespective of the subjects' typing skills, age of L2 learning, and L2 competence. Therefore, motor-language coupling effects seem to be present in both languages though they can arise differently in each. These results extend language grounding models, illuminating the role of embodied mechanisms throughout life.

1. Introduction

Research within the embodiment framework (Birba et al., 2020; García et al., 2019, 2020; Pulvermüller, 2013, 2018) has revealed intimate links between language processing and bodily movements, both in experimental (Birba et al., 2017; Cardona et al., 2013; García and Ibáñez, 2016a; Pulvermüller, 2005) and daily life (Tomasello, 2009) settings. In particular, several studies on first-language (L1) processing have shown that manual action verbs (MaVs) can affect concurrent manual movements, yielding predictable facilitation or interference effects depending on stimulus- and task-related factors (García and Ibáñez, 2016a). However, beyond incipient works (Ahlberg et al., 2017; Vukovic, 2013), little is known about how these dynamics are differentially modulated depending on when a language was acquired. Promisingly, useful insights can be obtained by contrasting motor-language coupling mechanisms in L1 and late-learned second languages (L2s) –namely, languages appropriated after age seven (Kogan et al., 2020). Built on this premise, the present study profited from a validated keyboard writing paradigm (García-Marco et al., 2019; García and Ibáñez, 2016b) to explore whether motor planning and execution dynamics are differentially affected during typing of MaVs and non-manual action verbs (nMaVs) in L1 and L2.

Motor-language coupling is a ubiquitous phenomenon whereby lexico-semantic information affects ongoing movement dynamics, and vice versa (Bergen et al., 2010; Mirabella et al., 2012; Spadacenta et al., 2014). Relative to nMaVs and other word classes, MaVs can delay

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single-key presses (Bergen et al., 2010) or hand displacements (Mirabella et al., 2012) and facilitate different object-targeted movements (Boulenger et al., 2006; Fargier et al., 2012; Gentilucci, 2003). Evidence on these functional links proves abundant in L1 research, boosting current understanding of the interactions between verbal and motoric processes in languages acquired since birth (García and Ibáñez, 2016a). Conversely, only a few studies have compared these synergies in L1s and L2s, prompting questions on how language and movement are integrated in the latter. This is unfortunate, not only because more than half the world's population communicates daily in L2 (Eberhard et al., 2019; Grosjean and Li, 2013), but also because L2 research has proven critical to fine-tune our understanding of language processing, in general (Grant et al., 2019; Hirosh and Degani, 2018), and the developmental determinants of embodied mechanisms, in particular (Kogan et al., 2020).

Still, a few relevant studies are available, yielding somewhat mixed results. For example, behavioral studies (Ahlberg et al., 2017; Dudschig, de la Vega and Kaup, 2014) have shown similar patterns of motor-language coupling for both languages. However, neurally speaking, motor system modulations during action-verb processing typically differ between L1 and L2, with some findings indicating weaker effects for the latter (De Grauwe, Willems, Rueschemeyer, Lemhofer and Schriefers, 2014; Vukovic and Shtyrov, 2014; Zhang et al., 2020) and others exhibiting the opposite pattern (Tian et al., 2020). Conceivably, these inconsistencies could reflect differences in subject-related variables across studies, especially considering that sensorimotor grounding during action language processing is associated with L2 proficiency and age of acquisition (Birba et al., 2020). Therefore, as proposed in an overarching review (Kogan et al., 2020), motor-language coupling dynamics may, under certain conditions, operate differentially for L1 and L2.

Such discrepant patterns can be interpreted in terms of the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model, a systematic account of synergies between lexico-semantic and manual processes (García and Ibáñez, 2016a). According to HANDLE, motor-language coupling may manifest as facilitation or interference depending on several factors, crucially including ongoing semantic demands: the higher these are, the greater the level of language-induced sensorimotor resonance, leading to reduced availability of motor resources for concomitant action performance (García and Ibáñez, 2016a). Indeed, behavioral (Dijkgraaf et al., 2019), electrophysiological (Moreno and Kutas, 2005), and neuroimaging (Chen et al., 2015) evidence convergently shows that lexico-semantic systems are significantly more taxed during L2 than L1 processing. These differential neurocognitive dynamics suggest that a task imposing high motoric and semantic demands could entail dissimilar motor-language coupling patterns in L1 and L2, owing to reduced availability of motor resources for the latter.

A promising framework to address the issue is afforded by embodied writing tasks (Afonso et al., 2019; García-Marco et al., 2019; García and Ibáñez, 2016b). Unlike classical language embodiment paradigms involving dual-task demands, such as recognizing a word/object via single-key presses (Buccino et al., 2017) or responding to a target word on a vertically oriented keyboard (Ahlberg et al., 2017; Dudschig et al., 2014), writing tasks offer a more ecological setting as they naturally imply the consubstantiation of linguistic and motoric processes in a highly frequent and automatized daily activity. Moreover, keyboard typing tasks in L1 (García-Marco et al., 2019; García and Ibáñez, 2016b) have allowed disentangling the impact of MaV processing on motor planning and execution, paving the way for fruitful research on how motor-language coupling manifests across different processing stages in a bilingual's two languages.

Against this background, we conducted the first assessment of motor-language coupling dynamics during keyboard typing in an early (L1) and a late (L2) language (here, Spanish and English, respectively). Considering that increased semantic demands during MaV processing reduce the availability of motor resources and delay concomitant hand movements (García and Ibáñez, 2016a), and given that lexico-semantic demands are typically higher for L2 than L1 (Chen et al., 2015; Dijkgraaf et al., 2019; Moreno and Kutas, 2005), we hypothesized that, relative to nMaVs, MaVs would be typed faster in L1-Spanish and more slowly in L2-English. Also, we explored whether such predicted effects were sensitive to relevant motoric (typing skills) and linguistic (age of L2 learning and L2 competence) factors. Overall, this study aims to further our understanding of the integration of verbal and bodily processes depending on when a language was appropriated.

2. Materials and methods

2.1. Participants

The study involved 45 native Spanish speakers with intermediate to high competence in English. However, three of them were dismissed because they failed to complete the tasks, and other three were discarded due to poor task compliance (they spent an average of roughly 10 s to initiate the typing routine). The final sample comprised 39 right-handed healthy adults (22 female) with normal or corrected-to-normal vision and means of 25.10 years of age ($SD = 6.86$) and 17.9 years of education ($SD = 3.06$). The group's mean age of L2 learning was 7.59 ($SD = 2.99$). L2 competence was established with an abridged version of the Language History Questionnaire 2.0, a validated (Li et al., 2013) and widely used (Gullifer and Titone, 2019; Hartanto and Yang, 2016, 2020; Hoversten and Traxler, 2020) self-report tool including measures of reading, writing, speaking, and listening skills. On a scale from 1 (null) to 7 (optimal), the sample's mean global L2 competence (averaging the outcomes in each macroskill) was 5.47 ($SD = .74$).

Participants self-rated their abilities as hardware, software, and keyboard users 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) and software (e.g., using various office automation programs) fell between intermediate and advanced, with means of 3.31 ($SD = .83$) and 3.29 ($SD = .67$), respectively. All subjects were frequent Windows users and declared a preference for QWERTY keyboards. Their overall typing skills (used for covariate analyses below) ranged from intermediate to advanced ($M = 3.77$, $SD = 0.80$), and they reported using a mean of 7.5 ($SD = 2.6$) fingers for such a task. As to gaze habits during typing, 18 participants were mostly screen-lookers, two were keyboard-lookers, and the rest reported equally distributing their gaze between screen and keyboard.

All participants provided written informed consent in accordance with the Declaration of Helsinki. The study was approved by the institutional ethics' committee.

2.2. Stimuli

Stimuli in both tasks consisted of brief sentences in present continuous tense, with the sentence-final target verb appearing as a 'gerundio' in L1-Spanish (e.g., *Estoy puliendo*) and as a 'present participle' in L2-English (e.g., *I am polishing*). The use of this grammatical construction served two purposes. First, it afforded a grammatical context (*Estoy /I am*) forcing the interpretation of the target words as verbs. This can rarely be achieved in English via decontextualized base forms, which are often identical to nouns –e.g., *pick* acts as a verb in *Guthrie Govan can pick every note with finesse* and as a noun in *Ritchie Kotzen no longer uses a pick to play guitar* (García et al., 2019). Second, the use of present continuous led to di-morphemic target words in both languages (e.g., *puliendo /polishing*), thus equating their structural processing demands. If isolated infinitive verbs had been used, as done in previous studies (Dalla Volta, Fabbri-Destro, Gentilucci and Avanzini, 2014; García and Ibáñez, 2016a; Mirabella et al., 2012), then L1 stimuli would have been di-morphemic (as infinitives in Spanish require both a root and a desinence) but L2 stimuli would have been mono-morphemic (as infinitives in English consist of a base form only).

In each task, the target verbs comprised 114 items organized in three blocks: MaVs ($N = 38$), denoting actions performed with the hands (e.g., *aplaudiendo* [*applauding*]); nMaVs ($N = 38$), denoting actions performed with body parts other than the hands (e.g., *mordiendo* [*biting*]); and NaVs ($N = 38$), denoting motionless cognitive or emotional states (e.g., *amando* [*loving*]). Univariate general linear model analyses showed that, within and across languages, all three blocks were comparable in frequency, age of acquisition, and orthographic length (see Appendix, Table 1). As expected, significant differences were observed in imageability across blocks for L1-Spanish and L2-English verbs, with *post hoc* analyses revealing that, in both languages, NaVs were less imageable than both MaVs and nMaVs, there being no significant differences between the latter two categories (see Appendix, Table 1).[1] Psycholinguistic measures for all stimuli were extracted from the EsPal database (Duchon et al., 2013) for L1-Spanish and from N-Watch (Davis, 2005) for L2-English –except for age of acquisition data, which was obtained through an *ad-hoc* questionnaire. Moreover, to keep motoric (typing) demands comparable across all three verb types, we ensured that the number of first-, second-, and third-row keys involving left- and right-hand actions was similar among all three categories within languages and between each individual category between languages (see Appendix, Tables 1–7). Finally, the use of diacritics (i.e., accent marks, umlaut, or the 'ñ' letter) was avoided for Spanish stimuli, so that none of the words required more than a single key press.

2.3. Design and procedure

The design and procedure was identical for the L1-Spanish and the L2-English tasks, which were counterbalanced across subjects. Participants were evaluated individually in a quiet room, where they sat comfortably at a desk facing a laptop equipped with a 15.6'' 16:9 HD (1366 x 768) LED backlight display and a QWERTY chiclet keyboard including both Spanish and English characters. In each trial, subjects were presented with a brief grammatical context (*Estoy*; in L1-Spanish; *I am*, in L2-English) followed by a target verb as described in section 2.2 (e.g., *puliendo*, in L1-Spanish; *polishing*, in L2-English). Participants were instructed to type the target verb as fast and accurately as possible in a single uninterrupted gesture. They were further told to press the spacebar after typing was complete, in order to launch the following trial. In each task (L1-Spanish, L2-English), stimuli from the three categories were pseudorandomly distributed to ensure that items with phonological or semantic similarity were at least two trials apart from each other.

Each trial began with an ocular fixation cross at the center of the screen. The verb remained on the screen until the participant gave a complete response. The fixation cross and the targets (font: Courier New; color: withe; size: 18; style: regular) were presented in the middle of a black panel occupying the upper half of the screen. Pressing the spacebar after the target was copied triggered the following trial. Trial-onset asynchrony randomly varied between 300 and 500 ms. The paradigm was designed and run on E-Prime software 2.1. A 1-min break was allowed between the L1-Spanish and the L2-English tasks. Before each task, ten extra trials in the corresponding language were included for familiarization purposes. For a detailed structure of a trial, see Fig. 1. The complete session lasted roughly 30 min.

3. Statistical analysis

As in previous keylogging studies (García-Marco et al., 2019; García and Ibáñez, 2016b), we considered three measures. First, accuracy was assessed in terms of failed typing responses, so that a trial was considered incorrect if its keyboard sequence included a typo and/or missing

[1] Given that NaVs are abstract and, consequently, less imageable than action verbs (Dalla Volta et al., 2014), these post hoc tests support the adequacy of the stimuli chosen for each category.

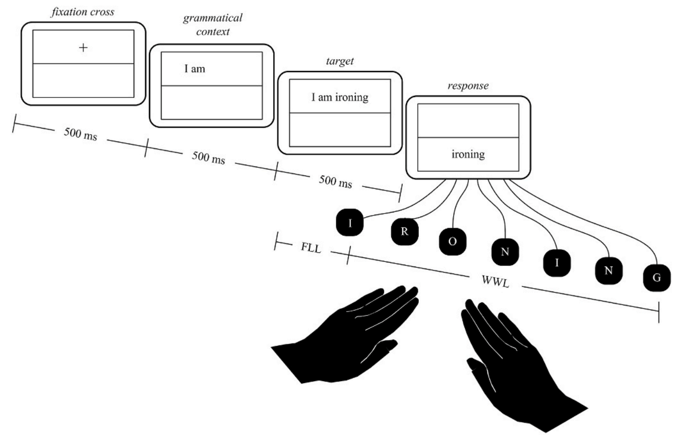

Fig. 1. Structure of a trial in the verb-copying task. Each trial began with a 500 ms ocular fixation cross at the center of the screen. A grammatical context then appeared (*Estoy*, in the L1-Spanish task; *I am*, in the L2-English task) on the screen during 500 ms until the target verb became visible. The target verb appeared as a *gerundio* in L1-Spanish (e.g., *planchando*) and as a present participle in L2-English (e.g., *ironing*). Participants were instructed to type the target verb as fast and accurately as possible in a single uninterrupted gesture. The verb remained on the screen until the participant gave a complete response. New trials were triggered by pressing the spacebar. Trial-onset asynchrony varied randomly between 300 and 500 ms. The same scheme was employed in both experiments. The figure illustrates a single trial from the L2-English task in the manual action verb condition. FLL: first-letter lag (lapse between target onset and first keystroke). WWL: whole-word lag (lapse between first and last keystroke).

or added characters (note that the 'delete' key was disabled during the tasks for this purpose). Second, motor programming was indexed by the first-letter lag (FLL) measure, defined as the time-lapse between word presentation and the first keystroke made thereon. Third, motor execution was operationalized as whole-word lag (WWL), namely, the time-lapse between the first and last keystroke on a trial –prior to a spacebar press for launching the following trial.

Data removal criteria were adopted directly from previous keylogging research (García-Marco et al., 2019). Within each condition, failed typing responses (as defined above) were automatically excluded from FLL and WWL analyses. Then, the E-Prime script automatically calculated FLL and WWL for each remaining trial, and responses were further rejected if they exceeded 2.5 *SDs* from the participant's mean in each measure and condition. Finally, with the remaining data we calculated the FLL and WWL means for each condition and participant.

Given that processing time typically differs between L1 and L2 (e.g., Dijkgraaf et al., 2019), to allow for comparability between languages we normalized data for each dependent variable (FLL, WWL) at the subject level. First, we calculated the mean and *SD* for each measure per subject across all conditions. Then, in line with standard procedures (Marmolejo-Ramos et al., 2014), we subtracted the subject's mean time from the latency of each correct item and divided the outcome by the corresponding *SD*. Transformed results for each variable (FLL, WWL) were analyzed with two-way ANOVAs including the factors of Language (L1, L2) and Verb Type (MaVs, nMaVs, NaVs). Follow-up analyses were applied for post-hoc examination of pairwise comparisons in significant ANOVA results. All results are expressed as z-scores.

As in previous writing experiments exploring embodied effects (Afonso et al., 2019; García-Marco et al., 2019), all analyses were performed with an exclusively by-subjects approach, as recommended for designs presenting carefully matched stimuli and sufficiently exhaustive lists of the key linguistic condition under study (here, MaVs) (Hutchinson et al., 2014; Raaijmakers, 2003; Wickens and Keppel, 1983). Under these circumstances, introduction of item variance would violate the assumptions of random effects models, thus compromising statistical power and potentially obscuring true effects (Hutchinson et al., 2014; Raaijmakers, 2003; Wickens and Keppel, 1983).

Effect sizes for main effects were calculated with partial eta squared (η_p^2), ranging from small (> .02) to medium (> .13) to large (> .26) (Cohen, 1988). Effect sizes for pairwise comparisons were calculated through Cohen's d (Cohen, 1988), an index that discriminates among small (0–0.20), medium (0.50–0.80), and large (>0.80) effects (Cohen, 1988). Also, to analyze the potential impact of task-relevant motor and linguistic factors on the observed results, all analyses yielding significant differences were subjected to ANCOVAs including three covariates: 'typing skills', 'age of L2 learning', and 'L2 competence'. Analyses were performed on R software (version 3.4.0), by means of the ULLRToolbox (https://sites.google.com/site/ullrtoolbox/home), and G*Power (version 3.1.9.2) (Erdfelder et al., 1996). All experimental data, as well as the scripts used for their collection and analysis, are fully available online (García-Marco and García, 2020).

4. Results

4.1. Failed typing responses in L1-Spanish and L2-English

The total average number of failed typing responses was 10.9% (SD = 5.7%). There were no significant differences between L1-Spanish (M = 10.6%, SD = 7.2%) and L2-English (M = 11.2%, SD = 6.7%) [$F(2, 38) = .97$, $p = 33$, $\eta_p^2 = .02$], or among MaVs (M = 10.6%, SD = 7.2%), nMaVs (M = 11.3%, SD = 6.9%), and NaVs (M = 10.8%, SD = 6.8%) [$F(2, 76) = .60$, $p = .55$, $\eta_p^2 = .004$]. No interaction emerged between Language and Verb Type [$F(2, 76) = .04$, $p = .96$].

4.2. FLL results in L1-Spanish and L2-English

Analysis of FLL showed a significant effect of Language [$F(1, 38) = 17.94$, $p < .001$, $\eta_p^2 = .32$], with lower normalized latencies for L1-Spanish ($M = -0.24$ z, $SD = .23$ z) than L2-English ($M = .06$ z, $SD = .27$ z). The effect of Verb Type on FLL was not significant [$F(2, 76) = 0.39$, $p = .68$, $\eta_p^2 = .02$]. However, a significant interaction emerged between Language and Verb Type [$F(2, 76) = 6.97$, $p < .01$, $\eta_p^2 = .24$]. Post-hoc tests revealed that normalized FLL latencies were lower in L1-Spanish than L2-English when contrasting MaVs [$t(190) = 5{,}23$, $p < .001$, $d = 1.28$; L1: $M = -0.25$, $SD = .23$; L2: $M = -0.06$, $SD = .24$)], nMaVs [$t(190) = 3.68$, $p < .001$, $d = .79$; L1: $M = -0.19$, $SD = .25$; L2: $M = -0.02$, $SD = .28$], and NaVs [$t(190) = 6.82$, $p < .001$, $d = 1.52$; L1: $M = -0.30$, $SD = .22$; L2: $M = 0.09$ z, $SD = .30$]. No pairwise comparison between Verb Types yielded significant differences in either language (all p-values > .06). FLL results are summarized in Fig. 2A.

The above results remained similar after including 'typing skills', 'age of L2 learning' and 'L2 competence' together as covariates, as seen in the main effects of Language [$F(1, 35) = 17.73$, $p < .001$, $\eta_p^2 = .34$] and Verb Type [$F(2, 70) = 0.4$, $p = .67$, $\eta_p^2 = .02$], as well as in the interaction between Language and Verb Type [$F(2, 70) = 6.64$, $p < .01$, $\eta_p^2 = .24$] –all pairwise comparisons between Verb Types remained non-significant (all p-values > .06).

4.3. WWL results in L1-Spanish and L2-English

WWL results yielded a significant effect of Language [$F(1, 38) = 312.21$, $p < .001$, $\eta_p^2 = .89$], with lower normalized latencies for L1-Spanish ($M = -0.45$, $SD = .16$) than L2-English ($M = .36$ z, $SD = -0.20$). We also found a significant effect of Verb Type [$F(2, 76) = 16.93$, $p < .001$, $\eta_p^2 = .49$]. Post-hoc contrasts revealed that normalized WWL was lower for NaVs ($M = -0.11$, $SD = .43$) than MaVs ($M = .00$, $SD = .5$) [$t(190) = 3.89$, $p < .001$] and nMaVs ($M = -0.03$, $SD = .39$) [$t(190) = 2.70$, $p < .01$)]. The interaction between Language and Verb Type was also significant [$F(2, 76) = 22.47$, $p < .001$, $\eta_p^2 = .62$]. Post-hoc tests revealed that WWL was shorter for L1-Spanish than L2-English when considering MaVs [$t(190) = 24.14$, $p < .001$, $d = 5.86$; L1: $M = -0.47$ z, $SD = .15$ z; L2: $M = .47$ z, $SD = .17$ z], nMaVs [$t(190) = 18.24$, $p < .001$, $d = 4.49$; L1: $M = -0.39$ z, $SD = .15$ z; L2: $M = .32$ z, $SD = .17$ z], and NaVs [$t(190) = 19.41$, $p < .001$, $d = 3.88$; L1: $M = -0.49$ z, $SD = .16$ z; L2: $M = .27$ z, $SD = .22$ z]. More crucially, significant pairwise differences were observed in each language. In L1-Spanish, normalized WWL for MaVs was significantly shorter than for nMaVs [$t(190) = 2.12$, $p < .05$, $d = .87$] and similar to those of NaVs [$t(190) = .38$, $p = .70$, $d = .09$]. Also, WWL for nMaVs was significantly higher than for NaVs [$t(190) = 2.5$, $p < .05$, $d = .62$]. In L2-English, normalized WWL for MaVs was higher than for nMaVs [$t(190) = 3.80$, $p < .001$, $d = .87$] and NaVs [$t(190) = .38$, $p < .001$, $d = 1.01$]. WWL did not significantly differ between nMaVs and for NaVs [$t(190) = 1.32$, $p = .18$, $d = 0.26$]. WWL results are summarized in Fig. 2B.

All these results remained similar after including 'typing skills', 'age of L2 learning' and 'L2 competence' together as covariates, as seen in the main effects of Language [$F(1, 35) = 293$, $p < .001$, $\eta_p^2 = .89$] and Verb Type [$F(2, 70) = 16.99$, $p < .001$, $\eta_p^2 = .50$], as well as in the interaction between Language and Verb Type [$F(2, 70) = 21.19$, $p < .01$, $\eta_p^2 = .63$]. Post-hoc contrasts for this interaction effect showed that, in L1-Spanish, normalized WWL for MaVs was significantly shorter than for nMaVs [$t(175) = 2.06$, $p < .05$] and similar to those of NaVs [$t(175) = .37$, $p = .71$]. Also, WWL for nMaVs was significantly higher than for NaVs [$t(175) = 2.4$, $p < .05$]. In L2-English, normalized WWL for MaVs was higher than for nMaVs [$t(175) = 3.70$, $p < .001$] and NaVs [$t(175) = 4.98$, $p < .001$]. WWL did not differ between nMaVs and for NaVs [$t(175) = 1.29$, $p = .20$].

5. Discussion

This is the first study assessing motor-language coupling dynamics during verb writing in L1 and L2. Crucially, we found that, as compared to nMaVs, MaVs facilitated typing in L1-Spanish but delayed it in L2-English. Importantly, these effects held irrespective of the subjects' typing skills, age of L2 learning, and L2 competence. Below we discuss these findings and their theoretical implications for the language embodiment framework.

The main result for L1-Spanish was that MaVs yielded shorter WWLs than nMaVs. This effector-specific facilitation seems to mirror previous findings from single-word writing tasks in L1. In fact, whereas the presence of primes can variously modulate embodied effects during typing (García and Ibáñez, 2016b), single (non-primed) MaVs were observed to accelerate handwriting execution relative to nMaVs (Afonso et al., 2019). Moreover, L1 MaVs can increase manual action speed in tasks other than writing. For example, object-grasping is performed faster when the target object is semantically related to a cue word denoting a compatible body part (Lindemann et al., 2006), the portion of the object being grasped (Gentilucci et al., 2000), or a relevant type of grasp (Masson et al., 2008). Taken together, this evidence suggests that, under certain conditions (to be discussed later on), L1-Spanish action verbs can quicken effector-congruent movements in both laboratory-specific and ecological tasks.

Indeed, the observed facilitation effect for MaVs was such that their WWLs did not differ from those of NaVs (namely, the category whose meanings did not critically hinge on motor resources). Admittedly, even though this pattern is consistent with the predictions of the HANDLE model (García and Ibáñez, 2016a), its manifestation is not systematic across embodied writing tasks. For instance, keyboard typing can be facilitated if preceded by congruent primes for both these categories (García and Ibáñez, 2016b), but handwriting is faster for MaVs relative to both nMaVs and NaVs (Afonso et al., 2019). Notwithstanding these mixed findings, the critical point is that, in the present study, MaVs were typed significantly faster than nMaVs, its more specific contrastive

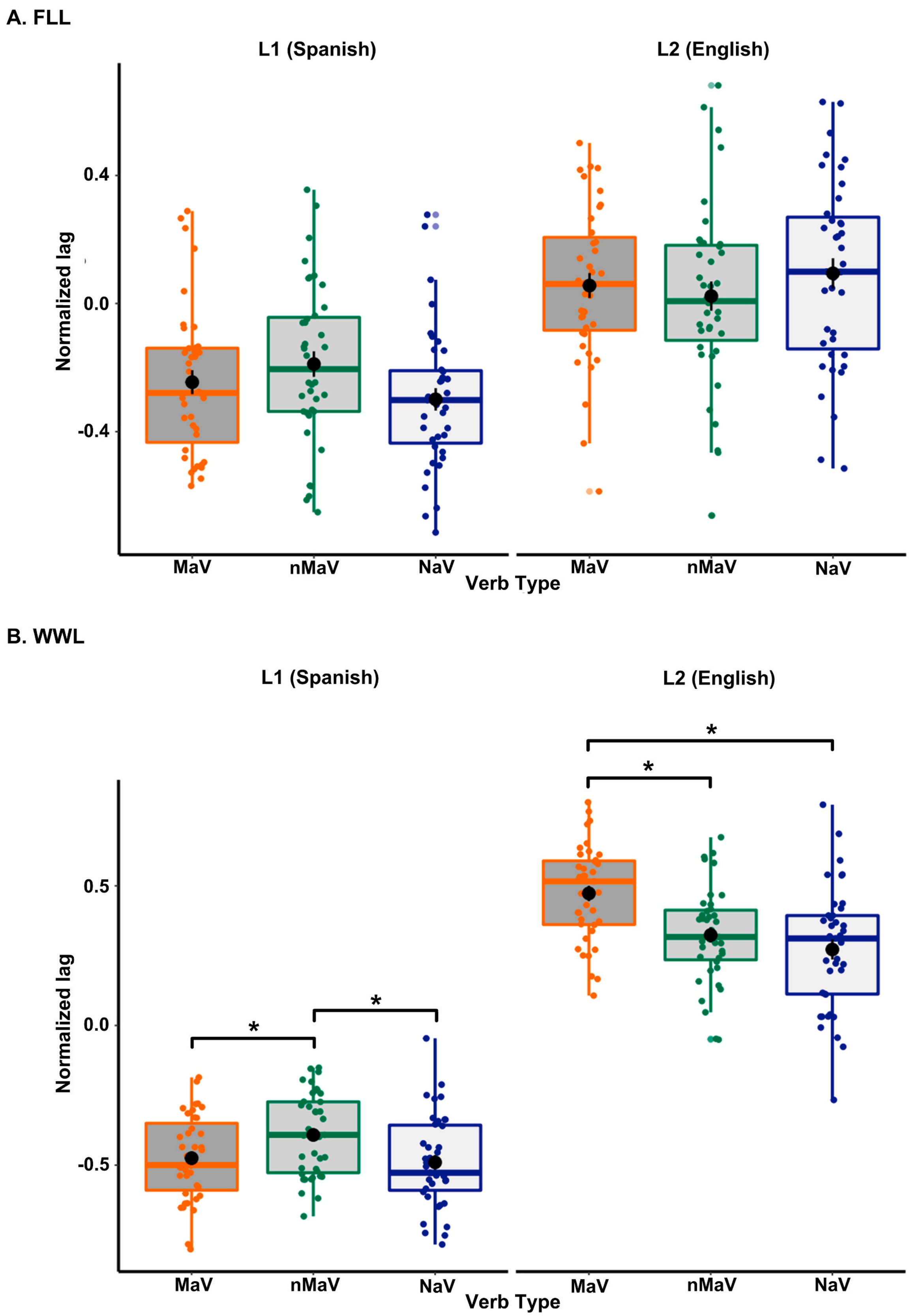

Fig. 2. First-letter lag (FLL) and whole-word lag (WWL) results in L1-Spanish and L2-English. (A) Normalized FLL for L1 and L2, reflecting motor planning latencies. The panel shows significantly faster performance for L1 than L2, with no significant differences between verb types within each language. (B) Normalized WLL for L1 (Spanish) and L2 (English), reflecting motor execution latencies. The panel shows significantly faster performance for L1 than L2, with different between-condition patterns in each language: in L1, WLL was shorter for MaVs than nMaVs and similar to that of NaVs; in L2, this measure yielded longer latencies for MaVs than nMaVs and NaVs. Error bars represent standard errors. Asterisks indicate statistically significant differences between conditions. MaVs: manual action verbs; nMaVs: non-manual action verbs; NaVs: non-action verbs.

condition, and that such facilitation seems to have been so strong that the ensuing WWL was similar to that yielded by words that did not compete for action-related resources (i.e., NaVs).

Conversely, in L2-English, MaVs involved longer WWLs than nMaVs. Although this seems to be the first evidence of motor-language coupling during L2 writing, it aligns with findings from other paradigms. For example, in L2 studies, specific manual actions (in particular, single key-presses) are performed more slowly when subjects face nouns denoting graspable objects (Buccino et al., 2017) or verb-picture pairs alluding to hand and/or arm actions (Bergen et al., 2010). Similarly, too, identification of translation equivalents in L2 via manual responses is delayed for MaVs relative to nMaVs (Vukovic, 2013). Our results could potentially extend these findings as they suggest that, at least in certain circumstances, processing of hand-related L2 words might delay not only paradigm-specific responses, but also highly automatized manual movements.

Such differences can be interpreted in light of the HANDLE model, originally proposed for L1s (García and Ibáñez, 2016a). According to HANDLE, MaVs can lead manual motor networks to sub-threshold states (during which partial activation of hand motor networks will favor faster manual actions) or supra-threshold states (during which manual actions will be delayed due to the transient unavailability of critical neural resources). Importantly, although long-latency manual responses, such as those involved in writing, are typically performed under sub-threshold states and thus become facilitated by MaVs (Afonso et al., 2019), a similar task could promote extended supra-threshold states and slower manual actions if semantic demands increase (García and Ibáñez, 2016a). Therein lies a plausible explanation for the opposite effects observed in L1-Spanish and L2-English. Whereas verb copying involves low semantic demands in L1 (Afonso et al., 2019; Bonin et al., 2015), these are presumably greater in L2. Indeed, in lexical tasks, even highly proficient bilinguals exhibit slower response latencies (Dijkgraaf et al., 2019), later N400 modulations (Moreno and Kutas, 2005), and increased activation in semantically-sensitive brain regions (Chen et al., 2015) in their L2 compared to their L1. Even more particularly, recent fMRI evidence shows that sluggish activations of motor regions, at least in certain circumstances, can be significantly higher during processing of L2 relative to L1 MaVs, irrespective of whether these are embedded in literal or metaphorical phrases (Tian et al., 2020). In fact, our results seem to be in line with this interpretation, given that measures of FLL and WWL consistently showed faster performance for L1-Spanish than L2-English (even when considering each verb type separately), tentatively suggesting increased processing demands for the latter. In sum, a combination of higher overall semantic demands and extended periods of motor-network hyper-activation by L2-English MaVs compared with L1-Spanish MaVs could partly explain why typing execution is delayed by the former though facilitated by the latter.

More generally, this discrepant pattern extends previous evidence of dissimilar neurocognitive effects during L1 and L2 processes. L1s and late L2s can be selectively affected by focal brain damage (García, 2015; Paradis, 2001) and they differ in their recruitment of declarative and procedural memory systems (Paradis, 2009; Ullman, 2001) as well as specific functional networks within anterior and posterior brain regions (Chee, 2009; Klein et al., 2006; Lucas et al., 2004; Ojemann and Whitaker, 1978). In fact, other embodied domains, such as syntactic processing (Birba et al., 2017; Casado et al., 2018; Pulvermüller, 2014), differentially recruit procedural motor networks in L1 and L2, as shown by evidence of greater deficits for the former than the latter language in Parkinson's disease patients (Johari et al., 2013; Zanini et al., 2004), characterized by disruptions of procedural/motor systems with relative sparing of declarative memory (Ullman, 2004) –for a detailed discussion, see Monaco et al., 2019. Also, and more crucially, action verbs in L1 and L2 differ in the patterns of sensorimotor resonance they induce across varying paradigms (De Grauwe et al., 2014; Tian et al., 2020; Vukovic and Shtyrov, 2014). Thus, motor-language coupling seems to mirror multiple other neurolinguistic effects in that its manifestation would depend on whether the language being used was incorporated since intra-uterine life (in L1s) or after the onset of middle childhood (in late L2s) (Kogan et al., 2020).

Note, too, that the differential effects observed for each language remained stable independently of typing skills. The point is non-trivial, given that several studies suggest that action-language processing can be modulated by bodily training (Trevisan et al., 2017), even in an effector-specific fashion (Glenberg et al., 2008). However, and in line with our results, MaV-specific motor-language coupling effects prove unaffected by daily motor practice during both handwriting (Afonso et al., 2019) and keyboard typing (García-Marco et al., 2019; García and Ibáñez, 2016b) tasks. In this sense, our results seem robust amidst inter-individual variability in task-specific (motoric) experience –although, admittedly, such variability may not be so large for tasks as highly automatized tasks as keyboard typing.

In the same vein, the present motor-language coupling effects did not covary with either age of L2 learning or L2 competence. These variables are well-known modulators of various language processes in bilinguals, including action-related sensorimotor resonance (Birba et al., 2020). Typically, lower language-learning ages involve more parallel co-activation of both languages (Canseco-Gonzalez et al., 2010), increased inhibition of the non-target language (Bylund et al., 2019), and differential reliance on lexical and conceptual routes (Sabourin et al., 2014), among other effects. Likewise, higher L2 competence is associated with more efficient lexical access (Kastenbaum et al., 2018) and reduced amplitudes of the N400 and the late positive complex during text processing (Yang et al., 2018). It is thus striking that our results proved uninfluenced by such two factors, especially considering that L2 experience has been previously observed to modulate embodied effects in bilinguals (Kogan et al., 2020). Tentatively, then, one could surmise that the impact of linguistic experience on L2 embodiment depends on task-related variables, although this conjecture should be systematically explored in future research.

On the other hand, motor planning outcomes (FLL) did not differ between MaVs and other categories in either language. This trade-off between motor planning and execution has been documented in previous keylogging (García-Marco et al., 2019) and handwriting (Afonso et al., 2019) studies, both showing significant effector-specific effects on WWL with null effects on FLL. Moreover, similar patterns have been observed in non-writing tasks. For example, across a variety of paradigms, analyses of hand-response dynamics following MaV processing have revealed effector-specific effects on motor execution but null outcomes on movement initiation (Boulenger et al., 2006, 2008; Dalla Volta, Gianelli, Campione and Gentilucci, 2009; Mirabella et al., 2012; Nazir et al., 2008). Moreover, whenever motor-language coupling paradigms yield significant action-planning effects, measures of action unfolding yield null (Mirabella et al., 2012) or inverse (Dalla Volta et al., 2009) effects. Our results not only seem to support the inconsistency of motor-language coupling effects across pre- and post-action-initiation stages, but they also suggest that such discrepancies may manifest for both L1s and L2s. A new avenue of research could thus be inaugurated to examine this intricate phenomenon in greater depth.

More generally, despite their preliminary nature, our results would be at odds with notion that L2 processing takes place without recruiting embodied mechanisms, as proposed by a review of emotional language processing in late bilinguals (Pavlenko, 2012). Indeed, that position seems untenable, not only because it is rooted in inadequate or unreliable methods (Kogan et al., 2020), but also because action words in late L2s systematically yield significant embodied effects (including effector-specific motor-language coupling) across multiple languages (e.g., English, Dutch, German) and tasks (e.g., lexical decision, image-verb matching, translation) (Kogan et al., 2020). In this sense, our results lend additional support to a full-blown embodied account of L2 processing, further suggesting that motor-language coupling may operate dissimilarly in L1s and late L2s.

Finally, and also in line with the framework advanced by Kogan et al.

(2020), our results seem to reinforce the notion that infant exposure is not necessary for words to be grounded in sensorimotor systems. If early exposure were indeed indispensable for embodied effects to emerge, then motor-language coupling patterns should be absent in late L2s. However, as shown elsewhere, effector-specific interference (Bergen et al., 2010; Buccino et al., 2017; Vukovic, 2013) has been observed when processing action-related words in languages acquired after age six. Moreover, enactment protocols in adults (ranging from 20 to 24 years old) have shown to improve novel word learning after only a few hours of training (García-Gámez and Macizo, 2018; Macedonia and Knösche, 2011; Macedonia and Mueller, 2016; Macedonia et al., 2011; Mayer et al., 2015). The present study offers further, ecologically valid evidence that language processing potentially hinges on embodied mechanisms even for languages learned well after early infancy.

6. Limitations and avenues for further research

Despite its contributions, this study carries a number of limitations which pave the way for a promising research agenda. First, though our sample size was fairly large compared to that of most behavioral studies in the field (Bergen et al., 2010; Buccino et al., 2017; De Grauwe et al., 2014; Dudschig et al., 2014; Ibáñez et al., 2010; Vukovic, 2013; Vukovic and Shtyrov, 2014; Vukovic and Williams, 2014; Xue et al., 2015), it would be desirable to replicate the present experiment with greater *N*s. Second, although typing abilities and L2 competence were controlled across participants and did not affect the observed outcomes, these data were self-reported. Thus, it would be useful for future studies to complement them with objective measures of keyboard skills (e.g., online typing tests) and objective measures of L2 skills –including various standardized tests for younger participants (Hulstijn, 2012) or even specific subscales of the Bilingual Aphasia Test (Paradis and Libben, 2014) for older samples (Juncos-Rabadán, 1994). Third, our study followed a standard practice in bilingualism research whereby only one language pair is tested without accompanying replications in different language pairs (e.g., Birba et al., 2020; Brouwer, 2020; Byers-Heinlein et al., 2017; Dottori et al., 2020; Jiao et al., 2020; Olguin et al., 2019; Vilas et al., 2019). Therefore, as is the case with most reports in the field, ensuing results cannot be a priori generalized to other language combinations or even to this very language dyad in the opposite direction (L1-English, L2-Spanish). Future renditions of our experiment in different language pairs would thus be crucial to assess whether the reported effects are language- or acquisition-time-dependent, ideally via pre-registered studies. Fourth, the target stimuli of our work (isolated MaVs) belong to a scarce lexical category. Given the number of stimuli per condition and our strict matching procedure, the present data did not lend itself to an analysis via mixed effects models. However, future studies targeting broader (and even randomly sampled) word categories should contemplate the impact of item variance under different settings. Also, as noted earlier, the lack of differences between MaVs and NaVs deviated from previous findings in the literature. This pattern invites more research to assess whether relative performance on these categories depends on the type of paradigm (e.g., primed vs no primed) and task (e.g., bimanual vs unimanual). Finally, despite its ecological properties, our paradigm employed relatively isolated stimuli. Hence, building on L1 (Desai et al., 2016; García et al., 2018; Trevisan et al., 2017) and L2 (Birba et al., 2020) embodiment studies, future renditions of our paradigm should include more context-rich materials, such as naturalistic narratives. This strategy would substantially enrich our understanding of motor-language coupling while meeting recent calls for more naturalistic language assessments at large (Kandylaki and Bornkessel-Schlesewsky, 2019; Verga and Kotz, 2019).

7. Conclusion

This is the first study to examine motor-language coupling during typing in an early and a late language. Compared to nMaVs, MaVs facilitated typing in L1-Spanish but delayed it in L2-English, a discrepant pattern that potentially reflects the greater semantic load imposed by the latter language. Remarkably, such effects remained present irrespective of the participants' typing abilities, age of L2 acquisition, and L2 competence. In sum, our results suggest that, across varying levels of motoric practice and linguistic experience, motor-language coupling effects might be present in L2-English, though they may manifest differently relative to L1-Spanish. More generally, this preliminary evidence suggests that motor-language coupling may take place even for languages lacking infant exposure, thus contributing tentative new insights on how embodied mechanisms operate throughout life.

Declarations of competing interest

None.

CRediT authorship contribution statement

Boris Kogan: Investigation, Writing - original draft. **Enrique García-Marco:** Formal analysis, Writing - original draft. **Agustina Birba:** Visualization, Writing - review & editing. **Camila Cortés:** Investigation. **Margherita Melloni:** Visualization, Writing - review & editing. **Agustín Ibáñez:** Writing - review & editing. **Adolfo M. García:** Conceptualization, Methodology, Resources, Validation, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

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