The embodied penman:
Effector-specific motor-language integration during handwriting

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Abstract

Several studies have yielded fine-grained insights on the embodied dynamics of language by revealing how processing of manual action verbs (MaVs) affects the programming or execution of concurrent hand movements. However, virtually all extant studies have relied on highly contrived dual tasks in which independent motoric and linguistic processes are arbitrarily related. To circumvent potential attentional confounds, we conducted the first assessment of motor-language integration during handwriting, an early acquired skill that necessarily integrates both types of processes. Using a digital pen, participants copied carefully matched MaVs, non-manual action verbs, and non-action verbs as we collected measures of motor programming (the time needed to start the writing routine after verb presentation) and motor execution (the time needed to write the whole verb). Whereas motor programming latencies were similar across conditions, the unfolding of motor routines was faster for MaVs than for the other two categories, irrespective of the subjects' daily writing time. Moreover, this effect remained consistent regardless of whether word meanings were accessed implicitly or explicitly. In line with the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model, such findings suggest that everyday manual movements can be primed by effector-congruent verbs, even in a highly automatized task that seamlessly combines linguistic and motoric processes. In addition, this effect differs from that observed for MaVs in a previous (keyboard-based) typing experiment, suggesting that language-induced sensorimotor resonance during writing depends on the motoric particularities of each production modality. More generally, our paradigm opens new avenues for fine-grained explorations of embodied language processes.

Keywords: embodied cognition; action verbs; motor-language integration; handwriting.

1. Introduction

Embodied cognition research has revealed intimate links between motoric and lexico-semantic mechanisms (García & Ibáñez, 2016a). A number of neuroimaging (e.g., Abrevaya et al., 2017; Liljestrom et al., 2008; Rodríguez-Ferreiro, Gennari, Davies, & Cuetos, 2011; Shtyrov, Butorina, Nikolaeva, & Stroganova, 2014) and brain stimulation (e.g., Kuipers, van Koningsbruggen, & Thierry, 2013; Papeo, Vallesi, Isaja, & Rumiati, 2009) experiments have illuminated such connections without forcing artificial relations between bodily movement and verbal operations –e.g., through passive reading tasks (for a review, see Pulvermüller, 2018). However, most behavioral evidence comes from highly contrived designs in which subjects must respond to target words by pushing a button with a closed hand, sliding a finger sideways on a computer screen or pinching objects from their lower end, among other examples –for a review, see García & Ibáñez (2016a). Though certainly informative, all such paradigms entail arbitrary relations between independent manual and linguistic processes and are thus potentially affected by attentional factors, since participants must keep track of two parallel sets of demands to coordinate verbal operations with artificially paired motoric responses. To examine these functional synergies while circumventing such limitations in behavioral research, we explored how processing of manual action verbs (MaVs) affects the kinematics of handwriting, a highly automatized human activity which seamlessly and necessarily integrates linguistic processing and hand movements.

Just as modality-specific (e.g., Mulatti, Treccani, & Job, 2014; Vermeulen, Corneille, & Niedenthal, 2008) and category-specific (e.g., Madebach, Wohner, Kieseler, & Jescheniak, 2017) information can yield varying grounding effects across perceptual dimensions, so can effector-specific words affect processes in the *motor* domain. Note, however, that action mechanisms possess unique functional features (Prinz, Beisert, & Herwig, 2013; Shadmehr, Smith, & Krakauer, 2010; Shin, Proctor, & Capaldi, 2010), so that their interaction with higher-order operations may not be directly inferred from perception-oriented studies. For example, contrary to most perceptual processes, bodily movements can be analyzed in terms of planning and execution stages, each of which can be differentially affected by ongoing cognitive operations. In particular, MaVs (e.g., *erase*, *applaud*, *caress*) can modulate concomitant manual responses in various ways, depending on task demands and the time-course of the ensuing motor resonance (García & Ibáñez, 2016a). To the best of our knowledge, the only framework that specifically accounts for such patterns is the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model (García & Ibáñez, 2016a), a proposal based on the analysis of 108 experiments and anchored in neuroimaging (Grabowski, Damasio, & Damasio, 1998) and predictive-coding (Bastos et al., 2012; Rao & Ballard, 1999) principles.

Couched in the embodied cognition framework, HANDLE is a neurolinguistic model aimed to explain why and how processing of MaVs can modulate overt manual behavior. Neuroanatomically, the model posits that MaVs (just like other action-related words) are subserved by widely distributed bidirectional systems spanning effector-specific sensorimotor circuits (along frontostriatal and parietal hubs) and multimodal semantic networks (with key hubs in the anterior and superior temporal gyri). In particular, MaV processing is proposed to distinctively modulate activity in somatotopic motor regions, creating specific interference or facilitation effects depending on stimulus- and task-related variables, such as the type of linguistic unit being processed, the complexity of the motoric response, the semantic demands involved by ongoing linguistic operations, and, more crucially, the time lapse between stimulus presentation and the associated hand movement.

Succinctly, HANDLE proposes that, upon presentation of a MaV, activation levels in hand motor networks will reach maximal (suprathreshold) activation levels for roughly 400 ms, followed by a progressive decline of (subthreshold) activation in subsequent time windows. This postulate follows from evidence that MaVs automatically enervate hand muscles within that temporal window –with gripping strength augmenting at 100 ms, peaking at 380 ms, and decaying after 400 ms (Frak et al., 2010)– and that they can delay or facilitate simple manual actions depending on whether these were performed before (Sato et al., 2008; Spadacenta et al., 2014) or after (Dalla Volta et al., 2009, 2014) the 400-ms mark, respectively. Building on such findings, HANDLE posits that, if a hand movement occurs while relevant motor networks are maximally activated, then both operations (MaV processing and manual action) would be competing for shared critical substrates; the ensuing manual action would not have optimal access to its underlying resources and would thus be delayed (Boulenger et al., 2006; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Nazir et al., 2008). By contrast, if a manual movement is performed when hand motor networks are in a given subthreshold (partially activated) state following MaV presentation, ensuing manual actions should be facilitated, as they would be primed by extant activity levels in those shared mechanisms –i.e., hand-specific processes would benefit from prior subthreshold excitation induced by MaVs (Dalla Volta, Fabbri-Destro, Gentilucci, & Avanzini, 2014; Dalla Volta et al., 2009). More particularly, the model further predicts that such facilitation effects could be observed even in long-latency windows when the task poses considerable linguistic or motoric demands (e.g., when one or two hands need to be coordinated to achieve fine-grained target-directed movements). Indeed, as observed in different studies (Glenberg & Kaschak, 2002; Kaschak & Borreggine, 2008; Lugli, Baroni, Gianelli, Borghi, & Nicoletti, 2012), such substantial demands can lead to durable subthreshold states capable of inducing priming even beyond two seconds after trial onset.

In addition to informing HANDLE, extant motor-language-coupling paradigms have illuminated numerous aspects of the interface between language and bodily action. Yet, despite their major contributions, virtually all such paradigms rely on dual tasks involving artificial, ad hoc combinations of verbal and motor processes, such as indicating sentence comprehension by pressing a predefined key on a vertically oriented keyboard (Borregine & Kaschak, 2006; Glenberg & Kaschak, 2002; Lugli et al., 2012), turning a knob (Zwaan & Taylor, 2006), pushing a huge button with a pre-assigned hand shape (Aravena et al., 2010), or grasping an object when reading a word (Lindemann, Stenneken, van Schie, & Bekkering, 2006).[1] In contrast to these tasks, writing affords a highly relevant framework to study dynamic embodied effects in a more naturalistic fashion, as in this activity hand movements are *necessary for and consubstantiated with* linguistic processes.

However, there is scant evidence on these dynamic synergies during written production. For example, using a keyboard typing task, García and Ibáñez (2016b) found that MaVs yielded distinct interference effects on motor planning (the time needed to type the first letter), which were notably reduced on motor execution (the time needed to type the whole word). Interestingly, this pattern mirrors previous research showing that interference on motor planning is usually accompanied by null (Mirabella, Iaconelli, Spadacenta, Federico, & Gallese, 2012) or facilitation (Dalla Volta, Gianelli, Campione, & Gentilucci, 2009) effects on execution measures, whereas execution effects often emerge alongside null motor-planning results (Boulenger et al., 2006; 2008; Dalla Volta et al., 2009; Nazir et al., 2008). In short, our results further indicate that embodied effects are characterized by a trade-off between both processing stages.

[1] Moreover, some of these tasks, including specific versions of the action-sentence compatibility effect paradigm, actually have low reliability across and within laboratories (Papesh, 2015). Further evidence on this issue has been garnered in a pre-registered, multi-centric replication study that is currently under revision (Kaschak et al., submitted).

While, *prima facie*, the effects observed for typewriting could be presumed valid for any writing modality, a different pattern could be expected for handwriting. Typewriting is a bimanual activity involving very similar motor patterns for each letter (downward finger motions), which basically vary in terms of which key is being pressed. Conversely, handwriting is accomplished with only one hand, and each letter requires a particular motor routine. Moreover, relative to studies on typing, those investigating handwriting usually report shorter response onsets but slower motor routine completion (Afonso, Suárez-Coalla, & Cuetos, 2015; Bertram, Tønnessen, Strömqvist, Hyönä, & Niemi, 2015; Delattre, Bonin, & Barry, 2006; García & Ibáñez, 2016b), further emphasizing the salient execution differences between both activities. In terms of the HANDLE model, these discrepancies should considerably modulate motor-language integration dynamics, resulting in different effects for each modality.

To address this issue, here we report the first investigation of motor-language coupling dynamics during handwriting of MaVs, non-manual actions verbs (nMaVs), and non-action verbs (nAVs). More particularly, we assessed the impact of these word classes on (a) motor programming, indexed by first-letter lag (FLL, the latency of writing onset); and (b) motor execution, represented by whole-word lag (WWL, the overall duration of a word's writing process). We conducted two word-copying experiments, one involving shallow processing and the other one requiring explicit semantic access. Guided by the HANDLE model, and considering that handwriting involves long response latencies (Afonso, Suárez-Coalla, González-Martín, & Cuetos, 2017; Damian & Stadthagen-Gonzalez, 2009; Delattre et al., 2006) which surpass those proper to typing (García & Ibáñez, 2016b) and fall within the timespan yielding facilitation effects on *motor execution* measures (e.g., Lugli et al., 2012), we hypothesized that production of MaVs would selectively reduce WWL –namely, the variable capturing motor execution latencies.

Moreover, by combining two separate experiments involving implicit and explicit semantic access, we examined the consistency of the predicted effects at different depths of processing. In particular, previous evidence indicates that embodied effects are varyingly sensitive to task-related factors, with some studies revealing them to emerge exclusively, more durably or similarly (for a review see García & Ibáñez, 2016a) in explicit relative to implicit semantic paradigms. However, previous writing studies in the embodied framework (García and Ibáñez, 2016b; García-Marco et al., 2019) have failed to consider both processing levels, thus casting doubts on the systematicity of such effects –which proves problematic, given that embodied effects may only be interpreted as primary if obtained via implicit tasks (García et al., 2019; Hauk et al., 2008; Kiefer et al., 2008; Mollo et al., 2016) and their thorough understanding calls for assessments contemplating both conditions (Fernandino et al., 2013). By addressing these questions, the present study aims to further illuminate the embodied synergy between linguistic and motoric processes during an early learned, highly automatized activity. In short, with this study we aim to further illuminate the embodied synergy between linguistic and motoric processes during an early learned, highly automatized activity.

2. Experiment 1

2.1. Methods

2.1.1. Participants

The study comprised 30 first-year undergraduate psychology students (23 female; 29 right-handed) from the University of Oviedo, who enrolled to fulfil a course credit requirement. A power estimation analysis on G*Power 3.1.9.2 (Faul, Erdfelder, Buchner, & Lang, 2009) revealed that this sample size ensured a power above .9, meaning that a true effect would almost certainly be detected.[2] The participants' age ranged from 20 to 36 (*M* = 21 years and 6 months, *SD* = 2 years and 7 months). All of them were native Spanish speakers, with no cognitive, linguistic, motor or perceptive disorders. Handwriting ability was assessed through a questionnaire (see Appendix, Table 1) including items about the average daily time spent handwriting (*M* = 108 minutes, *SD* = 109 minutes) and the estimated age at which they first began to develop such a skill (*M* = 4 years and 6 months, *SD* = 7 months). No subject had a history of handwriting difficulties. Importantly, at the time of testing, none of them had received any formal teaching about embodied cognition in their coursework. Before the study, all participants read and signed an informed consent form in accordance with the Declaration of Helsinki. The study was approved by the ethics' committee of the Faculty of Psychology of the University of Oviedo.

[2] Results from an a priori analysis of the required sample size to obtain a power of 0.9 in a repeated measures ANOVA –given the smallest size effect ($\eta_p 2 = 0.1$) obtained with a sample of 22 participants, and a value of $\alpha = 0.05$– revealed that a minimum sample size of 25 participants was required. This criterion was followed to establish the minimum sample size for both Experiment 1 and Experiment 2.

2.1.2. Materials

Experimental stimuli comprised 81 infinitive Spanish verbs, namely: 27 MaVs, denoting actions performed with the hands (e.g., *agarrar* [*grab*]); 27 nMaVs, evoking actions from other effectors (e.g., *agachar* [*bend down*]); and 27 nAVs, alluding to mental or affective processes that imply no bodily motion (e.g., *admirar* [*admire*]). To verify the adequacy of the stimuli selected for each category, we conducted a rating study following previously reported procedures (García-Marco et al., 2019). Thirty-eight native Spanish speakers were presented with the whole list of target verbs and asked 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 items for all three conditions were consistently associated to their assigned semantic category (MaVs = 99.22%, nMaVs = 94.05%, nAVs = 87.62%), with means similar to those obtained in previous validations of the same categories (García-Marco et al., 2019).

The adequacy of the stimuli selected for each condition was further confirmed by an analysis of their concreteness levels –based on data from BuscaPalabras (Davis & Perea, 2005). An ANOVA test revealed a significant effect of concreteness [$F(2, 44) = 10,776$, $p < .001$], with a post hoc analysis (Tukey's HSD test, MSE = .44852, $df = 44$) corroborating that nAVs were less concrete than both MaVs ($p = .001$) and nMaVs ($p < .001$). Crucially, however, no significant differences emerged between the latter two sets of words ($p = .83$). Note that, since nAVs are abstract by definition, they should in fact prove less concrete than action verbs at large (Dalla Volta et al., 2014; García & Ibáñez, 2016a).

Furthermore, verbs were matched across conditions in terms of (i) first-letter identity, (ii) total number of strokes [$F(2, 77) = .2$, $p = .82$], (iii) word frequency [$F(2, 77) = .01$, $p = .99$], (iv) orthographic length [$F(2, 77) = .47$, $p = .63$], (v) syllabic length [$F(2, 77) = .14$, $p = .87$], (vi) orthographic neighborhood [$F(2, 77) = .12$, $p = .89$], and (vii) mean bigram frequency [$F(2, 77) = .23$, $p = .79$] –based on data from BuscaPalabras (Davis & Perea, 2005)–, as well as (viii) age of acquisition [$F(2, 77) = .28$, $p = .75$] –based on validated norms (Alonso, Díez, & Fernández, 2016). The full set of experimental stimuli and descriptive statistics for each variable are provided in the Appendix (Tables 2 and 3, respectively). Forty-two additional words (21 verbs and 21 nouns) of the same orthographic length as the experimental words were selected as fillers to conceal the study's experimental manipulations. Prior to the task, participants completed a practice session with 10 words (5 nouns, 5 verbs) not included in the task.

2.1.3. Apparatus and procedure

The experiment consisted in an immediate copying task and was conducted individually in a sound-proof room. Participants were told that they would partake in a word writing experiment, but they remained unaware of its specific manipulations and underlying hypotheses until the task was over. They sat comfortably at a desk with a stimulus-display screen and a Wacom Intuos LD-1218-u digitizer, and they were given a digital pen. Stimulus presentation and digital recording of the responses were controlled by Ductus (Guinet & Kandel, 2010), a specialized software for the construction, implementation, and analysis of word-writing experiments, including kinematic measures of handwritten responses and detailed chronometric information of each response. The experiment was run on an Asus F9Eseries laptop. Each trial started with the presentation of a 300-ms fixation point in the center of the screen, immediately followed by a centered, lower-case, 16-point stimulus word that remained visible for 500 ms. Participants were instructed to use the digital pen to copy the word in upper case (print handwriting was not enforced), as fast and as accurately as possible, on a sheet of paper placed over the digitizer.[3] As in previous writing and spelling studies (Afonso, Álvarez, & Kandel, 2015; Afonso, Suárez-Coalla, et al., 2015; Tainturier & Rapp, 2004), the conversion of lower- to upper-case print ensured that the task forces sublexical and/or lexical access and the to-be-copied stimulus is processed as a linguistic form rather than a visual shape. Subjects were instructed to write each response on a line placed at the center of the paper, starting at the beginning of the line, which was marked with a cross (+). Once they had finished a response, they were further instructed to use the tip of the pen for tapping on a square labelled "next" (at the bottom right of the sheet) and to immediately return the pen to the response line without making any contact with the paper. Importantly, note that this first experiment did not require paying attention to the meaning of the stimuli. A whole experimental session lasted around 20 minutes.

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[3] The use of a piece of paper over the tablet is a common feature of handwriting experiments, because it increases ecological validity (given that daily handwriting is typically performed on paper) while protecting the writing surface from damage due to constant contact with the pen.

2.1.4. Measures of interest

As in previous embodiment research on written production (García-Marco et al., 2019; García & Ibáñez, 2016a), the main measures of interest were FLL, calculated as the time between stimulus onset and the first contact of the pen with the tablet; and WWL, defined as the time between the first contact of the pen with the tablet and the last pen lift for a given stimulus. In line with reported protocols (Afonso et al., 2017; Roux, McKeeff, Grosjacques, Afonso, & Kandel, 2013; (García-Marco et al., 2019; García & Ibáñez, 2016a), FLL yielded a measure of motor *programming*, whereas WWL reflected mechanisms operative in the *execution* of the writing routine.

2.1.5. Statistical analysis

Separate repeated measures analyses of covariance (ANCOVA) were conducted on FLLs and WWLs to determine the effects of verb type (MaV, nMaV, or nAV) including the average daily time spent handwriting as a covariate to control for the impact of writing abilities on the results. For these analyses, effect sizes were calculated through partial eta-squared (η_p^2). Significant effects were further analyzed via *t*-tests, and *p*-values were adjusted via the Holm-Bonferroni method. For *t*-tests, effect sizes were calculated through Cohen's *d*. Only correct responses were included in the analyses conducted on FLLs and WWLs. As in previous studies (García-Marco et al., 2019; García & Ibáñez, 2016a), trials containing misspellings or self-corrections (e.g., overwriting one letter with another), as well as those with faulty recordings, were considered errors and removed from the analyses. Note that, in line with other writing experiments on effector-specific embodiment effects (García-Marco et al., 2019), all analyses were performed with a by-subjects approach. Indeed, given that our stimuli were non-randomly sampled, strictly matched for multiple variables, and close to exhausting population of our target condition (MaVs), the inclusion of item variance would violate the assumptions of random effects models, leading to a substantial decrease in power and an unduly conservative overcompensation that could mask true effects (Hutchinson et al., 2014; Raaijmakers, 2003; Wickens and Keppel, 1983). Interested researchers can freely access all raw data used in this experiment and in Experiment 2 through the Open Science Framework repository (Suárez-Coalla, 2019).

2.2. Results

2.2.1. Incorrect responses and outliers

Overall, 2.06% of the responses were considered as errors and removed from the analyses (MaVs = 1.36%, nMaVs = 2.71%, and nAVs = 2.10%). There were no significant differences in the number of errors made across conditions [$F(2, 58) = 1.86$, $MSE = .00$, $p = .16$, $\eta_p^2 = .06$]. FLLs and WWLs above and below 3 standard deviations from each participant's mean (1.07% and 2.18%, respectively) were also excluded from the analyses (for FLLs, MaVs = .74%, nMaVs = .99%, nAVs = 1.48%; for WWLs, MaVs = 2.22%; nMaVs = 2.22%; nAVs = 2.10%). There were no significant differences in the number of rejected trials across conditions in FLL [$F(2, 58) = 1.08$, $MSE = .00$, $p = .35$, $\eta_p^2 = .04$] or WWL [$F(2, 58) = .33$, $MSE = .01$, $p = .72$, $\eta_p^2 = .01$].

2.2.2. FLL and WWL

The ANCOVA revealed no effect on FLL of verb type [$F(2, 56) = .23$, $p < .80$, $MSE = 81.26$, $\eta_p^2 = .01$] or an interaction between verb type and the covariate average daily time spent handwriting [$F(2, 56) = .48$, $p = .62$, $MSE = 173.25$, $\eta_p^2 = .02$] –Fig. 1A. By contrast, verb type did yield a significant effect on WWL [$F(2, 56) = 17.68$, $p < .001$, $MSE = 44{,}154.19$, $\eta_p^2 = .39$]. This effect did not interact with the covariate average daily time spent handwriting [$F(2, 56) = .27$, $MSE = 669.48$, $p = .77$, $\eta_p^2 = .01$). Planned comparisons revealed that MaVs were typed faster than nMaVs [$t(29) = 2.87$, $p = .007$, $d = .52$] and nAVs [$t(29) = 8.34$, $p < .001$, $d = 1.52$]. Also, WWLs were shorter for nMaVs than for nAVs [$t(29) = 7.26$, $p < .001$, $d = 1.33$] –Fig. 1B.

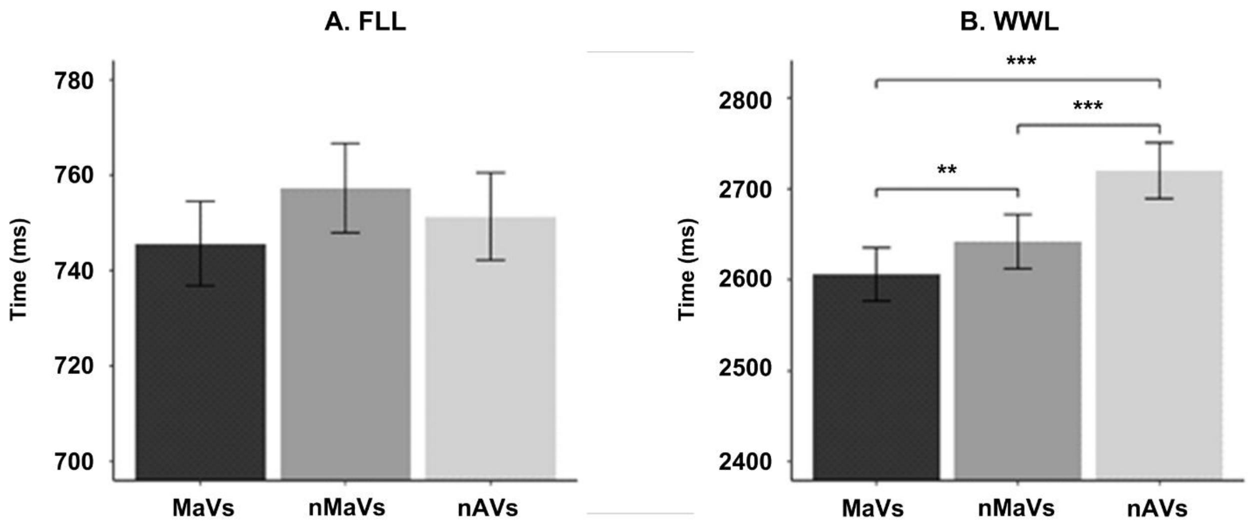

Fig. 1. Motor programming and execution latencies during handwriting obtained in Experiment 1. Outcomes for these variables are indexed by **(A)** first-letter lag (FLL) and **(B)** whole-word lag (WWL), respectively. The panels show results for manual action verbs (MaVs), non-manual action verbs (nMaVs) and non-action verbs (nAVs). Error bars represent standard errors. Asterisks indicate statistically significant results at $p < .001$.

2.3. Brief interim discussion

In Experiment 1 participants copied MaVs, nMaVs, and nAVs. Although the time required to initiate writing (FLL) was similar across conditions, the overall duration of handwriting proper (WWL) was reduced for action verbs, in general, with even greater facilitation for MaVs, in particular. These findings suggest that both gross and effector-general motor mechanisms are activated during action-verb processing and that this reactivation differentially affects the unfolding of concurrent hand movements. More particularly, the detection of this effect in a task that does not explicitly require semantic processing, such as the copying task (Bonin, Méot, Lagarrigue, & Roux, 2015), indicates that motor-language integration is a robust phenomenon that takes place even when word meanings are implicitly accessed. However, given that depth of processing seems to affect the nature of embodied effects (García & Ibáñez, 2016a), this result cannot be *a priori* assumed to hold identically when semantic operations are explicitly required. In Experiment 2, we address this issue by modifying the above copying task to unavoidably require semantic processing of the to-be-produced words.

3. Experiment 2

Experiment 2 was conducted as a conceptual replication of the first experiment, with the aim of examining the role of explicit semantic access on the observed effects. Specifically, we employed a go/no-go paradigm with word pairs, such that each target verb (MaVs, nMaVs, nAVs) had to be written only if the immediately preceding word was synonymous with it.

3.1. Methods

3.1.1. Participants

The study comprised a new sample of 27 first-year undergraduate psychology students (20 female; 25 right-handed) from the University of Oviedo, who enrolled to fulfil a course credit requirement. Their age ranged from 21 to 27 years of age (*M* = 21 years and 8 months, *SD* = 1 year and 6 months). All of them were native Spanish speakers, with no cognitive, linguistic, motor or perceptive disorders. As in Experiment 1, participants completed a questionnaire about their handwriting ability (see Appendix, Table 4), including items about the average daily time spent handwriting (*M* = 106 minutes, *SD* = 99.12) and the estimated age at which they acquired such a skill (*M* = 4 years and 2 months, *SD* = 1 year). None of the participants had a history of handwriting difficulties. Also, as in Experiment 1, no participant had received any formal teaching about embodied cognition in their coursework. Before the study, all participants read and signed an informed consent form in accordance with the Declaration of Helsinki. The study was approved by the ethics' committee of the Faculty of Psychology of the University of Oviedo.

3.1.2. Materials

Experimental stimuli comprised 144 trials composed of a word pair each. All items were Spanish verbs in the infinitive form. In half the trials (*n* = 72), the second (target) verb corresponded to the three categories under study, namely: 24 MaVs (e.g. *coger* [*grasp*]), 24 nMaVs (e.g., *caminar* [*walk*]), and 24 nAVs (e.g., *soñar* [*dream*]). All target verbs were also target verbs in Experiment 1 –note that the number of stimuli per condition was reduced in this experiment from 27 to 24, as we detected that specific words from the original lists did not have a clear synonym in any of the available lists. The remaining trials (*n* = 72) were composed of 72 semantically unrelated word pairs (e.g., *dry-suggest*) serving as fillers –note that none of these items appeared in the 72 target trials. The inclusion of these fillers requiring a no-response ensured that the items actually being copied were objectively driven by semantic processes. As in Experiment 1, target verbs for all three critical conditions were matched in terms of (i) first-letter identity, (ii) total number of strokes [$F(2, 71) = .66, p = .52$], (iii) word frequency [$F(2, 71) = .03, p = .97$], (iv) orthographic length [$F(2, 71) = .50, p = .58$], (v) syllabic length [$F(2, 71) = .21, p = .81$], (vi) orthographic neighborhood [$F(2, 71) = .18, p = .83$], (vii) mean bigram frequency [$F(2, 71) = .38, p = .68$], and (viii) age of acquisition [$F(2, 71) = .5, p = .91$]. The full set of experimental stimuli and descriptive statistics for each variable are provided in the Appendix (Tables 5 and 6, respectively). In line with previous protocols (Afonso and Álvarez, 2011), the synonymous word preceding each target verb was established by at least one dictionary of Spanish synonyms ("sinonimosonline", 2014; "synonimos", n.d.; "Wordreference, 1999"). Across conditions, synonyms were matched by (i) word frequency [$F(2, 71) = .47, p = .63$], (ii) orthographic length [$F(2, 71) = 1.00, p = .37$], (iii) syllabic length [$F(2, 71) = .99, p = .38$], (iv) orthographic neighborhood [$F(2, 71) = 1.15, p = .32$], (v) mean bigram frequency [$F(2, 71) = .13, p = .88$], and (vi) age of acquisition [$F(2, 71) = 1.15, p = .32$]. The full set of experimental stimuli and descriptive statistics for each variable are provided in the Appendix (Tables 5 and 6, respectively). Prior to testing, participants completed a practice session with 10 words (5 nouns, 5 verbs) not included in the task.

3.1.3. Apparatus and procedure

The same apparatus as that used in Experiment 1 was used in Experiment 2 to present the stimuli and record participants' responses. Each trial started with the presentation of a 300-ms fixation point in the center of the screen, immediately followed by centered, lower-case, 16-point word pair (e.g., *coger-agarrar*, both meaning *grasp*) that remained visible for 1,000 ms. Participants were instructed to use the pen to write the second word of the pair only if both words could be used with a similar meaning in an appropriate context. They were asked to write the word in upper case (print handwriting was not enforced), as fast and as accurately as possible, on a sheet of paper placed over the digitizer. The instructions to continue to the next stimulus were identical to those described for Experiment 1. A whole experimental session lasted around 25 minutes.

3.1.4. Measures of interest and statistical analysis

The same measures of interest and statistical analyses described in Experiment 1 were applied in Experiment 2. Trial rejection criteria were also identical to those adopted for the first experiment.

3.2. Results

3.2.1. Incorrect responses and outliers

Overall, 14.45% of the responses were considered as errors and removed from the analyses (MaVs = 10.65%, nMaVs = 19.91%, nAVs = 12.81%). There was a significant difference in the number of errors made across conditions [$F(2, 52) = 14.86$, $MSE = 36.49$, $p < .001$, $\eta_p^2 = .36$]. Results from *t*-tests revealed that participants made more errors on nMaVs than on MaVs [$t(26) = 5.07$; $p < .001$] and nAVs [$t(26) = 4.03$; $p < .001$]. There was no significant difference in the number of errors made in the MaV and the nAV conditions [$t(26) = 1.24$; $p = .23$]. FLLs and WWLs above and below 3 standard deviations from each participant's mean (1.59% and 3.19% respectively) were also excluded from the analyses (for FLLs: MaVs = 1.08%, nMaVs = 1.70%, nAVs = 2.01%; for WWLs: MaVs = 3.09%, nMaVs = 1.54%, nAVs = 4.94%). Across conditions, the number of rejected trials was similar for FLL [$F(2, 52) = 1.17$, $MSE = .35$, $p = .32$, $\eta_p^2 = .04$], but it did yield significant differences for WWL [$F(2, 52) = 7.08$, $MSE = 4.49$, $p < .004$, $\eta_p^2 = .21$], with *t*-tests showing that there were fewer outliers in the nMaV condition than in the MaV [$t(26) = 2.08$; $p = .048$] and the nAVs condition [$t(26) = 3.67$; $p = .001$] conditions. There was no significant difference in the number of outliers removed for the MaV and the nMaV conditions [$t(26) = 1.80$; $p = .08$].

3.2.2. FLL and WWL

The ANCOVA revealed no effect of verb type on FLL [$F(2, 50) = .16$, $MSE = 1256.55$, $p = .85$, $\eta_p^2 = .01$] –Fig. 2A. The interaction between verb type and the covariate 'daily time spent handwriting' was also non-significant [$F(2, 50) = .74$, $MSE = 5{,}788.62$, $p = .48$, $\eta_p^2 = .03$]. By contrast, WWL results showed a significant effect of verb type [$F(2, 50) = 22.57$, $p < .001$, $MSE = 50{,}615.85$, $\eta_p^2 = .47$]. Planned comparisons revealed that MaVs were written faster than nMaVs [$t(26) = 2.18$, $p = .04$, $d = .42$] and nAVs [$t(26) = 10.64$, $p < .001$, $d = 2.05$], while nMaVs were produced faster than nAVs [$t(26) = 8.6$, $p < .001$, $d = 1.65$] –Fig. 2B. The effect of verb type did not interact with the covariate 'daily time spent handwriting' [$F(2, 50) = .18$, $p = .83$, $MSE = 409.28$, $\eta_p^2 = .01$].

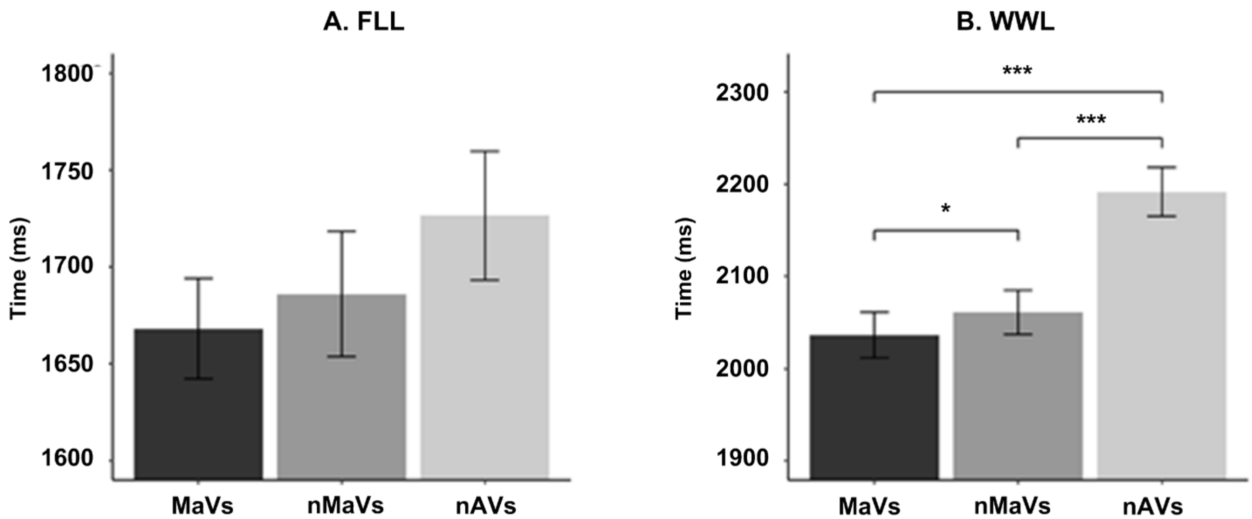

Fig. 2. Motor programming and execution latencies during handwriting obtained in Experiment 2. Outcomes for these variables are indexed by **(A)** first-letter lag (FLL) and **(B)** whole-word lag (WWL), respectively. The panels show results for manual action verbs (MaVs), non-manual action verbs (nMaVs) and non-action verbs (nAVs). Error bars represent standard errors. One, two and three asterisks indicate statistically significant results at $p < .05$, $p < .01$ and $p < .001$ respectively.

3.3. Brief interim discussion

Experiment 2 was conducted to investigate whether depth of processing affected the time course of embodiment effects on handwriting. We found that, in the presence of explicit semantic access, the effect of motor-language integration was similar to that observed in a standard copying task, with faster execution of the writing process for nMaVs than nAVs, and for MaVs over those two categories. This complementary result indicates that both effector-general and effector-specific facilitation are relatively independent of whether or not semantic processing is explicitly required to perform the linguistic task, attesting to the robustness and ubiquity of the motor-language coupling pattern reported in Experiment 1.

4. General discussion

This is the first study assessing motor-semantic integration via naturalistic handwriting tasks. In line with our predictions, we found that, relative to both nAVs and nMaVs, MaVs facilitated motor execution, irrespective of daily writing practice. By contrast, motor planning processes were similar among conditions. Notably, these patterns remained the same regardless of whether semantic information was accessed implicitly or explicitly. Taken together, such findings offer novel insights on the dynamics of motor-language coupling.

We found that action verbs, in general, facilitated motor execution, and that this effect was larger for MaVs. Such results align with previous studies assessing embodied phenomena via unimanual tasks entailing long execution times or long-latency responses (Fargier, Menoret, Boulenger, Nazir, & Paulignan, 2012; Glenberg, Sato, & Cattaneo, 2008; Glenberg & Kaschak, 2002; Lugli et al., 2012). For example, Fargier et al. (2012) found that wrist speed and velocity peak amplitudes during object grasping and displacement were higher during oral production of MaV pairs than for nMaV and nAV pairs. Moreover, evidence from action-sentence compatibility tasks (e.g., Diefenbach, Rieger, Massen, & Prinz, 2013; Glenberg & Raschak, 2002; Kaschak & Borreggine, 2008) shows that long-latency manual responses are faster if primed with directionally compatible MaVs (for a discussion, see García & Ibáñez, 2016a) –although the reliability of these outcomes has been called into question (Papesh, 2015; for a discussion, see García & Ibáñez, 2016a). Suggestively, too, note that MaVs have been shown to evoke somatotopic effects in the motor cortex (Hauk et al., 2004; Willems et al., 2010), reinforcing the notion that the observed facilitation effect may be driven by effector-specific patterns of sensorimotor resonance.

These results are in line with the predictions of the HANDLE model (García & Ibáñez, 2016a). As noted at the outset, HANDLE proposes that MaV processing involves a brief period of suprathreshold motor resonance in hand-specific circuits, followed by a progressive decrease of activation of those networks. Such subthreshold states, which may last for seconds under the motoric demands of writing (García-Marco et al., 2019; García & Ibáñez, 2016a, 2016b), are proposed to facilitate concomitant manual actions, as these would be primed by extant activity levels in embodied circuits (García & Ibáñez, 2016a). In fact, as pointed out before, MaVs have been reported to accelerate hand actions in similar long-latency windows (> 2 seconds) during other unimanual tasks (Glenberg & Kaschak, 2002; Kaschak & Borreggine, 2008; Lugli et al., 2012). Our results support this hypothesis, further showing that whereas various action-verb categories can facilitate handwriting mechanics, the effect was significantly greater for MaVs than nMaVs. This suggests that motor-language coupling during this naturalistic task is driven not only by coarse-grained motor resonance, but also, and more particularly, by effector-specific reactivations.

Of note, this effect did not interact with a self-reported measure of daily handwriting time. This would indicate that effector-specific motor-language coupling is not influenced by task-specific practice or dexterity. Although motor training can affect action-semantic integration (Glenberg et al., 2008; Trevisan, Sedeño, Birba, Ibáñez, & García, 2017), it seems that such factor does not affect the scope of embodiment effects on handwriting. This might be so because handwriting is an early-acquired, highly automatized skill, so that variability in (post-acquisition) daily practice would have little bearing on associated motor-language coupling effects. Accordingly, the embodied mechanism detected with our paradigm may be presumably generalizable across adult subjects irrespective of their dedication to handwriting in daily life.

The WWL effect was accompanied by null modulation of FLL, replicating the trade-off between motor planning and execution dynamics reported in the literature (García & Ibáñez, 2016b; Lindemann et al., 2006; Mirabella, Iaconelli, Spadacenta, & Gallese, 2012). In particular, MaV-specific effects on manual-action execution usually appear alongside null effects on movement initiation (Boulenger et al., 2008; Dalla Volta et al., 2009), even in other writing tasks like keyboard typing (García-Marco et al., 2019). This reflects a complex and dynamic relationship between lexico-semantic processing and manual actions, strongly influenced by the time-course of language-induced motor resonance. Although further research is necessary to obtain a complete picture of this intricate phenomenon, our results indicate that motor-language coupling manifests differentially on pre- and post-action onset stages, even in highly automatized, naturalistic tasks.

Also noteworthy is the fact that the selective reduction of WWL by MaVs emerged similarly in both experiments. Given the shallow nature of direct word-copying (Bonin et al., 2015), results from Experiment 1 indicate that such a facilitation of motor execution is strong enough to emerge even when lexical semantics is accessed implicitly. Therefore, this finding fulfills a key requisite for interpreting embodied effects as primary modulations rather than epiphenomenal, post-lexical effects (Hauk, Shtyrov, & Pulvermüller, 2008; Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008; Mollo, Pulvermüller, & Hauk, 2016). Yet, the detection of the same pattern in Experiment 2 indicates that the effect remains present even when word meanings are explicitly evoked. This result is informative on its own, since motor-language coupling effects can be modified (typically, magnified) when semantic information is directly accessed (García & Ibáñez, 2016a). Moreover, it is in line with previous findings by Fernandino et al. (2013), who found that Parkinson's disease patients, compared to age-matched controls, showed a similar impairment in the processing of action verbs both in tasks requiring implicit (i.e., lexical decision and priming) and explicit (semantic similarity judgment) access to meaning. Taken together, the convergent outcomes from previous studies and both experiments reported here suggest that MaV-induced facilitation during handwriting is pervasive enough to manifest irrespective of the depth of processing.

That being said, other embodied dimensions may not be fully indifferent to depth of processing. Indeed, a series of experiments investigating perceptual simulation (Lebois, Wilson-Mendenhall, and Barsalou, 2015) revealed that spatial congruency effects emerged only in tasks requiring explicit attention to the spatial properties of the stimuli, suggesting that features central to word meaning are not always automatically activated. In partial alignment with this finding, we found that only in Experiment 2 was there a significant effect of accuracy, with more errors for nMaVs than the other two categories. Tentatively, this could reflect an interference driven by effector incongruence, such that explicit activation of non-manual semantic features could engage broad motor-network processes required for accurate completion of the writing routine. Specific designs could be implemented in future research to directly examine this conjecture.

Note, too, that while handwriting is a strictly unimanual activity, a number of MaVs denoted actions that are either necessarily or optionally performed with both hands (e.g., *atar* [*tie*] or *tejer* [*knit*]). Though seemingly puzzling at first, this laterality pattern is consistent with the observed effect. Across both experiments, 95% of participants were right-handed. This means that, in daily life, they rely on their right hand not only for most unimanual activities (including handwriting) but also for all bimanual activities. Therefore, the patterns of sensorimotor resonance underlying the observed effect would be engaging right-hand (i.e., left-hemisphere) mechanisms in all MaVs. Indeed, in right-handed samples, MaVs and other action verbs are known to predominantly engage left-sided motor regions (e.g., Boulenger, Shtyrov, & Pulvermuller, 2012; Mollo et al., 2016; Shtyrov et al., 2014; Willems, Hagoort, & Casasanto, 2010), with those denoting bimanual (or bipedal) actions eliciting right-sided activation *in addition to* significant left-hemisphere motor resonance (Hauk & Pulvermüller, 2011; Klepp et al., 2014). Tentatively, then, effector-specific facilitation during handwriting could be presumed operative for dominant-hand actions in both unimanual and bimanual MaVs.

The relevance of these findings is highlighted by the nature of our paradigm. A limitation of previous studies using dual tasks is that findings may have been influenced by attentional demands for handling two arbitrarily paired processes –indeed, the need to coordinate disparate verbal and motoric operations trial after trial may strain limited cognitive control systems which are peripheral to the phenomena under study. Moreover, competition for executive resources is more pronounced when one of the tasks involves learning new motor routines (Schaefer, 2014), as is usually the case in dual-task motor-language coupling paradigms. By relying on an overlearned activity that seamlessly and necessarily conflates manual and linguistic operations, our paradigm circumvents the above-mentioned confounds and offers direct insights on effector-specific dynamics throughout the integration of motoric and lexico-semantic processes.

Finally, our findings also indicate that embodied effects during writing cannot be generalized to all production modalities. Keyboard-based action-verb typing has been shown to entail coarse-grained and effector-specific *interference* effects on motor planning, which considerably attenuate in the execution stage (García & Ibáñez, 2016b). This pattern differs radically from our finding of execution-exclusive effector-specific facilitation, supporting the idea that modality-specific demands play an important role on the manifestation of embodiment effects in written production. We surmise that differential execution efforts for handwriting, characterized by complex movements of the wrist and forearm, and a considerably longer execution stage (Afonso et al., 2015; Bertram et al., 2015; Delattre et al., 2006; García & Ibáñez, 2016b), may account for the distinct effects identified herein. Although this claim aligns with the observation that task demands constitute key determinants of motor-language coupling effects (for a review, see García & Ibáñez, 2016a), further research is necessary to directly compare motor-language coupling effects across diverse naturalistic tasks.

5. Limitations and avenues for further research

A number of limitations can be identified in the present study, paving the way for further investigation. First, the participants' handwriting profile was assessed via a self-report measure. Although this covariable spoke to the potential generalizability of our results, future extensions of our study should include objective measures of handwriting ability. Second, although we have strictly controlled for multiple variables across our stimulus lists, the reported effects might be possibly modulated by other factors, such as the ratio of verbs implying unilateral vs. bilateral bodily actions (Olaf Hauk & Pulvermuller, 2011; Klepp et al., 2014) or the motor complexity of denoted movements (Bocanegra et al., 2017). Further research would be necessary to elucidate this point. Third, as stated in section 2.1.5, our stringent stimulus selection criteria and the restrictive lexical category targeted in our study (MaVs) prevented us from adopting a mixed effects model and exploring how embodied effects could generalize to other lexical classes. Future studies could extrapolate our present rationale to settings that allow contemplating the impact of item variance across broader word categories.

At the same time, our study also carries an important methodological implication for handwriting studies in general: given that fine-grained semantic aspects of the target words can modulate writing kinematics, it seems crucial to control the ratio of action-to-non-action words in an experiment's stimulus sets, as gross outcomes could be partially driven by inconspicuous embodied effects differing between conditions. Moreover, this consideration could be contemplated in future studies extending our paradigm beyond the single-word level, so as to explore language-embodiment effects on more realistic linguistic materials (Desai et al., 2016; García et al., 2018; Trevisan et al., 2017).

6. Conclusion

This study is the first to examine the dynamics of motor-language coupling during handwriting. Whereas motor planning dynamics were impervious to the meaning of the target words, the unfolding of manual movements was faster for action than non-action verbs, and this effect was larger for MaVs in particular. Notably, such an effect remained present irrespective of whether word meanings were accessed implicitly or explicitly. This finding indicates that action-semantic integration is a pervasive process in language processing, occurring even in highly automatized tasks. Future applications of our naturalistic writing paradigm could shed new light on the subtle manifestations of embodied mechanisms during daily language processing.

Conflict of interest

None to declare.

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Appendix

Table 1. Overall pattern of responses obtained in Experiment 1 in the Handwriting Ability and Practice questionnaire.

Question	Responses
Age	*M* = 21 years and 6 months; *SD* = 2 years and 6 months
Gender	23 female; 7 male
Years of schooling	*M* = 15 years and 8 months; *SD* = 1 year and 9 months
At what age did you start learning to write?	*M* = 4 years and 2 months; *SD* = 1 year
How much time do you spend writing in an average day?	*M* = 108 min; *SD* = 109 min
How would you describe your calligraphy?	Poor = 7; Average = 16; Good = 7
How would you describe your handwriting speed?	Slow = 1; Average = 19; Fast = 10
What kind of handwriting do you use more often?	Cursive = 13; Print = 15; Uppercase = 2
Are you right- or left-handed?	Right = 29; Left = 1
Do you have any motor difficulty in your writing hand?	Yes = 0; No = 30
If you have responded yes to the previous question:	_____
a) Describe the nature of your difficulty.	_____
b) At which age you developed this difficulty?	_____

Table 2. Stimuli and approximate English translation (in brackets) used in Experiment 1.

Manual action verbs (MaVs)	Non-manual action verbs (nMaVs)	Non-action verbs (nAVs)
agarrar (*grab*)	avanzar (*advance*)	admirar (*admire*)
agitar (*shake*)	amagar (*feint*)	ahorrar (*economise*)
anudar (*knot*)	asomar (*lean out*)	asociar (*associate*)
aplaudir (*clap*)	arrollar (*sweep along*)	acatar (*obey*)
arañar (*scrape*)	asentir (*nod*)	alegrar (*make happy*)
arrojar (*toss*)	agachar (*bend down*)	aburrir (*bore*)
atar (*tie*)	apear (*get off*)	acordar (*agree*)
atrapar (*catch*)	abuchear (*jeer*)	adaptar (*adapt*)
barajar (*shuffle*)	bailar (*dance*)	bastar (*suffice*)
bordar (*embroider*)	besar (*kiss*)	brillar (*shine*)
borrar (*erase*)	brincar (*hop*)	burlar (*mock*)
cachear (*frisk*)	caminar (*walk*)	cuidar (*look after*)
coser (*sew*)	cantar (*sing*)	callar (*silence*)
dibujar (*draw*)	devorar (*devour*)	doler (*hurt*)
esculpir (*sculpt*)	engullir (*gobble down*)	enseñar (*teach*)
firmar (*sign*)	fruncir (*frown*)	fingir (*pretend*)
golpear (*hit*)	gritar (*shout*)	gustar (*like*)
lanzar (*throw*)	levitar (*levitate*)	liderar (*lead*)
lavar (*wash*)	lamer (*lick*)	lamentar (*regret*)
palpar (*palpate*)	pasear (*stroll*)	permitir (*allow*)
peinar (*brush*)	patinar (*skate*)	parecer (*look like*)
pintar (*paint*)	pisar (*step on*)	prohibir (*prohibit*)
rascar (*scratch*)	resbalar (*slip*)	respetar (*respect*)
saludar (*wave at*)	silbar (*whistle*)	soñar (*dream*)
señalar (*point at*)	saltar (*jump*)	sobrar (*be left over*)
tejer (*knit*)	toser (*cough*)	tardar (*be late*)
tocar (*touch*)	tragar (*swallow*)	temer (*fear*)

Table 3. Means and standard deviations (in brackets) for each controlled variable for stimuli used in Experiment 1. Data extracted from B-PAL (Davies & Perea, 2005), except for AoA, which was obtained from a subjective AoA norms (Alonso, Díez, & Fernández, 2016).

Condition	Log frequency	Orthographic length	Syllabic length	Orthographic neighbors	AoA	Mean bigram frequency	Number of strokes
MaVs	.75 (.38)	6.26 (.94)	2.52 (.51)	1.48 (1.42)	6.35 (2.25)	706.88 (278.18)	15.52 (2.78)
nMaVs	.66 (.45)	6.44 (.97)	2.59 (.57)	1.70 (2.07)	6.74 (2.77)	728.99 (262.19)	15.74 (2.71)
nAVs	.76 (.36)	6.59 (.89)	2.56 (.51)	1.44 (2.03)	6.79 (1.96)	748.03 (255.56)	16.07 (3.47)

Table 4. Overall pattern of responses obtained in Experiment 2 in the Handwriting Ability and Practice questionnaire.

Question	Responses
Age	*M* = 21 years and 8 months; *SD* = 1 year and 6 months
Gender	20 female; 7 male
Years of schooling	*M* = 15 years and 7 months; *SD* = 1 year and 2 month
At what age did you start learning to write?	*M* = 4 years and 2 months; *SD* = 1 year
How much time do you spend writing in an average day?	*M* = 110 min; *SD* = 101 min
How would you describe your calligraphy?	Poor = 6; Average = 14; Good = 7
How would you describe your handwriting speed?	Slow = 1; Average = 18; Fast = 8
What kind of handwriting do you use more often?	Cursive = 12; Print = 14; Uppercase = 1
Are you right- or left-handed?	Right = 25; Left = 2
Do you have any motor difficulty in your writing hand?	Yes = 0; No = 27
If you have responded yes to the previous question:	_____
a) Describe the nature of your difficulty.	_____
b) At which age you developed this difficulty?	_____

Table 5. Word pairs (target in bold) and approximate English translation (in brackets) used in Experiment 2.

Manual action verbs (MaVs)	Non-manual action verbs (nMaVs)	Non-action verbs (nAVs)
coger - agarrar (*grab*)	marchar - avanzar (*advance*)	apreciar - admirar (*admire*)
sacudir - agitar (*shake*)	esquivar - amagar (*feint*)	economizar - ahorrar (*economise*)
enlazar - anudar (*knot*)	surgir - asomar (*lean out*)	relacionar - asociar (*associate*)
palmear - aplaudir (*clap*)	aplastar - arrollar (*sweep along*)	aceptar - acatar (*obey*)
tirar - arrojar (*toss*)	encoger - agachar (*bend down*)	cansar - aburrir (*bore*)

amarrar - atar (*tie*)	desmontar - apear (*get off*)	convenir - acordar (*agree*)
entrmezclar - barajar (*shuffle*)	danzar - bailar (*dance*)	satisfacer - bastar (*suffice*)
hilvanar - bordar (*embroider*)	besuquear - besar (*kiss*)	relucir - brillar (*shine*)
quitar - borrar (*erase*)	botar - brincar (*hop*)	bromear - burlar (*mock*)
registrar - cachear (*frisk*)	andar - caminar (*walk*)	attender - cuidar (*look after*)
zurcir - coser (*sew*)	tararear - cantar (*sing*)	silenciar - callar (*silence*)
retratar - dibujar (*draw*)	deglutir - devorar (*devour*)	lastimar - doler (*hurt*)
tallar - esculpir (*sculpt*)	ingerir - engullir (*gobble down*)	instruir - enseñar (*teach*)
atizar - golpear (*hit*)	chillar - gritar (*shout*)	agradar - gustar (*like*)
echar - lanzar (*throw*)	volar - levitar (*levitate*)	dirigir - liderar (*lead*)
limpiar - lavar (*wash*)	chupar - lamer (*lick*)	sentir - lamentar (*regret*)
tentar - palpar (*palpate*)	deambular - pasear (*stroll*)	tolerar - permitir (*allow*)
cepillar – peinar (*brush hair*)	deslizar - patinar (*skate*)	aparentar - parecer (*look like*)
colorear - pintar (*paint*)	pisotear - pisar (*step on*)	denegar - prohibir (*prohibit*)
escarbar - rascar (*scratch*)	derrapar - resbalar (*slip*)	honrar - respetar (*respect*)
desasir - soltar (*put down*)	pitar - silbar (*whistle*)	ansiar - soñar (*dream*)
apuntar - señalar (*point at*)	rebotar - saltar (*jump*)	rebosar - sobrar (*be left over*)
hilar - tejer (*knit*)	carraspear - toser (*cough*)	demorar - tardar (*be late*)
acariciar - tocar (*touch*)	comer - tragar (*swallow*)	recelar - temer (*fear*)

Table 6. Means and standard deviations (in brackets) for each controlled variable for stimuli used in Experiment 1. Data extracted from B-PAL (Davies & Perea, 2005), except for AoA, which was obtained from a subjective AoA norms (Alonso, Díez, & Fernández, 2016). (A) Values for variables controlled for targets. (B) Values for variables controlled for synonyms (primes).

6A. Values for variables controlled for targets.

Condition	Log frequency	Orthographic length	Syllabic length	Orthographic neighbors	AoA	Mean bigram frequency	Number of strokes
MaVs	.74 (.38)	6.26 (.98)	2.46 (.51)	1.58 (1.47)	6.39 (2.34)	715.41 (291.88)	15.08 (2.8)
nMaVs	.71 (.46)	6.33 (.96)	2.54 (.51)	1.88 (2.13)	6.39 (2.73)	775.87 (236.93)	15.5 (2.64)
nAVs	.77 (.37)	6.58 (.93)	2.54 (.51)	1.58 (2.1)	6.64 (1.86)	769.62 (258.91)	16.08 (3.55)

6B. Values for variables controlled for synonyms (primes).

Condition	Log frequency	Orthographic length	Syllabic length	Orthographic neighbors	AoA	Mean bigram frequency
MaVs	.57 (.45)	7.08 (1.59)	2.79 (.66)	.92 (1.28)	7.61 (2.6)	640.96 (222.13)
nMaVs	.57 (.5)	7.13 (1.48)	2.79 (.78)	1.46 (2)	7.12 (2.4)	615.42 (232.09)
nAVs	.75 (.48)	7.63 (1.34)	3.04 (.69)	0.88 (.99)	8.15 (1.97)	605.97 (287.24)