

Hands typing what hands do: Action–semantic integration dynamics throughout written verb production



Adolfo M. García ^{a,b,c,d,*}, Agustín Ibáñez ^{a,b,e,f,g}

^aLaboratory of Experimental Psychology and Neuroscience (LPEN), Institute of Translational and Cognitive Neuroscience (INCYT), INECO Foundation, Favaloro University, Buenos Aires, Argentina

^bNational Scientific and Technical Research Council (CONICET), Buenos Aires, Argentina

^cFaculty of Elementary and Special Education (FEEyE), National University of Cuyo (UNCuyo), Mendoza, Argentina

^dUDP-INECO Foundation Core on Neuroscience (UIFCoN), Diego Portales University, Santiago, Chile

^eUniversidad Autónoma del Caribe, Barranquilla, Colombia

^fDepartment of Psychology, Universidad Adolfo Ibáñez, Santiago, Chile

^gARC Centre of Excellence in Cognition and its Disorders, New South Wales, Australia

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ABSTRACT

Processing action verbs, in general, and manual action verbs, in particular, involves activations in gross and hand-specific motor networks, respectively. While this is well established for receptive language processes, no study has explored action–semantic integration during written production. Moreover, little is known about how such crosstalk unfolds from motor planning to execution. Here we address both issues through our novel “action semantics in typing” paradigm, which allows to time keystroke operations during word typing. Specifically, we created a primed-verb-copying task involving manual action verbs, non-manual action verbs, and non-action verbs. Motor planning processes were indexed by first-letter lag (the lapse between target onset and first keystroke), whereas execution dynamics were assessed considering whole-word lag (the lapse between first and last keystroke). Each phase was differently delayed by action verbs. When these were processed for over one second, interference was strong and magnified by effector compatibility during programming, but weak and effector-blind during execution. Instead, when they were processed for less than 900 ms, interference was reduced by effector compatibility during programming and it faded during execution. Finally, typing was facilitated by prime–target congruency, irrespective of the verbs’ motor content. Thus, action-verb semantics seems to extend beyond its embodied foundations, involving conceptual dynamics not tapped by classical reaction-time measures. These findings are compatible with non-radical models of language embodiment and with predictions of event coding theory.

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1. Introduction

From an embodied cognition perspective, linguistic meaning is grounded in neural networks which subserve low-level information (Barsalou, 1999; Gallese & Lakoff, 2005). Abundant evidence supports this view. For instance, words denoting fear, smell, color, and form modulate activity in regions specialized for emotion (Naccache et al., 2005), olfaction (Gonzalez et al., 2006), chromatic perception (Simmons et al., 2007), and shape recognition (Wheatley, Weisberg, Beauchamp, & Martin, 2005), respectively. Even more compelling are the demonstrations of motor-network involvement during processing of action verbs, in general, and

manual action verbs (MaVs), in particular (Bak, 2013; Cardona et al., 2013; Fischer & Zwaan, 2008; García & Ibáñez, 2014, *in press*). The present study seeks to further progress in this direction. We report unprecedented evidence of such functional coupling in written production, while introducing a novel tool for language embodiment research: the “action semantics in typing” paradigm. Specifically, to assess action–semantic integration throughout motor planning and execution, we timed participants’ keyboard activity as they typed MaVs, non-manual action verbs (nMaVs), and non-action verbs (nAVs).

For decades, mainstream cognitive models of language popularized the view that word meaning relied on amodal, arbitrary symbols whose contents were unrelated to sensorimotor systems (Chomsky, 1980; Fodor, 2000; Fodor & Pylyshyn, 1988; Landauer & Dumais, 1997; Mahon & Caramazza, 2005). In the last 20 years, abundant research on receptive language processes has falsified

* Corresponding author at: Pacheco de Melo 1860, Buenos Aires, Postal Code 1126, Argentina.

E-mail address: adolfofomartingarcia@gmail.com (A.M. García).

this view. Comprehension of action verbs largely relies on motor-network activity, as shown in clinical (Bak, 2013; Cardona et al., 2014; Desai, Herter, Riccardi, Rorden, & Fridriksson, 2015; Fernandino et al., 2013; García & Ibáñez, 2014, *in press*; Ibanez et al., 2013; Kargieman et al., 2014; Melloni et al., 2015), neuroimaging (Dalla Volta, Fabbri-Destro, Gentilucci, & Avanzini, 2014; De Grauwe, Willems, Rueschemeyer, Lemhofer, & Schriefers, 2014; de Vega et al., 2014), and behavioral (Shiller et al., 2013) studies. Furthermore, such grounding is effector-specific. For example, MaVs elicit somatotopic activations in motor and premotor regions (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Buccino et al., 2005; Hauk, Johnsrude, & Pulvermuller, 2004; Oliveri et al., 2004; Papeo, Vallesi, Isaja, & Rumiat, 2009; Pulvermuller, Shtyrov, & Ilmoniemi, 2005; Tettamanti et al., 2005), and they differentially modulate reaction times (Bergen, Lau, Narayan, Stojanovic, & Wheeler, 2010; Dalla Volta, Gianelli, Campione, & Gentilucci, 2009; Dalla Volta et al., 2014; Mirabella, Iaconelli, Spadacenta, Federico, & Gallese, 2012; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008; Spadacenta, Gallese, Fragola, & Mirabella, 2014) and kinematic variables (Dalla Volta et al., 2009) for manual responses.

While motor resonance is well established in receptive language tasks, there seems to be no evidence for it during *written production*. In this sense, action–semantic integration effects cannot be *a priori* assumed to emerge in this modality as well. The neurofunctional mechanisms involved in writing are different and dissociable from those supporting reading and oral comprehension (Dehaene & Cohen, 2011; Luzzatti, Colombo, Frustaci, & Vitolo, 2000; Norton, Kovelman, & Petitto, 2007; Rapcsak & Beeson, 2004). Moreover, unlike the latter skills, writing is not a ballistic process which is automatically triggered by verbal stimuli (Margolin, 1984). Such distinctive characteristics warrant the overarching questions addressed in this paper: does action–semantic integration also emerge during written production? And if that is the case, does it also operate in an effector-specific fashion? Confirmatory evidence would suggest that action-verb processing depends on relevant motor networks irrespective of modality. Instead, failure to find motor resonance during written production would suggest that language embodiment occurs only for ballistic, unplanned verbal processes. Building on findings of effector-specific resonance during oral production (Barbieri, Buonocore, Volta, & Gentilucci, 2009; Bernardis & Gentilucci, 2006; Chieffi, Secchi, & Gentilucci, 2009; Fargier, Menoret, Boulenger, Nazir, & Paulignan, 2012; Kritikos, Dozo, Painter, & Bayliss, 2012; Rodriguez, McCabe, Nocera, & Reilly, 2012), here we align with the former hypothesis.

On such an assumption, we also advance specific predictions regarding the time course and functional nature of embodiment effects during writing. Previous studies have shown that motor resonance induced by MaVs may either delay (Bergen et al., 2010; Boulenger et al., 2006; Kemmerer, Miller, Macpherson, Huber, & Tranel, 2013; Mirabella et al., 2012; Nazir et al., 2008; Sato et al., 2008; Spadacenta et al., 2014) or facilitate (Boulenger et al., 2006; Dalla Volta et al., 2009; Dalla Volta et al., 2014; Nazir et al., 2008) planning and execution of manual movements. As proposed by various authors (Borreggine & Kaschak, 2006; Diefenbach, Rieger, Massen, & Prinz, 2013; Richardson, Spivey, & Cheung, 2001), these results may be reconciled by the theory of event coding (TEC, Hommel, Musseler, Aschersleben, & Prinz, 2001), a framework which accounts for several motor planning phenomena through a distinction between ‘feature activation’ and ‘feature integration’ stages. When features are activated, but not yet integrated into a full simulation of an event, actions which also evoke such features are primed and executed faster. Instead, when features have been activated sufficiently long, they are integrated into a full simulation and become temporarily unavailable to other processes. Following this framework, a MaV would acti-

vate several features related to manual actions. If one such action (e.g., typing) is initiated after the features have been integrated, it will be delayed. However, if the action starts before the features have been bound into a full simulation, then it will be facilitated. In other words, we propose that longer intervals between MaVs and typing initiation will favor interference, whereas shorter intervals should promote facilitation.

Finally, we will explore how motor resonance unfolds in the transition from motor planning (pre-action-onset processes) to execution (post-action-onset processes). Although both stages involve online control, they depend on partially different cognitive resources (Glover, Rosenbaum, Graham, & Dixon, 2004; Hommel et al., 2001). Studies on arrow blindness show that the integration of directional information may yield distinctive effects confined to the functional lifetime of action planning (Wuhr & Musseler, 2001). Also, tasks involving words (Glover & Dixon, 2002) and visual illusions (Glover & Dixon, 2001) show that significant effects on early phases of reaching and grasping tend to decrease and approach zero value by the time movements end. More particularly, (Mirabella et al., 2012) showed that MaV-induced interference on action initiation may dissipate as the motor routine unfolds. Accordingly, while both phases share several functional properties, we propose that significant effects observed during action planning will attenuate or even disappear as the response is fully deployed. We further surmise that the attenuation of embodiment effects will give room to non-motor-specific semantic effects (Toni, de Lange, Noordzij, & Hagoort, 2008).

In sum, we advance three interrelated hypotheses. First, action-verb typing will yield broad and effector-specific motor resonance. Second, such resonance will manifest as interference when the interval between MaV presentation and typing initiation is long, but it will lead to facilitation at shorter intervals. Third, the above effects will tend to disappear in the transition from motor planning to typing execution, giving room to non-embodied semantic effects.

Here we address these issues through our novel ‘action semantics in typing’ paradigm, which seamlessly integrates receptive and productive language processes. In this first application, we used the paradigm to create a primed-verb-copying task. Specifically, we logged participants’ keystroke times as they read and typed MaVs, nMaVs, and nAVs. Our analysis focused on two variables: *first-letter lag* (FLL, the lapse between target onset and first keystroke) and *whole-word lag* (WWL, the lapse between first and last keystroke). By comparing FLL and WWL for each verb type, we explored motor- and/or effector-specific effects during action planning and execution, respectively. Then, by examining prime–target congruency effects across conditions, we aimed to assess the role of non-motor-specific conceptual mechanisms throughout the process. In particular, the emergence of priming effects for same-category pairs – characterized by conceptual feature overlap – may reveal if and when non-motor semantic information plays a role during the task.

More generally, note that the written mode naturally engages manual activity during language processing, without the need to introduce dual-task contexts through language-irrelevant actions (such as object gripping, grasping, or displacement). Exploiting this scenario seems desirable, since dual tasks may increase reliance on executive functions, which are asymmetrically engaged by different word classes (Bocanegra et al., 2015). In brief, in this study, we aim to foster understanding of language embodiment and its temporal dynamics through a simple, ecologically valid task.

2. Materials and methods

2.1. Participants

Forty-four healthy adults carried out the experimental task and then completed an *ad hoc* questionnaire. The latter included demo-

graphic questions and various items to assess computer skills. Thirty-three individuals fulfilled the study's inclusion criteria, namely: Spanish as a mother tongue, high education level, normal or corrected-to-normal vision, good overall computer and keyboard operation skills, daily keyboard usage, and preference for QWERTY keyboards. The final sample consisted of 27 female and six male right-handed adults, with means of 25.4 years of age ($SD = 7.6$) and 18.9 years of education ($SD = 3.05$).

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., handling documents, using various office automation programs) fell between intermediate and advanced. Mean ratings for these variables were 3.43 ($SD = .62$) and 3.40 ($SD = .62$), respectively. The participants were frequent Windows users. Crucially, all of them reported typing on QWERTY keyboards for several hours each day. The sample's mean number of fingers used for typing was 6.1 ($SD = 2.3$). In terms of gaze habits during typing, 12 participants were mostly screen-lookers, seven were mostly keyboard-lookers, and eight reported equally distributing their gaze between screen and keyboard. Finally, the sample rated their overall keyboard-typing skills between intermediate and advanced ($M = 3.5$, $SD = .63$).

2.2. Stimuli

The stimuli comprised 30 Spanish verbs, organized in three blocks: MaVs ($N = 10$), denoting actions performed with the hands (e.g., *firmar* [sign]); nMaVs ($N = 10$), denoting actions performed with body parts other than the hands (e.g., *caminar* [walk]); and nAVs ($N = 10$), denoting cognitive or affective processes which do not involve bodily motion (e.g., *mejorar* [improve]). To prevent motor artifacts across blocks due to different typing distances between word-final keys, all verbs were in first-conjugation infinitive form (ending in *-ar*). We also calculated the number of left- and right-sided keystrokes required by each verb type (see [Supplementary data, Table A3](#)). Conventionally, in QWERTY keyboards all letters to the left of (and including) (t), (g), and (v) are mostly typed with the left hand. Instead, all remaining letters are typically typed with the right hand ([Marklin & Simoneau, 2004](#)). While our three verb blocks involved more left- than right-sided keystrokes [$F(1,9) = 83.96$, $p < .001$], this effect did not interact with any category (laterality and verb type: [$F(2,18) = 0.25$, $p > .05$]), and no differences were observed among verb categories [$F(2,18) = 0.57447$, $p > .05$]. Moreover, the number of first-, second-, and third-row keys requiring left- and right-hand actions was similar across categories ([Supplementary data, Tables A4 and A5](#)). Therefore, traveling distance of hands and fingers can be presumed similar for all verb types. Finally, none of the words included characters requiring more than a single key press (letters with diacritics, such as (ü) and (â), were avoided).

Psycholinguistic data for all stimuli were extracted from B-Pal ([Davis & Perea, 2005](#)), except for age-of-acquisition data, which were obtained through an *ad hoc* survey. One-way ANOVA tests showed that all blocks were similar in log frequency [$F(2,27) = .16$, $p = .85$], familiarity [$F(2,27) = .85$, $p = .44$], age of acquisition [$F(2,27) = 3.22$, $p = .06$], syllabic length [$F(2,27) = 1.01$, $p = .37$], orthographic length [$F(2,27) = .29$, $p = .75$], bigram frequency [$F(2,27) = 2.79$, $p = .08$], and number of orthographic neighbors [$F(2,27) = .32$, $p = .73$]. Note that all items had between four and seven letters; this guaranteed that the time needed for their recognition would remain constant ([Lavidor & Ellis, 2002](#); [Weekes, 1997](#)). As expected, an additional test revealed significant differences in imageability among blocks [$F(2,27) = 32.78$, $p = .001$]. A *post hoc* analysis (Tukey's HSD test, $MSe = .015$, $df = 33$) corrobo-

rated that nAVs were less imageable than both MaVs ($p < .001$) and nMaVs ($p < .001$). Crucially, however, no significant differences were observed between the latter two blocks ($p = .95$). Note that nAVs are by definition abstract and, hence, less imageable than action verbs ([Dalla Volta et al., 2014](#)). In this sense, such a difference attests to the adequacy of the verbs we chose for each category. For the full stimulus list (including approximate English translations) and additional statistical details, see [Supplementary data \(Section A\)](#).

Ninety prime–target pairs were then created by combining each verb with a triad of primes including an item from each category. This yielded nine conditions with ten pairs each. Each triad of primes was assigned to only one verb per block, as illustrated in [Table 1](#).

The prime triad assigned to each target was carefully chosen to minimize within-pair content-specific semantic relatedness and orthographic overlap between verb roots; to avoid repetition priming, congruent pairs were never composed of the same word. To corroborate that within-pair orthographic similarity was similar across conditions, we used the classical Levenshtein metric ([Levenshtein, 1966](#)) to calculate the edit distance for each prime–target pair, and then ran an ANOVA to assess potential differences among prime–target categories. No significant effects were observed for primes [$F(2,18) = 0.42$, $p > .05$], targets [$F(2,18) = 0.176$, $p > .05$], or the prime-by-target interaction [$F(4,36) = 1.5$, $p > .05$]. Also, to assess within-pair semantic similarity across conditions, we calculated the mean semantic distance for each prime–target pair via a latent-semantic analysis tool trained with a massive corpus of Spanish newspapers (<http://semantialab.com/>). No significant effects were observed for primes [$F(2,18) = 0.86$, $p > .05$], targets [$F(2,18) = 1.17$, $p > .05$], or the prime-by-target interaction [$F(4,36) = 1.16$, $p > .05$]. In sum, all nine prime–target conditions were similar in terms of within-trial orthographic and semantic similarity. Finally, the 90 pairs were distributed pseudo-randomly to minimize categorical interference as well as repetition, semantic, and form-level priming effects across trials.

2.3. Design and procedure

Participants were tested individually in a dimly illuminated room. They sat comfortably at a desk, facing a laptop. All participants carried out the experiment on the same computer, equipped with a 15.6" 16:9 HD (1366 × 768) LED backlight display and a QWERTY chiclet keyboard for Latin script including Spanish characters. Before the task, participants familiarized themselves with the keyboard by writing freely on a topic of their choosing for 15 min.

Instructions were first provided orally and then recapped on-screen. Participants were asked to look at two successively presented verbs and type the second one as fast and accurately as possible; it was emphasized that they should do so in a single, uninterrupted typing gesture. They were further instructed to press the spacebar upon completion of each trial. Before the actual

Table 1
Prime–target pair categories, examples, and approximate English translations.

Prime–target pairs	Example	Approximate English translation
MaV ^p –MaV ^t	lanzar–firmar	throw–sign
nMaV ^p –MaV ^t	caminar–firmar	walk–sign
nAV ^p –MaV ^t	mejorar–firmar	improve–sign
MaV ^p –nMaV ^t	lanzar–bailar	throw–dance
nMaV ^p –nMaV ^t	caminar–bailar	walk–dance
nAV ^p –nMaV ^t	mejorar–bailar	improve–dance
MaV ^p –nAV ^t	lanzar–negar	throw–deny
nMaV ^p –nAV ^t	caminar–negar	walk–deny
nAV ^p –nAV ^t	mejorar–negar	improve–deny

task, ten practice trials were presented with stimuli not included in the experimental blocks. Each trial began with an ocular fixation cross at the center of the screen, appearing 300 ms before the display of each prime. The prime and the target were then presented in succession, remaining on the screen for 300 and 500 ms, respectively. The fixation cross, the primes, and the targets (font: Microsoft Sans Serif; color: black; size: 48; style: regular) were presented in the middle of a white panel occupying the upper half of the screen. The participants' keyboard actions appeared on another white panel located below, with the same font features as those of the upper panel. Pressing the spacebar after the target was copied triggered the following trial. Trial-onset asynchrony randomly varied between 1500 and 2500 ms. The task was designed and performed through the 'Supervisor' and 'User' functions of Translog-II, a background-running program which logs the time at which the user makes each keystroke operation (Carl, 2012). Fig. 1 illustrates the structure of a trial, including the two measures of interest (see Section 2.1 below). The complete session for each participant lasted roughly 30 min.

2.4. Statistical analysis

Each participant's output file was individually analyzed via a custom-made script developed through the Python programming language (<https://www.python.org/>) and the NumPy package for scientific computing (<http://www.numpy.org/>). The script calculated the two measures of interest for each trial: FLL (the time-lapse between target presentation and the first keystroke made thereon) and WWL (the time-lapse between the first and last keystroke on a trial, prior to a spacebar press). FLL was taken as a proxy of motor programming. Instead, WWL indexed mechanisms at play during the unfolding of typing execution.

In addition, the script automatically rejected all mistrials. Specifically, responses were excluded from analysis if keystroke operations in a trial did not perfectly and exclusively match the

target's letter string. Thus, responses including typos or any keyboard operation other than letter-presses (e.g., deletions) were automatically rejected. Finally, the script yielded the FLL and WWL means for each condition per participant. Within each condition, values more than two SDs away from the participant's mean were also excluded.

The averages for FLL and WWL were separately analyzed through a 3×3 repeated-measures ANOVA with two factors including three levels each: prime (MaV^P , $nMaV^P$, nAV^P) and target (MaV^T , $nMaV^T$, nAV^T). Tukey's HSD *post hoc* test was used to examine pairwise comparisons for significant ANOVA results. When both factors interacted, separate ANOVAs were performed to individually test for effects of each target on all primes. In all cases, alpha levels were set at .05. Effect sizes were calculated through partial eta-squared (η^2) tests. We also performed by-item analyses (averaging among subjects) for both FLL and WWL, with the same ANOVA design: two factors including three levels each: prime (MaV^P , $nMaV^P$, nAV^P) and target (MaV^T , $nMaV^T$, nAV^T). Except for *p* values, results were rounded to the nearest second decimal place. All analyses were performed using Statistica 10.0 (Statsoft).

3. Results

3.1. First-letter lag

3.1.1. Invalid responses

Rejected trials for FLL analyses amounted to 14.21% in the sample. These ranged from 11.52% to 16.67% across conditions, there being no significant differences among the latter [prime: $F(2, 64) = .22$, $p = .79$; target: $F(2, 64) = 1.46$, $p = .23$; prime \times target interaction: $F(4, 128) = .96$, $p = .42$].

3.1.2. FLL effects

FLL analyses revealed a main effect of prime [$F(2, 64) = 25.13$, $p < .001$, $\eta^2 = 0.44$]. A *post hoc* test (Tukey's HSD, $MSe = 2264.8$,

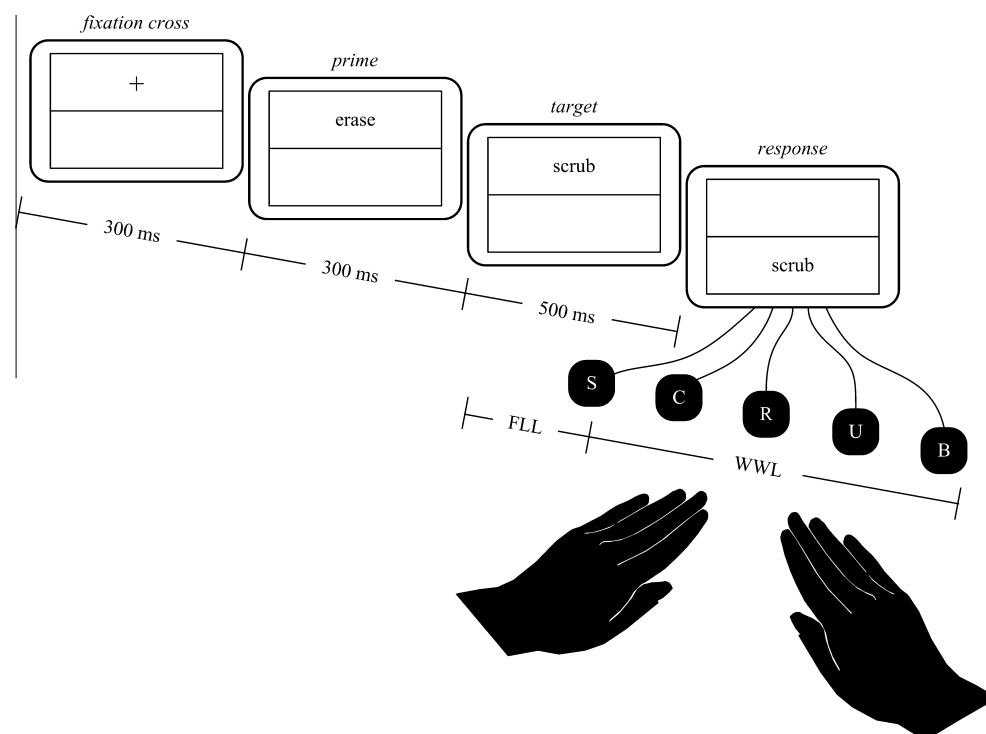


Fig. 1. Structure of a trial in the primed-verb-copying task (based on the "action semantics in typing" paradigm). FLL: first-letter lag (lapse from target onset to first key press). WWL: whole-word lag (lapse from first to last key press). Pressing the spacebar triggered a new trial. Trial-onset asynchrony randomly varied between 1500 and 2500 ms. The figure illustrates a trial in the MaV^P – MaV^T condition. The actual Spanish stimuli (*borrar-fregar*) have been replaced by their English translations (*erase-scrub*).

$df = 64$) showed that FLL was significantly shorter for nAV^P s than $nMaV^P$ s ($p < .05$) and MaV^P s ($p < .001$). Also, FLL was shorter for $nMaV^P$ s than MaV^P s ($p < .001$). For further details, see [Supplementary data \(Table B1\)](#). We also observed a significant effect of target [$F(2, 64) = 24.69, p < .001, \eta^2 = 0.44$]. According to a *post hoc* analysis (Tukey's HSD, $MSe = 1816.7, df = 64$), FLL was significantly shorter for nAV^T s than for $nMaV^T$ s ($p < .001$) and MaV^T s ($p < .001$). In addition, MaV^T s were processed significantly faster than $nMaV^T$ s ($p < .01$). For further details, see [Supplementary data \(Table B2\)](#). Finally, there was no interaction between primes and targets on FLL [$F(4, 128) = 1.95, p = .10, \eta^2 = 0.06$]. For further details, see [Supplementary data \(Table B3\)](#). Note that an additional by-item analysis of the prime and target factors for FLL replicated these results – see [Supplementary data, Table B4](#)). FLL results are depicted in [Fig. 2](#).

In sum, both primes and targets denoting motor actions interfered with the initiation of typing. Interference was greater when primes denoted manual actions. Intriguingly, the latter effect was reversed at the level of targets, where MaV s produced less significant interference than $nMaV$ s.

3.2. Whole-word lag

3.2.1. Invalid responses

Rejected trials for WWL analyses amounted to 13.57% in the sample. These ranged from 10.30% to 16.06% across conditions, there being no significant differences among the latter [prime: $F(2, 64) = .37, p = .68$; target: $F(2, 64) = .76, p = .46$; prime \times target interaction: $F(4, 128) = 1.49, p = .20$].

3.2.2. WWL effects

WWL analyses revealed a main effect of prime [$F(2, 64) = 9.04, p < .001, \eta^2 = 0.18$]. A *post hoc* test (Tukey's HSD, $MSe = 2334.1, df = 64$) showed that WWL was significantly shorter for nAV^P s than for $nMaV^P$ s ($p < .01$) and MaV^P s ($p < .001$). However, there was no difference between the latter two prime types ($p = .89$). For further details, see [Supplementary data \(Table C1\)](#). Analysis of WWL on targets revealed no significant differences among verb classes [$F(2, 64) = .42, p = .66, \eta^2 = 0.01$]. For further details, see [Supplementary data \(Table C2\)](#). Finally, there was a significant interaction of prime \times target [$F(4, 128) = 4.44, p < .01, \eta^2 = 0.14$]. Accordingly, we analyzed the effect of the primes on each target separately. First, we observed a significant effect of prime on MaV^T s [$F(2, 64) = 4.07, p = .02, \eta^2 = 0.11$]. A *post hoc* test (Tukey's HSD, $MSe = 2740.7, df = 64$) indicated that MaV^T s were typed faster when preceded by MaV^P s than $nMaV^P$ s ($p = .02$). No other effect was significant. Second, analysis of $nMaV^T$ s also revealed a significant effect of prime [$F(2, 64) = 8.72, p < .001, \eta^2 = 0.21$]. A *post hoc* test (Tukey's HSD, $MSe = 1687.9, df = 64$) showed that $nMaV^T$ s were typed faster when preceded by $nMaV^P$ s ($p = .01$) or nAV^P s ($p = .001$) than MaV^P s. Finally, a similar effect of prime was found for nAV^T s [$F(2, 64) = 5.85, p < .01, \eta^2 = 0.15$]. A *post hoc* test (Tukey's HSD, $MSe = 2334.1, df = 64$) revealed that nAV^T s were typed faster when primed by nAV^P s than either $nMaV^P$ s ($p < .01$) or MaV^P s ($p = .01$). For further details about these interaction effects, see [Supplementary data \(Tables C3–C5\)](#). Note that an additional by-item analysis of the prime and target factors for WWL replicated these results – see [Supplementary data, Table C6](#)). WWL results are summarized in [Fig. 3](#).

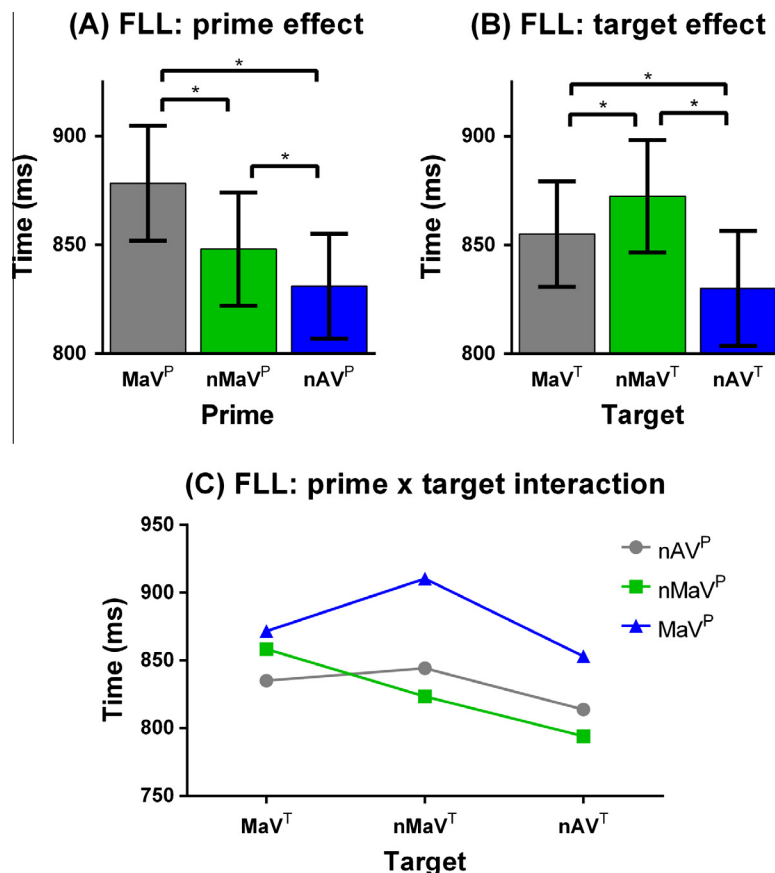


Fig. 2. First-letter lag (FLL) results. Error bars represent SDs. Asterisks indicate statistically significant differences. (A) Main effect of prime. (B) Main effect of target. (C) Prime \times target interaction.

Taken together, these results evinced two distinct behavioral patterns on WWL. On the one hand, primes denoting motor actions (be they manual or non-manual) interfered with target typing. On the other hand, typing was facilitated when the target was primed by a semantically congruent (same-type) verb. Thus, post-onset production was selectively facilitated by semantic congruency between primes and targets, irrespective of the verbs' motor content.

4. Discussion

This study explored the interplay between action and semantic processes during written verb production. Through our novel “action semantics in typing” paradigm, we inspected whether MaVs, nMaVs, and nAVs differentially affected programming and execution of the typing routine. The results were in line with our hypotheses, showing both effector-general and effector-specific motor resonance during written production. We observed that action verbs, as a whole, interfered with typing planning, with increased delays for MaV primes and nMaV targets. There was no evidence of conceptual priming effects in this phase (i.e., the prime \times target interaction was not significant for FLL). Instead, action–semantic integration evinced different dynamics as the motor routine unfolded. Crucially, interference was variously attenuated: first, it remained significant only for primes; second, it showed no modulation for MaVs relative to nMaVs; third, the effect size was notably reduced. At the same time, typing execution was facilitated by semantic compatibility, suggesting a role of non-motor-specific conceptual mechanisms during action execution.

This indicates that as motor features lose saliency in action-verb processing, more abstract amodal associations become engaged. To our knowledge, this is the first study to demonstrate such dynamic crosstalk between motor and language processes in the written mode. This suggests that language embodiment occurs irrespective of the processing modality, and that it also affects non-ballistic language mechanisms. In particular, our methodological innovation revealed late action–semantic integration effects which may not be captured through other approaches, such as reaction-time measures. Next, we discuss each set of results separately and then offer an integrative interpretation.

4.1. Action–semantic integration during motor planning

Action–semantic integration during motor planning was indexed by FLL, the lapse between target presentation and typing onset. This measure revealed that both MaVs and nMaVs, as either primes or targets, required longer programming than nAVs. Given that word meaning is automatically activated upon word perception (MacLeod, 1991), such findings may be elegantly explained from an embodied cognition perspective. We propose that motor networks do not intervene in processing semantic aspects of nAVs, as the latter allude to mental or affective operations involving no overt physical action. Thus, motor system activity can be fully devoted to planning the respective typing routine. Instead, during action-verb processing, motor networks are engaged by two simultaneous operations: semantic processing and motor programming. This competition for common resources would interfere with the latter process.

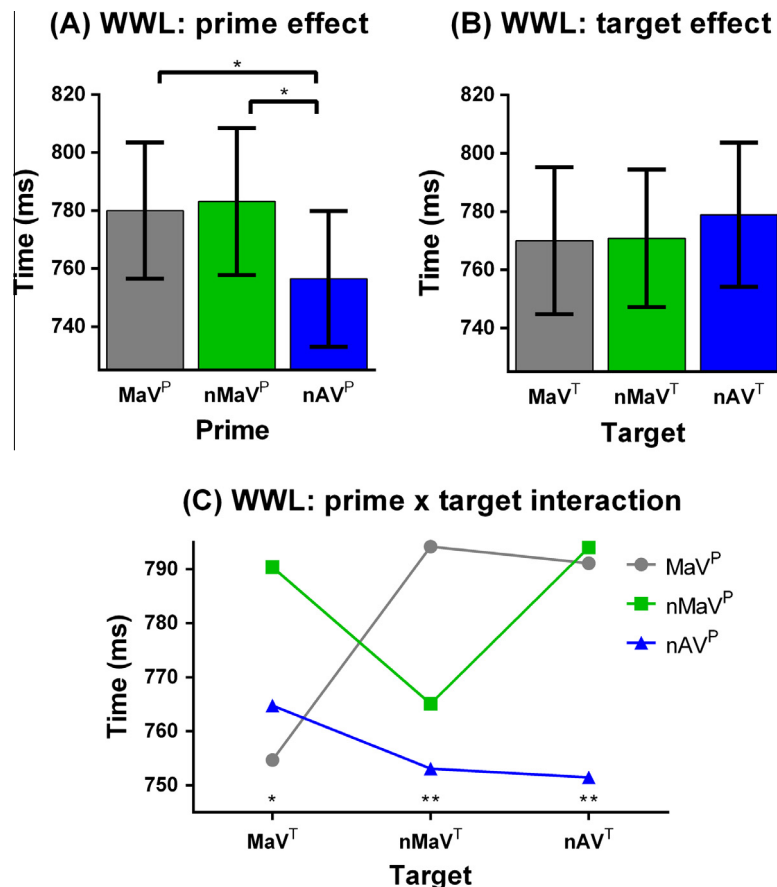


Fig. 3. Whole-word lag (WWL) results. Error bars represent SDs. Asterisks indicate statistically significant differences. (A) Main effect of prime. (B) Main effect of target. (C) Prime \times target interaction.

The only difference among our stimulus categories was that action verbs were (expectedly) more imageable than nAVs. This attests to the robustness of our results, given that imageability and reaction times are negatively correlated (Cortese & Fugett, 2004; Cortese & Schock, 2013; Schwänenflugel, 1991; Strain, Patterson, & Seidenberg, 1995). The fact that our action verbs were significantly delayed despite this processing advantage is an important demonstration of the strength of interference by motor resonance during action-verb typing.

In line with our findings, Springer and Prinz (2010) showed that action verbs, relative to non-action words, interfered with action continuity judgments. By the same token, hand-shape congruency during MaV processing was observed to delay responses at long intervals (Diefenbach et al., 2013). However, studies using different paradigms reported null effects of action verbs on reaction times (Kemmerer et al., 2013) and movement initiation time (Boulenger et al., 2006, Exp. 2; Boulenger, Silber, et al., 2008; Dalla Volta et al., 2009, Exp. 2). Such discrepancies corroborate that task demands modulate the nature of action–semantic integration effects (Diefenbach et al., 2013; Mirabella et al., 2012).

Unlike the studies just cited, ours required processing language in both the receptive and the productive modes. Tasks requiring a single button press or object-targeted movements do not necessarily activate the output lexicon or the graphemic system prior to action initiation. These two processes are indispensable in our task (see Nickels, 2008). Crucially, written production routines are tied to the verbs' lexico-semantic information: during typing, finger selection, direction, and sequencing depend on word-specific aspects, but lexical aspects play no role in action parameterizing for single button presses or object grasping.

Note that our participants were right-handers and typing is a bimanual behavior. Although our MaVs denoted mostly unimanual actions and involved more left-sided than right-sided keys (see Supplementary data, Table A3), this type of verbs yields interference and facilitation effects on overt dominant- and non-dominant-hand actions (Borghi & Scorolli, 2009; Marino, Gallese, Buccino, & Riggio, 2012). Moreover, observation of skilled yet non-expert typists, such as the ones in our sample, indicates that even left-sided keys are usually pressed with right-hand fingers. Hence, MaV processing in our study can be reasonably assumed to have elicited bilateral (and, crucially, left-hemisphere) gross and effector-specific motor resonance – even if their passive perception mainly involves premotor activity contralaterally to the dominant hand (Willemms, Hagoort, & Casasanto, 2010). Also, as stated in Section 2.2, the distribution of right- and left-hand keystrokes as well as the number of first-, second-, and third-row keystrokes per hand were similar for MaVs (see Supplementary data, Table A3), nMAVs, and nAVs. This rules out a differential effect of hand allocation on any verb type.

We propose that action planning processes during verb typing are characterized by extended word-semantic effects which cascade throughout lexical and sublexical systems (Bonin et al., 2012; Crump & Logan, 2010; Peterson & Savoy, 1998), and that this extended coactivation of motor and semantic information eventually leads to interference. Such percolation of word-specific properties would keep motor networks involved in language processes for a longer period than in language-irrelevant actions, ultimately delaying movement initiation. Thus, during typing, action verbs would require greater intervention of motor networks than non-action words. This view can be neatly integrated with the finding that motor cortical structures are inhibited in typing tasks to prevent the premature production of programmed keystrokes (Logan, Miller, & Strayer, 2011; Pinet, Hamame, Longcamp, Vidal, & Alario, 2015). Such task-specific inhibitory mechanism would place action verbs at a disadvantage, since their processing needs access to those inhibited structures. Note that this general result

was modulated by the specific motor content of the action verbs, as discussed below.

At the level of primes, interference was greater for MaVs than nMAVs, confirming that action–semantic integration effects can be effector-specific. Notably, effector congruency may magnify behavioral effects on planning in both directions. Relative to nMAVs, MaVs were found to increase facilitation in a few studies (Dalla Volta et al., 2009; Papeo et al., 2009) and to magnify interference in several others (Bergen et al., 2010; Kemmerer et al., 2013; Mirabella et al., 2012; Sato et al., 2008; Spadacenta et al., 2014). Together with these findings, our results indicate that language-related activity in motor networks does not simply spread randomly throughout the system; at some point, it infiltrates effector-specific circuits, enhancing whatever facilitatory or inhibitory process is taking place.

In the present study, interference may have resulted from increased lateral inhibition among motor circuits which process closely related information, as previously suggested by Bergen et al. (2010). Note that increased interference for MaVs over nMAVs occurred when these appeared roughly 1100–1200 ms before action initiation (primes were presented 300 ms before targets). This indicates that effector-specific interference in motor planning can be considerably long-lasting, as previously shown in studies yielding delays of over 100 ms starting 930 ms (Bergen et al., 2010) and even 2100 ms (Kemmerer et al., 2013) after word onset.

Interestingly, at the level of targets, interference was greater for nMAVs than MaVs. This pattern diametrically opposes the one observed for primes, suggesting that the time lapse between word presentation and action initiation modulates the impact of effector-specific overlaps (e.g., Spadacenta et al., 2014). As stated before, prior to typing onset, primes were processed for 300 ms more than targets (roughly 1150 ms). It is likely that effector-specific information did not have enough time to interfere with typing programming when processed within the window afforded by targets (roughly 850 ms). This interpretation is in keeping with TEC (Hommel et al., 2001).

TEC proposes that, during planning, parallel activation of features shared across cognitive events results in different effects depending on timing constraints. In a first phase, activating the codes of an intended action would prime other codes with overlapping features, resulting in facilitation. However, in a second phase, full integration of activated feature codes would render them unavailable for concurrent coding processes, thus turning facilitation into interference. Since these two phases operate in succession, shorter intervals between stimulus and response would promote facilitation, whereas longer intervals would favor interference. This rationale seems to account for our findings. MaV targets were processed for 300 ms less than MaV primes. We propose that their processing was done within the first phase, and that such time lapse was not enough for them to reach the second phase. Thus, relative to nMAVs, they were facilitated by concurrent activation of the typing routine, leading to faster processing (in TEC terms, compatibility benefits). Instead, the additional time span within which MaV primes were processed gave them access to the second phase, which triggered interference processes (in TEC terms, compatibility costs).

In other words, coactivation of overlapping features at short intervals may have promoted facilitation, whereas their integration at longer intervals may have resulted in interference. This, in fact, has been reported in other studies exploring hand-related action–semantic integration (Borreggine & Kaschak, 2006; Diefenbach et al., 2013; Richardson et al., 2001). For example, Diefenbach et al. (2013) observed that the typical facilitation effects in action-sentence compatibility tasks turned into interference if an added time lag was introduced during planning. They further suggested that interference may be caused by participants'

holding off a response, which may also have occurred upon perception of the primes in our experiment. Therefore, longer and shorter reaction times for MaVs as primes and targets, respectively, suggest that the nature of effector-specific action–semantic integration during programming is also sensitive to timing constraints.

In sum, action–semantic integration during planning yielded consistent interference effects. Verbs denoting motor actions of any kind delayed initiation of the typing routine. Moreover, there were clear effector-specific effects. Relative to nMaVs, MaVs interfered with manual action programming when presented at long intervals. Instead, they led to reduced interference when processed at shorter intervals.

4.2. Action–semantic integration during motor execution

To examine the impact of action–semantic integration on motor execution, we relied on WWL, the interval from first to last key-stroke during word typing. Overall, interference was variously attenuated: first, it remained significant only for primes; second, it showed no modulation for MaVs relative to nMaVs; third, the effect size was notably reduced. At the same time, typing was facilitated by semantic compatibility, suggesting a role of non-motor-specific conceptual mechanisms during execution.

Within the time window afforded by primes, action verbs as a whole yielded longer typing times than nAVs. Previous studies exploring the impact of action verbs on manual movements provided mixed results. Some found that processing these verbs prior to execution interferes with aspects of hand kinematics (Boulenger, Mechtouff, et al., 2008; Boulenger, Silber, et al., 2008; Dalla Volta et al., 2009), while others reported facilitation effects (Boulenger et al., 2006, Exp. 2; Fargier et al., 2012; Gentilucci, 2003), and still others showed no modulation of movement time (Spadacenta et al., 2014) – note that additional studies involving other word classes also yielded both interference (Barbieri et al., 2009; Bernardis & Gentilucci, 2006) and facilitation (Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Gentilucci & Gangitano, 1998; Glover et al., 2004). Thus, the precise effect of word semantics on subsequent manual actions seems to depend on task-related variables, such as timing and type of manual movement.

In the present experiment, delayed typing execution for action verbs may constitute a diluted after-effect of the strong interference caused by such words during programming. Crucially, the effect had a much smaller size ($\eta^2 = 0.18$) than it did during planning ($\eta^2 = 0.44$), and it showed no sensitivity to effector-specific information. This pattern suggests that, at some point during motor execution, action–semantic integration loses intensity and granularity. Previous research supports this conclusion. For example, Frak, Nazir, Goyette, Cohen, and Jeannerod (2010) observed that grip-force increments induced by action verbs fell abruptly 400 ms after word onset. Similarly, (Gentilucci & Gangitano, 1998; Gentilucci et al., 2000) noted that movement-related words affected hand kinematics only in early stages of movement. It appears, then, that the impact of semantic information on motor activity recedes as the motor routine physically unfolds.

Such a view is reinforced by the finding that interference fully disappeared within the time window afforded by targets. Once again, this pattern can be interpreted as an after-effect of motor planning processes. Following TEC, in Section 4.1 we proposed that interference was mainly operative at long intervals. Within the shorter span allotted by targets, effector-specific interference vanished during planning (possibly giving rise to facilitation). By the time the typing routine began to be executed, shorter-interval interference may have also disappeared from motor networks as a whole, perhaps even showing a tendency towards facilitation – which is in keeping with the shorter WWL means observed for all action-verb targets relative to nAV targets (Fig. 3). Thus,

although TEC principles are not intended to characterize effects emerging during motor execution (Hommel et al., 2001), the latter may be strongly influenced by preceding programming processes.

Finally, typing execution showed robust priming effects which were not specific to action verbs. Each verb type was typed faster when preceded by same-category primes. This interaction, which was absent during programming, indicates the presence of conceptual processes not rooted in the motor system. In this sense, we propose that the decrease of pre-execution control demands as typing unfolds allows the intervention of more abstract processing mechanisms, resulting in feature-based semantic priming (Kornblum, 1992; Moss, Ostrin, Tyler, & Marslen-Wilson, 1995; Myung, Blumstein, & Sedivy, 2006). The absence of similar interaction effects in FLL supports this conjecture.

The critical finding, in this respect, was that such priming effects occurred not only for action verbs, but also for nAVs. Hence, they cannot be attributed to action-specific information. This suggests that action-verb semantics is not *completely* rooted in motor networks. The meaning of these words extends beyond their embodied foundations, and may interact with varied mechanisms at different moments. This result is consistent with the symbol interdependency hypothesis (Louwerse & Jeuniaux, 2008), which claims that language processing involves both embodied and (non-embodied) symbolic mechanisms, and that these may be differentially called upon depending on task-related circumstances – see also (Barsalou, 1999). Our data indicate that in late windows – and even in earlier ones (Aravena et al., 2012) –, more abstract conceptual features may participate in action-verb processing, as postulated in a recent anatomical model (Cardona et al., 2013; García & Ibáñez, 2014) supported by multidimensional evidence (Melloni et al., 2015). Of course, the present results do not determine whether motor activity is *necessary* to understand an action verb. However, they do suggest that when its motor features lose saliency, it may actively engage amodal associations. Therefore, the evidence clashes against radical embodied approaches entirely reducing word semantics to lower-level sensorimotor grounding, while supporting the view that action-verb meaning is distributed throughout motor and non-motor circuits (Louwerse & Jeuniaux, 2008; Mirabella et al., 2012; Pulvermuller, 2005).

In brief, full typing of action verbs was characterized by reduced and less fine-grained interference, alongside the occurrence of non-motor-specific conceptual priming. This pattern clearly deviated from the one observed in the programming stage, corroborating that the dynamics of action–semantic integration are not uniform throughout the transition from motor planning to execution (Boulenger et al., 2006; Dalla Volta et al., 2009; Glover et al., 2004; Spadacenta et al., 2014).

4.3. Integrative view and methodological assessment

Taken together, our findings shed light on how action–semantic integration unfolds from typing planning to execution. When action verbs were processed for over one second, interference was first strong and magnified by effector compatibility, but weak and effector-blind during execution. Conversely, with shorter processing intervals, it was reduced by effector compatibility during programming and then completely faded. As interference dwindled, amodal conceptual processes came into play, suggesting that action-verb semantics is not completely rooted in motor networks. All in all, these results show that language-induced motor resonance is not exclusive to ballistic receptive processes; in fact, this phenomenon also occurs during intentional verbal processes, such as written production. At the same time, our findings are compatible with non-radical models of language embodiment (Barsalou, 1999; Gallese & Lakoff, 2005) and with general predictions of TEC (Hommel et al., 2001).

More generally, this study illustrates the potential of the “action semantics in typing” paradigm as a new approach to explore action–semantic integration. This novel paradigm features several advantages over other alternatives in the field, as it is inexpensive, easy to implement, and ecologically valid. Moreover, it goes a long way in diminishing the dual-task demands of other motor–language coupling tasks, as motor actions are here naturally integrated with their associated language processes. Finally, the paradigm opens an unprecedented window into embodiment effects during written production. In particular, unlike reaction-time measures (which offer a single-point measure of processes leading to simple, arbitrary movements), our method taps processes occurring both before and after action onset. This feature may even have far-reaching consequences for language studies at large. Consider our finding that semantic priming effects emerged *only* during typing execution. Hundreds of studies based on single-button presses are blind to these later dynamics occurring throughout complex, linguistically relevant actions. In this sense, current understanding of lexico–semantic mechanisms could be dramatically broadened by exploring their dynamics beyond response onset. Given these remarks, we share the view that simple behavioral tools may foster significant progress in the field (Aravena et al., 2012).

4.4. Limitations and suggestions for further research

A number of limitations must be recognized in this study. First, our sample size was somewhat small; however, it proves considerably larger than that of most behavioral experiments in the field (e.g., Aravena et al., 2012; Barbieri et al., 2009; Boulenger et al., 2006; Dalla Volta et al., 2009; Diefenbach et al., 2013; Fargier et al., 2012; Frak et al., 2010; Gentilucci, 2003; Gentilucci & Gangitano, 1998; Gentilucci et al., 2000; Glover et al., 2004; Kritikos et al., 2012; Mirabella et al., 2012; Nazir et al., 2008; Sato et al., 2008). Second, keyboard-usage habits varied across participants, as some were screen-lookers, some were keyboard-lookers, and some fell in between. It would be interesting to replicate the experiment with a more homogeneous sample and, if possible, with expert typists. Third, the extreme constraints adopted to ensure comparability among verb blocks resulted in a reduced stimulus list. Although reliable results have been obtained with even fewer stimuli (Barbieri et al., 2009; Bernardis & Gentilucci, 2006; Fargier et al., 2012; Gentilucci, 2003; Gentilucci & Gangitano, 1998; Gentilucci et al., 2000; Glover et al., 2004; Spadacenta et al., 2014), further research should contemplate incorporating longer and more varied word lists. Also, given its design, the study cannot reveal whether the observed embodiment effects reflect automatic activation of motor networks as part of action–verb access (as proposed by Boulenger, Mechtouff, et al., 2008; Boulenger, Silber, et al., 2008) or post-lexical motor imagery (as argued by Papeo et al., 2009). Fortunately, the paradigm is flexible enough to allow modifications aimed at disentangling the role of imagery during action–semantic integration (e.g., by manipulating stimulus-onset asynchronies or changing instructions to demand faster responses). This possibility should be exploited in future experiments. Finally, this paradigm could also be employed to investigate embodiment effects through different tasks (e.g., written picture naming, associated word typing, and action–sentence typing, copying or completion) and stimuli (e.g., subclasses of MaVs, nouns with different levels of manipulability).

5. Conclusion

Using our novel “action semantics in typing” paradigm, we offered the first exploration of language embodiment in written production. We found that typing programming and execution were delayed by processing of action verbs. When such verbs were

processed for more than one second, interference was strong and magnified by effector compatibility during programming, but weak and effector-blind during execution. Conversely, when action verbs were processed for less than 900 ms, it was reduced by effector compatibility during programming and it faded during typing, giving room to non-motor-specific semantic facilitation. Thus, our results show that language-induced motor resonance is (i) not exclusive to ballistic receptive processes, (ii) sensitive to time constraints, and (iii) differentially related to motor programming vs. execution. Moreover, they indicate that action–verb meaning is not entirely dependent on its embodied foundations, and that amodal conceptual information plays a role when motor associations lose intensity. Further applications of the paradigm could expand and refine current knowledge about language embodiment mechanisms, and even lexico–semantic processes at large.

Conflict of interest

None to declare.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.cognition.2016.01.011>.

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