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

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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.

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

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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, & Rumiati, 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 activate 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-