



# First and Second Language at Hand: A Chronometric Transcranial-Magnetic Stimulation Study on Semantic and Motor Resonance

Elisa Monaco<sup>1</sup> , Lea B. Jost<sup>1</sup>, Monica Lancheros<sup>1,2</sup>, Sylvain Harquel<sup>3</sup>, Eric Schmidlin<sup>1</sup>, and Jean-Marie Annoni<sup>1,4</sup>

## Abstract

■ According to embodied theories, motor and language processing bidirectionally interact: Motor activation modulates behavior in lexico-semantic tasks (semantic resonance), and understanding motor-related words entails activation of the corresponding motor brain areas (motor resonance). Whereas many studies investigated such interaction in the first language (L1), only few did so in a second language (L2), focusing on motor resonance. Here, we directly compared L1 and a late L2, for the first time both in terms of semantic and motor resonance and both in terms of magnitude and timing, by taking advantage of single-pulse TMS. Twenty-five bilinguals judged, in each language, whether hand motor-related (“grasp”) and non-motor-related verbs (“believe”), were physical or mental. Meanwhile, we applied TMS on the hand motor cortex at 125,

275, 350, and 500 msec post verb onset, and recorded behavioral responses and TMS-induced motor evoked potentials. TMS induced faster responses for L1 versus L2 motor and non-motor verbs at 125 msec (three-way interaction  $\beta = -0.0442$ , 95% CI [0.0814,  $-0.0070$ ]), showing a semantic resonance effect at an early stage of word processing in L1 but not in L2. Concerning motor resonance, TMS-induced motor evoked potentials at 275 msec revealed higher motor cortex excitability for L2 versus L1 processing (two-way interaction  $\beta = 0.095$ , 95% CI [0.017, 0.173]). These findings confirm action-language interaction at early stages of word recognition, provide further evidence that L1 and L2 are differently embodied, and call for an update of existing models of bilingualism and embodiment, concerning both language representations and processing. ■

## INTRODUCTION

Within the theoretical framework of embodiment, high-level cognitive processes, such as language comprehension, are grounded in specialized, modality-specific brain areas (e.g., Buccino, Colagè, Gobbi, & Bonaccorso, 2016; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012; Barsalou, 2008; Fischer & Zwaan, 2008; Gallese & Lakoff, 2005; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005). Accordingly, motor and premotor cortices not only subserve the execution of actions (e.g., “kick”) but also contribute to semantic representations of action-related language (e.g., understanding the written or spoken verb “kick”). Such interaction between action and language is bidirectional (Liepelt, Dolk, & Prinz, 2012). When language comprehension influences action components, we generally refer to it as *motor resonance*, based on the observation that understanding an action-related stimulus activates the same neural substrates encoding the planning and execution of the corresponding action (Zwaan & Taylor, 2006). On the other hand, when a motor component of an action modulates the lexico-semantic

processing, we refer to it as *semantic resonance* (e.g., Bidet-Ildei, Beauprez, & Badets, 2020; Mollo, Pulvermüller, & Hauk, 2016; Rueschemeyer, Lindemann, van Elk, & Bekkering, 2009). An example of such semantic resonance, that is, action-induced effects on word comprehension, can be found in the study by Lindemann et al. (Lindemann, Stenneken, van Schie, & Bekkering, 2006), where preparing a motor action (e.g., drinking from a cup) facilitated the processing of a subsequently presented action-consistent word (e.g., “mouth”). Importantly, this semantic resonance effect was not present (i) when participants prepared the control action of finger lifting or read action-inconsistent words (e.g., “eye”) and (ii) during a phonological task; it was found only during a lexico-semantic task. Another example of semantic resonance comes from a neurophysiological study, where activation of the arm and foot motor areas via TMS facilitated the processing of arm- and foot-related words, respectively (Pulvermüller et al., 2005).

Motor and semantic resonance have received considerable attention in terms of trying to define their time course, described both in early (e.g., Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017; Moseley, Pulvermüller, & Shtyrov, 2013; Boulenger, Shtyrov, & Pulvermüller, 2012; Boulenger et al., 2006, 2008; Tomasino, Fink, Sparing,

<sup>1</sup>University of Fribourg, Switzerland, <sup>2</sup>University of Geneva, Switzerland, <sup>3</sup>University of Grenoble Alpes, France, <sup>4</sup>Fribourg Cantonal Hospital, Switzerland

Dafotakis, & Weiss, 2008; Hauk & Pulvermüller, 2004) and late time windows (e.g., Papeo, Vallesi, Isaja, & Rumiati, 2009; Buccino et al., 2005). Another aspect that has received substantial attention is the direction of the effect, that is, if the effect is reflected by facilitation (e.g., Gianelli & Dalla Volta, 2015; Aravena et al., 2010; Candidi, Leone-Fernandez, Barber, Carreiras, & Aglioti, 2010; Papeo et al., 2009; Glenberg et al., 2008; Tomasino et al., 2008; Pulvermüller et al., 2005) or interference (e.g., Reilly, Howerton, & Desai, 2019; Cacciari et al., 2011; Boulenger et al., 2008; Buccino et al., 2005) effects. However, only a few studies have looked at these aspects of motor and semantic resonance in bilinguals.

Until recently, a late acquired second language (L2) was considered emotionally and cognitively distant and, therefore, “disembodied” (Pavlenko, 2012). This lack of affective embodiment in emotion studies was shown to have consequences on pragmatic aspects (e.g., Costa, Foucart, Arnon, Aparici, & Apesteguia, 2014; Costa, Foucart, Hayakawa, et al., 2014, but see Costa et al., 2019). However, when it comes to lexico-semantic processing, the few studies with bilinguals showed that even a late acquired L2 is grounded in sensorimotor areas, but presenting a lower degree or a different pattern of embodiment compared to the mother tongue (L1), as highlighted in the most recent reviews (Kogan, Muñoz, Ibáñez, & García, 2020; Monaco, Jost, Gygas, & Annoni, 2019). A possible reason for this difference is the fact that a late L2 is usually acquired in school setting, explicitly learned via L1, in a less interactive way and with less opportunities of integrating the sensorimotor experience as compared to the way an L1 is acquired (Macedonia, 2019; Adams, 2016; Dudschig, de la Vega, & Kaup, 2014; Yang & Li, 2012). Since then, two other fMRI studies (Tian et al., 2020; Zhang, Yang, Wang, & Li, 2020) have recently shown recruitment of sensorimotor regions during L2 processing, although with contrasting results. Zhang et al. (2020) showed different connectivity patterns for L2 speakers, who recruited a less integrated network to perform semantic judgments compared to L1 speakers. Tian et al. (2020) reported larger activation in motor areas for L2 when reading phrases with different abstraction levels. In their recently published EEG study, Birba et al. (2020) investigated L1 and L2 embodiment in action and non-action-laden narratives, and, despite showing motor-related connectivity in L2, they could not show differential activation between the two types of texts in L2. Overall, the first conclusions arising from this new emerging topic of research point toward the embodiment of a late acquired L2 as another aspect of action–language interaction deserving to be better delineated in its nuances (see the importance of framing embodiment research in terms of gradation in Kemmerer, 2015; Hauk & Tschentscher, 2013; Chatterjee, 2010) and mechanisms.

Importantly, previous studies on lexico-semantic processing and embodiment in bilinguals focused mainly on motor resonance effects. Targeting the semantic

resonance as well could offer new insights of action–language cross talk (Monaco et al., 2019) fostering both theoretical models and translational applications. Notably, it is possible that L2 differs from L1 in terms of onset and duration of motor resonance, reflecting delayed lexico-semantic processing for L2 compared to L1. Although this temporal dynamic was observed in studies with emotion-loaded stimuli (Baumeister, Foroni, Conrad, Rumiati, & Winkielman, 2017; Foroni, 2015), it has not yet been confirmed in studies with other (i.e., non-emotion laden) stimulus types and in terms of semantic resonance. These premises make TMS a particularly interesting technique to study the action–language cross talk. TMS has a temporal resolution in the order of milliseconds (Bolognini & Ro, 2010), making it appropriate to investigate such temporal dynamics. Moreover, it can be used to test the bidirectionality of the motor–language interaction when both behavioral and neurophysiological measures are recorded online, that is, during stimulation. Neurophysiological measures quantify the cortical excitability and therefore represent the neuronal correlate of the modulation by specific factors, whereas behavioral measures potentially demonstrate the disruption (or facilitation) of the ongoing task-related brain activity (Bergmann & Hartwigsen, 2021). Therefore, in the context of this study, the neurophysiological measures were used to detect a motor resonance effect, whereas the behavioral measures were used to detect a semantic resonance effect. The only TMS study on embodiment that involves bilinguals is the one by Gianelli, Kühne, Lo Presti, Mencaraglia, and Dalla Volta (2020), which compared the dynamics of motor resonance effects elicited by motor content expressed in the visual modality versus the linguistic modality in L1 and L2. Their exploratory analysis indicated a qualitative similarity of the TMS-induced inhibition of motor cortex excitability for the two languages, although admitting potential differences both in terms of timing and magnitude. However, the authors a) analyzed the two languages in different experiments and different participants, and b) did not record a behavioral outcome of the TMS.

Following these considerations, in this study, we directly compared the degree of embodiment between L1 and a late acquired, formally learned L2, with varying degrees of proficiency, applying a within-subject design. We took advantage of single pulse TMS to test, for the first time in bilinguals, whether and when the changes to the excitability of the motor cortex influence RTs during a semantic task (motor-to-language effect, i.e., semantic resonance), while measuring the modulation of motor cortex excitability (motor evoked potentials, MEPs) during the same semantic processing (language-to-motor effect, i.e., motor resonance). We expected that RTs during semantic judgment of verbs would be shorter in L1 than L2, as supported by the literature on bilinguals (Khateb, Pegna, Michel, Mouthon, & Annoni, 2016). Taking into account that a TMS pulse on the motor cortex given after

verb presentation would modulate the L1 advantage over L2, specifically for motor verbs, we raise the question if this modulation would happen at a specific SOA between verb presentation and TMS. Such SOA would show if the interference or facilitation effect of the semantic resonance would occur at an early or late temporal stage of lexico-semantic processing and if this would be similar for L1 and L2. We also expected that the modulation of MEP amplitudes induced by TMS pulses administered shortly after the presentation of motor verbs would manifest at an early SOA for L1, while such motor resonance effect might manifest at a later SOA for L2, mirroring the timing differences found in studies with emotion-loaded stimuli (e.g., Baumeister et al., 2017; Foroni, 2015).

## METHODS

### Participants

Thirty-four healthy late bilinguals participated in the experiment. All participants were native French speakers (L1) and learned English (L2) after the age of 7 years mainly in a school context.

They were all right-handed (Oldfield, 1971), with normal or corrected-to-normal vision, and they had no history of psychiatric, neurological, or reading disorders. From the original group, two participants had to be excluded because of technical problems during the recording. In addition, seven more participants had to be excluded for the analyses because of low numbers of acceptable MEP trials per condition ( $< 5$ ). All participants were enrolled on campus and had either a high school diploma (Matura) or a university degree (bachelor or master), which is a minimum of 13 years of education. The detailed linguistic profile of the final group of 25 participants (six men, age  $23.5 \pm 2.9$  years) is presented in Table 1.

All participants gave written, informed consent and were compensated with 25 Swiss francs/hour. Prior to the experiment, participants filled out a safety form to check for contraindications to TMS (Rossi, Hallett, Rossini, & Pascual-Leone, 2009, 2011). The study protocol was approved by the Commission cantonale d'éthique de la recherche sur l'être humain of Lausanne, Vaud, Switzerland, protocol #2016–02010. The experiment was carried out in the Neurology Unit, Department of Neuro- and Movement Sciences, University of Fribourg.

### Stimuli

We chose to use verbs because they would more easily refer to the target hand area in a TMS experiment and we wanted to follow what was prevalently done in this domain of research in order to better compare our results with the previous literature (e.g., Innocenti, Stefani, Sestito, & Gentilucci, 2014; Vukovic & Shtyrov, 2014; Papeo et al., 2009). To select the stimuli for the study, 10 L1-French participants and 9 L1-English

**Table 1.** L2-related Factors Assessed by LEAP-Q and DIALANG

	Mean	SD	Range
<i>LEAP-Q</i>			
Age of L2 acquisition [years]	12.04	1.65	8–15
Self-Reported Proficiency [0–10 scale]	6.69	0.94	5–9
Speaking	6.00	1.29	4–9
Understanding	7.04	0.98	5–9
Reading	7.04	0.93	5–9
Immersion duration [months]	17.08	25.55	0–108
In a country	5.60	14.36	0–72
In a family	1.48	3.02	0–12
In a school or work place	10.00	22.08	0–108
<i>DIALANG LD score [0–1000]</i>			
L2	728.40	159.77	266–1000
L1	922.32	55.56	761–1000

participants rated a pool of written motor-, mental-, and weather-related action verbs on a 1–7 Likert scale regarding their degree of embodiment. We followed the same procedure of Sidhu, Kwan, Pexman, and Siakaluk (2014), asking them to what degree each verb easily implies the human body, with high ratings representing verbs that readily involve the human body and low ratings representing verbs that did not easily imply the human body. Participants were encouraged to use the whole range of values to make their choice. None of these participants took part in the TMS experiment, and their age did not statistically differ from the age of the study sample. Participants rated the verbs only in their mother tongue and chose the body effector related to each verb. Per language, a list of 15 hand/upper-limb-related motor verbs (e.g., *coudre*[sew] in L1 or *dial* in L2) and a list of 15 non-motor-related verbs (e.g., *déduire*[deduce] in L1 or *forgive* in L2) different in terms of embodiment ( $t$  test  $p < .001$ ) were selected for the study. The L1-motor, L1-nonmotor, L2-motor, and L2-nonmotor lists were matched for number of syllables and frequency ( $t$  tests  $p > .05$ , frequency in Zipf values from the Lexique 3.8 database [New, Brysbaert, Veronis, & Pallier, 2007; New, Pallier, Brysbaert, & Ferrand, 2004] and the SUBTLEX-UK database [van Heuven, Mandera, Keuleers, & Brysbaert, 2014]).

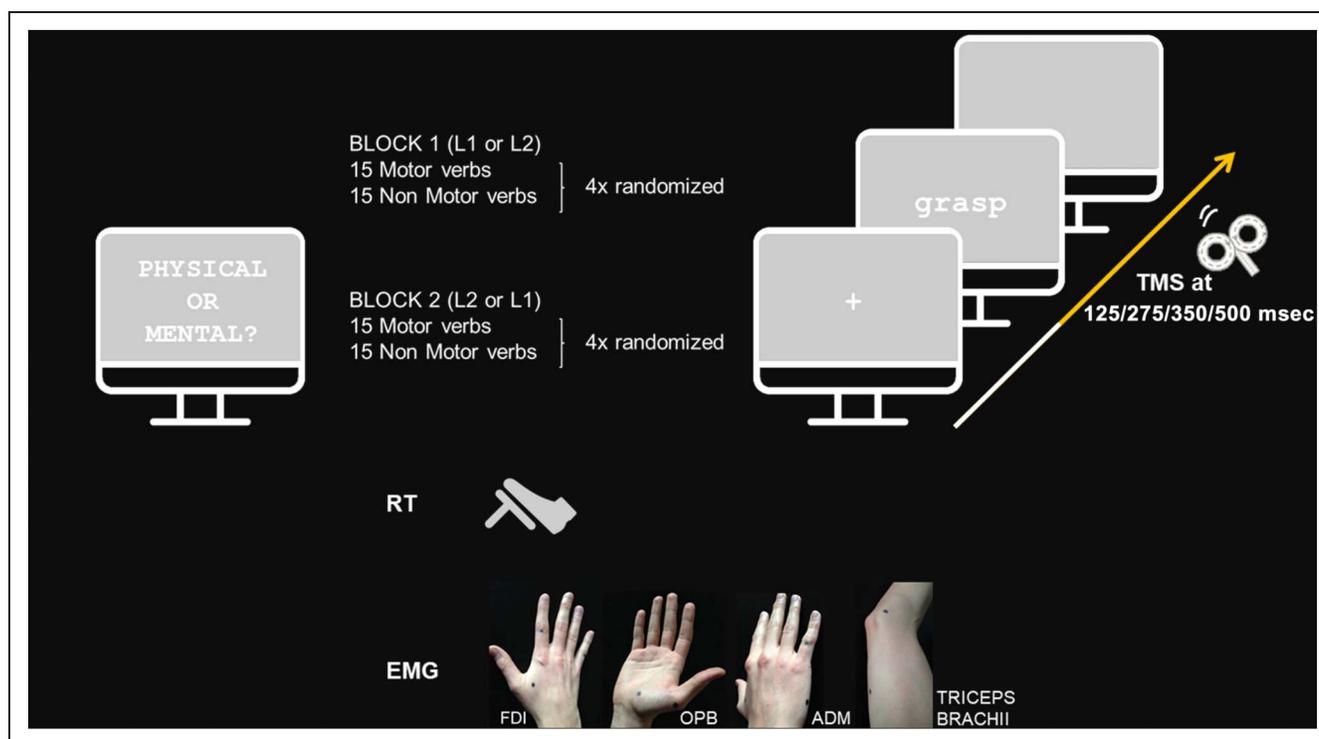
### Procedure

Upon arrival, participants filled out several questionnaires assessing TMS safety, general health, and handedness

(Edinburgh Handedness Scale; Oldfield, 1971). They filled out a language proficiency questionnaire (Language Experience and Proficiency Questionnaire [LEAP-Q]; Marian, Blumenfeld, & Kaushanskaya, 2007) in its translated and adapted form for Switzerland (de León Rodríguez et al., 2016). They completed also an on-line lexical decision task from the DIALANG (Zhang & Thompson, 2004), evaluating their receptive vocabulary in both L1 and L2. For the experimental task, participants sat on a comfortable chair placed at 100 cm from a DELL screen 22-in. (1680 × 1050 pixel resolution and 60-Hz refresh rate) with their right arm rested in a prone position on a table. TMS was delivered with a butterfly coil (C-B60) fixed on an articulated mechanical arm and connected to a MagPro X100 biphasic stimulator (MagVenture). Single pulses were applied to a relative hot-spot, defined as the cortical-left hand motor area from which the largest twitch was visible in the fingers of the participant, and delivered at 110% of the individual resting motor threshold (mean of  $53.68 \pm 7.8\%$  of maximal stimulator output). This value was chosen as compromise between having an intensity sufficiently high for constantly measuring the outcome of the stimulation (MEPs) but low enough to not hide the assumed small effect of interest. The individual resting motor threshold was defined as the minimum intensity of the stimulator output eliciting a visible twitch of the index or other fingers in the relaxed hand in at least five out of 10 consecutive pulses (Rossini et al., 1994). Participants wore a swimming cap to allow marking the optimal TMS spot to record MEPs.

After a short training, participants performed a semantic judgment task in both languages. The task consisted of deciding for each verb presented on the screen whether it represented a physical or a mental action. The languages were assigned in two blocks, one in L1 and the other one in L2, and counterbalanced across participants, whereas physical and mental action verbs were randomly distributed across these blocks. Each language-block included 120 stimuli (15 verbs per motor condition, repeated for four different SOAs) and lasted about 14 min (see Figure 1). Participants answered with their left foot on a custom-made double pedal, based on the SR-response Box (Psychology Software Tools). A foot pedal was chosen to prevent motor interference between hand-motor response preparation and hand-motor cortex activation by stimulation or semantic processing (Tomasino et al., 2008). We explicitly instructed the participants that all stimuli were verbs in their infinitive form, with the “to” intentionally omitted for the English verbs.

Single TMS pulses were randomly delivered on-line at four different delays after each verb presentation (SOAs): 125, 275, 350, and 500 msec. These SOAs were chosen based on studies showing early (within 200 msec, e.g., Vukovic et al., 2017; Moseley et al., 2013; Boulenger et al., 2012; Hauk & Pulvermüller, 2004) as well as late (350–500 msec, e.g., Papeo et al., 2009; Buccino et al., 2005) lexico-semantic effects during word processing and to allow comparisons with previous literature (e.g., Innocenti et al., 2014; Vukovic & Shtyrov, 2014; Papeo et al., 2009). It should be noted that a constant delay



**Figure 1.** Experimental setup and procedure.

of word presentation of about 8.7 msec was registered with a photodiode. The actual delays of TMS are thus 116.3, 266.3, 341.3, and 491.3 msec. Each trial began with a white fixation cross on a gray background lasting 500–1500 msec, followed by a verb presented for 800 msec and a gray screen for 5175 msec. Hence, a minimum distance between pulses of 6100 msec prevented interaction among them, which could affect MEPs' size (Vaseghi, Zoghi, & Jaberzadeh, 2015; Robertson, Théoret, & Pascual-Leone, 2003). Ag/AgCl surface electrodes (Biosemi V.O.F.) were placed on the first dorsal interosseous muscle (FDI), opponens pollicis brevis (OPB), abductor digiti minimi (ADM), and triceps brachii muscles of the right arm in a tendon-belly configuration, based on anatomical landmarks as illustrated in Figure 1. The EMG trace was continuously recorded and digitalized at a sampling frequency of 2048 Hz (Biosemi V.O.F.). The E-Prime 2.0 software (Psychology Software Tools) was used for verb presentation and TMS pulse-delivery, and for recording accuracy and RTs for the behavioral semantic judgment task.

After completion of the experiment, each participant's knowledge of the verbs presented in L2 was verified with a vocabulary task as we assumed that participants had a semantic representation only for known L2 verbs. For each L2 verb, participants were allowed to translate, create a sentence with, or mimic the L2 verbs presented on the screen. Responses were recorded and coded off-line by three different raters; interjudge agreement on a random sample of the data was 84%, with a Krippendorff's alpha for interrater reliability of 0.8.

### Data Preprocessing and Analysis

Trials with incorrect responses during the semantic judgment task (mean per participant = 19 trials, tot = 8%) and unknown L2 verbs (mean per participant = 21 trials, tot = 8%) were excluded from the analyses. With respect to the behavioral data from the semantic judgment task, we converted the RTs into inversed RTs, defined as  $-1000/\text{RTs}$ . This transformation is a common practice in mixed model analysis and allows to meet the statistical assumptions for our analysis, and items with the lowest RT have the lowest inverse RT as well, while avoiding too small numbers (Brysbaert & Stevens, 2018). Overall, a mean number of 209 trials per participant (87.1% of the total) was analyzed.

With respect to the neurophysiological data, we looked at the two muscles mainly involved in two different types of grip: the FDI for the precision grip and the ADM for the power grip (Ehrsson et al., 2000). Off-line EMG analysis and visualization of the MEPs recorded from the FDI and the ADM muscle were performed with the CortExTool MATLAB toolbox (Harquel et al., 2016). The EMG traces were preprocessed using a band-pass Butterworth filter of 5–600 Hz, and peak-to-peak amplitudes of MEPs were first automatically detected and then

trial by trial visually inspected to check for misdetections of MEPs, artifacts, and voluntary contractions. Only trials with amplitudes of at least 50  $\mu\text{V}$  were included in the analysis. We then transformed the raw MEP amplitudes into standard  $z$  scores, separately for each participant and muscle. Amplitudes falling outside of the individual participant's mean  $\pm 3$  SDs were not included in the analysis (5.4% of the data set with only correct and known stimuli). Overall, a mean number of 198 trials per participant (82.5% of the total) were analyzed. Because we stimulated a relative FDI, ADM, or combined hotspot (Bastani & Jaberzadeh, 2012), for each participant, the muscle with the largest mean MEP amplitude across conditions was included in the analysis (FDI for 18 participants, ADM for 7 participants). Seven participants with less than 5 data points per condition were excluded (Bastani & Jaberzadeh, 2012).

Both behavioral and neurophysiological data were then analyzed with linear mixed effects models (LMEM) in R (R Core Team, 2018) Version 3.5.1, using the packages *lme4* (Bates, Mächler, Bolker, & Walker, 2014), *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2017), *tidyverse* (Wickham et al., 2019), and the restricted maximum likelihood estimation method. The factors Language (L1 vs. L2), Verb\_Type (motor vs. nonmotor), TMSdelay (125, 275, 350, and 500 msec after stimulus onset) and their interactions were modeled as fixed predictors. Random slopes were required to account for the nonindependence of repeated measures (all participants responded to all items in all conditions, with four responses for each item in the conditions Language and Verb\_Type) and in order to minimize Type I error rates (Judd, Westfall, & Kenny, 2017; Linck & Cunnings, 2015). In the maximal model possible by design (Barr, Levy, Scheepers, & Tily, 2013), the random structure included intercepts for participants, items, and their interaction; by-subject random slope for all the predictors and their interactions; and a by-item random slope for TMSdelay. For both RTs and MEP amplitudes, this model was degenerate and risked reducing the statistical power. Hence, we reduced the model, following the “keep-it-maximal” guidelines until it converged successfully (Brauer & Curtin, 2018; Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017; Barr, 2013). We simplified the maximal model (which was still overparameterized) by removing the lowest variance components in the random structure until this procedure was justified and did not reduce the goodness of fit (verified by the likelihood ratio test; Baayen, Davidson, & Bates, 2008). The final random structure for RTs included a by-subject random slope for Language, Verb\_Type, and their interaction. The final random structure for MEPs included a by-subject random slope for Language, Verb\_Type, and TMSdelay with no interaction. Both models lost the by-item random slope for TMSdelay. The resulting selected models (see Table 2 and Table 3) were the most parsimonious we could obtain, which are the ones

**Table 2.** Linear Mixed Effects Model Results for RTs

Predictors	Estimates	CI (95%)	Statistic	p Value
Intercept	-1.0508	-1.1306, -0.9710	-25.7990	< .001
Language	0.0687	0.0192, 0.1182	2.7220	.009
Verb_Type	0.0556	0.0134, 0.0977	2.5853	.012
TMSdelay (125 msec)	-0.0351	-0.0444, -0.0258	-7.3909	< .001
TMSdelay (275 msec)	-0.0022	-0.0115, 0.0071	-0.4565	.648
TMSdelay (500 msec)	0.0334	0.0241, 0.0428	7.0450	< .001
Language:Verb_Type	-0.0367	-0.1152, 0.0418	-0.9157	.363
Language:TMSdelay (125 msec)	0.0148	-0.0038, 0.0334	1.5552	.120
Language:TMSdelay (275 msec)	-0.0142	-0.0327, 0.0044	-1.4928	.136
Language:TMSdelay (500 msec)	-0.0011	-0.0197, 0.0176	-0.1109	.912
Verb_Type:TMSdelay (125 msec)	0.0173	-0.0013, 0.0359	1.8203	.069
Verb_Type:TMSdelay (275 msec)	-0.0064	-0.0250, 0.0122	-0.6753	.500
Verb_Type:TMSdelay (500 msec)	-0.0136	-0.0323, 0.0050	-1.4367	.151
Language:Verb_Type:TMSdelay (125 msec)	-0.0442	-0.0814, -0.0070	-2.3270	.020
Language:Verb_Type:TMSdelay (275 msec)	0.0204	-0.0167, 0.0576	1.0772	.281
Language:Verb_Type:TMSdelay (500 msec)	-0.0053	-0.0425, 0.0319	-0.2778	.781
Observations	5225			
R model equation: $\text{invRT} \sim \text{Language} * \text{Verb\_Type} * \text{TMSdelay} + (\text{Language} * \text{Verb\_Type}   \text{Subject}) + (1   \text{verbs}) + (1   \text{Subject: verbs})$ .				

Estimate for the 350-msec SOA can be computed by adding the estimate values of the other SOAs. However, it did not reach significance. The significance threshold of  $p$  values in **boldface** is  $\alpha \leq .05$ .

with the maximal random effects structure justified by the data (as recommended by Bates, Kliegl, Vasishth, & Baayen, 2018).

Language and Verb\_Type predictors were centered with contrast coding (-0.5, 0.5). Because we had no predictions about the possible temporal pattern of the effect of TMSdelay, for this predictor, we deemed more useful and appropriate to use “sum coding.” This type of contrast allows comparing the mean of each level of TMSdelay to the grand mean (GM) of all levels of TMSdelay, where the GM represents the intercept.<sup>1</sup> The coding scheme looks as follows:

	D2	D3	D4
125 msec	-1	-1	-1
275 msec	1	0	0
350 msec	0	1	1
500 msec	0	0	1

where each coding variable (D2, D3, D4) represents the difference between the intercept and each delay (D2 = 275 msec vs. GM, D3 = 350 msec vs. GM, D4 = 500 msec vs. GM). A posteriori, we changed the order in which the TMSdelay levels appear in the output to make visible the significant results at the 125-msec level (note that the values do not change with rearrangement).

## RESULTS

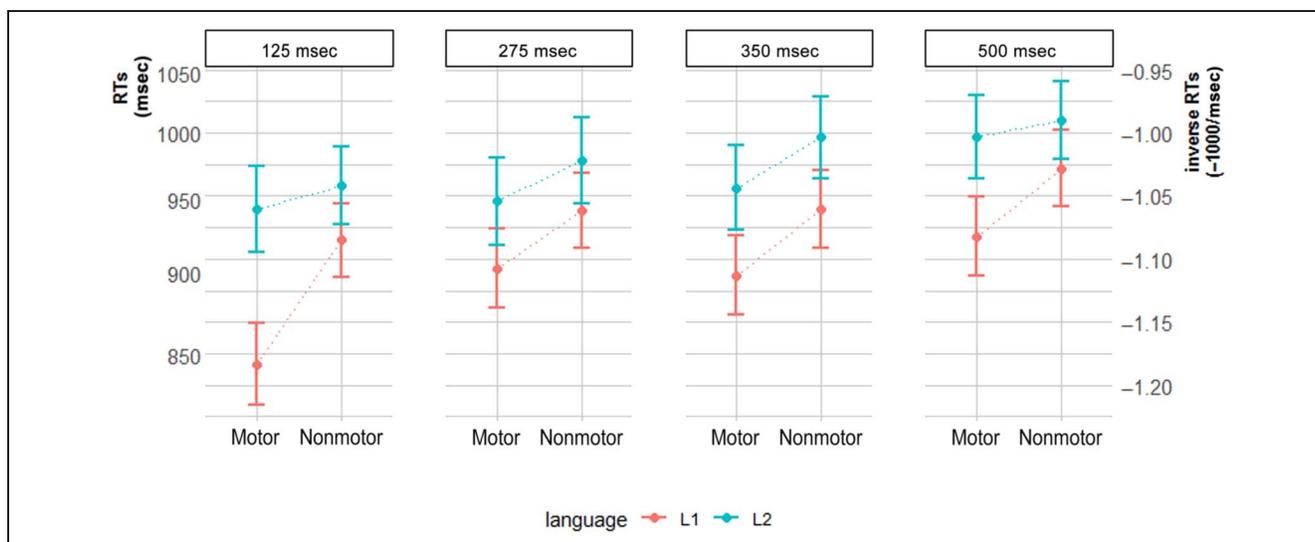
### Behavioral Results

A summary of the RTs across conditions is presented in Figure 2.

As shown in Table 2, there was a significant three-way interaction between Language, Verb\_Type, and TMSdelay ( $\beta = -0.04$ ,  $t = -2.33$ ,  $p = .020$ ) driven by faster responses for L1 compared to L2 motor verbs at 125-msec SOA. Post hoc analysis with the Tukey method for multiple corrections of four estimates confirmed that at 125 msec, RTs in response to L1 motor verbs were faster than for L2 motor verbs ( $p = .004$ ). Moreover, they revealed that RTs in response to L1 motor verbs were faster compared to L1 nonmotor verbs ( $p = .002$ ), driving the trend for a two-way interaction Verb\_Type and TMSdelay ( $\beta = 0.02$ ,  $t = 1.82$ ,  $p = .069$ ). Another trend of L1 motor verbs faster than L2 motor verbs was present at 500 msec ( $p = .072$ ).

The regression table also shows a significant main effect of Language ( $\beta = 0.07$ ,  $t = 2.72$ ,  $p = .009$ ), reflecting faster responses (mean = 14.6 msec) for L1 compared to L2, and a significant main effect of Verb\_Type ( $\beta = 0.06$ ,  $t = 2.58$ ,  $p = .012$ ), reflecting faster responses (mean = 17.9 msec) for motor compared to nonmotor verbs.

The coefficients of TMSdelay for the 125- and 500-msec SOAs were also significantly different from the GM ( $\beta = -0.04$ ,  $t = -7.39$ ,  $p < .001$ ;  $\beta = 0.03$ ,  $t = 7.05$ ,  $p < .001$ ),



**Figure 2.** RTs in L1 (orange) and L2 (blue) in response to motor and nonmotor verbs are shown for the four different SOAs of TMS. The y axis depicts the original RTs in msec (left side) and the transformed inverse RTs in  $-1000/\text{msec}$  (right side). For both scales, low values correspond to faster responses, whereas higher values correspond to slower responses. Error bars represent confidence intervals.

**Table 3.** Linear Mixed Effects Model Results for MEPs

Predictors	Estimates	CI (95%)	Statistic	p Value
Intercept	-0.047	-0.077, -0.017	-3.056	<b>.003</b>
Language	0.080	-0.142, 0.303	0.706	.487
Verb_Type	0.022	-0.040, 0.083	0.691	.492
TMSdelay (125 msec)	-0.088	-0.158, -0.018	-2.466	<b>.021</b>
TMSdelay (275 msec)	0.113	0.063, 0.162	4.466	<b>&lt; .001</b>
TMSdelay (500 msec)	-0.051	-0.104, 0.001	-1.930	.064
Language:Verb_Type	0.005	-0.110, 0.121	0.090	.928
Language:TMSdelay (125 msec)	-0.061	-0.140, 0.017	-1.525	.127
Language:TMSdelay (275 msec)	0.095	0.017, 0.173	2.382	<b>.017</b>
Language:TMSdelay (500 msec)	0.013	-0.065, 0.091	0.324	.746
Verb_Type:TMSdelay (125 msec)	-0.036	-0.115, 0.042	-0.907	.365
Verb_Type:TMSdelay (275 msec)	-0.007	-0.085, 0.071	-0.179	.858
Verb_Type:TMSdelay (500 msec)	0.031	-0.047, 0.109	0.778	.436
Language:Verb_Type:TMSdelay (125 msec)	0.026	-0.131, 0.183	0.327	.744
Language:Verb_Type:TMSdelay (275 msec)	0.087	-0.069, 0.243	1.091	.275
Language:Verb_Type:TMSdelay (500 msec)	-0.070	-0.226, 0.086	-0.879	.379

Observations

4943

R model equation:  $\text{MEP\_ampl\_target\_z} \sim \text{Language} * \text{Verb\_Type} * \text{TMSdelay} + (\text{Language} + \text{Verb\_Type} + \text{TMSdelay} \mid \text{Subject}) + (1 \mid \text{verbs}) + (1 \mid \text{Subject:verbs})$ .

Estimate for the 350-msec SOA can be computed by adding the estimate values of the other SOAs. However, it did not reach significance. The significance threshold of  $p$  values in **boldface** is  $\alpha \leq .05$ .

conveying the shorter RTs at the 125 msec and the longer RTs at 500 msec.

Post hoc analysis with the Tukey method for multiple corrections of four estimates reveals significant differences ( $p < .001$ ) in RTs between all the delays with the exception of the contrast 275 and 350 msec ( $p = .86$ ).

Because verbs were repeated four times, in order to assess the influence of a “repetition effect”, we exploratory performed a  $t$  test between the first appearance and the last appearance of the verbs in the motor and in the nonmotor condition. We did so for the native language, so that we could take all stimuli (considered as semantically processed). Results show faster responses for the fourth appearance compared to the first appearance ( $p < .001$  for motor verbs,  $p = .004$  for nonmotor verbs). We refrained from performing the same analysis for L2, because of the high disparity of number of trials among conditions, which was due to both random presentation of the stimuli and of trials exclusion after preprocessing.

### Neurophysiological Results

A summary of the amplitudes of MEPs ( $z$  scores) across conditions is presented in Figure 3.

As shown in Table 3, the three-way interaction was not significant. There was, however, a significant two-way interaction between language and TMSdelay ( $\beta = 0.09$ ,  $t = 2.38$ ,  $p = .017$ ) in which at 275 msec the two languages differently modulated the motor cortex excitability, with larger MEP amplitudes for L2 compared to L1. Post hoc analysis with the Tukey method of multiple corrections of eight estimates confirmed a significant difference between 125 and 275 msec for L2 ( $p < .0001$ ), with larger

MEP amplitudes at 275 msec, which was not present for L1 ( $p = .3$ ).

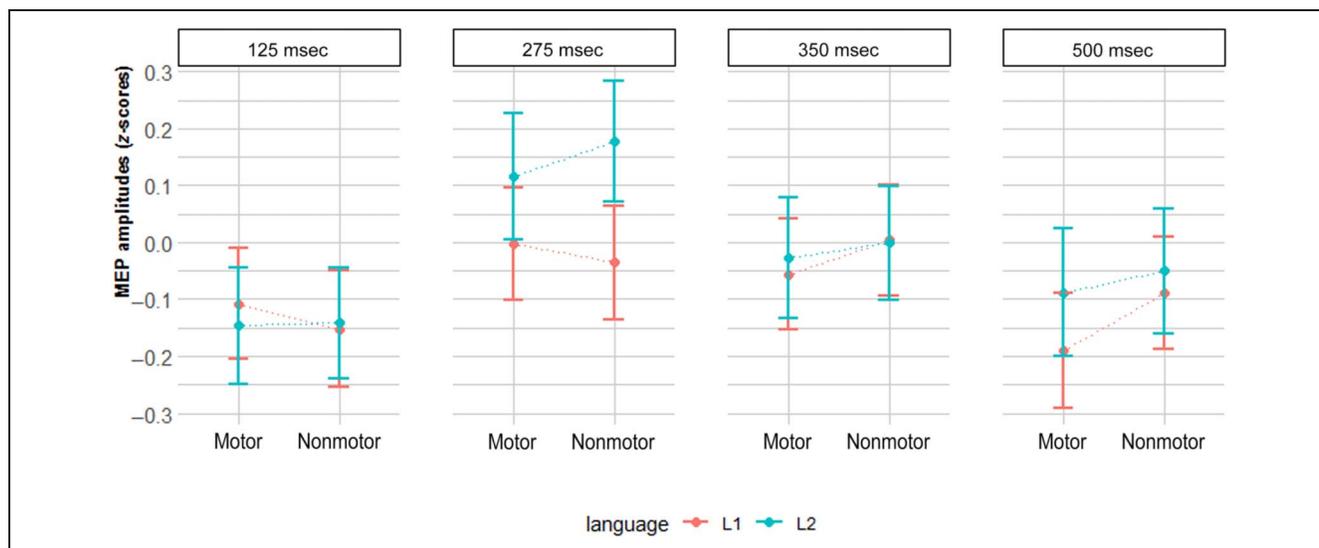
The regression table also shows the coefficients of TMSdelay for the 125- and 275-msec SOAs were significantly different from the GM ( $\beta = -0.09$ ,  $t = -2.47$ ,  $p = .021$ ;  $\beta = 0.11$ ,  $t = 4.47$ ,  $p < .001$ ), with decreasing MEP amplitudes for the 125-msec SOA and increasing MEP amplitudes for the 275-msec SOA. Moreover, there was a trend for the 500-msec SOA ( $\beta = -0.05$ ,  $t = -1.93$ ,  $p = .064$ ).

Post hoc analysis with the Tukey method of multiple corrections of four estimates reveals a significant difference only between 275 and 125 msec ( $p < .001$ ) and between 275 and 500 msec ( $p = .001$ ).

Because verbs were repeated four times, in order to assess the influence of a “repetition effect,” we exploratory performed a  $t$  test between the first appearance and the last appearance of the verbs in the motor and in the nonmotor condition. We did so for the native language, so that we could take all stimuli (considered as semantically processed). Results are nonsignificant. We refrained from performing the same analysis for L2, because of the high disparity of number of trials among conditions, which was due to both random presentation of the stimuli and of trials exclusion after preprocessing.

### Covariate

All participants were late learners of English, with an intermediate self-rated proficiency and generally scarce L2 immersion context (see Table 1 for details). Nonetheless, their knowledge of L2 was enough to perform the task with an acceptable rate of accuracy (88.2% in L2, 96% in L1). Because self-rating scores of speaking, understanding, and reading proficiency from the LEAP-Q were correlated to each other, we averaged those ratings into a



**Figure 3.** The transformed ( $z$  scores) MEP amplitudes in L1 (orange) and L2 (blue) in response to motor and nonmotor verbs are shown for the four different SOAs of TMS. Error bars represent confidence intervals.

composite global proficiency index for each participant, as previously done in the literature (Kaushanskaya, Blumenfeld, & Marian, 2020). In order to assess the modulating role of L2 proficiency on our results, we added the global proficiency index to both RT and MEP mixed models as a fixed predictor after centering its values (Judd et al., 2017). In both models, L2 proficiency had no significant effect and did not mediate the other effects investigated, which remained significant.

In order to control for proficiency and age of acquisition specifically related to the items of the experiment, a post hoc verification on 28 English verbs with the English Vocabulary Profile, based on the Cambridge Learner Corpus ([www.englishprofile.org](http://www.englishprofile.org)), confirmed that 82% of the verbs presented had a reference level ranging between A1 and B2 on the Common European Framework of Reference for Languages, corresponding to a level of proficiency ranging from basic to intermediate (Buccino, Marino, Bulgarelli, & Mezzadri, 2017). The Common European Framework of Reference for Languages level and the number of trials corresponding to how many times (i.e., for how many participants) each verb was known and processed correctly (measure of verb-related proficiency), as expected, were significantly correlated (Pearson's  $r = -.417, p = .027$ ).

## DISCUSSION

The current study aimed to investigate whether and when the degree of embodiment of semantic representations in a late-acquired L2 is different compared to L1, in terms of semantic resonance (on the behavioral level) and motor resonance (on the neurophysiological level).

### Semantic Resonance (Motor-to-language Directional Effect)

On the behavioral level, the stimulation of the motor cortex at 125 msec after stimulus presentation facilitated semantic judgment of L1 motor verbs more than L1 nonmotor verbs and more than L2 motor verbs compared to the other SOAs. This significant three-way interaction between Language, Verb\_Type, and TMSdelay has a twofold interpretation. First, it reveals a different degree of embodiment for L2 compared to L1 for the first time in terms of semantic resonance, which occurs in a specific time window of word processing. This finding corroborates the results of previous studies investigating motor resonance and L2, and their claim of a lower degree of L2 embodiment—or a different pattern—compared to L1 (Monaco et al., 2019). Second, this interaction suggests that the differential involvement of the motor cortex between L1 and L2 when processing motor verbs takes place at a very early latency in the word recognition process, possibly at the level of lexical access. Furthermore, compared to the overall mean, RTs were

shorter at 125-msec SOA and longer at 500-msec SOA (across Language and Verb\_Type). Considering the results overall, it is likely that the semantic resonance in L1 drove the early facilitation effect of the stimulation at 125-msec SOA. An early involvement of the motor system during semantic processing (within 200 msec) is consistent with the literature on L1 embodiment (e.g., Moseley et al., 2013; Boulenger et al., 2006) and other TMS studies (Tomasino et al., 2008; Pulvermüller et al., 2005). Noteworthy, whereas in other studies with monolingual participants, semantic resonance occurs also at later latencies (e.g., Tomasino et al., 2008), the semantic resonance did not reach significance at 500-msec SOA in this study. However, the trend in the post hoc analysis, together with the main effect of TMSdelay showing also longer RTs at 500 msec, points toward a potential difference between L1 and L2 embodiment at this later latency as well. Future studies with a technique appropriate to investigate the duration of the effect of interest (e.g., EEG microstate analysis) and a baseline or reference level could better shed light on the duration of an embodied effect and the difference in duration of the embodiment effect in L1 versus L2.

The result, in light of the present design including online behavioral measurements of the TMS, speaks for a causal involvement of the motor cortex in the modulation of L2 disadvantage compared to L1 motor verbs processing. Therefore, as for motor involvement in semantic judgments, our results describe it as (a) functional, (b) of different magnitude compared to L2, and (c) early present. Its role, however, is yet to determine. The task in the present experiment necessitated a deep semantic processing, and early lexico-semantic processing has been shown to occur between 130–150 and 200 msec after stimulus presentation (e.g., Amsel, Urbach, & Kutas, 2013; Hauk, Coutout, Holden, & Chen, 2012; Chan et al., 2011; Pulvermüller, Shtyrov, & Hauk, 2009). Still, some researchers claim that the motor cortex next to its main role of action planning and execution plays a role not only in lexico-semantic processing but also in other functions, such as cognitive control, inhibition, memory retrieval, and so forth that could take place at such early stages (see Tian et al., 2020, for a discussion on this topic). A future combined EEG and TMS study could clarify if at 125 msec the motor cortex serves the lexico-semantic access of motor versus nonmotor verbs, or if it assumes a more general cognitive role.

The polarity of the interaction may at first seem in contrast with the literature in L1, claiming interference effects at early latencies and facilitation at later latencies (e.g., García & Ibáñez, 2016; de Vega, Moreno, & Castillo, 2013; Chersi, Thill, Ziemke, & Borghi, 2010; Boulenger et al., 2006). However, other factors are to be considered when looking at the temporal relation between language and motor processing. First of all, an important difference of this study with the aforementioned ones is the use of a different effector in performing the task from the one

activated by the TMS (stimulation of right-hand area and response with the ipsilateral foot). We did so in order to avoid the contribution of motor preparation for the answer to the activation of the hand motor cortex (already activated by the stimulation and by the semantic processing). Other TMS studies made use of a different effector (e.g., left hand [Reilly et al., 2019] or vocal response [Papeo et al., 2009], brisk lip movement [Pulvermüller et al., 2005], and left foot [Scorolli et al., 2012; Tomasino et al., 2008]), and some of them did find an early facilitation effect. Interestingly, the two studies showing an embodiment effect at a similar SOA, that is, 150 msec (Tomasino et al., 2008; Pulvermüller et al., 2005), used a subthreshold intensity of stimulation. The intensity of stimulation could then be another factor influencing the polarity of action–language interaction, especially keeping in mind that, according to Shebani and Pulvermüller (2018), single pulse TMS can be considered as a weak activation of the motor cortex, which should not interfere with, but is enough to prime the semantic system and therefore facilitate the RTs. Last but not least, the present experiment was designed around the contrast L1 versus L2, another factor that conditionally influences the analyses and their interpretations compared to other studies.

In addition to the semantic resonance facilitation effect, behavioral results showed a main effect of Language and a main effect of Verb\_Type, with faster RTs for L1 and motor verbs in general. The former is consistent with the well-known L1 processing advantage over L2 (e.g., Khateb et al., 2016). The latter corresponds to the well-established concreteness effect and is consistent with results from other TMS studies (e.g., Papeo et al., 2009). Indeed motor verbs are more concrete and imaginable than nonmotor (mental) verbs, characteristics that correlate with the embodiment dimension (Sidhu et al., 2014) and that facilitate recognition of words (e.g., Della Rosa, Catricalà, Vigliocco, & Cappa, 2010; Jessen et al., 2000; Paivio, 1991; Schwanenflugel & Shoben, 1983), also in bilinguals (e.g., Hell & Groot, 1998). Because a statistical difference between verb types was present independent of the TMS SOAs and of the language, and considering that the participants knew the L2 verbs included in the analysis, we can assume that motor and nonmotor verbs were processed as different semantic categories in both languages.

As a final note, an exploratory analysis in L1 investigating potential “repetition effects” because of repeated stimulus presentation suggested a facilitation in the processing of the stimuli presented the fourth time versus the first time. These results adhere to the semantic repetition priming effect found in the literature (e.g., Kiefer, 2005). Importantly, however, (i) the TMS pulses were randomly delivered at four specific latencies; therefore, the first appearance of a verb could correspond to any of the 125-, 275-, 350-, or 500-msec SOAs; and (ii) the stimuli were repeated across all conditions. As such, it

is unlikely that this repetition effect could explain the semantic resonance effect.

### **Motor Resonance (Language-to-motor Directional Effect)**

On the neurophysiological level, we found a significant differential modulation of motor cortex excitability in L2 compared to L1 at 275-msec SOA across motor and non-motor verbs. Specifically, higher motor cortex excitability indexed by higher MEPs for L2 compared to L1 reflects how L2 processing activates more than L1 the motor neuronal population. Still, we cannot exclude the role of other afferent connections to the motor cortex (apparently, only L2 processing-dependent) during the task. This result is in line with the larger activation of motor areas during L2 compared to L1 processing found in the fMRI studies by Rüschemeyer, Zysset, and Friederici (2006) and by Tian et al. (2020). Rüschemeyer et al. (2006) attributed the involvement of motor-related areas to the cost of covert foreign articulation. Tian et al., who specifically manipulated action–language sentences, suggested that the larger activation in L2 processing was not necessarily a sign of a higher degree of embodiment for L2. The authors claimed that the motor system may have a dual-functional role and suggested looking into cognitive control and inhibition, memory retrieval, and information integration in language processing in addition to the more classical embodiment role (i.e., motoric simulation during semantic retrieval). Likewise, yet in the field of speech perception, other authors using repetitive TMS found the motor system to be involved more in L2 than in L1 processing (Barragan et al., 2018) and put this result in relation to task difficulty (Nuttall, Kennedy-Higgins, Hogan, Devlin, & Adank, 2016). Given that in those studies the interpreted effects are not associated to a precise timing, the role of the motor cortex in L2 processing is yet to be related to semantic representations.

With respect to the time course of motor–language cross talk, looking more closely to our neurophysiological results, they showed that MEP amplitudes decreased when stimulating at 125 msec compared to the overall mean and increased when stimulating at 275-msec SOA (across Language and Verb\_Type). Post hoc analysis and the two-way interaction between language and TMSdelay suggest that MEP amplitudes following L2 verbs increased with respect to MEP amplitudes following L1 verbs, as discussed earlier, and that the locus of the stimulation effect is the 275-msec SOA. Modulation of activation of motor areas in response to action-related language in the time range of 200–300 msec post-stimulus onset has previously been reported in studies using electrophysiological data (e.g., Dalla Volta, Fabbri-Destro, Gentilucci, & Avanzini, 2014) and noninvasive brain stimulation (Scorolli et al., 2012; Papeo, Corradi-Dell’Acqua, & Rumiati, 2011, for a comprehensive review, see Hauk, Shtyrov, & Pulvermüller, 2008).

Because of the absence of a baseline condition or of a control site stimulation in our design and all the more so in absence of a three-way interaction in the amplitudes results, we cannot exclude the presence of a sustained effect of the TMS across all the latencies. Gianelli et al. (2020) found an early modulation effect of TMS, described as inhibition effect compared to their control and baseline conditions, which was present at all SOAs (150–350–500 msec) and persistent across experiments (the one in L1 and the one in L2). Drawing a parallel with this study, it cannot be ruled out by our data that what we measured at the neurophysiological level was a modulation for both languages across all the latencies. Even so, we report a significant difference between 125 and 275 msec for L2, which was not present for L1. Hence, looking overall at the data and the post hoc analysis, our interpretation is that the modulation of motor excitability by the language happens differently for L2 versus L1 at early latencies, which is around 275 msec post stimulus presentation.

Contrary to our expectations, we did not find any difference between motor and nonmotor verbs in terms of motor resonance, whereas, behaviorally, the two categories of verbs differed in terms of embodiment values and succeeded to elicit the concreteness effect typically found in the literature. This is not the first study to show that both motor and nonmotor verbs had a similar impact on the motor cortex. For example, Tian et al. (2020) found motor involvement for literal, metaphoric, and abstract sentence processing, even if with decremental tendency. Other examples of weak motor resonance can be found in Papeo et al.'s (2011) study, where motor facilitation was found for L1 action versus non-action verbs when conjugated at the first person but not at the third person, or in Birba et al.'s study (2020), where motor-related connectivity was found for both action and non-action-laden narratives during L2 processing. Moreover, some authors claim that it is the context and the strategy adopted—hence a top-down modulation—more than the type of stimulus to influence motor preparation and sensorimotor processing (Papeo, Rumiati, Cecchetto, & Tomasino, 2012). In our experiment, different factors could have indeed created a motor cognitive context, which in turn may have modulated motor excitability independently of the type of verbs: Participants were aware of the motor stimulation, a visible twitch was always present when stimulating the cortex, and the semantic task focused on motor properties of the stimuli. As a matter of fact, even the use of motor imagery to perform the task is a likely possibility, a strategy found to have a resonance effect at early and later latencies for both motor and nonmotor stimuli (Tomasino & Rumiati, 2013; Papeo et al., 2012; Scorolli et al., 2012). In addition, we should mention that the adjacent mouth motor area could have been active via the covert pronunciation of the abstract verbs and therefore spread the activation to the hand area (Dalla Volta et al., 2014).

In summary, converging evidence supports our results and suggests that modulation of the motor excitability happens differently depending of the language context (L1 or L2). We argue for a weak effect of embodiment, and we suggest that a stronger motor resonance could have been measured if the verbs had not been repeated 4 times across the SOAs. Future studies could separate the SOAs into different blocks or present each verb only once (which was unfortunately not possible in this study without using words that are not well-matched for embodiment, length, and frequency across languages). Even if our exploratory analysis in L1 did not show a repetition effect for MEP data, we cannot rule out its presence, even for L2, where such an analysis would not be conclusive because of the low number of trials in certain conditions. Nevertheless, according to the literature, repetition of the stimuli can decrease the activation of the motor cortex (Innocenti, 2014; Pulvermüller 2013b; Kiefer, 2005), “thus making it less likely to obtain semantic category differences in brain activation (see, e.g., Pulvermüller, Cook, & Hauk, 2012; Tomasino et al., 2008; Tomasino, Werner, Weiss, & Fink, 2007)” (Pulvermüller, 2013b, p. 97). Therefore, being able to solve the repetition issue may, on the one hand, detect the motor versus nonmotor differences at the neurophysiological level and, on the other hand, make even more strong the claim of a motor resonance effect of this paper. Indeed, finding a motor resonance effect despite an eventual interfering repetition effect seems even more in favor of a language-to-motor influence.

### Comparing Semantic and Motor Resonance

To the best of our knowledge, this is the first study to directly assess the effect of motor modulation to the behavioral responses in a language task (motor-to-language effect, i.e., semantic resonance), in healthy late bilinguals. We found preliminary evidence of different semantic resonance in L2 compared to L1 at a specific early time window of word recognition. Compared to L2 and to nonmotor verbs, L1 motor verbs are recognized faster when stimulating the motor cortex at 125 msec after verb presentation. This difference between L1 and L2 in terms of semantic resonance adds knowledge to the heterogeneous framework of dissimilarity between L1 and L2 degree of motor resonance, which, until now, has been described in terms of diminished magnitude (e.g., Foroni, 2015; Vukovic & Shtyrov, 2014), different timing (Foroni, 2015), different pattern (Ahlberg, Bischoff, Kaup, Bryant, & Strozyk, 2018; Sheikh & Titone, 2016; but see also De Grauwe, Willems, Rueschemeyer, Lemhöfer, & Schriefers, 2014), and even as different polarity of interaction when writing verbs (Kogan, García-Marco, et al., 2020). Nonetheless, the fact that this motor resonance dissimilarity was not detected in this study, whereas semantic resonance differences were, suggests that the factors influencing bilingual semantic embodiment are not the same for semantic and motor resonance

effects. Furthermore, in this study, L2 proficiency did not modulate the results, in none of the two directions of action–language interaction. According to relevant theoretical models of bilingualism, however (e.g., Dijkstra & van Heuven, 2002; Kroll & Stewart, 1994), and as suggested by previous studies (see Kogan, Muñoz, et al., 2020; Kühne & Gianelli, 2019; Monaco et al., 2019, for a review), L2 proficiency should modulate embodiment effects. Similar to our study, Kogan, García-Marco, et al. (2020) did not find an influence of L2 proficiency either, suggesting that the null result could be because of task-related variables, needing systematic investigation. We believe that more variability in the sample with respect to L2 proficiency could help assessing its potential modulating role and could show us whether this linguistic factor impacts motor and semantic resonance to a similar degree. Considering that proficiency is linked to the knowledge of the stimuli, studies on new or artificial languages can maybe better shed light on this issue. It is also worth mentioning that studies on novel word learning showed early and stable motor grounding effects (e.g., Vukovic & Shtyrov, 2019, see Kogan, Muñoz, et al., 2020, for a review), suggesting that embodied mechanisms are recruited shortly after exposure to the new language. With this in mind, L2 proficiency should modulate the magnitude of the motor–language interaction,<sup>2</sup> and not its presence. Birba et al. (2020) found a correlation between L2 proficiency and motor-related connectivity in the action-related condition, still without evidence of motor resonance during L2 processing (i.e., larger connectivity in action-laden versus non-action-laden narratives). However, it should be noted that the mode of L2 acquisition is also important, and in the case of the aforementioned studies on artificial and new languages, the new words were learned via sensorimotor associations, which is rarely the common practice for an L2 learned in school settings (Macedonia, 2019).

One may argue that motor-related factors have a major influence on semantic resonance, whereas linguistic-related factors have it on motor resonance. Speculatively, factors impacting the degree of embodiment more in terms of semantic resonance could be the response effector, the stimulation intensity, the individual differences in motor experience, or familiarity with the action (e.g., Lyons et al., 2010; Willems, Hagoort, & Casasanto, 2010; Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008, see also Bidet-Ildei et al., 2020). Factors influencing motor resonance could be the interplay within the specific L1 and L2, cultural differences which can influence the polarity of motor language interaction (Ghandhari, Fini, Da Rold, & Borghi, 2020), and L2 proficiency. Because we adopted a within-participant design and took participants as random effect and random slope in our LMEM analyses, we took into account the impact of interindividual sociolinguistic differences and other subject-related sources of variability. It is plausible that factors more related to the L1 and L2 interaction remained opaque to the present

investigation and influenced the results. An example of these parameters shown to potentially impact the motor resonance is the orthographic transparency specific to the languages investigated. Although English and French are quite similar from this point of view, English is still more transparent than French. In deeper-than-L1 L2s, Liu and Cao (2016) found different brain activation patterns, among which a larger implication of the left frontal cortex. In the same line, de León Rodríguez et al. (2016) found that both language opacity and proficiency impact the reading strategy, hence the access to the lexical representation.

As a final note, top–down and bottom–up factors may also play a different role in motor (e.g., García & Ibáñez, 2016) and semantic resonance. As already discussed, the strategy adopted by the participants, which includes both motor imagery and covert articulation, could influence motor resonance, and more than bottom–up factors such as stimulus type (e.g., Tomasino & Rumiat, 2013; Rueschemeyer, Glenberg, Kaschak, Mueller, & Friederici, 2010). The question is if semantic resonance is susceptible to the same top–down and bottom–up modulating factors as motor resonance and how they interact, in terms of timing and magnitude. This is not trivial, especially in paradigms like the present one where both types of effects were assessed and likely interacted in an unknown manner. It is possible that, in our study, semantic resonance effects preceded motor resonance effects, assuming the interaction between language and TMSdelay in the neurophysiological results as a weak form of motor resonance. More evidence on semantic resonance in bilinguals is needed to complete existing theoretical models in which predictions on a parallel or cascade activation of motor and language components of embodied semantics are delineated. The dynamics and timing of the motor–language interaction is not the only aspect in which data from bilinguals can be used to advance current models of embodiment (e.g., Barsalou, 1999, 2016; García & Ibáñez, 2016; Pulvermüller, 2013a). Current evidence—including this paper—indicates that L2 processing indeed involves the motor system and that it does so differently from L1 processing (Kogan, Muñoz, et al., 2020; Monaco et al., 2019). However, the question if these observations are the result of differences in terms of embodiment of semantic representations and/or language processing between L1 and L2 is still open, even more so that no consensus is reached on such theoretical issues in bilingualism literature. Bilingual language models differ in the way semantic content is accessed in each language, in the way the two languages interact depending on L2 competence and—most importantly—if the two languages share or not the lexica and/or the semantic system. One of the most influential models (the Revised Hierarchical Model [RHM]; Kroll & Stewart, 1994) assumes shared conceptual representations between L1 and L2. Therefore, if the semantic representations are rich (i.e., grounded)

for L1, they should also be for L2. On the contrary, revisions of the RHM or other models (e.g., the Shared [Distributed] Asymmetrical Model, Dong, Gui, & Macwhinney, 2005; the Modified Hierarchical Model, Pavlenko, 2009) assume only partially shared conceptual systems or a shared conceptual system with only partially shared activated semantic features (e.g., The Distributed Conceptual Feature Model; De Groot, 1995). This partial sharing could i) explain why L1 and L2 differences are not always clearly detected and could ii) also be a reason for the potential dependency of these differences on stimulus or task. Moreover, most models do not specify the format (e.g., embodied or not) of semantic representations (e.g., RHM, Distributed Conceptual Feature Model), whereas others do (e.g., representational units in the bilingual Dual Code Theory; Paivio, 2014; Paivio & Desrochers, 1980; the Modified Hierarchical Model, Pavlenko, 2009). Crucially, they do not usually specify how those semantic representations are acquired (one exception is in the bilingual Dual Code Theory; Paivio, 2014), a potential decisive factor to be taken into account (see also Jared, Poh, and Paivio [2013] for a review of the mentioned models).

More speculatively, L1 versus L2 differences could be based on the number of sensorimotor features of semantic representations activated during language processing. Alternatively, they could depend on a different network activated during a specific task. Pointing into this direction is the study of Zhang et al. (2020), which reports a more integrated neural network and different areas involved during L1 as compared to L2 processing. Future studies could investigate if these network differences are specific to the lexico-semantic processing per se, to language control, or to the sensorimotor properties implicated in the task. We believe that time-sensitive methods are needed to study embodiment both at early and later stages, so that motor involvement can be more specifically related to L1 or L2. For instance, because of language co-activation in the early stages of word recognition (e.g., Kroll, Gullifer, & Rossi, 2013; Dijkstra & van Heuven, 2002), one must discern if motor involvement during L2 processing is specific to L2 or just a manifestation of L1-coactivated embodiment. If the trend of later embodiment differences between L1 and L2 in our data should be confirmed in further studies, one could argue that early embodiment effects reflects cross-language embodiment or L1-only embodiment effects, whereas later embodiment differences reflects the magnitude of L2-specific embodiment in comparison to L1.

In summary, our research adds evidence to the panorama of different nuances of language embodiment, with L2 embodiment being less evident than L1 embodiment in terms of semantic resonance, a result that was not completely mirrored on the neurophysiological level in terms of motor resonance. However, this field of research is still very young and our understanding of semantic representations and their neural underpinnings is still scarce, even in monolinguals.

As discussed in Monaco et al. (2019), new insights on the action–language cross talk will have not only important theoretical implications but also translational, grounding predictions for L2 recovery, motor interventions for language impairments, or linguistic markers for early detecting motor impairment. Future studies should i) bring additional evidence to semantic resonance in bilinguals, by making use of complementary techniques, such as motor training and kinematic analysis, while taking into account potential inter- and intra-individual influencing factors, and ii) integrate the new data on embodiment and bilingualism in existing or new models that will allow operationalization of the mechanisms behind semantic and motor resonance.

## Conclusion

This study explored both directions of motor–language coupling in healthy late bilinguals, adding important data to the underinvestigated topic of L2 embodiment. We showed for the first time a difference in L2 versus L1 semantic resonance, taking place in an early time window of word processing. On the other hand, motor resonance was partially confirmed, reflected in different motor cortex excitability for L1 versus L2. We therefore provide further evidence that L1 and L2 are differently embodied and confirmed previous findings on the early action–language interaction in the context of word recognition.

## Acknowledgments

We are very grateful to Lucas Spierer for the helpful comments and discussions throughout the preparation of the paper.

Reprint requests should be sent to Elisa Monaco, Laboratory for Cognitive and Neurological Sciences, Department of Neuroscience and Movement Science, Faculty of Science and Medicine, University of Fribourg, Switzerland, or via e-mail: [elisa.monaco@unifr.ch](mailto:elisa.monaco@unifr.ch).

## Author Contributions

Elisa Monaco: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Visualization; Writing—Original draft; Writing—Review & editing. Lea B. Jost: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Writing—Review & editing. Monica Lancheros: Conceptualization; Data curation; Formal analysis; Investigation; Resources; Writing—Review & editing. Sylvain Harquel: Data curation; Formal analysis; Resources; Software; Writing—Review & editing. Eric Schmidlin: Conceptualization; Methodology; Resources; Writing—Review & editing. Jean-Marie Annoni: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing—Original draft; Writing—Review & editing.

## Funding Information

The Swiss National Science Foundation (<https://dx.doi.org/10.13039/501100001711>), SNF grants 325130\_156937/2, and 325130\_182594 supported this study.

## Diversity in Citation Practices

A retrospective analysis of the citations in every article published in this journal from 2010 to 2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were  $M(\text{an})/M = .408$ ,  $W(\text{oman})/M = .335$ ,  $M/W = .108$ , and  $W/W = .149$ , the comparable proportions for the articles that these authorship teams cited were  $M/M = .579$ ,  $W/M = .243$ ,  $M/W = .102$ , and  $W/W = .076$  (Fulvio et al., *JoCN*, 33:1, pp. 3–7). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows:  $M/M = .564$ ,  $W/M = .168$ ,  $M/W = .05$ , and  $W/W = .218$ .

## Notes

1. In a simple model with TMSdelay as unique factor.
2. Or it could be a modulator of control processing, if we accept the motor system having such a role.

## REFERENCES

Adams, A. M. (2016). How language is embodied in bilinguals and children with specific language impairment. *Frontiers in Psychology*, 7, 1209. <https://doi.org/10.3389/fpsyg.2016.01209>

Ahlberg, D. K., Bischoff, H., Kaup, B., Bryant, D., & Strozyk, J. V. (2018). Grounded cognition: Comparing language  $\times$  space interactions in first language and second language. *Applied Psycholinguistics*, 39, 437–459. <https://doi.org/10.1017/S014271641700042X>

Amsel, B. D., Urbach, T. P., & Kutas, M. (2013). Alive and grasping: Stable and rapid semantic access to an object category but not object graspability. *Neuroimage*, 77, 1–13. <https://doi.org/10.1016/j.neuroimage.2013.03.058>, PubMed: 23567884

Aravena, P., Hurtado, E., Riveros, R., Cardona, J. F., Manes, F., & Ibáñez, A. (2010). Applauding with closed hands: Neural signature of action–sentence compatibility effects. *PLoS One*, 5, e11751. <https://doi.org/10.1371/journal.pone.0011751>, PubMed: 20676367

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, 59, 390–412. <https://doi.org/10.1016/j.jml.2007.12.005>

Barr, D. J. (2013). Random effects structure for testing interactions in linear mixed-effects models. *Frontiers in Psychology*, 4, 428. <https://doi.org/10.3389/fpsyg.2013.00328>

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it

maximal. *Journal of Memory and Language*, 68. <https://doi.org/10.1016/j.jml.2012.11.001>, PubMed: 24403724

Barragan, B., Liss, J., Berisha, V., Rogalsky, C., Restrepo, A., & Arizona State University. (2018). The role of primary motor cortex in second language word recognition. In *ASU electronic theses and dissertations*. Arizona State University. <https://hdl.handle.net/2286/R.I.49034>

Barsalou, L. W. (1999). Perceptions of perceptual symbols. *Behavioral and Brain Sciences*, 22, 637–660. <https://doi.org/10.1017/S0140525X99532147>

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59, 617–645. <https://doi.org/10.1146/annurev.psych.59.103006.093639>

Barsalou, L. W. (2016). On staying grounded and avoiding quixotic dead ends. *Psychonomic Bulletin & Review*, 23, 1122–1142. <https://doi.org/10.3758/s13423-016-1028-3>, PubMed: 27112560

Bastani, A., & Jaberzadeh, S. (2012). A higher number of TMS-elicited MEP from a combined hotspot improves intra- and inter-session reliability of the upper limb muscles in healthy individuals. *PLoS One*, 7, e47582. <https://doi.org/10.1371/journal.pone.0047582>, PubMed: 23077645

Bates, D., Kliegl, R., Vasishth, S., & Baayen, H. (2018). Parsimonious mixed models. *arXiv:1506.04967 [stat]*. <https://arxiv.org/abs/1506.04967>

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv:1406.5823 [stat]*. <https://arxiv.org/abs/1406.5823>

Baumeister, J. C., Foroni, F., Conrad, M., Rumiati, R. I., & Winkielman, P. (2017). Embodiment and emotional memory in first vs. second language. *Frontiers in Psychology*, 8, 394. <https://doi.org/10.3389/fpsyg.2017.00394>, PubMed: 28386240

Beilock, S. L., Lyons, I. M., Mattarella-Micke, A., Nusbaum, H. C., & Small, S. L. (2008). Sports experience changes the neural processing of action language. *Proceedings of the National Academy of Sciences, U.S.A.*, 105, 13269–13273. <https://doi.org/10.1073/pnas.0803424105>, PubMed: 18765806

Bergmann, T. O., & Hartwigsen, G. (2021). Inferring causality from noninvasive brain stimulation in cognitive neuroscience. *Journal of Cognitive Neuroscience*, 33, 195–225. [https://doi.org/10.1162/jocn\\_a\\_01591](https://doi.org/10.1162/jocn_a_01591), PubMed: 32530381

Bidet-Ildei, C., Beuprez, S.-A., & Badets, A. (2020). A review of literature on the link between action observation and action language: Advancing a shared semantic theory. *New Ideas in Psychology*, 58, 100777. <https://doi.org/10.1016/j.newideapsych.2019.100777>

Birba, A., Beltrán, D., Martorell Caro, M., Trevisan, P., Kogan, B., Sedeño, L., et al. (2020). Motor-system dynamics during naturalistic reading of action narratives in first and second language. *Neuroimage*, 216, 116820. <https://doi.org/10.1016/j.neuroimage.2020.116820>, PubMed: 32278096

Bolognini, N., & Ro, T. (2010). Transcranial magnetic stimulation: Disrupting neural activity to alter and assess brain function. *Journal of Neuroscience*, 30, 9647–9650. <https://doi.org/10.1523/JNEUROSCI.1990-10.2010>, PubMed: 20660247

Boulenger, V., Roy, A. C., Paulignan, Y., Deprez, V., Jeannerod, M., & Nazir, T. A. (2006). Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Journal of Cognitive Neuroscience*, 18, 1607–1615. <https://doi.org/10.1162/jocn.2006.18.10.1607>, PubMed: 17014366

Boulenger, V., Shtyrov, Y., & Pulvermüller, F. (2012). When do you grasp the idea? MEG evidence for instantaneous idiom understanding. *Neuroimage*, 59, 3502–3513. <https://doi.org/10.1016/j.neuroimage.2011.11.011>, PubMed: 22100772

Boulenger, V., Silber, B. Y., Roy, A. C., Paulignan, Y., Jeannerod, M., & Nazir, T. A. (2008). Subliminal display of action words

- interferes with motor planning: A combined EEG and kinematic study. *Journal of Physiology-Paris*, *102*, 130–136. <https://doi.org/10.1016/j.jphysparis.2008.03.015>, PubMed: 18485678
- Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables that vary within-subjects and/or within-items. *Psychological Methods*, *23*, 389–411. <https://doi.org/10.1037/met0000159>, PubMed: 29172609
- Brysbaert, M., & Stevens, M. (2018). Power analysis and effect size in mixed effects models: A tutorial. *Journal of Cognition*, *1*, 9. <https://doi.org/10.5334/joc.10>, PubMed: 31517183
- Buccino, G., Colagè, I., Gobbi, N., & Bonaccorso, G. (2016). Grounding meaning in experience: A broad perspective on embodied language. *Neuroscience & Biobehavioral Reviews*, *69(Suppl. C)*, 69–78. <https://doi.org/10.1016/j.neubiorev.2016.07.033>, PubMed: 27477443
- Buccino, G., Marino, B. F., Bulgarelli, C., & Mezzadri, M. (2017). Fluent speakers of a second language process graspable nouns expressed in L2 like in their native language. *Frontiers in Psychology*, *8*, 1306. <https://doi.org/10.3389/fpsyg.2017.01306>, PubMed: 28824491
- Buccino, G., Riggio, L., Melli, G., Binkofski, F., Gallese, V., & Rizzolatti, G. (2005). Listening to action-related sentences modulates the activity of the motor system: A combined TMS and behavioral study. *Cognitive Brain Research*, *24*, 355–363. <https://doi.org/10.1016/j.cogbrainres.2005.02.020>, PubMed: 16099349
- Cacciari, C., Bolognini, N., Senna, I., Pellicciari, M. C., Miniussi, C., & Papagno, C. (2011). Literal, fictive and metaphorical motion sentences preserve the motion component of the verb: A TMS study. *Brain and Language*, *119*, 149–157. <https://doi.org/10.1016/j.bandl.2011.05.004>, PubMed: 21684590
- Candidi, M., Leone-Fernandez, B., Barber, H. A., Carreiras, M., & Aglioti, S. M. (2010). Hands on the future: Facilitation of cortico-spinal hand-representation when reading the future tense of hand-related action verbs. *European Journal of Neuroscience*, *32*, 677–683. <https://doi.org/10.1111/j.1460-9568.2010.07305.x>
- Chan, A. M., Baker, J. M., Eskandar, E., Schomer, D., Ulbert, I., Marinkovic, K., et al. (2011). First-pass selectivity for semantic categories in human anteroventral temporal lobe. *Journal of Neuroscience*, *31*, 18119–18129. <https://doi.org/10.1523/JNEUROSCI.3122-11.2011>, PubMed: 22159123
- Chatterjee, A. (2010). Disembodiment cognition. *Language and Cognition*, *2*, 79–116. <https://doi.org/10.1515/langcog.2010.004>, PubMed: 20802833
- Chersi, F., Thill, S., Ziemke, T., & Borghi, A. M. (2010). Sentence processing: Linking language to motor chains. *Frontiers in Neurobotics*, *4*, 4. <https://doi.org/10.3389/fnbot.2010.00004>, PubMed: 20725506
- Costa, A., Corey, J. D., Hayakawa, S., Aparici, M., Vives, M.-L., & Keysar, B. (2019). The role of intentions and outcomes in the foreign language effect on moral judgements. *Quarterly Journal of Experimental Psychology*, *72*, 8–17. <https://doi.org/10.1177/1747021817738409>, PubMed: 30803340
- Costa, A., Foucart, A., Arnon, I., Aparici, M., & Apesteguia, J. (2014). “Piensa” twice: On the foreign language effect in decision making. *Cognition*, *130*, 236–254. <https://doi.org/10.1016/j.cognition.2013.11.010>, PubMed: 24334107
- Costa, A., Foucart, A., Hayakawa, S., Aparici, M., Apesteguia, J., Heafner, J., et al. (2014). Your morals depend on language. *PLoS One*, *9*, e94842. <https://doi.org/10.1371/journal.pone.0094842>, PubMed: 24760073
- Dalla Volta, R., Fabbri-Destro, M., Gentilucci, M., & Avanzini, P. (2014). Spatiotemporal dynamics during processing of abstract and concrete verbs: An ERP study. *Neuropsychologia*, *61*, 163–174. <https://doi.org/10.1016/j.neuropsychologia.2014.06.019>, PubMed: 24956569
- De Grauwe, S., Willems, R. M., Rueschemeyer, S.-A., Lemhöfer, K., & Schriefers, H. (2014). Embodied language in first- and second-language speakers: Neural correlates of processing motor verbs. *Neuropsychologia*, *56(Suppl. C)*, 334–349. <https://doi.org/10.1016/j.neuropsychologia.2014.02.003>, PubMed: 24524912
- De Groot, A. M. B. (1995). Determinants of bilingual lexicosemantic organisation. *Computer Assisted Language Learning*, *8*, 151–180. <https://doi.org/10.1080/0958822940080204>
- de León Rodríguez, D., Buetler, K. A., Eggenberger, N., Preisig, B. C., Schumacher, R., Laganaro, M., et al. (2016). The modulation of reading strategies by language opacity in early bilinguals: An eye movement study. *Bilingualism: Language and Cognition*, *19*, 567–577. <https://doi.org/10.1017/S1366728915000310>
- de Vega, M., Moreno, V., & Castillo, D. (2013). The comprehension of action-related sentences may cause interference rather than facilitation on matching actions. *Psychological Research*, *77*, 20–30. <https://doi.org/10.1007/s00426-011-0356-1>, PubMed: 21755368
- Della Rosa, P. A., Catricalà, E., Vigliocco, G., & Cappa, S. F. (2010). Beyond the abstract—Concrete dichotomy: Mode of acquisition, concreteness, imageability, familiarity, age of acquisition, context availability, and abstractness norms for a set of 417 Italian words. *Behavior Research Methods*, *42*, 1042–1048. <https://doi.org/10.3758/BRM.42.4.1042>, PubMed: 21139171
- Dijkstra, T., & van Heuven, W. J. B. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and Cognition*, *5*, 175–197. <https://doi.org/10.1017/S1366728902003012>
- Dong, Y., Gui, S., & Macwhinney, B. (2005). Shared and separate meanings in the bilingual mental lexicon. *Bilingualism: Language and Cognition*, *8*, 221–238. <https://doi.org/10.1017/S1366728905002270>
- Dudschig, C., de la Vega, I., & Kaup, B. (2014). Embodiment and second-language: Automatic activation of motor responses during processing spatially associated L2 words and emotion L2 words in a vertical Stroop paradigm. *Brain and Language*, *132(Suppl. C)*, 14–21. <https://doi.org/10.1016/j.bandl.2014.02.002>, PubMed: 24681402
- Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*, 528–536. <https://doi.org/10.1152/jn.2000.83.1.528>, PubMed: 10634893
- Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *Quarterly Journal of Experimental Psychology*, *61*, 825–850. <https://doi.org/10.1080/17470210701623605>, PubMed: 18470815
- Foroni, F. (2015). Do we embody second language? Evidence for ‘partial’ simulation during processing of a second language. *Brain and Cognition*, *99(Suppl. C)*, 8–16. <https://doi.org/10.1016/j.bandc.2015.06.006>, PubMed: 26188846
- Gallese, V., & Lakoff, G. (2005). The brain’s concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology*, *22*, 455–479. <https://doi.org/10.1080/02643290442000310>, PubMed: 21038261
- García, A. M., & Ibáñez, A. (2016). A touch with words: Dynamic synergies between manual actions and language. *Neuroscience & Biobehavioral Reviews*, *68(Suppl. C)*, 59–95. <https://doi.org/10.1016/j.neubiorev.2016.04.022>, PubMed: 27189784

- Ghandhari, M., Fini, C., Da Rold, F., & Borghi, A. M. (2020). Different kinds of embodied language: A comparison between Italian and Persian languages. *Brain and Cognition*, *142*, 105581. <https://doi.org/10.1016/j.bandc.2020.105581>, PubMed: 32442816
- Gianelli, C., & Dalla Volta, R. (2015). Does listening to action-related sentences modulate the activity of the motor system? Replication of a combined TMS and behavioral study. *Frontiers in Psychology*, *5*, 1511. <https://doi.org/10.3389/fpsyg.2014.01511>
- Gianelli, C., Kühne, K., Lo Presti, S., Mencaraglia, S., & Dalla Volta, R. (2020). Action processing in the motor system: Transcranial magnetic stimulation (TMS) evidence of shared mechanisms in the visual and linguistic modalities. *Brain and Cognition*, *139*, 105510. <https://doi.org/10.1016/j.bandc.2019.105510>, PubMed: 31923805
- Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology*, *61*, 905–919. <https://doi.org/10.1080/17470210701625550>, PubMed: 18470821
- Harquel, S., Beynel, L., Guyader, N., Marendaz, C., David, O., & Chauvin, A. (2016). *CortExTool: A toolbox for processing motor cortical excitability measurements by transcranial magnetic stimulation*. <https://hal.archives-ouvertes.fr/hal-01390016>
- Hauk, O., Coutout, C., Holden, A., & Chen, Y. (2012). The time-course of single-word reading: Evidence from fast behavioral and brain responses. *Neuroimage*, *60*, 1462–1477. <https://doi.org/10.1016/j.neuroimage.2012.01.061>, PubMed: 22281671
- Hauk, O., & Pulvermüller, F. (2004). Neurophysiological distinction of action words in the fronto-central cortex. *Human Brain Mapping*, *21*, 191–201. <https://doi.org/10.1002/hbm.10157>, PubMed: 14755838
- Hauk, O., Shtyrov, Y., & Pulvermüller, F. (2008). The time course of action and action-word comprehension in the human brain as revealed by neurophysiology. *Journal of Physiology-Paris*, *102*, 50–58. <https://doi.org/10.1016/j.jphysparis.2008.03.013>, PubMed: 18485679
- Hauk, O., & Tschentscher, N. (2013). The body of evidence: What can neuroscience tell us about embodied semantics? *Frontiers in Psychology*, *4*, 50. <https://doi.org/10.3389/fpsyg.2013.00050>, PubMed: 23407791
- Hell, J. G. V., & Groot, A. M. B. D. (1998). Conceptual representation in bilingual memory: Effects of concreteness and cognate status in word association. *Bilingualism: Language and Cognition*, *1*, 193–211. <https://doi.org/10.1017/S1366728998000352>
- Innocenti, A., Stefani, E. D., Sestito, M., & Gentilucci, M. (2014). Understanding of action-related and abstract verbs in comparison: A behavioral and TMS study. *Cognitive Processing*, *15*, 85–92. <https://doi.org/10.1007/s10339-013-0583-z>, PubMed: 24113915
- Jared, D., Poh, R. P. Y., & Paivio, A. (2013). L1 and L2 picture naming in Mandarin–English bilinguals: A test of bilingual dual coding theory. *Bilingualism: Language and Cognition*, *16*, 383–396. <https://doi.org/10.1017/S1366728912000685>
- Jessen, F., Heun, R., Erb, M., Granath, D.-O., Klose, U., Papassotiropoulos, A., et al. (2000). The concreteness effect: Evidence for dual coding and context availability. *Brain and Language*, *74*, 103–112. <https://doi.org/10.1006/brln.2000.2340>, PubMed: 10924219
- Judd, C. M., Westfall, J., & Kenny, D. A. (2017). Experiments with more than one random factor: Designs, analytic models, and statistical power. *Annual Review of Psychology*, *68*, 601–625. <https://doi.org/10.1146/annurev-psych-122414-033702>, PubMed: 27687116
- Kaushanskaya, M., Blumenfeld, H. K., & Marian, V. (2020). The Language Experience and Proficiency Questionnaire (LEAP-Q): Ten years later. *Bilingualism: Language and Cognition*, *23*, 945–950. <https://doi.org/10.1017/S1366728919000038>, PubMed: 33628083
- Kemmerer, D. (2015). Are the motor features of verb meanings represented in the precentral motor cortices? Yes, but within the context of a flexible, multilevel architecture for conceptual knowledge. *Psychonomic Bulletin & Review*, *22*, 1068–1075. <https://doi.org/10.3758/s13423-014-0784-1>, PubMed: 26193986
- Khateb, A., Pegna, A. J., Michel, C. M., Mouthon, M., & Annoni, J.-M. (2016). Semantic relatedness and first-second language effects in the bilingual brain: A brain mapping study. *Bilingualism: Language and Cognition*, *19*, 311–330. <https://doi.org/10.1017/S1366728915000140>
- Kiefer, M. (2005). Repetition-priming modulates category-related effects on event-related potentials: Further evidence for multiple cortical semantic systems. *Journal of Cognitive Neuroscience*, *17*, 199–211. <https://doi.org/10.1162/0898929053124938>, PubMed: 15811233
- Kogan, B., García-Marco, E., Birba, A., Cortés, C., Melloni, M., Ibáñez, A., et al. (2020). How words ripple through bilingual hands: Motor–language coupling during L1 and L2 writing. *Neuropsychologia*, *146*, 107563. <https://doi.org/10.1016/j.neuropsychologia.2020.107563>, PubMed: 32682797
- Kogan, B., Muñoz, E., Ibáñez, A., & García, A. M. (2020). Too late to be grounded? Motor resonance for action words acquired after middle childhood. *Brain and Cognition*, *138*, 105509. <https://doi.org/10.1016/j.bandc.2019.105509>, PubMed: 31855702
- Kroll, J. F., Gullifer, J. W., & Rossi, E. (2013). The multilingual lexicon: The cognitive and neural basis of lexical comprehension and production in two or more languages. *Annual Review of Applied Linguistics*, *33*, 102–127. <https://doi.org/10.1017/S0267190513000111>
- Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connections between bilingual memory representations. *Journal of Memory and Language*, *33*, 149–174. <https://doi.org/10.1006/jmla.1994.1008>
- Kühne, K., & Gianelli, C. (2019). Is embodied cognition bilingual? Current evidence and perspectives of the embodied cognition approach to bilingual language processing. *Frontiers in Psychology*, *10*, 108. <https://doi.org/10.3389/fpsyg.2019.00108>, PubMed: 30787892
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*, 1–26. <https://doi.org/10.18637/jss.v082.i13>
- Liepert, R., Dolch, T., & Prinz, W. (2012). Bidirectional semantic interference between action and speech. *Psychological Research*, *76*, 446–455. <https://doi.org/10.1007/s00426-011-0390-z>, PubMed: 22075764
- Linck, J. A., & Cunnings, I. (2015). The utility and application of mixed-effects models in second language research. *Language Learning*, *65*(Suppl. 1), 185–207. <https://doi.org/10.1111/lang.12117>
- Lindemann, O., Stenneken, P., van Schie, H. T., & Bekkering, H. (2006). Semantic activation in action planning. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 633–643. <https://doi.org/10.1037/0096-1523.32.3.633>, PubMed: 16822129
- Liu, H., & Cao, F. (2016). L1 and L2 processing in the bilingual brain: A meta-analysis of neuroimaging studies. *Brain and Language*, *159*, 60–73. <https://doi.org/10.1016/j.bandl.2016.05.05.013>, PubMed: 27295606
- Lyons, I. M., Mattarella-Micke, A., Cieslak, M., Nusbaum, H. C., Small, S. L., & Beilock, S. L. (2010). The role of personal experience in the neural processing of action-related

- language. *Brain and Language*, 112, 214–222. <https://doi.org/10.1016/j.bandl.2009.05.006>, PubMed: 19628276
- Macedonia, M. (2019). Embodied learning: Why at school the mind needs the body. *Frontiers in Psychology*, 10, 2098. <https://doi.org/10.3389/fpsyg.2019.02098>, PubMed: 31632311
- Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research*, 50, 940–967. [https://doi.org/10.1044/1092-4388\(2007\)067](https://doi.org/10.1044/1092-4388(2007)067)
- Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & Bates, D. (2017). Balancing type I error and power in linear mixed models. *Journal of Memory and Language*, 94, 305–315. <https://doi.org/10.1016/j.jml.2017.01.001>
- Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*, 48, 788–804. <https://doi.org/10.1016/j.cortex.2010.11.002>, PubMed: 21163473
- Mollo, G., Pulvermüller, F., & Hauk, O. (2016). Movement priming of EEG/MEG brain responses for action-words characterizes the link between language and action. *Cortex*, 74, 262–276. <https://doi.org/10.1016/j.cortex.2015.10.021>, PubMed: 26706997
- Monaco, E., Jost, L. B., Gygax, P. M., & Annoni, J.-M. (2019). Embodied semantics in a second language: Critical review and clinical implications. *Frontiers in Human Neuroscience*, 13, 110. <https://doi.org/10.3389/fnhum.2019.00110>, PubMed: 30983983
- Moseley, R. L., Pulvermüller, F., & Shtyrov, Y. (2013). Sensorimotor semantics on the spot: Brain activity dissociates between conceptual categories within 150 ms. *Scientific Reports*, 3, 1–7. <https://doi.org/10.1038/srep01928>, PubMed: 23732850
- New, B., Brysbaert, M., Veronis, J., & Pallier, C. (2007). The use of film subtitles to estimate word frequencies. *Applied Psycholinguistics*, 28, 661–677. <https://doi.org/10.1017/S014271640707035X>
- New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers*, 36, 516–524. <https://doi.org/10.3758/BF03195598>, PubMed: 15641440
- Nuttall, H. E., Kennedy-Higgins, D., Hogan, J., Devlin, J. T., & Adank, P. (2016). The effect of speech distortion on the excitability of articulatory motor cortex. *Neuroimage*, 128, 218–226. <https://doi.org/10.1016/j.neuroimage.2015.12.038>, PubMed: 26732405
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4), PubMed: 5146491
- Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*, 45, 255–287. <https://doi.org/10.1037/h0084295>
- Paivio, A. (2014). Bilingual dual coding theory and memory. In R. R. Heredia & J. Altarriba (Eds.), *Foundations of bilingual memory* (pp. 41–62). Springer. [https://doi.org/10.1007/978-1-4614-9218-4\\_3](https://doi.org/10.1007/978-1-4614-9218-4_3)
- Paivio, A., & Desrochers, A. (1980). A dual-coding approach to bilingual memory. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*, 34, 388–399. <https://doi.org/10.1037/h0081101>
- Papeo, L., Corradi-Dell'Acqua, C., & Rumiati, R. I. (2011). “She” is not like “I”: The tie between language and action is in our imagination. *Journal of Cognitive Neuroscience*, 23, 3939–3948. [https://doi.org/10.1162/jocn\\_a\\_00075](https://doi.org/10.1162/jocn_a_00075), PubMed: 21671735
- Papeo, L., Rumiati, R. I., Cecchetto, C., & Tomasino, B. (2012). On-line changing of thinking about words: The effect of cognitive context on neural responses to verb reading. *Journal of Cognitive Neuroscience*, 24, 2348–2362. [https://doi.org/10.1162/jocn\\_a\\_00291](https://doi.org/10.1162/jocn_a_00291), PubMed: 22971086
- Papeo, L., Vallesi, A., Isaja, A., & Rumiati, R. I. (2009). Effects of TMS on different stages of motor and non-motor verb processing in the primary motor cortex. *PLoS One*, 4, e4508. <https://doi.org/10.1371/journal.pone.0004508>, PubMed: 19240793
- Pavlenko, A. (2009). Conceptual representation in the bilingual lexicon and second language vocabulary learning. In *The bilingual mental lexicon: Interdisciplinary approaches* (pp. 125–160). Bristol, Blue Ridge Summit: Multilingual Matters. <https://doi.org/10.21832/9781847691262-008>
- Pavlenko, A. (2012). Affective processing in bilingual speakers: Disembodied cognition? *International Journal of Psychology*, 47, 405–428. <https://doi.org/10.1080/00207594.2012.743665>, PubMed: 23163422
- Pulvermüller, F. (2013a). How neurons make meaning: Brain mechanisms for embodied and abstract-symbolic semantics. *Trends in Cognitive Sciences*, 17, 458–470. <https://doi.org/10.1016/j.tics.2013.06.004>, PubMed: 23932069
- Pulvermüller, F. (2013b). Semantic embodiment, disembodiment or misembodiment? In search of meaning in modules and neuron circuits. *Brain and Language*, 127, 86–103. <https://doi.org/10.1016/j.bandl.2013.05.015>, PubMed: 23932167
- Pulvermüller, F., Cook, C., & Hauk, O. (2012). Inflection in action: Semantic motor system activation to noun- and verb-containing phrases is modulated by the presence of overt grammatical markers. *Neuroimage*, 60, 1367–1379. <https://doi.org/10.1016/j.neuroimage.2011.12.020>, PubMed: 22206964
- Pulvermüller, F., Hauk, O., Nikulin, V. V., & Ilmoniemi, R. J. (2005). Functional links between motor and language systems. *European Journal of Neuroscience*, 21, 793–797. <https://doi.org/10.1111/j.1460-9568.2005.03900.x>, PubMed: 15733097
- Pulvermüller, F., Shtyrov, Y., & Hauk, O. (2009). Understanding in an instant: Neurophysiological evidence for mechanistic language circuits in the brain. *Brain and Language*, 110, 81–94. <https://doi.org/10.1016/j.bandl.2008.12.001>, PubMed: 19664815
- R Core Team. (2018). *R: A language and environment for statistical computing* (Version 3.5.1) [Computer software]. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Reilly, M., Howerton, O., & Desai, R. H. (2019). Time-course of motor involvement in literal and metaphoric action sentence processing: A TMS study. *Frontiers in Psychology*, 10, 371. <https://doi.org/10.3389/fpsyg.2019.00371>, PubMed: 30863346
- Robertson, E. M., Théoret, H., & Pascual-Leone, A. (2003). Studies in cognition: The problems solved and created by transcranial magnetic stimulation. *Journal of Cognitive Neuroscience*, 15, 948–960. <https://doi.org/10.1162/089892903770007344>, PubMed: 14614806
- Rossi, S., Hallett, M., Rossini, P. M., & Pascual-Leone, A. (2009). Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clinical Neurophysiology*, 120, 2008–2039. <https://doi.org/10.1016/j.clinph.2009.08.016>, PubMed: 19833552
- Rossi, S., Hallett, M., Rossini, P. M., & Pascual-Leone, A. (2011). Screening questionnaire before TMS: An update. *Clinical Neurophysiology*, 122, 1686. <https://doi.org/10.1016/j.clinph.2010.12.037>, PubMed: 21227747
- Rossini, P. M., Barker, A. T., Berardelli, A., Caramia, M. D., Caruso, G., Cracco, R. Q., et al. (1994). Non-invasive electrical and magnetic stimulation of the brain, spinal cord and roots:

- Basic principles and procedures for routine clinical application. *Electroencephalography and Clinical Neurophysiology*, *91*, 79–92. [https://doi.org/10.1016/0013-4694\(94\)90029-9](https://doi.org/10.1016/0013-4694(94)90029-9), PubMed: 7519144
- Rueschemeyer, S.-A., Glenberg, A. M., Kaschak, M., Mueller, K., & Friederici, A. (2010). Top-down and bottom-up contributions to understanding sentences describing objects in motion. *Frontiers in Psychology*, *1*, 183. <https://doi.org/10.3389/fpsyg.2010.00183>
- Rueschemeyer, S.-A., Lindemann, O., van Elk, M., & Bekkering, H. (2009). Embodied cognition: The interplay between automatic resonance and selection-for-action mechanisms. *European Journal of Social Psychology*, *39*, 1180–1187. <https://doi.org/10.1002/ejsp.662>
- Rüschemeyer, S.-A., Zysset, S., & Friederici, A. D. (2006). Native and non-native reading of sentences: An fMRI experiment. *Neuroimage*, *31*, 354–365. <https://doi.org/10.1016/j.neuroimage.2005.11.047>, PubMed: 16427323
- Schwanenflugel, P. J., & Shoben, E. J. (1983). Differential context effects in the comprehension of abstract and concrete verbal materials. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*, 82–102. <https://doi.org/10.1037/0278-7393.9.1.82>
- Scorolli, C., Jacquet, P. O., Binkofski, F., Nicoletti, R., Tessari, A., & Borghi, A. M. (2012). Abstract and concrete phrases processing differentially modulates cortico-spinal excitability. *Brain Research*, *1488*, 60–71. <https://doi.org/10.1016/j.brainres.2012.10.004>, PubMed: 23044471
- Shebani, Z., & Pulvermüller, F. (2018). Flexibility in language action interaction: The influence of movement type. *Frontiers in Human Neuroscience*, *12*, 252. <https://doi.org/10.3389/fnhum.2018.00252>, PubMed: 29988612
- Sheikh, N. A., & Titone, D. (2016). The embodiment of emotional words in a second language: An eye-movement study. *Cognition and Emotion*, *30*, 488–500. <https://doi.org/10.1080/02699931.2015.1018144>, PubMed: 25786993
- Sidhu, D. M., Kwan, R., Pexman, P. M., & Siakaluk, P. D. (2014). Effects of relative embodiment in lexical and semantic processing of verbs. *Acta Psychologica*, *149*, 32–39. <https://doi.org/10.1016/j.actpsy.2014.02.009>, PubMed: 24657828
- Tian, L., Chen, H., Zhao, W., Wu, J., Zhang, Q., De, A., et al. (2020). The role of motor system in action-related language comprehension in L1 and L2: An fMRI study. *Brain and Language*, *201*, 104714. <https://doi.org/10.1016/j.bandl.2019.104714>, PubMed: 31790907
- Tomasino, B., Fink, G. R., Sparing, R., Dafotakis, M., & Weiss, P. H. (2008). Action verbs and the primary motor cortex: A comparative TMS study of silent reading, frequency judgments, and motor imagery. *Neuropsychologia*, *46*, 1915–1926. <https://doi.org/10.1016/j.neuropsychologia.2008.01.015>, PubMed: 18328510
- Tomasino, B., & Rumiati, R. I. (2013). At the mercy of strategies: The role of motor representations in language understanding. *Cognitive Science*, *4*, 27. <https://doi.org/10.3389/fpsyg.2013.00027>, PubMed: 23382722
- Tomasino, B., Werner, C. J., Weiss, P. H., & Fink, G. R. (2007). Stimulus properties matter more than perspective: An fMRI study of mental imagery and silent reading of action phrases. *Neuroimage*, *36*, T128–T141. <https://doi.org/10.1016/j.neuroimage.2007.03.035>, PubMed: 17499160
- van Heuven, W. J. B., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). Subtlex-UK: A new and improved word frequency database for British English. *Quarterly Journal of Experimental Psychology*, *67*, 1176–1190. <https://doi.org/10.1080/17470218.2013.850521>, PubMed: 24417251
- Vaseghi, B., Zoghi, M., & Jaberzadeh, S. (2015). Inter-pulse interval affects the size of single-pulse TMS-induced motor evoked potentials: A reliability study. *Basic and Clinical Neuroscience*, *6*, 44–51. PubMed: 27504156
- Vukovic, N., Feurra, M., Shpektor, A., Myachykov, A., & Shtyrov, Y. (2017). Primary motor cortex functionally contributes to language comprehension: An online rTMS study. *Neuropsychologia*, *96(Suppl. C)*, 222–229. <https://doi.org/10.1016/j.neuropsychologia.2017.01.025>, PubMed: 28122198
- Vukovic, N., & Shtyrov, Y. (2014). Cortical motor systems are involved in second-language comprehension: Evidence from rapid mu-rhythm desynchronisation. *Neuroimage*, *102*, 695–703. <https://doi.org/10.1016/j.neuroimage.2014.08.039>, PubMed: 25175538
- Vukovic, N., & Shtyrov, Y. (2019). Learning with the wave of the hand: Kinematic and TMS evidence of primary motor cortex role in category-specific encoding of word meaning. *Neuroimage*, *202*, 116179. <https://doi.org/10.1016/j.neuroimage.2019.116179>, PubMed: 31505271
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., et al. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, *4*, 1686. <https://doi.org/10.21105/joss.01686>
- Willems, R. M., Hagoort, P., & Casasanto, D. (2010). Body-specific representations of action verbs: Neural evidence from right- and left-handers. *Psychological Science*, *21*, 67–74. <https://doi.org/10.1177/0956797609354072>, PubMed: 20424025
- Yang, J., & Li, P. (2012). Brain networks of explicit and implicit learning. *PLoS One*, *7*, e42993. <https://doi.org/10.1371/journal.pone.0042993>, PubMed: 22952624
- Zhang, S., & Thompson, N. (2004). DIALANG: A Diagnostic Language Assessment System (review). *Canadian Modern Language Review/La Revue Canadienne Des Langues Vivantes*, *61*, 290–293. <https://doi.org/10.1353/cml.2005.0011>
- Zhang, X., Yang, J., Wang, R., & Li, P. (2020). A neuroimaging study of semantic representation in first and second languages. *Language, Cognition and Neuroscience*, *35*, 1223–1238. <https://doi.org/10.1080/23273798.2020.1738509>
- Zwaan, R. A., & Taylor, L. J. (2006). Seeing, acting, understanding: Motor resonance in language comprehension. *Journal of Experimental Psychology: General*, *135*, 1–11. <https://doi.org/10.1037/0096-3445.135.1.1>, PubMed: 16478313