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Too late to be grounded? Motor resonance for action words acquired after middle childhood

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ABSTRACT

Though well established for languages acquired in infancy, the role of embodied mechanisms remains poorly understood for languages learned in middle childhood and adulthood. To bridge this gap, we examined 34 experiments that assessed sensorimotor resonance during processing of action-related words in real and artificial languages acquired since age 7 and into adulthood. Evidence from late bilinguals indicates that foreign-language action words modulate neural activity in motor circuits and predictably facilitate or delay physical movements (even in an effector-specific fashion), with outcomes that prove partly sensitive to language proficiency. Also, data from newly learned vocabularies suggest that embodied effects emerge after brief periods of adult language exposure, remain stable through time, and hinge on the performance of bodily movements (and, seemingly, on action observation, too). In sum, our work shows that infant language exposure is not indispensable for the recruitment of embodied mechanisms during language processing, a finding that carries non-trivial theoretical, pedagogical, and clinical implications for neurolinguistics, in general, and bilingualism research, in particular.

1. Introduction[1]

Embodied brain systems encompass sensorimotor circuits grounding modality-specific meanings, such as those evoked by sound-related words (Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008), smell-related words (González et al., 2006) or, more abundantly, action-related words (García et al., 2019). Accruing research shows that such mechanisms are critical for native-language (L1) processing (García & Ibáñez, 2016; Pulvermüller, 2013, 2018). Yet, do they also play a putative role for words learned after middle childhood? To address this issue and assess the relevance of sensorimotor networks for word processing and learning across the lifespan, we reviewed 29 studies exploring embodied effects via action-word paradigms in languages learned between middle childhood and adulthood.

In L1, action verbs (words which denote bodily movements) elicit activation increases in sensorimotor networks (García et al., 2019; Hauk, Johnsrude, & Pulvermüller, 2004; Tomasino, Fink, Sparing, Dafotakis, & Weiss, 2008; Tomasino, Werner, Weiss, & Fink, 2007), become selectively affected upon electrical or magnetic stimulation of movement-related regions (Gerfo et al., 2008; Liuzzi et al., 2010; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005; Repetto, Colombo, Cipresso, & Riva, 2013; Willems, Labruna, D'Esposito, Ivry, & Casasanto, 2011), and trigger specific facilitation (i.e., shorter response latencies) or interference (i.e., longer response latencies) effects on same-effector movements (García & Ibáñez, 2016b, Mirabella, Iaconelli, Spadacenta, Federico, & Gallese, 2012; Spadacenta, Gallese, Fragola, & Mirabella, 2014). Together with evidence that gesturing facilitates vocabulary development in infancy (LeBarton, Goldin-Meadow, & Raudenbush, 2015; Novack, Goldin-Meadow, & Woodward, 2015; Rowe & Goldin-Meadow, 2009), such findings indicate that L1 words

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[1] **Acronyms:** L1: Native language; L2: Later-learned language; BOI: Body-object-interaction, AoA: Age of acquisition.

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are at least partially embodied –i.e., grounded in neurocognitive systems mediating relevant sensorimotor experiences (Gallese & Lakoff, 2005; Pulvermüller, 2013). However, this finding cannot be extrapolated a priori to *later-learned second languages* (L2s), namely, those incorporated after the age of 7 (Hull & Vaid, 2006, 2007; Long, 1990; Mahendra, Plante, Magloire, Milman, & Trouard, 2003; Mayo, Florentine, & Buus, 1997; Perani et al., 2003; Vilas et al., 2019; Waldron & Hernandez, 2013), when optimal windows for the incidental acquisition of several language functions have elapsed (Paradis, 2009; Ullman, 2001a).[2]

Indeed, the neurocognitive bases of a lately-learned L2 are variously different from those of a language acquired during infancy. L1s and late L2s can be doubly dissociated by brain damage (García, 2015b; Paradis, 1989) and they differ in their recruitment of specific functional networks within anterior and posterior brain regions (Chee, 2009; Klein et al., 2006; Lucas, McKhann, & Ojemann, 2004; Ojemann & Whitaker, 1978), their reliance on procedural and declarative memory systems (Paradis, 2009; Ullman, 2001a), and their behavioral correlates across varying paradigms (García, 2015a; Kroll & Stewart, 1994; Kroll, Van Hell, Tokowicz, & Green, 2010). Moreover, L2 processing effects (such as parallel co-activation of both languages, inhibition of a non-target language, and the predominant recruitment of lexical or conceptual routes during cross-linguistic processing) can be attenuated or nullified in subjects with a high age of acquisition (AoA), as shown by studies on fluency (Bennett & Verney, 2018), lexical access (Bylund, Abrahamsson, Hyltenstam, & Norrman, 2019), and cross-linguistic priming (Sabourin, Brien, & Burkholder, 2014). Therefore, the detection of embodied effects in an L1 does not necessarily guarantee their presence in subsequent languages. In fact, a selective overview of *affective* language processing in bilinguals prompted the speculation that L2s may actually be disembodied (Pavlenko, 2012).

Research on affective language embodiment assesses potential links between words with emotional associations and markers of affective activation (e.g., arousal-sensitive electrodermic modulations, activation of brain networks mediating emotional experiences, behavioral effects driven by congruency/incongruency between these words and other emotion-laden stimuli), typically involving sub-cortical networks with key nodes in the insula, the amygdala, part of the caudate nucleus, and connections among these structures and frontotemporal regions (Dalgleish, 2004; Lindquist, Wager, Kober, Bliss-Moreau, & Barrett, 2012). Importantly, despite the relevance of this framework to explore grounding effects in late L2s, it can hardly be taken to support the disembodied conjecture. Whereas some studies on emotion-laden words lend preliminary support to such a claim (Colbeck & Bowers, 2012; Opitz & Degner, 2012), several others have actually found similar embodied effects in L1 and L2 (Altarriba & Basnight-Brown, 2011; Dudschig, de la Vega, & Kaup, 2014; Eilola, Havelka, & Sharma, 2007; Fan et al., 2018; Ferré, García, Fraga, Sánchez-Casas, & Molero, 2010; Sutton, Altarriba, Gianico, & Basnight-Brown, 2007). For example, studies employing emotional Stroop, and affective Simon tasks have revealed similar interference and facilitation effects for both languages not only in early (Altarriba & Basnight-Brown, 2011; Sutton et al., 2007) but also in late (Dudschig et al., 2014; Fan et al., 2018) bilinguals. Furthermore, some of the methods contemplated in Pavlenko's (2012) review (e.g., skin conductance) may not be sufficiently sensitive and reliable to capture relevant embodied markers during language processing – e.g., arousal effects (Cacioppo, Berntson, Larsen, Poehlmann, & Ito, 2000; Mauss & Robinson, 2009).

Alternatively, the issue can be much more reliably explored by considering links between action language and motor mechanisms (e.g., activation of brain circuits mediating language and action, or behavioral effects driven by word-induced sensorimotor resonance), involving modulations along the primary motor cortex, the supplementary motor cortex, the premotor cortex, the basal ganglia, and the cerebellum, among other regions (Birba et al., 2017; Klaus, Alves da Silva, & Costa, 2019). While measures of affective language embodiment yield highly variable outcomes (Pavlenko, 2012), action-language paradigms are known to reveal systematic effects in measures of motor-system engagement, such as changes in the speed of concurrent bodily movements (García & Ibáñez, 2016a) and activation peaks in the above-mentioned motor circuits (Pulvermüller, 2013, 2018). Also, subjective ratings of motility (e.g., García, Bocanegra, Herrera, Moreno, et al., 2018) and effector-specificity (e.g., Afonso et al., 2019; García-Marco et al., 2019) are considerably more consistent than those of affective dimensions in emotional language (Stadthagen-Gonzalez, Ferre, Perez-Sanchez, Imbault, & Hinojosa, 2018; Warriner, Kuperman, & Brysbaert, 2013).[3] Moreover, research on action-word processing in lately-learned languages has accrued considerably in recent years, offering a rich corpus to track potentially robust patterns. Importantly, whereas previous works have surveyed selected subsets of the literature (Kühne & Gianelli, 2019; Macedonia, 2014) and outlined relevant theoretical reflections (Adams, 2016; Monaco, Jost, Gygax, & Annoni, 2019), no study has yet offered an integrative assessment of the evidence.

Against this background, here we report a systematic review of 34 experiments aiming to specify (i) whether action-word processing in non-native languages relies on motor-system activity and, if so, (ii) how fast such grounding effects can emerge after late language exposure. To this end, we consider studies assessing processing of lately-learned L2s and others employing artificial or newly-learned languages. Thereupon, we provide an overarching discussion of the main findings, focusing on the swiftness with which embodied mechanisms are recruited after late language exposure, the durability of relevant behavioral outcomes, the similarities and differences between L1 and L2 effects, their biological foundations, and the possible neurocognitive routes involved. Moreover, we address the key theoretical, educational, and clinical implications of the evidence, finally outlining outstanding challenges for the field. All in all, this work seeks to establish the relevance of bodily experience for grounding lexical concepts throughout life.

2. Review criteria

The literature review was conducted on PubMed and Google Scholar through combinations of the following terms: 'embodiment', 'embodied', 'gesture', 'enaction' 'action language', 'motor', 'sensorimotor' AND 'bilingualism', 'foreign language', 'L2', 'novel word learning'. All pertinent results were downloaded and their references were checked in search of additional relevant works. The whole search process yielded 55 papers. Of those, 26 references were excluded after close examination because they (a) focused on emotional (as opposed to action-

[2] However, note that this conventional cut-off delimits the distinction between an L1 (which surrounds individuals since intrauterine life) and a lately-acquired L2 (appropriated after age 7) (Hull & Vaid, 2006, 2007; Long, 1990; Mahendra et al., 2003; Mayo et al., 1997; Perani et al., 2003; Vilas et al., 2019; Waldron & Hernandez, 2013). Admittedly, results from late-L2 studies could also be fruitfully interpreted against other relevant benchmarks, such as early L2s (languages appropriated before age 7 but without intrauterine exposure). However, evidence on the latter has been seldom produced in the embodied cognition literature (Ahlberg et al., 2018; Tellier, 2008). Therefore, where appropriate, comparisons between late L2s and early-acquired languages will be made by reference to L1s, as this allows us to address our objectives with robust empirical corpora.

[3] Still, note that emotional valence can interact with action-relatedness during word processing. For example, Spadacenta et al. (2014) found that compared to affectively neutral hand-related verbs (e.g., *pettinare*, meaning TO COMB), those with negative connotations (e.g., *acoltellare*, meaning TO STAB) can delay or facilitate hand displacements in lexical and semantic decision tasks, respectively. This indicates that affective connotations evoked by specific action verbs may distinctively modulate ongoing bodily actions, inviting further research on the integration of motoric and emotional associations in verbal tasks.

related) language; and/or (b) consisted in theoretical, opinion, or review articles; and/or (c) proved otherwise incongruent with the inclusion criteria listed below. The remaining papers were incorporated into the review because they met the following criteria: (i) inclusion of at least one experiment involving a non-native language (namely, a bilingual's late L2, an artificial language, or a language unbeknownst to the participants); (ii) presence of at least one experimental condition involving action verbs, words implying spatial relations, nouns denoting manipulable objects or concrete words associated to self-initiated or visually presented gestures; and (iii) reporting of at least one dependent variable capable of revealing motor-system engagement (e.g., motor-network activation, relevant electrophysiological modulations, bodily motion speed, word learning rate following action enactment training or motor-network stimulation). Crucially, in all studies, the AoA of (or first exposure to) the non-native language was above 7 –as seen above, a conventional cutoff for identifying late bilinguals (Hull & Vaid, 2006, 2007; Long, 1990; Mahendra et al., 2003; Mayo et al., 1997; Perani et al., 2003; Vilas et al., 2019; Waldron & Hernandez, 2013).

The final selection comprised a total of 29 articles (spanning 34 experiments), which were organized in two groups: one focusing on lately-learned L2s and another one dealing with artificial or newly-learned languages. On the one hand, studying embodiment effects in late L2s allows evaluating sensorimotor grounding patterns in well-consolidated languages that were learned after the closure of optimal windows for incidental language acquisition (Paradis, 2009; Ullman, 2001a). On the other hand, assessing such effects in newly-acquired languages sheds light on the initial stages of these phenomena –revealing, for example, the swiftness with which they emerge upon initial contact with a new language. Each paper from both sets was systematically reviewed in terms of these variables: (a) sample description, (b) stimuli and conditions, (c) type of task, (d) neural correlates (if available), and (e) main results. The ensuing information is condensed in the Appendix (Tables 1 and 2).

3. Evidence from lately-acquired second languages

A suitable model to study the pervasiveness of embodied mechanisms is afforded by experiments on the L2s of late bilinguals (see Appendix, Table 1). In fact, the detection of motor-resonance effects in such conditions would indicate that embodied mechanisms are pivotal for linguistic processing across maturational stages. Focused on samples with an AoA between 7 and 20, the studies reviewed below offer vital data on the matter.

Evidence in this direction has been obtained through studies on content-word processing. Buccino, Marino, Bulgarelli, and Mezzadri (2017) employed a go/no-go paradigm in which participants had to press a key only if the stimulus (L2 noun or picture) represented a real object (which could be graspable or non-graspable). As previously observed in L1 users (Marino et al., 2014), graspable objects were processed more slowly than non-graspable ones regardless of stimulus type. Thus, it seems that sensorimotor activations evoked by an L2 item's motor affordances can interfere with concomitant action-execution processes.

In another study, Bergen, Lau, Narayan, Stojanovic, and Wheeler (2010) presented non-native English speakers with action pictures and asked them to judge whether each image matched an English verb presented immediately afterwards. Responses were slower when the verb and the depicted action shared the same effector, this interference effect being positively correlated with the participants' L2 proficiency. This suggests that the more competent the L2 user, the greater the engagement of motor networks by action words.

Compatibly, Vukovic (2013) found somatotopic interference effects only in highly proficient bilinguals (Fig. 1A). Participants saw mouth-, hand-, and leg-related Serbo-Croatian verbs (L1) followed by English verbs (L2) and had to identify translation equivalents by pressing a button or by uttering them. Crucially, mouth responses were slower following L2 mouth verbs and hand responses were slower when made after L2 hand verbs. This shows that effector-specific effects in L2 can emerge for different body parts provided high proficiency levels are attained.

Additional evidence has revealed that L2 embodiment effects are accompanied by specific neural markers. In an electroencephalography (EEG) experiment (Vukovic & Shtyrov, 2014), German-English bilinguals were instructed to silently read action and abstract verbs in their L1 and L2. Analyses of oscillatory activity revealed significantly greater desynchronization of (motor-sensitive) mu rhythms over the left hemisphere for action words in both languages, with stronger effects for L1 than L2 over the right hemisphere (Fig. 1B). Moreover, source-reconstruction results revealed significantly greater activations in left motor areas for action words in L1 compared to L2 (these results are not shown in Fig. 1B). Once again, this differential pattern of engagement of action-perception circuits during action-word processing could reflect the reduced time of exposure of a lately learned L2 (appropriated after age 7) compared to that of an L1 (pervasively present since intrauterine life).

By the same token, an ERP study compared low- and high-proficiency L2 users (Ibáñez et al., 2010) via a gesture-based paradigm involving literal and metaphorical expressions (e.g., *Those telephones are mobile phones* vs. *Those warriors are lions*) accompanied by congruent and incongruent gestures (e.g., bodily postures reminiscent of a phone or a lion). Crucially, only the highly proficient group exhibited modulations of the N400 component –a robust marker of semantic integration effort (Kutas & Federmeier, 2011)– over left anterior sites, discriminating not only between literal and metaphorical expressions, but also, and more crucially, between those supported by congruent and incongruent gestures (with greater amplitude for the latter). No such modulation was observed in low-proficiency subjects. This indicates that late embodiment effects also have distinctive electrophysiological signatures, and that these may be traceable only after mid- or high-competence levels are attained.

For their part, in an experiment targeting L2 processing only, Xue, Marmolejo-Ramos, and Pei (2015) tested Chinese-English bilinguals in a sentence acceptability task comparing high and low body-object-interaction (BOI) words within rich (e.g., *You brush the small sticky crumb*) or poor (e.g., *You brush pieces of a baked crumb*) sensorimotor contexts. The authors found that, relative to low BOI L2 words, high BOI L2 items were more acceptable, processed faster, and characterized by larger N400 modulations in rich contexts –with poor contexts yielding marginal effects in the same direction. Also, there was a trend indicating that L2 BOI words, in general, were processed slower if embedded in rich sensorimotor contexts. Hence, it appears that processing of L2 BOI words can be affected by the information nested in contextual sensorimotor cues.

Importantly, however, L2 embodiment effects seem to be absent in shallow processing conditions. In a lexical decision experiment conducted by De Grauwe, Willems, Rueschemeyer, Lemhofer, and Schriefers (2014), measures of accuracy revealed no significant differences between action and non-action verbs in both L1 and L2 users of Dutch. Still, the two groups showed significant activation increases for the former category over motor and somatosensory regions, with complementary differences in premotor areas observed only for the L1 group. These results suggest that sensorimotor resonance may be present even in the absence of overt behavioral effects, and that they may overlap greatly (though not totally) between L1 and L2 speakers.

Furthermore, embodied effects in L2 have also been revealed through stimuli implying different spatial relations. Vukovic and Williams (2014) presented Dutch-English bilinguals with L2 sentences implying short and long distances (e.g., *Right next to you in the kitchen you can see the cook* vs. *At the far end of the kitchen you can see the cook*), followed by pictures that varied in size and perceived distance (with large and small pictures appearing to be close to or away from the

Table 1
Studies exploring embodiment effects in lately-acquired second languages.

Experiment	Sample description	Stimuli and conditions	Type of task	Neural correlates	Main results
Buccino et al. (2017)	26 Italian-English bilinguals (age: 22.07; AoA: not reported)	36 English nouns (18 graspable objects, 18 non-graspable objects), 36 pseudowords, 36 photos (18 graspable objects, 18 non-graspable objects), 36 scrambled images.	Go-no go paradigm: pressing a key when the stimulus denotes a real object (otherwise, no response).	None	Interference on graspable relative to non-graspable for both stimuli (nouns or pictures)
Bergen et al. (2010), Exp. 4	35 non-native English Speakers (mainly Japanese and other Asian languages as L1; AoA: not reported)	48 images depicting motor actions (16 mouth/face, 16 hand/arm, 16 foot/leg) followed by a verb in three conditions (matching, nonmatching with same effector, nonmatching with different effector).	Image-verb matching task: Do the images and verbs depict the same action?	None	Interference on same-effector verbs, positively correlated with language proficiency.
Vukovic (2013)	24 Serbo-Croatian-English bilingual 12 high-proficiency (AoA: 8.08) 12 low-proficiency (AoA: 7.58)	36 Serbo-Croatian verbs (12 mouth, 12 hand, 12 leg),36 English verbs (12 mouth, 12 hand, 12 leg)	Translation equivalent recognition either by key-presses or uttering	None	Somatotopic interference on hand- and mouth-related verbs only in high proficient bilinguals.
Vukovic and Shtyrov (2014)	18 German-English bilinguals (age: 26; AoA: 10.19	135 L1 and 135 L2 action words, 135 L1 and 135 L2 abstract words	Passive word reading in L1 and L2	EEG	Reduced mu rhythm modulations for L1 and L2 action words over the right hemisphere, with stronger effects for L1. Greater source-level activation in left motor areas for action words in L1 than in L2.
Ibáñez et al. (2010)	27 Spanish-German bilingual 14 high-proficiency (age: 23.4) 13 low-proficiency (age: 21.1)	176 clips of an actress uttering literal (44) or metaphorical (44) expressions accompanied by congruent (44) or incongruent (44) gestures.	Deciding whether the utterance and the gestures conveyed the same meaning via key-pressing.	ERP	Greater N400 modulations for literal than metaphorical expressions and, only in high-proficiency bilinguals, for those accompanied by congruent gestures.
Xue et al. (2015)	17 Chinese-English bilinguals (age: 24.33; AoA: 12.89)	48 high BOI words sentences (24 rich sensorimotor context, 24 poor sensorimotor context), 48 low BOI words sentences (24 rich sensorimotor context, 24 poor sensorimotor context), 96 semantic anomaly sentences as fillers.	Semantic acceptability via key-presses	ERP	High BOI items were more acceptable, processed faster and evinced larger N400 modulations in rich contexts. Same effects were marginally observed in poor contexts except for RTs. Also, a trend indicated that rich contexts seem to slow down the processing of BOI words in general.
De Grauwe et al. (2014)	20 native Dutch speakers (age: 21.95), 18 German advanced learners of Dutch (age: 24.44; AoA: 19.94)	96 Dutch simple verbs (48 cognates (24 motor,24 non-motor) and 48 non-cognates (24 motor,24 non-motor). 48 Dutch complex verbs (24 motor, 24 non-motor). 24 pseudo-words	Lexical decision task	fMRI	Null behavioral effects. Similar activation over motor and somatosensory regions for action verbs in L1 and L2. Differential activation of premotor areas for action verbs (present in L1 but absent in L2)
Vukovic and Williams (2014)	20 proficient Dutch-English bilinguals (age: 29.35; AoA: 8.65)	24 paired English sentences (one implying closeness and the other distance) using an interlingual English-Dutch homophone at the final position and 24 paired color images (one big, one small).	Participants had to judge whether presented pictures depicted something mentioned in a previously heard sentence via key-presses	None	Interference by compatibility.
Ahlberg et al. (2017)	49 native German speakers (age: 22.9), 45 L2 German speakers (age: 25.9; AoA: 16) with a similar split of the upper subspace as German (L1 = English and Russian) 43 L2 German speakers (age: 24.7; AoA: 14.5) with a dissimilar split of the upper subspace as German (L1 = Korean and Turkish).	Three German words (*über*, *auf* , *unter*) presented in compatible condition (e.g. upward response to *über*) and incompatible condition (e.g. downward response to *über*). The word *ab* was included as a filler.	Stroop adaptation through a vertically-oriented keyboard	None	Facilitation by compatibility
Dudschig et al. (2014), Exp. 1	20 German-English bilinguals (age: 24.70; AoA: 11–13)	40 German-English translation equivalents typically associated either to an up or down location.	Same as Ahlberg et al. (2017)	None	Facilitation by compatibility.
Dudschig et al. (2014), Exp. 2	20 German-English bilinguals (age: 24.3; AoA: 11–13)	Same as Dudschig et al. (2014) exp. 1 but only L2 words were presented.	Same as Ahlberg et al. (2017)	None	Facilitation by compatibility

fMRI: functional magnetic resonance imaging; ERP: event-related potentials; EEG: electroencephalography; ERD: event-related desynchronization; BOI: body-object interaction; BA: Brodmann area; RT: reaction time; L1: native language; L2: foreign language.

Table 2
Studies exploring embodiment effects in artificial and newly-learned languages.

Experiment	Sample description	Stimuli and conditions	Type of task	Neural correlates	Main results
Macedonia et al. (2011)	33 native German speakers (age: 23.17) 18 native German speakers (age: 23.44) for the fMRI experiment.	92 Vimmi nouns and its German translation taught by a video-recorded actress in four conditions: accompanied by iconic gestures or meaningless gestures (both with or without face).	Unknown word detection after training via single key press Written translation task in both directions	fMRI	Significantly better translation outcomes for words learned through iconic gestures Greater activity in the premotor cortices for words learned through iconic gestures
Macedonia and Klimesch (2014)	29 native German speakers (age: 20.4)	36 Tessetisch words and is German translation (nouns, adjectives, verbs, prepositions) learned audiovisually (reading, hearing, repeating) or through enactment (reading, hearing, repeating, self-performing the gesture).	Cued recall test from German into Tessetisch at the end of the two training sessions (day 1 and day 8) and 15, 73, and 444 days later.	None	Words learned through enactment were better remembered than those learned through the audiovisual condition. This pattern remained stable upon retesting 14 months later.
Mayer et al. (2015), Exp. 1	22 native German speakers (age: 24.6)	90 Vimmi words (45 abstract German nouns, 45 concrete German nouns) audiovisually presented by an actress in three conditions (gesture, picture, no enrichment).	Participants had to learn as many Vimmi words as possible during five days). Videos were shown twice. At the first presentation, subjects only had to view it. At the second, they had to perform the gesture, draw the picture in the air with their right index finger, or only view it. Cued translation task in both directions Free recall task. fMRI translation task via multiple choice. All vocabulary tests were conducted from day two to five as well as on day eight, two months and six months after the last session. fMRI task was conducted only on day eight.	fMRI	Better translation for words learned through self-performed gestures upon re-testing two and six months later. Activation of superior temporal sulcus and motor areas for words learned through self-performed gestures.
Macedonia and Mueller (2016)	18 native German speakers (age: 23.44)	92 Vimmi words accompanied either by 46 iconic or by 46 semantically unrelated gestures learned through enactment (hearing, repeating, self-performing the gesture) during 4 days.	Cued recall tests from day two to five, followed by a paired free recall test 60 days later. All tasks were performed in both languages. fMRI task: word recognition	fMRI	Short- and long-term retention and translation were better for words learned through iconic gestures. These elicited increased activation in left premotor and primary motor cortices and the basal ganglia.
García-Gámez and Macizo (2018), Exp. 1	25 native Spanish speakers (age: 21.72)	40 manipulable Vimmi nouns and its Spanish translation learned by repeating them and either performing or not a gesture (which could be related to the word's semantic or associated or not to a different manipulable object)	Forward and backward translation task during the three-day training sessions	None	Words learned through congruent gestures were better translated than in the other conditions in both directions. No differences in RTs were observed between conditions.
García-Gámez and Macizo (2018), Exp. 2	32 native Spanish speakers (age: 20.97)	Same as experiment 1 but action verbs were used instead of nouns.	Same as experiment 1.	None	Action verbs learned through congruent gestures were translated faster and more accurately than in the other conditions in both directions.
Macedonia and Knösche (2011)	20 native German speakers (age: 21.14)	32 transitive Vimmi sentences and their German translation learned through enactment (reading, hearing, self-performing gestures) during six days. Nouns were assigned concrete meanings, the remaining words were abstract. Conditions were shown by an actress: symbolic gesture (each single word was accompanied by a symbolic gesture), no gesture.	Free and cued recall tests in both languages. Written task: production of sentences and correspondent translation by using the learned words	None	Better recall for German gesture-encoded words over the entire training period. Enactment superiority for Vimmi recall only on day three. Marginal enactment superiority on days three, five and six for matched recall. In cued recall, words encoded through enactment were better retrieved in both directions from day three. Higher recruitment of items encoded through enactment in order to produce the sentences. Concrete nouns were best memorized, followed by verbs, abstract nouns, and adverbs.
Öttl et al. (2017)	24 participants (age: 21.33)	8 artificial 2-syllable words randomly assigned to an object (realized as a stuffed animal). 4attached to a wall in a spatially upper location, 4 attached to the same wall in a spatially lower location.	Learning phase: First, the experimenter introduced all objects by presenting a card with the corresponding name while simultaneously pointing, touching, and naming the object. Then, participants imitated the experimenter behavior across four cycles.	None	Words learned in the upper location led to faster upward responses compared to downward responses. Conversely, no differences were observed for words learned in the lower location.

(*continued on next page*)

Table 2 (*continued*)

Experiment	Sample description	Stimuli and conditions	Type of task	Neural correlates	Main results
			Stroop adaptation: pressing upward or downward buttons according to font color.		
Morett (2014)	52 native English speakers (age: 20.15)	Same as Morett (2017).	Same as Morett (2017), but memory tests were administered to both explainers and instructors.	None	Null effect for viewing non-spontaneous representational gestures during L2 word learning. Better recall through beat gesture production for explainers. Better recall through representational gesture production for learners.
Morett (2017)	52 native English speakers (age: 20.15)	20 Hungarian words video-presented by an actress (10 with non-spontaneous representational gestures, 10 without gestures).	Roleplay dialogic task: Two roles: (explainer or interlocutor). Explainers learned the words presented (with and without gestures) in the videos in order to teach them to the interlocutor (visible and non-visible). After that, a memory test was conducted on the explainers	None	Null effect for viewing non-spontaneous representational gestures during L2 word learning. Better recall through spontaneous deictic co-speech gesture production Explainers spontaneously produced more gestures when conveying words learned through gestures (significant for representational gestures and marginal for beat gestures).
Krönke et al. (2013)	11 native German speakers (range age: 23–28)	42 pseudowords, 42 German words (root words), 42 videos of meaningful iconic gestures, 14 videos of meaningless grooming gestures. For the fMRI session, 24 additional words were used (10 German words, 14 untrained pseudowords). Participants were presented the written root words followed by novel words auditorily. In the verbal condition, participants had to repeat the novel word aloud. In the others, novel words were accompanied either by a meaningful iconic or a meaningless grooming gesture. In the active conditions, participants had to perform the respective gesture while naming the novel word. In the passive condition, subjects were instructed to watch the videos without performing the gestures while naming the novel word.	Free recall Cued recall in both directions. fMRI experiment: Lexical decision	fMRI	Better performance for the iconic and verbal conditions. Trained novel words increased activation in the left medial temporal lobe. The iconic condition involved higher activation in the inferior frontal, inferior temporal, and supramarginal gyri. Active condition revealed significant differences in the bilateral inferior temporal gyrus and the right cerebellum.
Kelly et al. (2009), Exp. 1	27 native English speakers (age: 18.5)	10 Japanese verbs. During training session, participants learned the words presented by an instructor in four conditions (Speech, Speech with congruent gesture, Speech with incongruent gesture and repeated speech).	Free recall test Recognition test	None	Participants remembered/correctly recognized the most words that were learned through the Speech + congruent gesture condition, fewer in the Repeated Speech condition, fewer still in the Speech condition and the fewest in the Speech + incongruent gesture condition. No effects of test time were observed
Kelly et al. (2009), Exp. 2	24 native English speakers (age: 18.5)	10 Japanese verbs. Words were learned in two conditions (Speech and congruent gesture and Speech) and the training session was video training (three separate training sessions over three days)	Memory recognition test: Trained Japanese words plus 5 new ones were presented and participants had to discriminate them via key-pressing Free recall test: Same as exp. 1 (following the ERP sessions).	ERP	RTs and accuracy revealed no differences between conditions. Better recall for words learned through Words learned through gestures elicited a larger LPC in bilateral parietal regions (from 500 to 650 ms) No N400 differences were observed between conditions.
Macedonia and Repetto (2016)	32 native German speakers (age: 24.45) split in two groups (high and low memory performers) for statistical purposes	30 Vimmi words and its German translation audiovisually presented in three conditions: visual (reading), audiovisual (reading, hearing), sensorimotor (hearing, reading, observing congruent gestures).	Free recall (in both languages), paired free recall and cued recall.	None	Free recall in German: Better recall for high performers through sensorimotor learning. Low performers gradually improved performance if learning was enriched. Free recall in Vimmi and paired free recall: only high performers took advantage from sensorimotor learning. Cued recall from German to Vimmi: only high performers benefited from sensorimotor learning. Null effects for cued recall from Vimmi to German.
Macedonia et al. (2019)	31 native German speakers (age: 24.35)	Same as Macedonia and Repetto (2016) but words were encoded within an fMRI session.	Same as Macedonia and Repetto (2016) but, in addition, a retest was conducted after 45 days.	fMRI	Advantage of sensorimotor learning only for free recall in both languages. In the follow-up tests, only the free

(*continued on next page*)

Table 2 (*continued*)

Experiment	Sample description	Stimuli and conditions	Type of task	Neural correlates	Main results
					recall in German nearly reached significance. fMRI analysis showed a growing complexity of sensorimotor networks as conditions were more enriched.
Morett (2019)	28 native English speakers (age: 18.70)	20 concrete Hungarian words (10 nouns and 10 verbs) and their English glosses. In a within-subject design, participants were instructed to learn the words in three conditions: 1) accompanied by a video of an iconic gesture, 2) accompanied by a still image, and 3) accompanied by its L1 gloss.	Four memory tests at five minutes and one week after learning phase: free recall, depiction (images were used as cues), translation (glosses were used as cues), and translation plus depiction (both images and glosses were used as cues).	None	Words learned through still images were recalled better in all tasks and across time-tests intervals.
Repetto et al. (2015)	40 native Italian speakers (age: 33.17)	15 Czech verbs (five hand-related, five foot/leg-related and five abstract) and their Italian translations. Participants had to memorize 15 Czech verbs presented auditorily through a virtual reality environment. In the Run condition, participants performed the task as if they were walking or running through a park by moving the joypad. In the baseline condition, no virtual action was allowed except visual exploration by turning their heads.	Cued recall task Recognition task via multiple choice	None	Action verbs were better remembered than abstract verbs. No somatotopic effects were observed. Hand action verbs were more easily recognized in the Baseline condition when subjects evinced high levels of “engagement” and low levels of “negative effects”. Also, fewer errors were observed in the Run condition when participants showed high levels of a subscale that measured the tendency of the participants to recognize the environment as real.
Freundlieb et al. (2012)	19 native German speakers for paradigm A (age: 25) and 10 native German speakers for paradigm B (age: 26.2)	Paradigm A: 76 four-letter pseudowords coupled with photos of 76 different concrete body-relation actions. Paradigm B: 34 pseudowords coupled with 34 photos (17 objects, 17 actions).	Picture-pseudoword matching via single key press Translation from pseudoword into German	None	Learning performance increased across sessions and proved to be stable up to four weeks after training in paradigm A. No differences between action-related and object-related words in paradigm B Better translation for object-related words compared to action-related words. Transitive words were learned and retained significantly better than intransitive words.
Liuzzi et al. (2010), Exp. 1	30 young healthy subjects (age: 24.97)	76 four-letter pseudowords coupled with photos (76 concrete body-relation actions). Participants underwent tDCS over the left motor cortex in three conditions (cathodal: n = 10; anodal: n = 10; sham: n = 10) prior to each learning session (four days of training)	First, Language learning paradigm: pseudowords were presented auditorily while pictures appeared on the screen. Subjects had to decide if the presented coupling was correct or incorrect via key-pressing. After the four days of training, participants were instructed to translate the 76 learned words into German.	tDCS	Significant reduction of correct translated words after cathodal tDCS compared to sham stimulation. No such effect was observed after anodal stimulation. Hand action words were more affected by cathodal tDCS than non-hand related ones.
Liuzzi et al. (2010), Control exp. 1	27 young healthy subjects (age: 24.96)	Same as exp. 1	Same as in exp. 1 but tDCS was administered over the left dorsolateral prefrontal cortex. The aim of this control task was to test the topographic specificity of the effect observed in exp. 1.	tDCS	No effects on translation were observed after administration of tDCS.
Liuzzi et al. (2010), Control exp. 2	Six young healthy subjects (age: 24.50)	34 pseudowords from exp. 1 and control exp. 1 coupled with 34 photos of everyday objects.	Same as exp. 1 but different stimuli (i.e. instead of action-related words, object-related words were evaluated). The aim of this control task was to test the semantic specificity of the effect observed in exp. 1.	tDCS	No effects on translation were observed after administration of tDCS.
Branscheidt et al. (2017)	18 healthy older native speakers of German (age: 70.6)	Same as Freundlieb et al. (2012) paradigm B	First, participants were administrated tDCS over the left motor cortex in three conditions (cathodal, anodal and sham) prior to each learning session (three days of training). Associative learning task was the same as in Freundlieb et al. (2012) paradigm B.	tDCS	Cathodal stimulation led to a decrease of the number of correct responses for action-related words but not for object-related words. No effects of tDCS stimulation were observed on translation rates.
Bechtold et al. (2019)				fMRI	

(*continued on next page*)

Table 2 (*continued*)

Experiment	Sample description	Stimuli and conditions	Type of task	Neural correlates	Main results
	41 healthy adults split in two groups (age of group one: 23.30; age for group two: 23.19)	36 novel-tool-like objects with their respective videos (some instructional and some showing explicit manipulation of pseudoobjects), 36 novel object pseudowords, 36 German nouns for the functional localizer task.	Participants had to learn novel object pseudowords while actively manipulating them or while observing their manipulation, and while seeing its perceptual features (within-subjects factor). After training phase, lexical decision task during an fMRI session.		Null behavioral effects were observed between conditions No regional activation effects were observed between conditions Post-hoc Functional connectivity analyses: Increased functional connectivity in the left parahippocampal gyrus for words learned through the manipulating condition. Increased connectivity between left superior frontal gyrus and the cerebellum for words learned through the manipulating condition. Increased functional connectivity in the left middle temporal gyrus and the cerebellar lobes for words learned through the active manipulating condition

fMRI: functional magnetic resonance imaging; ERP: event-related potentials; tDCS: transcranial direct current stimulation LPC: late positive complex; BA: Brodmann area; RT: reaction time; L2: foreign language.

participant, respectively). Crucially, some target words in the sentences were homophones of the name of the picture in the other language –e.g., the noun implied by the picture of a cookie (/kuki/) sounds like the Dutch word *koek* (/kuk/), meaning ‘cake’. Subjects had to decide whether the object in each picture had been mentioned in the preceding sentence. Interestingly, response latencies were longer when the distances implied in the pictures and the sentences were compatible, but only in the homophone condition. This suggests that competition for sensorimotor resources due to tacit simulations of the movements implied by the stimuli might be increased by the parallel activation of L1 and L2 equivalents.

Also, Ahlberg, Bischoff, Kaup, Bryant, and Strozyk (2017) tested native and non-native speakers of German with a Stroop task involving spatial prepositions and different response directions. Crucially, relative to German, the L1 of the non-native users (i.e., English, Russian, Korean, and Turkish) could employ either similar or different terms to denote spatial relations. Irrespective of their L1, all groups exhibited facilitation effects for prepositions that matched the response direction (e.g., faster upward responses for *auf*). Also, such facilitation by congruency emerged irrespective of L2 proficiency. Notably, this effect was also observed in another study (Dudschig et al., 2014) with L1 and L2 translation equivalents implying specific locations (i.e., faster upward responses for up-words, like *star*, and faster downward responses for down-words, like *earth*) –see Fig. 1C. Interestingly, the same effect was observed when L2 words were presented in the absence of their L1 counterparts (Dudschig et al., 2014). This evidence reinforces the view that sensorimotor networks play critical roles in L2 word processing, further indicating that some embodied effects may operate irrespective of language competence.

In sum, these data suggest that sensorimotor grounding is pervasive in processing action-related words from lately-acquired languages, while warranting four preliminary specifications. First, overt embodied effects are more likely to occur if the body part denoted by the word matches the effector used to respond. Second, those effects may manifest as either facilitation or interference, possibly depending on task- and stimulus-related factors. Third, motor-network engagement increases for action-related words from both L1 and L2, although such effects can be attenuated in the latter case. Finally, at least some sensorimotor grounding effects seem related to language proficiency. For a full treatment of these issues, see the “Discussion” section below.

4. Evidence from artificial and newly-learned languages

The evidence above indicates that embodied effects can emerge even for languages learned after middle childhood. However, such evidence fails to reveal *how soon* motor systems become distinctively engaged upon the acquisition of new action-related words. Fortunately, this issue can be assessed through word-learning paradigms in languages previously unknown to the participants, be they real or artificial (see Appendix, Table 2).

Direct insights have been reached through paradigms in which subjects perform predetermined bodily movements as they process lexical items from a new language. Some of them have focused on gesture-based word-learning paradigms using Vimmi and Tessetisch, two artificial corpora made up of pseudowords (Macedonia & Klimesch, 2014; Macedonia, Muller, & Friederici, 2011). This flexible approach has afforded highly convergent findings.

Vimmi and Tessetisch words practiced over five (Mayer, Yildiz, Macedonia, & von Kriegstein, 2015), four (Macedonia & Mueller, 2016; Macedonia et al., 2011), three (García-Gámez & Macizo, 2018) or even two (Macedonia & Klimesch, 2014) days are better recalled and/or translated when learned through self-performed congruent gestures, relative to incongruent (i.e., semantically unrelated) gestures. This motor-language coupling effect was found to increase steadily over the first three days of training (Macedonia et al., 2011) and to remain significant upon retesting two (Macedonia & Mueller, 2016), six (Mayer

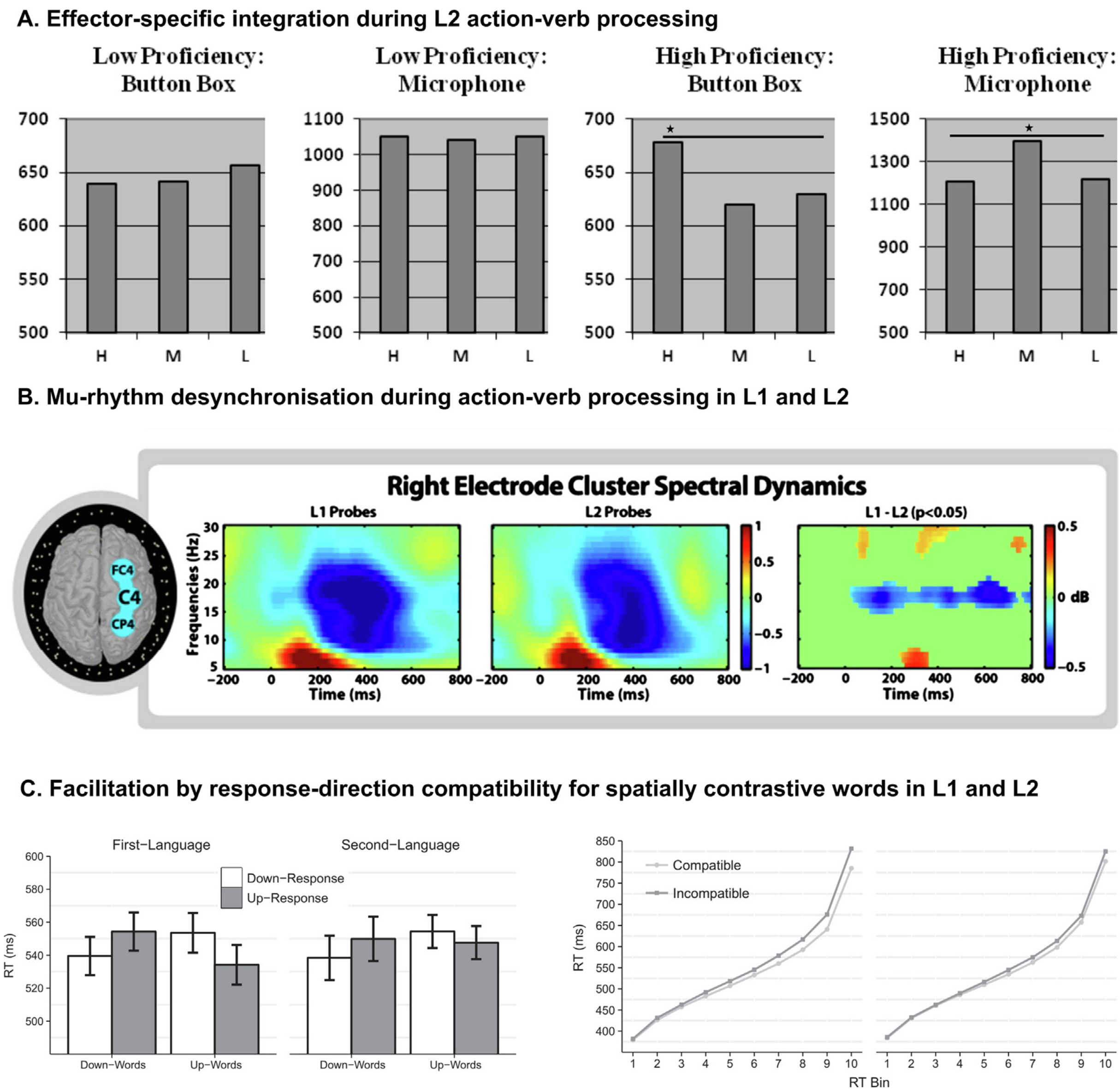

Fig. 1. Outstanding results showing embodied effects in lately-acquired second languages. (A) Results from a lexical decision task with action verbs: Mean reaction times for both participant groups in all conditions (H = hand; M = mouth; L = leg). Significant differences in response latencies ($p < .05$) are marked with an asterisk. (B) Results from a passive reading task with action verbs during an EEG session: Time-frequency power changes (relative to 200 ms pre-stimulus baseline) in the different experimental conditions, for sensor-level activity. The rightmost column shows the difference of conditions masked using FDR correction. Though both L1 and L2 probes always produced significant mu event-related desynchronization (ERD), in the right electrode cluster, ERD was stronger when the participants read L1 action words compared to L2 action words (upper mu bandwidth, 14–20 Hz). (C) Results from a Stroop adaptation task with spatially contrastive words: Top row: Mean RTs for L1 (left panel) and L2 (right panel) separately for each response-direction and word-direction. Error bars represent confidence intervals for within-subject designs. Bottom row: Mean RTs according to decile (increasing from 1st to 10th decile) for the compatible and incompatible condition for L1 (left panel) and L2 (right panel). Panel A: reprinted from Proceedings of the Annual Meeting of the Cognitive Science Society, volume 35, by Nikola Vukovic, When words get physical: evidence for proficiency-modulated somatotopic motor interference during second language comprehension (open access), Copyright 2017, https://beta.escholarship.org/uc/item/0jb6s58t. Authorized reproduction under the open access policies of the University of California. Panel B: reprinted from NeuroImage, 102, N. Vukovic and Y. Shtyrov, Cortical motor systems are involved in second-language comprehension: Evidence from rapid mu-rhythm desynchronization, 695–703, Copyright (2014), with permission from Elsevier. Panel C: reprinted from Brain and Language, 132, C. Dudschig & I. B. Kaup, Embodiment and second-language: Automatic activation of motor responses during processing spatially associated L2 words and emotion L2 words in a vertical Stroop paradigm, 14–21, Copyright (2014), with permission from Elsevier.

et al., 2015), and even fourteen (Macedonia & Klimesch, 2014) months later (Fig. 2A). Moreover, as shown in Fig. 2B, recognition of such novel words learned through iconic gestures involves activation increases in premotor, motor, and sensorimotor brain areas (Macedonia & Mueller, 2016; Macedonia et al., 2011; Mayer et al., 2015) –note, however, that the figure depicts comparisons with silent events rather than audio-visually learned words, thus leaving doubts as to the categorical specificity of this effect. Interestingly, too, the use of congruent gestures over six days also boosts learning of Vimmi words framed in sentential contexts, with most robust effects for concrete nouns, notably followed by abstract verbs (Macedonia & Knösche, 2011). Together, these results suggest that sensorimotor networks are quickly and durably recruited during learning of new action-related words, and that this process is boosted by fine-grained couplings between lexical meanings and physical actions.

An additional study found similar congruency effects using a Stroop

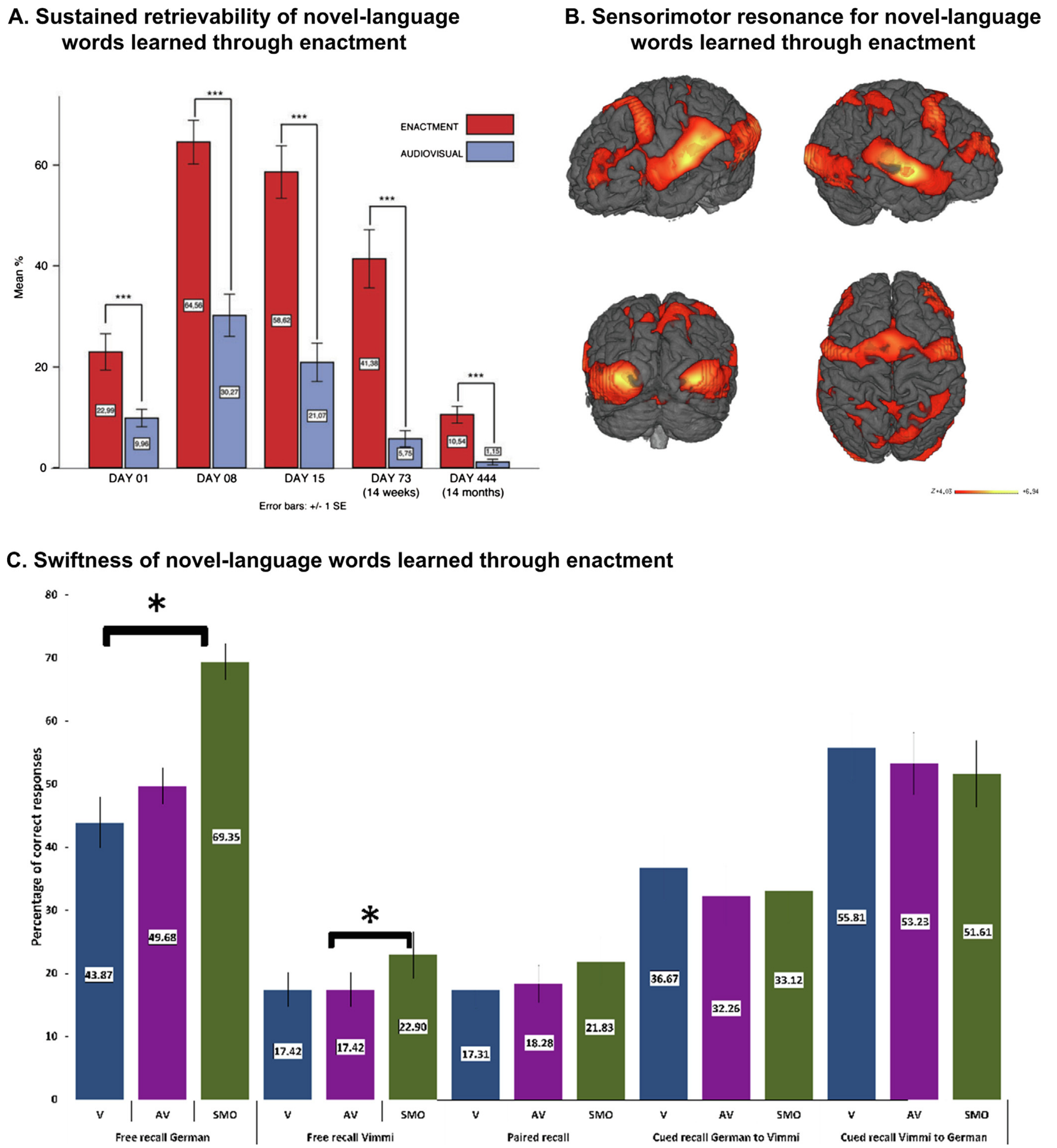

Fig. 2. Outstanding results showing embodied effects in artificial and newly-learned languages. (A) Results from post-training memory tasks with novel-language words learned through enactment: Training results for the written translation tests from German into Tessetisch. Words encoded through enactment (EN) are significantly superior in retrieval at all time points. (B) Results from a post-training recognition task during an fMRI with novel-language words learned through enactment: Main contrast for words learned with iconic gestures vs. silence. Learning through iconic gestures creates extended sensorimotor networks that resonate upon audio-visual word presentation. The networks map the modalities engaged during learning. The color-coded areas show clusters with high Bayesian posterior probability of condition. The bar represents the z-values. (C) Results from a memory test conducted 25 min after enactment training with novel-language words: Memory performance in the pencil-to-paper tests immediately after encoding. Error bars indicate one standard deviation. $* p < .05$. Panel A: reprinted from Mind, Brain and Education, 8, M. Macedonia and W. Klimesch, Long-Term Effects of Gestures on Memory for Foreign Language Words Trained in the Classroom, 74–88, Copyright (1999–2019), with permission from John Wiley and Sons. Panel B: reprinted from Frontiers in Psychology, 7, by M. Macedonia and K. Mueller, Exploring the Neural Representation of Novel Words Learned through Enactment in a Word Recognition Task, article 953 (open access), Copyright 2016, https://doi.org//10.3389/fpsyg.2016.00953. Authorized reproduction under the terms of the Creative Commons Attribution License. Panel C: reprinted from Frontiers in Psychology, 10, by M. Macedonia, C. Repetto, A. Ischebeck and K. Mueller, Depth of Encoding Through Observed Gestures in Foreign Language Word Learning, article 33 (open access), Copyright 2019, https://doi.org//10.3389/fpsyg.2019.00033. Authorized reproduction under the terms of the Creative Commons Attribution License.

adaptation task (Öttl, Dudschig, & Kaup, 2017). Participants learned artificial words randomly assigned to an object either in an upper or a lower location by pointing and touching the object while exposed to the corresponding word. Crucially, words learned in the upper location led to faster upward responses, suggesting an intimate link between novel word meanings and the location of their referents relative to one's body. Further evidence comes from a dialogic roleplay task in which participants learned Hungarian verbs, nouns, and adjectives presented in videos with or without representational gestures, and then taught them to an interlocutor (Morett, 2014, 2017). A subsequent memory test conducted on both learners and instructors showed that L2-word learning was significantly improved when participants produced rhythmic movements, deictic gestures, and representational co-speech gestures (for a detailed explanation of the gesture taxonomy, see McNeill, 1992). Of note, as shown by Krönke, Mueller, Friederici, and Obrig (2013), even in cases when active gesture training fails to boost learning outcomes, words incorporated with such compatible actions are associated with greater engagement of regions subserving not only multimodal semantic processes (a left-hemispheric network comprising inferior temporal and supramarginal gyri) but also, and more crucially, sensorimotor skills (left inferior frontal gyrus). Therefore, motor-language coupling quickly modulates the engagement of embodied mechanisms during novel-word learning, even before congruent movement training yields outwardly observable advantages.

Strikingly, embodied mechanisms seem to be quickly recruited even when word-compatible gestures are simply observed in the absence of self-initiated movements. For example, a study on Japanese verbs learned through observation of either iconic or meaningless gestures showed that, over three days, the former condition yielded better translations, more accurate recognition, and larger modulations of the late positive complex (LPC) in bilateral parietal regions (Kelly, McDevitt, & Esch, 2009). Better learning of novel (Vimmi) words has also been reported in subjects with and without high global memory skills, who show advantages in paired, free, and cued recall for items learned with videos of iconic gestures relative to those learned without gestures –even after only 25 min of training (Macedonia & Repetto, 2016; Macedonia, Repetto, Ischebeck, & Mueller, 2019) –Fig. 2C. Of note, learning performance was also gradually improved in subjects with low global memory outcomes if learning was enriched with iconic gestures across conditions (Macedonia & Repetto, 2016). Also, as shown by this very paradigm, novel word encoding involves a differential recruitment of sensorimotor circuits only when accompanied by the observation of iconic gestures (Macedonia et al., 2019).

However, the observation of iconic gestures does not always lead to better outcomes. In fact, Morett (2019) found better results for novel words learned through observation of still action images compared to iconic gestures even at one week post-training. Interestingly, a virtual reality experiment showed that oral recall of novel action verbs proves faster and more accurate than that of abstract verbs when participants observe a dynamic digital rendition of a park as if they were walking through it, although the same pattern was observed when no motion was implied (Repetto, Colombo, & Riva, 2015). Therefore, under certain conditions, novel word learning seems quickly boosted by concomitant action observation, although evidence on this effect in context-rich paradigms remains preliminary and inconclusive.

More evidence comes from associative learning paradigms. In a study conducted by Freundlieb et al. (2012), participants were shown pseudowords coupled with action pictures over four days, without receiving any feedback, and then decided whether they matched (paradigm A). Learning performance increased across sessions and remained stable upon retesting at 7, 14, and 28 days later, with better performance for transitive actions (e.g., a person cutting a paper) than intransitive actions (e.g., a person swimming). However, no such effects emerged when training lasted only one day (Freundlieb et al., 2012). Moreover, when this protocol is performed after non-invasive neuromodulation of the left motor cortex (via transcranial direct current stimulation), performance on action pseudowords (but not object pseudowords) is significantly reduced in young (Liuzzi et al., 2010) and elderly (Branscheidt, Hoppe, Freundlieb, Zwitserlood, & Liuzzi, 2017) participants –still, note that no stimulation was attempted over the right motor cortex in these studies, raising doubts about the hemispheric specificity of the results. Importantly, no comparable effect emerges following cathodal stimulation of non-motor regions, such as the left dorsolateral prefrontal cortex (Liuzzi et al., 2010).

Finally, in a study by Bechtold et al. (2019), participants spent three days learning novel object pseudowords in three conditions: while actively manipulating them, while observing their manipulation, or while watching their visual features. After that, they performed a lexical decision task during an fMRI session. Although neither manipulation condition yielded significant behavioral or regional activation effects, both self-initiated and observed object manipulation increased functional connectivity for novel object pseudowords between the left parahippocampal gyrus and the left middle/inferior temporal gyri. Also, compared to the observational condition, active manipulation yielded enhanced connectivity between multimodal regions (e.g., left middle temporal gyrus) and structures involved in the observation and execution of movements (e.g., cerebellum). This suggests that active experience with particular objects implies increased co-activation between general semantic hubs and sensorimotor networks. Therefore, motor circuits seem to play a differential role in grounding novel action words accompanied by visual percepts and/or concomitant actions.

In short, the evidence reviewed above converges in three main findings. First, embodiment effects during novel word learning can take place rapidly after initial contact with a previously unknown language. Second, those effects can remain stable at least up to 14 months, in the company of distinct activations patterns across premotor, motor, and otherwise sensorimotor areas. Third, the motor grounding of action-related words from a new language is supported by the performance of relevant movements and, perhaps less critically, by their observation. Below we discuss these findings and those of the previous section in terms of their overall theoretical implications for the embodied cognition framework.

5. Discussion

As seen throughout the review, sensorimotor networks seem to be quickly recruited for processing action-related words from lately-learned languages. In particular, embodied language effects seem to be operative for words learned after middle-childhood (including adulthood), stable even after brief periods of exposure, traceable on behavioral and neural dimensions, and marked by functional dynamics that partially resemble those proper to L1 embodiment. As detailed below, these patterns provide foundations for a "late language grounding" model, with theoretical, educational, and even clinical ramifications.

The most general implication of the evidence is that infant exposure is not necessary for words to be grounded in sensorimotor systems. In fact, the well-established role of embodied mechanisms for L1 words (Birba et al., 2017; García et al., 2017; García & Ibáñez, 2016a; García et al., 2019; Pulvermüller, 2005, 2013, 2018; Tomasino et al., 2008) also seems to characterize lexical processing in languages learned after age 7. As seen above, action-related words in late L2s can interfere with effector-specific movements (Bergen et al., 2010; Buccino et al., 2017; Vukovic, 2013) and delay (Vukovic & Williams, 2014) or facilitate (Ahlberg et al., 2017; Dudschig et al., 2014; Öttl et al., 2017) spatially congruent motor responses. Also, they can be learned better (Freundlieb et al., 2012; García-Gámez & Macizo, 2018; Kelly et al., 2009; Macedonia & Klimesch, 2014; Macedonia & Knösche, 2011; Macedonia & Mueller, 2016; Macedonia et al., 2011; Macedonia et al., 2019; Mayer et al., 2015; Morett, 2014, 2017; Repetto et al., 2015) and more durably (Freundlieb et al., 2012; Macedonia & Klimesch, 2014; Macedonia & Mueller, 2016; Mayer et al., 2015) when accompanied by compatible bodily movements. Moreover, their processing involves increased activation of sensorimotor regions (De Grauwe et al., 2014; Ibáñez et al., 2010; Kelly et al., 2009; Krönke et al., 2013; Macedonia & Mueller, 2016; Macedonia et al., 2011; Macedonia et al., 2019; Mayer et al., 2015; Vukovic & Shtyrov, 2014; Xue et al., 2015) and it becomes selectively affected after motor-network stimulation (Branscheidt et al., 2017; Liuzzi et al., 2010). It would thus seem that the recruitment of embodied mechanisms for language processing is critical across an individual's maturational stages.

In fact, such mechanisms seem to be recruited quite shortly after adult exposure to a new language. If sensorimotor grounding required long periods of coupling between verbal and motoric experiences, brief enactment protocols should yield no embodied effects on artificial or unknown vocabularies. However, as shown in multiple studies, action-related word learning is boosted by exposure to relevant sensorimotor cues after a few hours of training over less than a week (García-Gámez & Macizo, 2018; Macedonia & Knösche, 2011; Macedonia & Mueller, 2016; Macedonia et al., 2011; Mayer et al., 2015). In addition, these fast embodied learning processes involve specific neural markers, such as increased activation of motor, premotor, and sensorimotor areas (Macedonia & Mueller, 2016; Macedonia et al., 2011; Mayer et al., 2015). It follows that embodied mechanisms can be recruited for processing a specific language not only in the absence of infant exposure, but also in the absence of lengthy periods of situated experience.

Moreover, in addition to self-initiated actions, late embodiment effects would also seem partially rooted in the perception of other people's movements. Encoding of novel words while observing congruent gestures has been related to better learning outcomes (Freundlieb et al., 2012; Kelly et al., 2009; Macedonia & Repetto, 2016; Macedonia et al., 2019), larger amplitudes of the LPC in bilateral parietal regions (Kelly et al., 2009), and increased activation of sensorimotor regions (Macedonia et al., 2019). Furthermore, new action-related words can be selectively impaired upon cathodal stimulation of the left motor cortex (Branscheidt et al., 2017; Liuzzi et al., 2010). Arguably, these late-language processes are partially supported by the mirror neuron system: indeed, motor networks are activated by the perception of movement in other individuals (Cook, Duffy, & Fenn, 2013; Rizzolatti, 2005; Rizzolatti & Craighero, 2004), and even by the observation of still pictures implying motion (e.g., Kourtzi & Kanwisher, 2000; Urgesi et al., 2010; Urgesi, Moro, Candidi, & Aglioti, 2006). Therefore, an observed action may favor motor simulation processes (Eaves, Riach, Holmes, & Wright, 2016; Knoblich & Sebanz, 2006; Prinz, 1997; Reed & Farah, 1995) which, in turn, provide an experiential anchorage for new co-occurring action-related words.

However, motor mechanisms may not be equally recruited when actions are self-initiated compared to when they are observed. For example, as shown by electrocorticographic results, alpha, beta, and gamma oscillations in the human mirror neuron system (including sensorimotor, premotor, and prefrontal areas) are differentially modulated by own actions relative to those of other individuals (Babiloni et al., 2016). Moreover, in the delta-theta range, lagged linear connectivity between lateral premotor and ventral prefrontal hubs proves higher when actions are executed than when they are observed (Babiloni et al., 2017). Therefore, although the fast recruitment of embodied mechanisms seems supported by both action execution and observation, the latter condition might yield milder motor grounding effects. Still, more research is needed to directly test this claim.

Be that as it may, the swiftness of these effects could be related to (at least) two interacting factors. On the one hand, Hebbian learning processes (Hebb, 1949) might be deployed immediately upon joint exposure to lexical and (self-initiated or observed) motor information (Pulvermüller, 1999, 2005). Insofar as novel action-related words tend to be used in relevant kinetic contexts since their first occurrences, even in formal learning settings (Rosborough, 2014), motor-language coupling patterns could become entrenched shortly after initial exposure –as discussed below, such associations may also be influenced by crosslinguistic associations with already embodied L1 words. On the other hand, congruent action execution or perception during word learning might indirectly favor embodiment effects through attentional boosts. In fact, attentional allocation can be enhanced by language enactment relative to exclusively perceptual (verbal, audiovisual) exposure, leading to better performance (Backman, Nilsson, & Nourp, 1993; Pereira, Ellis, & Freeman, 2012). Moreover, these processes may be further favored by sleep; indeed, only a few hours of sleep can consolidate both declarative and procedural memory systems (Diekelmann & Born, 2010), which are differentially recruited by the lexical and sensorimotor processes involved in naturally occurring motor-language integration processes – for a general overview of the role of these systems in language processing, see Ullman (2001b).

Of note, even after brief periods of exposure, embodiment effects for newly-learned languages are durable in time. In fact, retrieval advantages for words learned in compatible sensorimotor contexts has proven stable upon retesting 28 (Freundlieb et al., 2012), 60 (Macedonia & Mueller, 2016), 180 (Mayer et al., 2015), and even 444 (Macedonia & Klimesch, 2014) days later. This delay in memory decay could reflect the co-dependent support of declarative and procedural systems (Macedonia & Mueller, 2016) or multimodal and modality-specific semantic systems (Bechtold et al., 2019; García et al., 2019) jointly recruited during action-supported learning. Plausibly, too, sensorimotor enrichment during semantic encoding of new words might increase their cross-modal associations and multiply the pathways supporting item retrievability through time –for compatible claims, see Macedonia et al. (2019). In this sense, L2 action-word acquisition would be partly supported by mechanisms which are also operative during L1 acquisition.

These are not the only aspects in which embodied mechanisms would function similarly for L1s and lately-acquired languages. As it happens, most behavioral patterns detected in the L2 embodiment literature mirror those reported in L1 studies. In particular, research on both languages has revealed interference due to effector and hand-position compatibility in image-verb matching, word identification, and lexical decision tasks (in L1: Bergen et al., 2010; García & Ibáñez, 2016b; Marino et al., 2014; in L2: Bergen et al., 2010; Buccino et al., 2017; Vukovic, 2013) as well as facilitation by response-direction congruency in tasks involving spatially contrastive words (in L1: Ahlberg et al., 2017; Borghi, Glenberg, & Kaschak, 2004; Dudschig et al., 2014; Dudschig, Lachmair, de la Vega, De Filippis, & Kaup, 2012; Dudschig, Souman, Lachmair, Vega, & Kaup, 2013; Lachmair, Dudschig, De Filippis, de la Vega, & Kaup, 2011; Thornton, Loetscher, Yates, & Nicholls, 2013; in L2: Ahlberg et al., 2017; Dudschig et al., 2014; Öttl et al., 2017). This suggests that, under varying processing demands, the outward manifestation of motor-grounding effects can prove broadly similar irrespective of when language exposure began.

In fact, at least under certain circumstances, the alternation of interference and facilitation effects in L2 tasks might reflect the same temporal and functional constraints that account for such variability in L1. According to the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model (García & Ibáñez, 2016a), originally postulated for L1s only, action-related words interfere with effector-congruent responses if these occur within 400 ms post-stimulus onset. This precise pattern was observed for L2, for instance, in the study by Buccino et al. (2017), who found that graspable (as opposed to non-graspable) nouns delayed hand responses at roughly 380 ms. However, as also captured by HANDLE, embodied effects can manifest as facilitation if responses are performed at later intervals (450–750 ms). In line with multiple L1 studies (García & Ibáñez, 2016a), this was observed in L2s for nouns (Dudschig et al., 2014) and prepositions (Ahlberg et al., 2017) presented before directionally compatible responses. Finally, just as effector-specific interference in L1 may be prolonged well beyond the 400-ms mark by semantically demanding tasks (García & Ibáñez, 2016a), the same occurs in L2, as observed in tasks requiring image-verb matching (Bergen et al., 2010) or translation equivalent recognition (Vukovic, 2013).

According to HANDLE, these varying effects reflect the dynamic modulation of motor-network activation during action-language processing. If an effector-congruent response is performed when an action-related word has triggered supra-threshold activation, putative motor resources will not be optimally available for task performance and ensuing responses will be delayed. This would be the case for fast responses (~ 400 ms) in semantically simple tasks and for longer-latency responses (> 400 ms) in semantically complex tasks. However, if the response is made when language-induced sensorimotor resonance is dwindling during a semantically simple task (450–750 ms), extant levels of subthreshold activation will prime the ensuing movement, leading to faster completion. Theoretical subtleties aside, the point is that the same parsimonious principles accounting for effector-congruency effects in L1 seem valid to explain such phenomena in L2.

Yet, it does not follow that embodied effects have identical biological foundations in both languages. Bilingualism research has solidly identified general differences between L1 and L2, including reduced recruitment of frontobasal regions for the latter at low proficiency levels (Paradis, 2009; Ullman, 2001a), as well as lower fluency (Bergmann, Sprenger, & Schmid, 2015) and less efficient lexical retrieval (Sullivan, Poarch, & Bialystok, 2017) for bilinguals relative to monolinguals. These differential patterns are echoed by discrepant embodiment patterns between L1 and L2. In fact, although motor networks are engaged by action-related words in both languages, sensorimotor resonance proves weaker (Vukovic & Shtyrov, 2014) and less distributed (De Grauwe et al., 2014) in L2. Moreover, under certain conditions, even behavioral effects may vary between languages. For example, manual verification of object-pictures whose size is congruent with the distance implied by a target word may be accelerated in L1 (Winter & Bergen, 2014) but delayed in L2 (Vukovic & Williams, 2014). Although existing evidence is insufficient to advance robust claims in this sense, the bottom line is that a plausible account of embodied mechanisms mediating action-word processing in lately-acquired languages must be flexible enough to encompass broad similarities with L1 processing and distinguishing properties driven by the specificities of bilingualism.

In this sense, the grounding effects summarized here may be influenced not only by action execution and visualization (Holler, Kendrick, & Levinson, 2018; Vigliocco, Perniss, & Vinson, 2014), but also by interlinguistic dynamics. Indeed, semantic access during processing of L2 words can be partly mediated by their L1 equivalents (Kroll & Stewart, 1994; Kroll et al., 2010; Menenti, 2006), which are unconsciously activated even during L2-only tasks (Thierry & Wu, 2007; Wu & Thierry, 2010, 2012). Therefore, the recruitment of sensorimotor networks during L2 action-word processing may be further driven by derivative embodied effects associated with the implicitly activated L1 counterpart. Indeed, according to so-called co-activation accounts of L2 processing (Blumenfeld & Marian, 2013; Kroll, Bobb, & Hoshino, 2014), the L1 is not only reactivated in its lexical form, but alongside its perceptual and experiential attributes.

This hypothesis is partially supported by some of the studies reviewed. For instance, Vukovic and Williams (2014) found embodiment effects only for those items which entailed crosslinguistic overlap (interlingual homophones, as opposed to non-homophones), further suggesting a competition between the L1 and L2 meanings because of the parallel co-activation of both languages and the mental simulation triggered by the L1 counterpart. For their part, Ahlberg et al. (2017) observed facilitation by congruency in L2 speakers of German whose L1 could employ either similar or different terms to denote spatial relations. However, subtle differences were found depending on the speakers' L1. For example, compared to native speakers and the "similar-term" group, the "dissimilar-term" group showed attenuated effects for *auf* compared to *über*, arguably because their L1s (i.e., Korean and Turkish) did not distinguish between those spatial relations. This supports the claim that experiential traces of the L1 are also reactivated during L2 processing.

Note, however, that cross-language dynamics are probably not the main driving force behind L2 grounding dynamics. In fact, most of the reviewed studies showed embodied effects without manipulating cross-linguistic overlap levels, and De Grauwe et al. (2014) found comparable resonance in L2 for both cognates and non-cognates. Succinctly, then, the pervasive embodied effects surveyed above may be jointly driven by both direct (L2-specific) and indirect (L1-mediated) patterns of sensorimotor reactivation. Notwithstanding, the latter pathway may play only a minor, secondary role: indeed, as seen in enactment studies, although embodied L1 equivalents are available for new-language words presented in both motion-rich and strictly audiovisual settings, learning proves better and more durable in the former condition (e.g., Macedonia & Klimesch, 2014; Macedonia et al., 2011). However, further research is needed to ascertain the relative contributions of each of these mechanisms.

Also, at least some late embodiment effects seem sensitive to another bilingualism-related factor, namely: L2 proficiency. For example, effector-specific interference during action-word processing was observed in high- (but not in low-) proficiency bilinguals during image-verb matching (Bergen et al., 2010) and translation equivalent recognition (Vukovic, 2013). Moreover, greater N400 modulations for action-related expressions accompanied by incongruent gestures were observed only in highly competent L2 speakers (Ibáñez et al., 2010). Therefore, although embodied effects might well prove pervasive across non-native users, they are likely magnified when putative mechanisms are consolidated through sustained, efficient use. More generally, considering that L2 proficiency is a core modulator of both linguistic (Indefrey, 2006; Perani & Abutalebi, 2005) and executive (Bonfieni, Branigan, Pickering, & Sorace, 2019; Costa, Hernández, & Sebastián-Gallés, 2008; Singh & Mishra, 2013; Tse & Altarriba, 2014; Xie, 2018) processes in bilinguals, its impact on sensorimotor grounding might be seen as an extension of its cross-dimensional neurocognitive effects.

As a corollary, and from a broader theoretical perspective, the evidence strongly questions the claim that lately-learned L2s may be disembodied (Pavlenko, 2012). As noted at the outset, this claim stemmed from a review suggesting that late bilinguals process emotional stimuli semantically but not affectively. Yet, some of the methods contemplated in that work (e.g., skin conductance) have shown mixed and highly variable results across different studies (Cacioppo et al., 2000; Mauss & Robinson, 2009), while others (e.g., introspective approaches) are unreliable and fail to create clear-cut links between semantic variables and possible embodied foundations (Otto, Kröhne, & Richter, 2018). More generally, typical affective language paradigms may not be optimally suited to explore embodied mechanisms, given that dominant effects linked to emotional word valence (e.g., response speed) are often unaffected by differences in arousal (Vinson, Ponari, & Vigliocco, 2014). More generally, emotion-processing paradigms at large yield greatly heterogeneous outcomes (from null to strong effects) (Cacioppo et al., 2000; Kreibig, 2010), even if stimuli are matched for single variables (Mauss & Robinson, 2009). As seen throughout our work, these challenges to the "disembodied L2" position are now complemented with abundant evidence from action-language paradigms. In fact, 26 of the 34 reviewed experiments showed significant L2 embodiment effects across varied paradigms (e.g., translation, association, recognition), multiple word types (e.g., verbs, prepositions, manipulable nouns), and different types of sensorimotor associations (e.g., congruent gestures, action images, visualization of other-initiated movements), with some such effects being accompanied by distinct neurophysiological signatures. Therefore, the disembodied view seems untenable as a framework to understand the functional organization of lexical information in lately-acquired languages.

6. Implications

The evidence gleaned above has noteworthy implications in several levels. First, from a theoretical perspective, it allows broadening and refining well-established models within the fields of bilingualism, on the one hand, and language embodiment, on the other. In particular, models of bilingual language processing, such as the Revised Hierarchical Model (Kroll & Stewart, 1994; Kroll et al., 2010), the Bilingual Interactive Activation account (Dijkstra & van Heuven, 1998, 2002), and the Declarative/Procedural framework (Paradis, 2009; Ullman, 2001a), offer only a coarse-grained view of L1 and L2 lexico-semantic systems, failing to recognize differential patterns of organization for specific linguistic categories or links with sensorimotor mechanisms for subsets therefrom. On the contrary, our review suggests that particular sub-domains within the L2 lexicon might have differential neurocognitive bases –with action-related meanings being distinctively grounded in sensorimotor mechanisms. Therefore, new elaborations of such models would benefit from the inclusion of fine-grained distinctions within their accounts of word processing in bilinguals.

Also, these models further propose that the neurocognitive mechanisms involved in L2 processing are necessarily different depending on when that language was learned (i.e., at early or late ages). However, our review indicates that, at least for some lexico-semantic domains, the same (sensorimotor) mechanisms are engaged irrespective of when the L2 was appropriated. Therefore, developmental hypotheses within bilingual memory frameworks (French & Jacquet, 2004) should acknowledge that certain aspects of the organization of the lexical system (specifically, the recruitment of embodied networks) could be less susceptible to AoA than others.

Regarding language embodiment models, note that these typically emphasize the role of early (infant) experience as a critical factor for semantic grounding (Barsalou, 2008; Wellsby & Pexman, 2014a). Moreover, some of these models also assume the necessity of extended periods of sensorimotor and linguistic co-activation for grounding effects to occur (Pulvermüller, Moseley, Egorova, Shebani, & Boulenger, 2014; Wellsby & Pexman, 2014b). Just as previous studies have shown that very little situated exposure suffices to acquire new vocabulary in infancy (Childers & Tomasello, 2002), our evidence from lately-learned languages suggests that these grounding effects can arise in later stages of life (e.g., Vukovic & Williams, 2014), consolidating swiftly after initial contact with the language (e.g., García-Gámez & Macizo, 2018) and manifesting durably even when exposure is interrupted (e.g., Macedonia & Klimesch, 2014). Such findings speak to the "developmental ubiquity" of embodied effects, calling for a refinement of leading models in the field.

Furthermore, anatomical (e.g., Pulvermüller, 2005) and behavioral (e.g., García & Ibáñez, 2016a) models of language embodiment propose specific neural and behavioral patterns during action-language processing. Yet, although no specifications are made in this sense, it does not follow that these patterns should operate in the same way in a lately-learned language. In fact, motor-network engagement (De Grauwe et al., 2014; Vukovic & Shtyrov, 2014) and behavioral embodied effects (Vukovic & Williams, 2014) during processing of action-related words are not always identical between L1 and L2. Therefore, these frameworks should explicitly recognize that their principles might account only for L1 operations or incorporate additional constraints to explicitly capture specific dynamics of late L2 processing. In this sense, such extended models should embrace the possibility that L2 grounding effects could at least operate via two different mechanisms: (i) the direct route (i.e., recruitment of embodied resources by L2 words) or (ii) the indirect route (i.e., indirect recruitment of such resources through the co-activation of embodied L1 words). Of note, these routes need not be conceived as mutually exclusive, as both could operate in parallel and to different degrees, as postulated for dual-model routes of other aspects of lexico-semantic processing in bilinguals (Kroll & Stewart, 1994).

Second, our review also carries pedagogical implications. Historically, most approaches to foreign-language teaching (e.g., the grammar-translation method, the audio-lingual method, the natural approach, the communicative method, task-based learning) have been almost exclusively based on the combination of oral or written language and pictorial, auditory, or audiovisual materials. However, few methods have acknowledged the importance of active bodily experience for language learning. Two well-known exceptions are drama-based teaching, which encourages learners to incarnate specific roles via full body engagement as they incorporate or practice specific contents (Cancienne, 2019; Lee, Patall, Cawthon, & Steingut, 2014); and the total physical response framework, which requires students to accompany their production or comprehension of verbal materials with congruent bodily actions rather than through mere declarative associations (Asher, 1969; Zhai, 2019). The reviewed evidence substantiates the basic principles of those approaches, offering empirical demonstrations of an intimate relationship between corporal dynamics and vocabulary learning.

What is more, our conclusions suggest non-trivial refinements for those frameworks. These specifications include (i) the notion that L2-word learning can be optimized via effector-congruent (rather than general bodily) actions (García-Gámez & Macizo, 2018; Mayer et al., 2015), (ii) the discovery that even brief training periods are useful to enhance item retrievability through time (Macedonia & Klimesch, 2014; Macedonia et al., 2011), and (iii) the preliminary observation that analogous results can be obtained through action observation (Kelly et al., 2009; Macedonia et al., 2019). In short, as proposed elsewhere (Buccino et al., 2017; Buccino & Mezzadri, 2015), these findings should encourage both teachers and learners to adopt experience-based strategies to complement traditional declarative methods.

Finally, this empirical corpus also has clinical implications. For example, in L1 assessments, action-language processing outcomes have been proposed as potential biomarkers of both developmental coordination disorder (Mirabella et al., 2017) and neurodegenerative motor diseases (Abrevaya et al., 2017; Bak, 2013; Birba et al., 2017; Cervetto et al., 2018; García, Bocanegra, Herrera, Moreno, et al., 2018; García, Bocanegra, Herrera, Pino, et al., 2018; García et al., 2017; Melloni et al., 2015; Steeb et al., 2018), even in preclinical stages (Birba et al., 2017; García, Bocanegra, Herrera, Pino, et al., 2018; García & Ibáñez, 2018; García et al., 2017; Kargieman et al., 2014), thus affording promising tools for early diagnosis. Now, given that embodied effects seem to be systematically present in L2, such markers could also prove relevant for assessments conducted in a patient's L2. This could be important in several scenarios. For instance, in varied forms of bilingual aphasia, the L1 is more compromised than the L2 (García, 2015b; Paradis, 1989, 2004; Paradis & Libben, 2014), so that initial and follow-up assessments are only viable in the latter. In addition, it might be the case that suitable evaluation instruments are exclusively designed in the patient's L2 or that qualified clinicians know that language only, which would render L1 examinations unfeasible. Accordingly, the present evidence should also be acknowledged to inform promising clinical proposals within translational embodied research (Birba et al., 2017; García & Ibáñez, 2018).

In addition, key conclusions stemming from this review align with recent findings in the therapeutic arena. For example, multilingual aphasic patients who conduct their rehabilitation in L2 show improvements both for the treated (i.e., the L2) and the untreated (i.e., the L1) language (Knoph, Lind, & Simonsen, 2015; Knoph, Simonsen, & Lind, 2017), this effect being typically explained in terms of cross-linguistic transfer. Insofar as enactment approaches prove effective for L2 word learning, their application in language rehabilitation settings might prove beneficial for both of the patients' languages. Though conjectural at present, these considerations might pave the way for new developments at the crossing of embodiment research and clinical neuroscience.

7. Limitations and avenues for future research

Despite its merits and implications, the evidence collected so far has a number of shortcomings which lay the ground for a promising research agenda. First, only 15 out of 34 experiments have examined neural correlates of L2 embodiment, and the figure is even lower if one considers studies grouped by specific techniques. Moreover, most of the analytical approaches used so far (e.g., measures of regional activation via fMRI studies or event-related potentials through EEG) are blind to potentially critical signatures of L2 grounding, such as functional connectivity (Abrevaya et al., 2017; García et al., 2017; Melloni et al., 2015) and oscillatory activity (Klepp, Niccolai, Buccino, Schnitzler, & Biermann-Ruben, 2015; Moreno, de Vega, & León, 2013) markers. Major strides could be made by incorporating these techniques in future experiments within the field.

Also, although several L2 embodiment patterns resemble those found in L1, available evidence is scarce to ascertain what drives the similarities or differences between grounding effects in each language. In fact, only four experiments have assessed both languages, yielding a mix of comparable behavioral outcomes (Ahlberg et al., 2017; Dudschig et al., 2014) and distinct neurophysiological patterns (De Grauwe et al., 2014; Vukovic & Shtyrov, 2014). A need thus arises for more direct comparisons between L1 and L2 patterns, ideally including measures of relevant subject-level variables (AoA, L2 proficiency) as potential modulators of the effects.

In addition, a substantial part of the evidence comes from artificial rather than real languages, which may cast doubts on the relevance and generalizability of ensuing results. However, note that these paradigms are widely accepted to replicate the basic determinants of real-word acquisition –in particular, the establishment of arbitrary associations between phonological and semantic patterns through sustained exposure (Jobard, Crivello, & Tzourio-Mazoyer, 2003). Moreover, as shown by dual-route models, both pseudowords and unknown/new words yield identical outcomes across varied tasks (Fiebach, Friederici, Müller, & Cramon, 2002; Schurz et al., 2010), further highlighting the linguistic relevance of the former. Still, although this attests to the relevance of such paradigms, it would be highly informative to complement them with more systematic assessments of lately-learned L2s (as done by Kelly et al., 2009), ideally manipulating their degree of similarity with the participants' L1.

Available studies are further undermined by their exclusive reliance on isolated, decontextualized stimuli, which challenges their ecological validity. Promisingly, core findings obtained through similar approaches in L1 embodiment studies (Bocanegra et al., 2017; Locatelli, Gatti, & Tettamanti, 2012; Pulvermüller, 2013) were then replicated and/or extended in experiments using naturalistic textual materials (Desai, Choi, Lai, & Henderson, 2016; García, Bocanegra, Herrera, Moreno, et al., 2018; Trevisan, Sedeño, Birba, Ibáñez, & García, 2017). Building on these antecedents, future works on lately and newly acquired languages should aim to enrich current findings via relevant discourse-level tasks.

Furthermore, few studies have assessed the role of key variables known to modulate bilingual processing (e.g., AoA, L2 proficiency and degree of exposure). In particular, only four of the studies reviewed have addressed this issue (Ahlberg et al., 2017; Bergen et al., 2010; Ibáñez et al., 2010; Vukovic, 2013), suggesting that, at least under certain circumstances, they may influence L2 embodiment effects. Further examination of these factors would thus be highly desirable, either by entering them as manipulated variables during group formation or framing them as regressors or covariates in single-group designs.

Note, too, that we have explicitly focused on the contrast between L1s (which are acquired since birth) and late L2s (which are learned since age 7) as there is a large scientific corpus on the issue. Conversely, little evidence has been produced on embodied effects in *early* L2s (as one would find in studying simultaneous bilinguals). Therefore, it would be interesting for a similar review to be conducted on that topic when a robust set of studies becomes available. For relevant examples, see Tellier (2008) and Ahlberg, Bischoff, Strozyk, Bryant, and Kaup (2018).

Finally, another interesting and underexplored topic concerns the integration of embodied mechanisms by words that are both motorically and affectively marked. For example, Spadacenta et al. (2014) found that, compared to hand-related verbs with neutral affective connotations, those with negative connotations differentially modulate hand displacements in lexical and semantic tasks. This preliminary result suggests that motor-language coupling may be complementarily driven by affective factors. Further work in this direction could illuminate the *interaction* between diverse embodied domains beyond the typical isolationist focus on the links between action language and motor circuits on their own.

8. Conclusion

In short, research on action-word paradigms in lately-acquired and artificial or newly-learned L2s offers a unique way to understand the role of embodied mechanisms during language learning across the lifespan. Crucially, available findings demonstrate that infant exposure is not indispensable for word-learning to hinge on modality-specific systems, which attests to the developmental ubiquity of sensorimotor grounding. More specifically, such late embodied effects can arise relatively fast and remain significant through time. Taken together, these findings can inspire theoretical, educational, and clinical innovations in language-related disciplines. Thus, future work in this direction should be pursued to forge useful bridges between cognitive neuroscience and bilingualism research.

CRediT authorship contribution statement

Boris Kogan: Investigation, Writing - original draft. **Edinson Muñoz:** Writing - review & editing. **Agustín Ibáñez:** Writing - review & editing. **Adolfo M. García:** Conceptualization, Methodology, Writing - review & editing.

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Declaration of Competing Interest

None to declare.

Appendix A

See Tables 1 and 2.

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2019.105509.

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