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EMBODIED SECOND LANGUAGE PROCESSING AND LEARNING FROM A NEUROCOGNITIVE PERSPECTIVE

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Abstract

Numerous studies have shown that physical activity facilitates lexical integration (i.e., the “enactment effect”), indicating that action boosts memory performance and supports language encoding. This phenomenon has more recently been described as “embodied learning,” or learning that involves self-performed or self-generated action that is directly linked to the learned content. Embodied semantics posits that cognition is grounded in multimodal representations originating in human experience and that motor processes play an essential role in language processing. Much of the evidence for this lies in neuroimaging studies showing that sensory and motor systems are recruited during lexical processing, both during development and in adults. Studies of adult second language (L2) learners have generally shown that sensorimotor networks are also involved in L2 processing, but less so than in the L1. It has been suggested that this is likely due to L2 learning often being decontextualized, compared to L1 acquisition. Recently, there has been a growing interest in the neurocognitive processes behind facilitated embodied learning and their implications for L2 learning. In this chapter we review the main results reported by behavioral and neurocognitive studies exploring embodied language processing and learning both in native language processing and in adult L2 learners.

1. Embodied Semantics

Finding the key to how we associate concepts to linguistic labels is fundamental for our understanding of how we acquire a first language and, later in life, learn a second one (see also Tokowicz & Tkacikova, this volume). Despite decades of research there is still little consensus as to how the human brain associates the acoustic signal (e.g., [gɪ'tɑ:]) to a specific concept (e.g., GUITAR) (Saussure, 1916; Shapiro, 2011). There are currently two opposing views, which differ in relation to the type of representation that is constructed for conceptual information. According to classic amodal theories, cognition is a computational process that creates meaning from perception and for action through the manipulation of mental symbols (Fodor, 1998; Landauer & Dumais, 1997). This has been described via the “sandwich model” metaphor: sensorimotor systems simply perceive information (input) and subsequently produce action (output) (Hurley, 1998). Meanwhile, cognition is sandwiched between the two in order to 1) transform perceived input into amodal symbols and link them to relevant information in our semantic memory and 2) perform operations on these symbols for output. In essence, knowledge is stored in an isolated semantic memory system, independent from sensorimotor processes. Classical amodal theories do not, however, provide an explanation for how we understand the real-world meaning of these symbols, themselves defined by other symbols.

Challenging some of the fundamental beliefs of traditional cognitive research, embodied theories stipulate that conceptual symbols must, at some point, relate to the real world and be grounded in sensorimotor experience (Hauk & Tschentscher, 2013). According to embodied semantics, conceptual representations are highly influenced by or even dependent on sensorimotor processes, and linguistic forms are grounded in our body’s system of perception and action planning (Barsalou, 1999). One of the key concepts behind this is the “correlational learning principle,” according to which the co-occurrence of action-perception and meaning results in the common firing of neurons, forming neural connections, or distributed neural networks that subservise semantic processing (Pulvermüller, 1999; 2013). In short, “What fires together, wires together” (Hebb, 1949) so, for instance, if a child often hears the word “kick” while kicking a ball, lexico-semantic networks responsible for processing the word “kick” and those responsible for preparing and executing the movement necessary to kick a ball, will become a shared network over time. This could also apply to more abstract concepts such as *freedom*, which are, at least initially, tied to personal experience (e.g., a child extracting herself from a playpen and hearing “You’re free!”). This idea stands in stark contrast to amodal theories, which claim that representations used for conceptual knowledge and language are independent from the body and its experiences. Whereas the embodied vs. disembodied debate was originally quite black and white, recent research in this area has become more nuanced and focused on *when* and *how* language is embodied, as illustrated by many of the studies described in this chapter.

2. Embodied learning

The role of the body in encoding new linguistic information has been examined from an embodied semantics point of view. Similarly to the above-described Hebbian theory of associative learning, Zwaan and Madden's (2005) theory of experiential traces posits that when linguistic labels co-occur with our interactions with the environment, 'experiential traces' are formed and associated with these labels. Later, when we encounter the same linguistic labels, these experiential traces are automatically reactivated. Supporting these theories, behavioral studies conducted in the last 40 odd years have amply demonstrated that when new linguistic content is learned with congruent physical movement, retention is improved. This is often referred to as the "enactment effect" (Engelkamp & Krumnacker, 1980; Engelkamp & Zimmer, 1984). As early as 1980, Engelkamp and Krumnacker showed that verb phrases (e.g., "shuffle the cards") were better memorized when representative gestures were performed during learning, as opposed to watching someone else perform the action, imagining the action or just listening to the sentence. Encoding new information with action has more recently been termed "embodied learning". Truly embodied learning is thought to involve "self-performed" or "self-generated" action that is congruent with learned content (James & Bose, 2011; James & Swain, 2011; Johnson-Glenberg & Megowan-Romanowicz, 2017). In line with studies showing that mathematical (Kontra et al., 2015) and scientific (Johnson-Glenberg & Megowan-Romanowicz, 2017) principles are better integrated with physical activity compared to just verbally, language learning has also been shown to be enhanced by action and gestures, which we will discuss in sections 3.3 and 3.4. But first we will review empirical research on embodied semantics more generally, in first (L1) and second (L2) language processing in sections 3.1 and 3.2.

3. Embodied semantics in the L1 and L2

3.1 Behavioral evidence of embodied language processing

With the goal of putting embodied semantics to the test, several behavioral studies have manipulated both the timing and compatibility of semantic and motor processes to examine motor-semantic interactions. L1 studies combining these two processes have found effects of both facilitation, as shown by facilitated movement primed by compatible meaning (Boulenger et al., 2006; de Vega et al., 2013; Diefenbach et al., 2013; Kaschak & Borreggine, 2008; Zwaan & Taylor, 2006), and inhibition, as illustrated by hindered movement when motor and linguistic processes overlap (Buccino et al., 2005; Boulenger et al., 2006). These interactions have generally been interpreted as evidencing that motor and semantic processes share resources. While the inhibition resulting from motor-semantic interactions may seem counterintuitive, the Hand-Action-Network Dynamic Language Embodiment (HANDLE) model (García and Ibañez, 2016) holds that when motor and linguistic processes occur simultaneously, competition for shared neural resources causes interference (García & Ibañez, 2016).

A few behavioral studies have reported a similar pattern of effects in L2 learners (see Kogan et al., 2020 for a review). One such study, reported by Buccino and colleagues (2017), assessed the modulation of motor responses in proficient bilinguals during the processing of both auditory nouns and visual images as a function of the properties of these stimuli. As has been found in L1 speakers (Marino et al. 2014), L2 speakers' motor responses (i.e., the time needed to manually indicate whether the stimuli represented real objects) was delayed for graspable objects, whether depicted by images or auditory words. Similarly, in line with L1 studies showing that detecting a target is facilitated if the location of the target matches the location of a word's referent (Kaup et al., 2012), words referring to a known location (e.g., "star") facilitated congruent motor responses (upward response for "star") in the L2 (Dudschig et al., 2014). These results imply that physical experiences are reactivated during language processing in an L2, as in an L1.

However, embodied effects in an L2 are sometimes attenuated compared to L1 effects and may be at least partially contingent on language proficiency. Vukovic (2013) showed that the time needed to identify L2 verbs as the correct translation of L1 verb primes was significantly affected by the overlap of parts of the body between the L2 verb and the response mode. Manual responses were inhibited by L2 verbs involving the hand (e.g., "write") but not by L2 verbs involving the mouth (e.g., "bite"); conversely, L2 verbs involving the mouth but not those involving the hand inhibited oral responses. This pattern of inhibition was only found, however, for participants with high L2 proficiency. In line with the Hebbian theory of associative learning, the authors suggested that the difference between their L2 participants stemmed from the amount of "real-life" usage of the L2, which over time becomes more situated due to being used in varied contexts,

and hence leads to co-activation of extra-linguistic neural substrates, including the motor cortex. Despite possible differences between L1 and L2 embodiment as a function of L2 proficiency, motor-semantic effects in both the L1 and the L2 have been interpreted as evidencing shared neural resources for motor and semantic processes. Nevertheless, behavioral studies are limited in revealing the underlying neurocognitive mechanisms that govern embodied processes in language comprehension.

3.2 Neurocognitive evidence of embodied language processing

Neurocognitive studies have provided further support for the concept of embodied semantics by showing motor-semantic interactions during native language processing. These studies suggest that linguistic processes may employ the same neural substrates as those used in perception and action. Given its high spatial resolution, functional magnetic resonance (fMRI) can reveal cerebral cortical networks and their organization, which can be key in embodied studies, allowing for the observation of networks that underlie semantic and motor processes, and their possible overlap. Indeed, in their seminal fMRI study, Hauk and colleagues (2004) showed that, during passive reading, action verbs referring to actions performed with the mouth, hand/arm or foot/leg (e.g., lick, pick or kick) specifically activated overlapping or adjacent areas to those responsible for planning and executing actions involving those specific areas of the body. Several other fMRI studies have since shown similar somatotopical activation along the motor strip during action verb processing (Boulenger et al., 2009; Esopenko et al., 2012; Raposo et al., 2009). These activations would suggest that sensory and action language automatically triggers the areas involved in sensorial processes or action execution.

A handful of fMRI studies have since compared the neural correlates of L1 and L2 processing. Native Dutch speakers and German learners of Dutch performed a lexical decision task in which they saw Dutch action and non-action verbs (De Grauwe et al., 2014). Both groups showed greater motor and somatosensory area activation for action verbs, independent of cognate status, indicating that L2 semantic representations are embodied and cause motor activations. In contrast to this study, Zhang and colleagues (2020) found smaller effects in the L1 compared to the L2. L1 and L2 speakers of English performed a semantic judgment task while being scanned. L1 speakers outperformed L2 speakers behaviorally when it came to both accuracy and speed of response. Importantly, L1 speakers recruited a larger cortical network during the task and showed more strongly engaged connections between the “semantic integration hub” (see Patterson & Ralph., 2016 for an explanation of the “hub-and-spoke” model) and sensorimotor regions than L2 speakers. The authors concluded that weaker connections between the semantic integration hub and sensorimotor regions during L2 processing indicated that embodiment in the L2 differs from that of the L1.

Despite its spatial accuracy, fMRI is limited as concerns temporal precision (see Kousaie & Klein, this volume), making it difficult to pinpoint the processing stage at which these activations occur (Hauk & Tschentscher, 2013). Indeed, classical models of language processing often argue that the activations described above are post-lexical and do not play a causal role in understanding language (Mahon & Caramazza, 2008). Electroencephalography (EEG; see Dickson & Pelzl, this volume) on the other hand, offers much higher temporal resolution and can better identify cortical activity that contributes to earlier semantic processes, beginning around 150-200 msec after word onset (Amsel et al., 2013; Moseley et al., 2013, Pulvermüller et al., 2009). EEG has proven well-suited for measuring early occurring motor-semantic interactions that could be interpreted as showing that motor processes influence semantic processes or vice versa, as opposed to motor resonance indexing post-lexical effects. For example, Boulenger et al. (2008) presented action verbs and nouns subliminally as participants performed a grasping movement. EEG analyses showed that very early motor planning, as shown by the “readiness potential” (indexing motor preparation 200 msec prior to actual movement) was disrupted by linguistic processing as a function of word type (reduced motor preparation for action verbs as compared to nouns). This was interpreted as showing interference due to motor and semantic processes occurring simultaneously. Similarly, Aravena and colleagues (2010) manipulated action and language compatibility to examine the brain markers of the bidirectional impact between linguistic and motor processes. Participants processed sentences describing hand actions while performing hand actions using a congruent or incongruent hand position (fist or open hand). As predicted, not only was motor preparation facilitated by compatible meaning, incompatible language/action pairs produced semantic interference, as shown by an N400-like effect. These results were

interpreted as revealing clear bidirectional impact between language and motor processes, and hence shared resources for these processes.

Ibañez and colleagues (2010) showed that linguistic embodied processes were affected by L2 proficiency, as illustrated by a differences in semantic effects as a function of motor-semantic congruency. While watching videos combining literal and metaphorical expressions with congruent and incongruent gestures, high and low proficiency L2 speakers showed an N400 effect for metaphorical vs. literal sentences. More importantly, this effect was present for congruent vs. incongruent gestures, though only for advanced L2 speakers, indicating shared resources between visual and linguistic processing in an L2 for high-, but not for low-proficiency speakers. Similarly, Birba and colleagues (2020) examined the effect of age of acquisition and proficiency on the recruitment of embodied processes during reading. They measured functional connectivity (temporal coincidence) using EEG during naturalistic reading of action vs. neutral texts and were particularly interested in observing motor-related connectivity across central electrodes and source-space activity modulations in motor regions. In the L1, action texts produced greater motor connectivity, which the authors associated with participants reenacting sensorimotor experiences described by language. Although no effects emerged for L2 speakers (i.e., differences between action and neutral texts), a positive correlation was found between enhanced motor-related connectivity and L2 proficiency during action text reading. Similarly, a negative correlation was found between motor-related connectivity and age of L2 acquisition. Both studies described above indicate that although non-native speakers can show embodied effects in L2 processing, proficiency of the L2 is likely what leads robust and reliable effects (Kogan et al., 2020).

Time-frequency analysis has often been used to measure motor activation during language processing. Suppression, or desynchronization, of the μ (8-13Hz), and β (13-30Hz) rhythms (see Pfurtscheller & Lopes da Silva, 1999 for an explanation) reflects activity in the sensorimotor cortex, associated with performing and observing movement (Caetano et al., 2007; Niccolai et al., 2014; Pfurtscheller & Lopes da Silva, 1999) as well as motor imagery (Matsumoto et al., 2010). In the L1, action-related sentences produced early μ and β Event-Related Desynchronization, suggesting that motor resonance occurs during the retrieval of lexical-semantic information, as opposed to post-lexical imagery (van Elk et al., 2010). Other L1 studies have contrasted action and abstract language and shown greater motor activation for action language (Alemanno et al., 2012, Moreno et al, 2015). In order to go beyond language comprehension and observe motor-language interactions using real action, we combined virtual reality and EEG in a novel paradigm (Zappa et al., 2019). Participants heard action verbs prior to manipulating virtual objects using real and varied actions, in a virtual environment. We found μ and β ERD during verb processing, and prior to movement proper, for both Go and Nogo trials, but μ ERD was greater for Go trials, suggesting an involvement of motor processes in language comprehension. Finally, a study comparing bilinguals' L1 and L2 processing during a silent reading task, showed significantly greater μ ERD over the left hemisphere for action compared to abstract words, around 150 msec post-stimulus, for both languages (Vukovic & Shtyrov, 2014). Once again, the early onset of motor activation was interpreted as indicating that it was involved in lexico-semantic access as opposed to post-lexical processes, such as mental imagery. Interestingly, in the right hemisphere, effects were greater for the L1 in comparison to the L2. While verb-processing induced motor activation in both languages, these results confirm that such effects are weaker in the L2 than in the L1.

Generally, both behavioral and neurocognitive studies have found similar embodied effects in the L2 and the L1. However, these effects are often attenuated in the L2, and language proficiency seems to have a significant impact on the extent to which they resemble L1 embodiment. Furthermore, there is no consensus as to why these differences exist. Numerous possibilities have been put forward such as L2 speakers relying on mechanisms like lexical association or shallow translation instead of embodied mechanisms, or less experience leading to a poorer representational system in the L2 compared to the L1. The studies above point to the importance of taking proficiency and possibly age of acquisition into account when examining embodied effects in the L2. Indeed, similarities between effects across the L1 and the L2 seem to be contingent on these factors, which could have important implications for both embodied semantics and the L2 processing literature. As we will further discuss in section 3, one way of gaining understanding as regards the relationship between language proficiency and embodied effects (i.e., how early on these effects emerge) is to examine these effects from the very beginning of new word encoding.

3.3 Behavioral evidence of embodied language learning

Studies using gestures to teach artificial languages and novel vocabulary in the L1 and the L2 have provided behavioral evidence that enacted or embodied learning enhances memory performance, in line with embodied semantics (Macedonia & Knösche, 2011; Mayer et al., 2015; de Nooijer et al., 2013; Tellier, 2008). Association between sensorimotor experiences (eg. the location of an object) during novel word-learning have been shown to be reactivated during retrieval (Öttl et al., 2017). Along similar lines, gesture studies have investigated the influence of learning new vocabulary with concurrent gestures as form of embodied learning. Children showed improved semantic encoding of L2 words when these were learned with iconic gestures, compared to images (Tellier, 2008), and imitating gestures during encoding and retrieval helped children to learn novel verbs describing object manipulation (but not abstract words or words describing locomotion) (de Nooijer et al., 2013). As for adults, performing a congruent gesture to word meaning (or “enactment”) supports learning an artificial language or novel words as evidenced by short and long term retention, as well as accessibility in memory (Macedonia, 2003; Macedonia & Knösche, 2011).

But is improved encoding for words learned with action is simply a result of motor activation, independent of its meaning, during learning? A handful of studies have suggested that words learned with iconic gestures are better retained, both short and long-term, compared to those learned with meaningless gestures (“devoid of any symbolic image related to the words semantics”) (Macedonia et al., 2011) or no gestures (García-Gómez & Macizo, 2019). This indicates that the learning advantage associated with iconic gestures does not merely rely on motor processes but on their semantic content, or their *motor image*. Another frequent question is whether the learning advantage is a result of performing gestures or simply seeing them be performed (Macedonia & Knösche, 2011). Indeed, it has been argued that inducing a mental simulation of performing an action, or motor imagery, is enough to benefit recall (Kormi-Nouri, 2000). Sweller and colleagues (2020) taught participants L2 verbs verbally compared to a condition where they also saw iconic gestures and one where they saw *and* performed iconic gestures. Short and long-term recollection was improved for both gesture conditions compared to the verbal condition. Interestingly, no differences in learning were found between these two gesture conditions, suggesting that observing gestures may sufficiently activate the sensorimotor system to benefit learning.

On the other hand, Morett et al. (2018) found that, although viewing gestures did not enhance learning, retention was significantly improved when gestures were spontaneously produced, possibly due to a more direct involvement of the motor system. This implies that encoding new L2 words with action links motor traces to meaning, in line with the Hebbian and experiential trace theories (Hebb, 1949; Pulvermüller 1999; Zwaan & Madden, 2005). The discrepancies between the results from Morett et al. (2018) and Sweller et al.’s (2020) studies may be due to Sweller et al. asking participants to imitate gestures versus Morett et al. observing the effect of spontaneously produced gestures on learning. Sweller and colleagues suggested that conscious imitation may have minimized embodied benefits. That said, most of the gesture studies showing a learning advantage for performing gestures also involved conscious imitation of iconic gestures. Further investigation is necessary to better understand whether and in which cases self-performance is a pre-requisite for benefitting from an embodied advantage in language learning.

3.4 Neurocognitive evidence of embodied language learning

As is the case with embodied language *processing*, cortical measures allow for a deeper examination of the neural correlates of embodied language *learning*. All in all, there is no clear answer as to whether words learned with action directly reactivate sensorimotor information, nor whether a correlation exists between motor activation post-embodied word learning and improved learning outcomes. Both Fargier et al., (2012) and Bechtold et al. (2018) taught participants novel words in association with self-performed actions and then measured motor activation as participants process these novel words post-training. Neither study clearly indicated that learning with actions lead to greater motor activation post-training. Very recently, Garagnani and colleagues (2021) explored the neural correlates of teaching participants to associate images of objects and actions to novel spoken words. Post-training, fMRI results showed that listening to novel object words associated with objects activated the primary visual cortex and secondary and higher visual areas, indicating that associative semantic links had been established between the word forms and concepts, and that the meaning of these newly learned object words was localized to the primary visual cortex. On the other hand, contrary to the authors’ hypothesis, listening to action words did not yield significant

activation in the extrastriate body area, possibly because action words were not as successfully learned as object words, as shown by behavioral results.

fMRI studies that focused on using iconic gestures during novel word encoding resulted in more reliable neural evidence of how embodied processes support word encoding. Mayer and colleagues (2015) showed that learning novel words was better supported when accompanied by self-performed congruent gestures compared to more traditional learning using images, which were more efficient than verbal content alone (Mayer et al., 2015). Most significantly, fMRI results showed a positive correlation between activity in specialized visual and motor brain areas and improved behavioral performance, suggesting that learning new linguistic content with accompanying gestures enhances learning by creating embodied representations of those words. Along similar lines, Macedonia and colleagues (2019) used fMRI to compare the effects of learning new L2 words through written translations of either printed or auditory words accompanied or not by the visualization of semantically related gestures. As expected, behavioral results showed improved learning for L2 words learned in conjunction with visualizing gestures. Imaging results revealed more distributed sensorimotor networks contingent on the number of modalities to which the participants were exposed during learning; this was interpreted as showing deeper encoding. As in Sweller and colleagues' (2020) behavioral study, these results seem to indicate that an embodied learning advantage can result from action observation alone. Finally, Macedonia and Mueller (2016) analyzed the BOLD response during the recognition of the words learned with iconic gestures in order to identify the networks that subserved learning these words. Results showed activation not only of the core language network, but of several premotor, motor and sensorimotor areas during word recognition. Importantly, as participants heard and read the novel words, a significant portion of the left premotor cortex, which is involved in movement preparation and simulation, became engaged. These activations were attributed to the embodied encoding of novel words engaging a complex sensorimotor network and improving retention.

In line with Macedonia et al. (2011), Krönke and colleagues (2013) aimed to identify the neural correlates of novel object words learned with meaningful gestures, meaningless gestures and without gestures (purely verbally). Although no behavioral differences were found between conditions, BOLD fMRI data showed deeper semantic encoding for words learned with meaningful gestures (greater activation in a semantic network including the left inferior frontal and inferior temporal gyri). This supports the idea that semantic meaning of novel object names is grounded in brain networks responsible for processing experiences with such objects. Finally, using event related potentials, Kelly and colleagues (2009) examined the impact of gesture on learning L2 verbs. Words learned with iconic gestures were better learned compared to observing meaningless gestures, as evidenced by a larger late positive complex in bilateral parietal regions, an index of recollection. However, no differences were found as concerns the N400 component. These results were interpreted as showing that embodied learning contributes to recollection of new L2 words, due to deeper memory traces, but not to their familiarity, as shown by the lack of differences in the N400 component (associated with familiarity, among other processes). The authors further speculated that rather than facilitating memory for newly learned words and making them “superficially familiar”, gestures contribute to a later stage in learning that involves meaning retrieval. Overall, the above-described studies provide evidence that embodied learning, mostly through performing iconic gestures, improved retention of novel words. Learning with gestures or action also resulted in greater activations in motor, pre-motor and sensorimotor areas while processing learned words compared to control conditions. Importantly, embodied learning can rapidly engage embodied mechanisms, sometimes even before behavioral effects can be seen (Krönke et al., 2013). These results seem to evidence a rapid, robust and lasting implication of sensorimotor networks during action verb learning.

4. Current trends and future directions

Virtual reality to investigate embodied word learning

A major challenge faced by embodied language learning studies is that of attaining ecological validity while maintaining strict experimental control. According to embodied semantics, physical contexts are essential for language processing and learning. Hence the need for experimental protocols that are multimodal and as close to real life as possible (Tromp et al., 2018; Peeters, 2019). VR has been thought to eliminate the spatial divide between stimulus and participant, which is particularly relevant for investigating embodied semantics (Peeters, 2019). L2 learning research has become increasingly invested in providing participants with more ecologically valid, multimodal environments where they can engage in semi-natural actions,

leading to results that can generalize to everyday situations (Peeters, 2019; see also Jeong & Li, this volume). The rationale behind this is that the more real-world and situated a language processing environment is, the more physically involved and natural participants will feel and the more similar their behavior will be to real-life processing. VR environments are both interactive and immersive, making them better suited to engage the sensorimotor system, compared to traditional experiments, and elicit real-life responses (Bohil et al., 2011).

The most appealing aspect of using virtual environments in this line of investigation is that they can be manipulated to be ecologically valid and remain highly controlled. While computer monitors occupy a small percentage of the learner's visual field, the CAVE system visually surrounds and HMDs visually isolate learners, creating a deeper sense of immersion (Repetto, 2014). Furthermore, these technologies can provide a sense of agency, given participants' ability to move their arms and hands freely and manipulate objects (Johnson-Glenberg, 2018). One study taught adults pseudo-words describing graspable objects (Macedonia et al., 2020). While immersed in a VR Deep Space cave, participants learned words verbally, with an added projection of a virtual object or by also grasping the virtual object. Post-training, word recognition was faster for words learned with grasping compared to the two other conditions. The authors suggested that this learning enhancement was due to greater sensorimotor enrichment in this condition. However, a cued recall showed no differences between conditions and, one month later, L1 translations of words learned with grasping were better retained but not the novel words themselves.

In order to explore the neural correlates of L2 learning in virtual environments (VE), Legault and colleagues (2019) examined structural brain changes during L2 processing, as a function of L2 learning context. Participants who learned in a VE condition showed increased structural changes in the right inferior parietal lobe (IPL) compared to those who learned via word-word association. Furthermore, two positive correlations emerged for the VE group: one between cortical thickness of the right IPL and learning performance across training sessions and the other between cortical thickness in the right supramarginal gyrus and accuracy in the delayed retention test. Given the IPL's association with embodied cognition networks, VE learning was thought to stimulate the IPL's involvement in interactive learning, which simulates real-life learning (Li & Jeong, 2020). Another study used transcranial magnetic stimulation (TMS) to examine the involvement of motor processes in L2 encoding more directly. Vukovic and Shtyrov (2019) tested whether inhibiting the primary motor cortex (M1) would hamper action verb learning (see Pandža, this volume, for more details about TMS). Participants learned novel labels for object nouns and action verbs via an interactive VR computer game where they manually manipulated virtual objects. In line with embodied semantics, the authors hypothesized that applying theta-burst TMS to the M1 prior to learning would prevent a motor trace from forming for the verb labels, impinging on learning. Indeed, stimulating the hand area of the left M1 led to less successful encoding of novel verbs compared to nouns. This was not the case for the two control groups, indicating that motor cortex activity could be involved in the early stage of word encoding. Finally, Legault and colleagues (2019) used immersive VR (iVR) (i.e., encountering kitchen items in a kitchen) to teach participants Mandarin words and compared this to word-word paired association. Only less successful learners showed improved accuracy immediately post-training for words learned in iVR, suggesting these learners might reap more benefits from embodied learning in iVR environments than successful learners. iVR allows for a fine-grained examination of embodied language learning through the manipulation of naturalistic movement and learning environments. In the future, the combination of iVR and neural data would provide a novel and highly precise measure of the neural correlates of embodied word learning.

5. Applications

The above evidence that embodied processes can be involved in both L2 processing and learning supports pedagogical approaches that teach semantic content using physical action. For instance, the Total Physical Response (TPR) method has children “act out” the meaning of L1 new vocabulary words using gestures, facial expressions and props. Along similar lines, the Accelerative Integrative Method (AIM) uses drama, singing, dance and creative writing to help children to learn an L2. Children embody different characters in plays and sing and act out stories in the L2. Meanwhile, iconic gestures are associated to lexical items and syntactic content, building a repertoire of gesture-verbal couples over time. Methods such these are thought to decrease learners' inhibition and increase their confidence engaging and motivating children both

physically and emotionally during language learning. Examining the neurocognitive effect of embodied L2 learning using these methods would likely add to the ecological validity of embodied L2 learning research.

6. Further reading

As further reading we recommend: 1. Monaco and colleagues' (2019) in-depth review of both behavioral and neurocognitive L2 studies that consider embodiment. 2. A consensus paper by Bechtold et al., (*in press*) which covers a wide range of neurobiological studies that address the role of motor and perceptual processes in language representation as indexed by language comprehension and learning. 3. A review by Li and Jeong (2020) that examines the neural correlates of social L2 learning from a social cognitive perspective as well as the contribution of virtual environments to such.

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6. References

- Alemanno, F., Houdayer, E., Cursi, M., Velikova, S., Tettamanti, M., Comi, G., Cappa, S. F., & Leocani, L. (2012). Action-related semantic content and negation polarity modulate motor areas during sentence reading: An event-related desynchronization study. *Brain Research*, *1484*, 39–49. <https://doi.org/10.1016/j.brainres.2012.09.030>
- Amsel, B. D., Urbach, T. P., & Kutas, M. (2013). Alive and grasping: Stable and rapid semantic access to an object category but not object graspability. *NeuroImage*, *77*, 1–13. <https://doi.org/10.1016/j.neuroimage.2013.03.058>
- Aravena, P., Hurtado, E., Riveros, R., Cardona, J. F., Manes, F., & Ibáñez, A. (2010). Applauding with closed hands: Neural signature of action-sentence compatibility effects. *PLoS One*, *5*(7), e11751. <https://doi.org/10.1371/journal.pone.0011751>
- Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*(4), 577–660. <https://doi.org/10.1017/S0140525X99002149>
- Bechtold, L., Cosper, S., Malyshevskaya, A., Maria Montefinese, M., Morucci, P., Niccolai, V., Repetto, C., Zappa, A., & Shtyrov, Y., (*in press*). Brain Signatures of Embodied Semantics and Language: A Consensus Paper. *Journal of Cognition*.
- Bechtold, L., Ghio, M., Lange, J., & Bellebaum, C. (2018). Event-related desynchronization of mu and beta oscillations during the processing of novel tool names. *Brain and Language*, *177–178*, 44–55. <https://doi.org/10.1016/j.bandl.2018.01.004>
- Birba, A., Beltrán, D., Caro, M. M., Trevisan, P., Kogan, B., Sedeño, L., Ibáñez, A., & García, A. M. (2020). Motor-system dynamics during naturalistic reading of action narratives in first and second language. *NeuroImage*, *216*. <https://doi.org/10.1016/j.neuroimage.2020.116820>
- Bohil, C. J., Alicea, B., & Biocca, F. A. (2011). Virtual reality in neuroscience research and therapy. *Nature Reviews Neuroscience*, *12*(12), Article 12. <https://doi.org/10.1038/nrn3122>
- Boulenger V, Silber BY, Roy AC, Paulignan Y, Jeannerod M, Nazir TA. Subliminal display of action words interferes with motor planning: a combined EEG and kinematic study. (2008) *J Physiol Paris*. Jan-May;102(1-3):130-6. doi: 10.1016/j.jphysparis.2008.03.015.
- Boulenger V, Hauk O, Pulvermüller F. (2009) Grasping ideas with the motor system: semantic somatotopy in idiom comprehension. *Cereb Cortex*. Aug;19(8):1905-14. doi: 10.1093/cercor/bhn217.
- Boulenger, V., Roy, A., Paulignan, Y., Deprez, V., Jeannerod, M., & Nazir, T. (2006). Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Journal of Cognitive Neuroscience*. <https://doi.org/10.1162/jocn.2006.18.10.1607>
- Buccino, G., Marino, B. F., Bulgarelli, C., & Mezzadri, M. (2017). Fluent Speakers of a Second Language Process Graspable Nouns Expressed in L2 Like in Their Native Language. *Frontiers in Psychology*, *8*, 1306. <https://doi.org/10.3389/fpsyg.2017.01306>
- Buccino, G., Riggio, L., Melli, G., Binkofski, F., Gallese, V., & Rizzolatti, G. (2005). Listening to action-related sentences modulates the activity of the motor system: A combined TMS and behavioral study. *Brain Research. Cognitive Brain Research*, *24*(3), 355–363. <https://doi.org/10.1016/j.cogbrainres.2005.02.020>

- Caetano, G., Jousmäki, V., & Hari, R. (2007). Actor's and observer's primary motor cortices stabilize similarly after seen or heard motor actions. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, *104*(21), 9058–9062. <https://doi.org/10.1073/pnas.0702453104>
- De Grauwe, S., Willems, R. M., Rueschemeyer, S.-A., Lemhöfer, K., & Schriefers, H. (2014). Embodied language in first- and second-language speakers: Neural correlates of processing motor verbs. *Neuropsychologia*, *56*, 334–349. <https://doi.org/10.1016/j.neuropsychologia.2014.02.003>
- de Nooijer, J. A., van Gog, T., Paas, F., & Zwaan, R. A. (2013). Effects of imitating gestures during encoding or during retrieval of novel verbs on children's test performance. *Acta Psychologica*, *144*(1), 173–179. <https://doi.org/10.1016/j.actpsy.2013.05.013>
- de Vega, M., Moreno, V., & Castillo, D. (2013). The comprehension of action-related sentences may cause interference rather than facilitation on matching actions. *Psychological Research*, *77*(1), 20–30. <https://doi.org/10.1007/s00426-011-0356-1>
- Diefenbach, C., Rieger, M., Massen, C., & Prinz, W. (2013). Action-Sentence Compatibility: The Role of Action Effects and Timing. *Frontiers in Psychology*, *4*. <https://doi.org/10.3389/fpsyg.2013.00272>
- Dudschig, C., de la Vega, I., & Kaup, B. (2014). Embodiment and second-language: Automatic activation of motor responses during processing spatially associated L2 words and emotion L2 words in a vertical Stroop paradigm. *Brain and Language*, *132*, 14–21. <https://doi.org/10.1016/j.bandl.2014.02.002>
- Engelkamp, J., & Krumnacker, H. (1980). Image- and motor-processes in the retention of verbal materials. [Image- and motor-processes in the retention of verbal materials.]. *Zeitschrift Für Experimentelle Und Angewandte Psychologie*, *27*(4), 511–533.
- Engelkamp, J., & Zimmer, H. D. (1984). Motor programme information as a separable memory unit. *Psychological Research*, *46*(3), 283–299. <https://doi.org/10.1007/BF00308889>
- Esopenko, C., Gould, L., Cummine, J., Sarty, G. E., Kuhlmann, N., & Borowsky, R. (2012). A neuroanatomical examination of embodied cognition: Semantic generation to action-related stimuli. *Frontiers in Human Neuroscience*, *6*. <https://doi.org/10.3389/fnhum.2012.00084>
- Fargier, R., Paulignan, Y., Boulenger, V., Monaghan, P., Reboul, A., & Nazir, T. A. (2012). Learning to associate novel words with motor actions: Language-induced motor activity following short training. *Cortex*, *48*(7), 888–899. <https://doi.org/10.1016/j.cortex.2011.07.003>
- Fodor, J. A. (1998). *Concepts: Where Cognitive Science Went Wrong*. Oxford University Press.
- Frontiers | Viewing photos and reading nouns of natural graspable objects similarly modulate motor responses | Human Neuroscience*. (n.d.). Retrieved December 22, 2021, from <https://www.frontiersin.org/articles/10.3389/fnhum.2014.00968/full>
- Garagnani, M., Kirilina, E., & Pulvermüller, F. (2021). Semantic Grounding of Novel Spoken Words in the Primary Visual Cortex. *Frontiers in Human Neuroscience*, *15*, 66. <https://doi.org/10.3389/fnhum.2021.581847>
- García, A. M., & Ibáñez, A. (2016). A touch with words: Dynamic synergies between manual actions and language. *Neuroscience and Biobehavioral Reviews*, *68*, 59–95. <https://doi.org/10.1016/j.neubiorev.2016.04.022>
- García-Gámez, A. B., & Macizo, P. (2019). Learning nouns and verbs in a foreign language: The role of gestures. *Applied Psycholinguistics*, *40*(2), 473–507. <https://doi.org/10.1017/S0142716418000656>
- Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic Representation of Action Words in Human Motor and Premotor Cortex. *Neuron*, *41*(2), 301–307. [https://doi.org/10.1016/S0896-6273\(03\)00838-9](https://doi.org/10.1016/S0896-6273(03)00838-9)
- Hauk, O., & Tschentscher, N. (2013). The body of evidence: What can neuroscience tell us about embodied semantics? *Frontiers in Psychology*, *4*.
- Hebb, D. O. (1949). *The organization of behavior; a neuropsychological theory* (pp. xix, 335). Wiley.
- Hurley, S. L. (1998). *Consciousness in Action* (1st Edition). Harvard University Press.
- Ibanez, A., Manes, F., Escobar, M., Trujillo, N., Andreucci, P., & Hurtado, E. (2010). Gesture influences the processing of figurative language in non-native speakers: ERP evidence. *Neuroscience Letters*, *471*, 48–52. <https://doi.org/10.1016/j.neulet.2010.01.009>
- James, K. H., & Bose, P. (2011). Self-generated actions during learning objects and sounds create sensori-motor systems in the developing brain.. *Cognition, Brain, Behavior: An Interdisciplinary Journal*, *15*(4), 485–503.

- James, K. H., & Swain, S. N. (2011). Only self-generated actions create sensori-motor systems in the developing brain. *Developmental Science*, 14(4), 673–678. <https://doi.org/10.1111/j.1467-7687.2010.01011.x>
- Johnson-Glenberg, M. C. (2017). Embodied Education in Mixed and Mediated Realities. In D. Liu, C. Dede, R. Huang, & J. Richards (Eds.), *Virtual, Augmented, and Mixed Realities in Education* (pp. 193–217). Springer. https://doi.org/10.1007/978-981-10-5490-7_11
- Johnson-Glenberg, M. C. (2018). Immersive VR and Education: Embodied Design Principles That Include Gesture and Hand Controls. *Frontiers in Robotics and AI*, 5. <https://doi.org/10.3389/frobt.2018.00081>
- Johnson-Glenberg, M. C., & Megowan-Romanowicz, C. (2017). Embodied science and mixed reality: How gesture and motion capture affect physics education. *Cognitive Research: Principles and Implications*, 2(1), 24. <https://doi.org/10.1186/s41235-017-0060-9>
- Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical Experience Enhances Science Learning. *Psychological Science*. <https://doi.org/10.1177/0956797615569355>
- Kaschak, M. P., & Borreggine, K. L. (2008). Temporal dynamics of the action-sentence compatibility effect. *Quarterly Journal of Experimental Psychology (2006)*, 61(6), 883–895. <https://doi.org/10.1080/17470210701623852>
- Kaup B, De Filippis M, Lachmair M, de la Vega I, Dudschig C. When up-words meet down-sentences: evidence for word- or sentence-based compatibility effects? *Cogn Process*. 2012 Aug;13 Suppl 1:S203-7. doi: 10.1007/s10339-012-0453-0.
- Kelly, S. D., McDevitt, T., & Esch, M. (2009). Brief training with co-speech gesture lends a hand to word learning in a foreign language. *Language and Cognitive Processes*, 24(2), 313–334. <https://doi.org/10.1080/01690960802365567>
- Kogan, B., Muñoz, E., Ibáñez, A., & García, A. M. (2020). Too late to be grounded? Motor resonance for action words acquired after middle childhood. *Brain and Cognition*, 138, 105509. <https://doi.org/10.1016/j.bandc.2019.105509>
- Kormi-Nouri, R. (2000). The Role of Movement and Object in Action Memory: A Comparative Study between Blind, Blindfolded and Sighted Subjects. *Scandinavian Journal of Psychology*, 41(1), 71–76. <https://doi.org/10.1111/1467-9450.00173>
- Krönke, K.-M., Mueller, K., Friederici, A. D., & Obrig, H. (2013). Learning by doing? The effect of gestures on implicit retrieval of newly acquired words. *Cortex*, 49(9), 2553–2568. <https://doi.org/10.1016/j.cortex.2012.11.016>
- Lan, Y.-J., Fang, S.-Y., Legault, J., & Li, P. (2015). Second language acquisition of Mandarin Chinese vocabulary: Context of learning effects. *Educational Technology Research and Development*, 63(5), 671–690. <https://doi.org/10.1007/s11423-015-9380-y>
- Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato’s problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review*, 104(2), 211–240. <https://doi.org/10.1037/0033-295X.104.2.211>
- Legault, J., Fang, S.-Y., Lan, Y.-J., & Li, P. (2019). Structural brain changes as a function of second language vocabulary training: Effects of learning context. *Brain and Cognition*, 134, 90–102. <https://doi.org/10.1016/j.bandc.2018.09.004>
- Li, P., & Jeong, H. The social brain of language: grounding second language learning in social interaction. *npj Sci. Learn.* 5, 8 (2020). <https://doi.org/10.1038/s41539-020-0068-7>
- Macedonia, M. (2003). *Sensorimotor Enhancing of Verbal Memory Through “Voice Movement Icons” During Encoding of Foreign Language*. Ph.D. thesis, University of Salzburg.
- Macedonia, M., & Knösche, T. R. (2011). Body in Mind: How Gestures Empower Foreign Language Learning. *Mind, Brain, and Education*, 5(4), 196–211. <https://doi.org/10.1111/j.1751-228X.2011.01129.x>
- Macedonia, M., Müller, K., & Friederici, A. D. (2011). The impact of iconic gestures on foreign language word learning and its neural substrate. *Human Brain Mapping*, 32(6), 982–998. <https://doi.org/10.1002/hbm.21084>
- Macedonia, M., & Mueller, K. (2016). Exploring the Neural Representation of Novel Words Learned through Enactment in a Word Recognition Task. *Frontiers in Psychology*, 7, 953. <https://doi.org/10.3389/fpsyg.2016.00953>

- Macedonia, M., Repetto, C., Ischebeck, A., & Mueller, K. (2019). Depth of Encoding Through Observed Gestures in Foreign Language Word Learning. *Frontiers in Psychology, 10*, 33. <https://doi.org/10.3389/fpsyg.2019.00033>
- Macedonia, M., Lehner, A. E., & Repetto, C. (2020). Positive effects of grasping virtual objects on memory for novel words in a second language. *Scientific Reports, 10*(1), 10760. <https://doi.org/10.1038/s41598-020-67539-9>
- Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology-Paris, 102*(1), 59–70. <https://doi.org/10.1016/j.jphysparis.2008.03.004>
- Marino, B. F. M., Sirianni, M., Volta, R. D., Magliocco, F., Silipo, F., Quattrone, A., & Buccino, G. (2014). Viewing photos and reading nouns of natural graspable objects similarly modulate motor responses. *Frontiers in Human Neuroscience, 8*. <https://doi.org/10.3389/fnhum.2014.00968>
- Matsumoto, J., Fujiwara, T., Takahashi, O., Liu, M., Kimura, A., & Ushiba, J. (2010). Modulation of mu rhythm desynchronization during motor imagery by transcranial direct current stimulation. *Journal of Neuroengineering and Rehabilitation, 7*, 27. <https://doi.org/10.1186/1743-0003-7-27>
- Mayer, K. M., Yildiz, I. B., Macedonia, M., & von Kriegstein, K. (2015). Visual and motor cortices differentially support the translation of foreign language words. *Current Biology: CB, 25*(4), 530–535. <https://doi.org/10.1016/j.cub.2014.11.068>
- Monaco, E., Jost, L. B., Gygas, P. M., & Annoni, J.-M. (2019). Embodied Semantics in a Second Language: Critical Review and Clinical Implications. *Frontiers in Human Neuroscience, 13*. <https://www.frontiersin.org/articles/10.3389/fnhum.2019.00110>
- Moreno, I., de Vega, M., León, I., Bastiaansen, M., Glen Lewis, A., & Magyari, L. (2015). Brain dynamics in the comprehension of action-related language. A time-frequency analysis of mu rhythms. *NeuroImage, 109*, 50–62. <https://doi.org/10.1016/j.neuroimage.2015.01.018>
- Morett, L. M. (2018). In hand and in mind: Effects of gesture production and viewing on second language word learning. *Applied Psycholinguistics, 39*(2), 355–381. <https://doi.org/10.1017/S0142716417000388>
- Moseley, R. L., Mohr, B., Lombardo, M. V., Baron-Cohen, S., Hauk, O., & Pulvermüller, F. (2013). Brain and behavioral correlates of action semantic deficits in autism. *Frontiers in Human Neuroscience, 7*. <https://doi.org/10.3389/fnhum.2013.00725>
- Niccolai, V., Klepp, A., Weissler, H., Hoogenboom, N., Schnitzler, A., & Biermann-Ruben, K. (2014). Grasping hand verbs: Oscillatory beta and alpha correlates of action-word processing. *PLoS One, 9*(9), e108059. <https://doi.org/10.1371/journal.pone.0108059>
- Patterson, K., & Ralph, M. (2016). *The Hub-and-Spoke Hypothesis of Semantic Memory* (pp. 765–775). <https://doi.org/10.1016/B978-0-12-407794-2.00061-4>
- Peeters, D. (2019). Virtual reality: A game-changing method for the language sciences. *Psychonomic Bulletin & Review, 26*(3), 894–900.
- Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology, 110*(11), 1842–1857. [https://doi.org/10.1016/S1388-2457\(99\)00141-8](https://doi.org/10.1016/S1388-2457(99)00141-8)
- Pulvermüller, F. (1999). Words in the brain's language. *Behavioral and Brain Sciences, 22*(2), 253–336. <https://doi.org/10.1017/S0140525X9900182X>
- Pulvermüller, F. (2013). How neurons make meaning: Brain mechanisms for embodied and abstract-symbolic semantics. *Trends in Cognitive Sciences, 17*(9), 458–470. <https://doi.org/10.1016/j.tics.2013.06.004>
- Pulvermüller, F., Shtyrov, Y., & Hauk, O. (2009). Understanding in an instant: Neurophysiological evidence for mechanistic language circuits in the brain. *Brain and Language, 110*(2), 81–94. <https://doi.org/10.1016/j.bandl.2008.12.001>
- Raposo, A., Moss, H. E., Stamatakis, E. A., & Tyler, L. K. (2009). Modulation of motor and premotor cortices by actions, action words and action sentences. *Neuropsychologia, 47*(2), 388–396. <https://doi.org/10.1016/j.neuropsychologia.2008.09.017>
- Repetto, C. (2014). The use of virtual reality for language investigation and learning. *Frontiers in Psychology, 5*. <https://doi.org/10.3389/fpsyg.2014.01280>
- Saussure (1857-1913), F. de. (1916). *Cours de linguistique générale*. https://data.bnf.fr/fr/12042896/ferdinand_de_saussure_cours_de_linguistique_generale/
- Shapiro, L. (2011). *Embodied cognition* (pp. xiii, 237). Routledge/Taylor & Francis Group.

- Sweller, N., Shinooka-Phelan, A., & Austin, E. (2020). The effects of observing and producing gestures on Japanese word learning. *Acta Psychologica*, 207(103079), 1–11.
<https://doi.org/10.1016/j.actpsy.2020.103079>
- Tellier, M. (2008). The effect of gestures on second language memorisation by young children. *Gesture*, 8(2), 219–235.
- Tromp, J., Peeters, D., Meyer, A. S., & Hagoort, P. (2018). The combined use of virtual reality and EEG to study language processing in naturalistic environments. *Behavior Research Methods*, 50(2), 862–869.
- van Elk, M., van Schie, H. T., Zwaan, R. A., & Bekkering, H. (2010). The functional role of motor activation in language processing: Motor cortical oscillations support lexical-semantic retrieval. *NeuroImage*, 50(2), 665–677. <https://doi.org/10.1016/j.neuroimage.2009.12.123>
- Vukovic, N. (2013). When words get physical: Evidence for proficiency-modulated somatotopic motor interference during second language comprehension. *Proceedings of the Annual Meeting of the Cognitive Science Society*, 35(35). <https://escholarship.org/uc/item/0jb6s58t>
- Vukovic, N., & Shtyrov, Y. (2014). Cortical motor systems are involved in second-language comprehension: Evidence from rapid mu-rhythm desynchronisation. *NeuroImage*, 102, 695–703. <https://doi.org/10.1016/j.neuroimage.2014.08.039>
- Vukovic, N., & Shtyrov, Y. (2019). Learning with the wave of the hand: Kinematic and TMS evidence of primary motor cortex role in category-specific encoding of word meaning. *NeuroImage*, 202, 116179. <https://doi.org/10.1016/j.neuroimage.2019.116179>
- Zappa, A., Bolger, D., Pergandi, J.-M., Mallet, P., Dubarry, A.-S., Mestre, D., & Frenck-Mestre, C. (2019). Motor resonance during linguistic processing as shown by EEG in a naturalistic VR environment. *Brain and Cognition*, 134, 44–57.
- Zhang, X., Yang, J., Wang, R., & Li, P. (2020). A neuroimaging study of semantic representation in first and second languages. *Language, Cognition and Neuroscience*, 35(10), 1223–1238. <https://doi.org/10.1080/23273798.2020.1738509>
- Zwaan, R. A., and Madden, C. J., D. (2005). “Embodied sentence comprehension,” in *Grounding Cognition: The Role of Perception and Action in Memory, Language, and Thinking*. Cambridge University Press.
- Zwaan, R. A., & Taylor, L. J. (2006). Seeing, acting, understanding: Motor resonance in language comprehension. *Journal of Experimental Psychology: General*, 135(1), 1–11. <https://doi.org/10.1037/0096-3445.135.1.1>