

Embodied Cognition: Is Activation of the Motor Cortex Essential for Understanding Action Verbs?

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In 8 experiments using language processing tasks ranging from lexical decision to sensibility judgment, participants made hand or foot responses after reading hand- or foot-associated words such as action verbs. In general, response time (RT) tended to be faster when the hand- versus foot-associated word was compatible with the limb that was required to respond (e.g., hand response to a hand-associated word) than when it was incompatible (e.g., foot response to a hand-associated word). To see whether this compatibility effect reflects differential hand- versus foot-specific motor activation produced by the words, as suggested by some embodied theories of language understanding, we monitored 2 event-related potential (ERP) measures previously found to be sensitive to the activation of these limbs. As expected, the ERP results replicated previous findings that the monitored ERPs differ for hand versus foot movements. More importantly, the ERPs provided no evidence of any difference for hand- versus foot-associated words. Thus, the results weaken previous claims that the understanding of action verbs *requires* activation of the motor areas used to carry out the named action. Instead, they support claims that language-related compatibility effects on RT may arise prior to motor processes, which implies that such effects are not decisive evidence for embodied language understanding.

Keywords: action compatibility effects, embodied cognition, hand and foot movements, motor processes

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In recent years, traditional “amodal” models of language processing (e.g., McKoon & Ratcliff, 1992; Van Dijk & Kintsch, 1983) have been challenged by an emerging trend toward alternative “embodied cognition” models (e.g., Tomasino & Rumiati, 2013). According to the traditional models, language processing is best understood as an abstract, rule-based system carried out by dedicated, highly specialized brain areas such as Broca’s and Wernicke’s areas (e.g., Kolb & Whishaw, 1996). In contrast, according to more recent embodied cognition models (e.g., Barsalou, 1999; Glenberg, 1997; Pulvermüller, 2013), language processing is heavily dependent upon sensorimotor systems—so dependent that brain areas traditionally thought to carry out

exclusively sensory or motor activities are actually also intimately involved in language comprehension. In short, according to embodied models, “language is not housed in two small areas in the left hemisphere” (Pulvermüller, Härle, & Hummel, 2001, p. 144).

To contribute to this debate, the present experiments examined the activation of the motor areas by the semantic processing of action verbs. As is reviewed next, a variety of both behavioral and psychophysiological results have been argued to support the embodied viewpoint that the understanding of action verbs typically involves—or even requires—activation of the motor areas that would be involved in carrying out the named actions (for reviews see, e.g., Fischer & Zwaan, 2008; Kemmerer, 2015; Pulvermüller, 2005). As will also be reviewed, however, there are serious questions about the strength of this support (for critical reviews and analyses, see, e.g., Bedny & Caramazza, 2011; Caramazza, Anzellotti, Strnad, & Lingnau, 2014; Goldinger, Papesh, Barnhart, Hansen, & Hout, 2016; Mahon, 2015a; Mahon & Caramazza, 2008; Masson, 2015). Thus, it is not surprising that the embodied cognition model has been called “one of the most controversial theories of knowledge representation” (Kemmerer, Miller, MacPherson, Huber, & Tranel, 2013, p. 13). To address this controversy, the present experiments tested for effects of hand- versus foot-associated action verbs on two EEG-based measures of the motor processing associated with actual hand versus foot movements. The temporal precision and functional specificity of these measures of motor activity make them ideal for investigating the involvement of the motor system in the semantic processing of action verbs.

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Language Effects on Motor Processing: Behavioral Evidence

Intriguing support for embodied cognition comes from behavioral evidence that the reading of linguistic materials affects subsequent motor processing. For example, [Glenberg and Kaschak \(2002\)](#) had participants indicate whether or not sentences made sense by responding with hand movements toward or away from the body. Some of the sensical sentences suggested the transfer of objects toward the participant's body (e.g., "Andy delivered the pizza to you"), whereas other sentences suggested transfer away from the body (e.g., "You delivered the pizza to Andy"). Responses were faster when the direction of action required by the sensibility judgment was compatible with the direction of action suggested by the sentence. Glenberg and Kaschak named this the *action-sentence compatibility effect* (ACE), and many analogous RT-based compatibility effects have since been reported (e.g., [Borghi, Glenberg, & Kaschak, 2004](#); [Borreggine & Kaschak, 2006](#); [Cacciari & Pesciarelli, 2013](#); [Dudschig, de la Vega, De Filippis, & Kaup, 2014](#); [Liepelt, Dolk, & Prinz, 2012](#); [Scorolli & Borghi, 2007](#); [Taylor & Zwaan, 2008](#); [Zwaan & Taylor, 2006](#)). Clearly, such compatibility effects are predicted by the idea that language processing activates the motor system.

Although some researchers regard ACEs as a strong source of support for the idea that language understanding produces motor system activation (e.g., [Boulenger et al., 2006](#); [Glenberg, 2015](#); [Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008](#)), there are reasons to question the strength of this support. One problem is that the effects themselves are empirically somewhat inconsistent, sometimes appearing to be absent ([Papesh, 2015](#)) or even to reverse ([Borreggine & Kaschak, 2006](#); [Buccino et al., 2005](#); [Klepp, Niccolai, Buccino, Schnitzler, & Biermann-Ruben, 2015](#); [Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008](#)). Even when an ACE in the appropriate direction is found, it can depend in complex ways on the stimulus materials (e.g., [Bergen & Wheeler, 2010](#)), task context (e.g., [Bottini, Bucur, & Crepaldi, 2016](#); [Lebois, Wilson-Mendenhall, & Barsalou, 2015](#)), and experimental timing parameters (e.g., [Borreggine & Kaschak, 2006](#)). Such dependencies are not easily explained within a model in which the motor cortex is necessarily involved in the understanding of action words.

Perhaps a more major problem, which is well known in the mental chronometry literature (e.g., [Meyer, Osman, Irwin, & Yantis, 1988](#)), is that RT is a global measure sensitive to the durations of all processes intervening between stimulus onset and response execution (e.g., perception, decision). This makes it difficult to assign an RT effect to a specific processing stage, such as motor activation. In particular, the ACE might arise from processes preceding motor activation, such as decision making (e.g., [Bardolph & Coulson, 2014](#); [Chatterjee, 2010](#); [Masson, 2015](#); [Weiskopf, 2010](#)). As [Liepelt et al. \(2012\)](#) put it, the ACE on RT can be explained by the assumptions "that action and language are mediated by higher-level semantic representations ([Meltzoff and Moore, 1997](#)) that are not restricted to a specific modality" (p. 453; for similar accounts, see, e.g., [Weiskopf, 2010](#), and [Bottini et al., 2016](#)). More specifically, a sentence like "You delivered the pizza to Andy" might activate the amodal concept 'away,' and a compatibility effect could arise if this concept affects decision making rather than motor activation (e.g., [Cho & Proctor, 2011](#); [Masson, 2015](#); [Santiago, Ouellet, Román, & Valenzuela, 2012](#)), as some

evidence from the psychological refractory period (PRP) paradigm suggests that it does ([Andres, Finocchiaro, Buiatti, & Piazza, 2015](#)). Clearly, psychophysiological measures of motor activation could also be very helpful in determining whether the ACE arises at the motor level, as they have been for numerous experimental effects (for reviews see, e.g., [Leuthold, 2011](#); [Luck & Kappenman, 2012](#); [Mulder et al., 1995](#); [Smulders & Miller, 2012](#)).

Language Effects on Motor Processing: Psychophysiological Evidence

Stronger evidence for the involvement of motor areas in language processing comes from direct psychophysiological measurement of neural activation in areas of the brain primarily involved in motor processing.¹ In particular, there is evidence that the neural activity evoked during the understanding of action verbs is similar to that observed when performing the named actions. For example, [Hauk, Johnsrude, and Pulvermüller \(2004\)](#) recorded fMRI while participants passively read action verbs associated with face, hand, or leg actions (e.g., "lick," "pick," or "kick"). They found evidence of increased neural activity in the motor areas associated with the effector that would be involved in making the indicated action, although the strength of their empirical findings has been questioned (e.g., [Bedny & Caramazza, 2011](#)). Similar changes in motor activity have sometimes been found when people read short phrases describing actions (e.g., [Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006](#); [Boulenger, Hauk, & Pulvermüller, 2009](#)), when they hear spoken action words or sentences (e.g., [Raposo, Moss, Stamatakis, & Tyler, 2009](#); [Tettamanti et al., 2005](#)), and when they make judgments about the similarity of different actions (e.g., [Kemmerer et al., 2008](#)).

Again, there is considerable controversy regarding both the replicability of these results and their interpretation (e.g., [Goldinger et al., 2016](#); [Kemmerer et al., 2013](#); [Mahon, 2015a](#); [Mahon & Caramazza, 2008](#); [Maieron, Marin, Fabbro, & Skrap, 2013](#); [Meteyard et al., 2012](#); [Wilson, 2002](#)). The effects themselves are empirically inconsistent even within quite similar tasks (e.g., [Boulenger et al., 2009](#); [Raposo et al., 2009](#)), which has been taken to suggest that "sensorimotor activation is not automatically triggered by the type of stimulus and it is not necessary but accessory to linguistic processing" ([Tomasino & Rumiat, 2013](#), p. 2). Indeed, two meta-analyses of the neuroimaging evidence for embodiment reached the rather negative conclusions that "the results do not support...the idea that verb lexical-semantic representations are heavily based on embodied motoric information" ([Crepaldi et al., 2013](#), p. 1) and "we observed no significant concordance in pre-motor or motor cortices in any analysis, despite recent research efforts indicating a role for the motor system in representing action semantics" ([Watson, Cardillo, Ianni, & Chatterjee, 2013](#), p. 1198).

Inconsistency across tasks is also an issue. For example, [Willem, Toni, Hagoort, and Casasanto \(2010\)](#) found that action verbs activated *different* motor areas in lexical decision versus motor

¹ In the interests of brevity, our review does not consider the converse type of evidence concerning the effects of neuropsychological differences (e.g., produced by stroke or transcranial magnetic stimulation) on language processing. Such evidence comes from paradigms that are very different from those used in the present experiments, and it has been thoroughly reviewed and discussed elsewhere (e.g., [Mahon & Caramazza, 2008](#); [Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012](#)).

imagery tasks, which seems problematic for the idea that understanding an action verb always activates the same motor areas that would be involved in carrying out that action.

In addition to the empirical problems, at least two inferential problems weaken the interpretation of language effects on motor activation (e.g., Chatterjee, 2010; Mahon, 2015a; Mahon & Caramazza, 2008; Meteyard et al., 2012). First, in many cases these motor activations might have arisen *after* the language processing was complete, by virtue of activation spreading “from activated concepts to sensorimotor systems that are connected with those concepts” (Mahon, 2015a, p. 173). This possibility is particularly severe with fMRI because of its poor temporal resolution, which leaves open the possibility that observed activation differences could have arisen 1–2 s after stimulus presentation (e.g., due to action imagery; Hauk, 2016; Mahon & Caramazza, 2008; Willems et al., 2010).² EEG-based measures are potentially useful in addressing this problem because of their superior temporal resolution (e.g., Pulvermüller et al., 2001).

Second, it is uncertain whether the activation observed in motor areas really reflects motor processes per se. A specific technical problem is that poor spatial resolution, especially for the more temporally precise EEG-based measures, often prevents the localization of activation to specifically motor brain areas. A more general and serious problem, however, is that the “motor areas” of the brain are not *exclusively* motor (e.g., Mahon & Hickok, 2016); for example, they are also involved in planning and recognizing nonmotor sequences (Bedny & Caramazza, 2011). To address the potential problem that neural activity in these areas might arise from nonmotor processes, advocates of embodied cognition have sought to show that action verbs are somatotopically associated with specific regions within the “motor homunculus,” just as the control of specific effectors is somatotopically mapped to these regions (e.g., Hauk et al., 2004; Klepp et al., 2014; Nicolai et al., 2014). In a study measuring activation with fMRI, for example, Postle, McMahon, Ashton, Meredith, and de Zubicaray (2008) included a phase in which movement execution tasks were used to localize motor areas specifically involved with hand, foot, and mouth movements. The results from this movement phase were compared with those from a different language-processing phase. Contrary to the embodied cognition view, however, the motor areas activated by action verbs were not a good somatotopic match to those activated during movements. Moreover, motor area activation during the language-processing phase was not limited to action verbs; in some areas, it was also present for nonwords and for concrete nouns that were not related to body parts or actions. This pattern suggests that “some automatic premotor activity for action-verbs may reflect a general role of premotor cortex in language and higher-order cognition, and not its contribution to motor aspects of action-verb meanings” (Bedny & Caramazza, 2011, p. 88).

Interim Summary

As this selective review indicates, much evidence is consistent with the idea that understanding action verbs activates the motor areas responsible for carrying out the indicated actions, but no findings establish this view decisively because each line of evidence is open to alternative interpretations. The RT-based effects (e.g., Glenberg & Kaschak, 2002) leave open the possibility of nonmotoric effects by virtue of the global nature of the RT mea-

sure. Likewise, limitations of the psychophysiological measures allow alternative interpretations in which the effects arise after the action verbs have been understood or arise from nonmotor processes. Stronger evidence for motor activation from action verbs would require a psychophysiological measure with good temporal resolution and with an unambiguous functional relationship to motor processing.

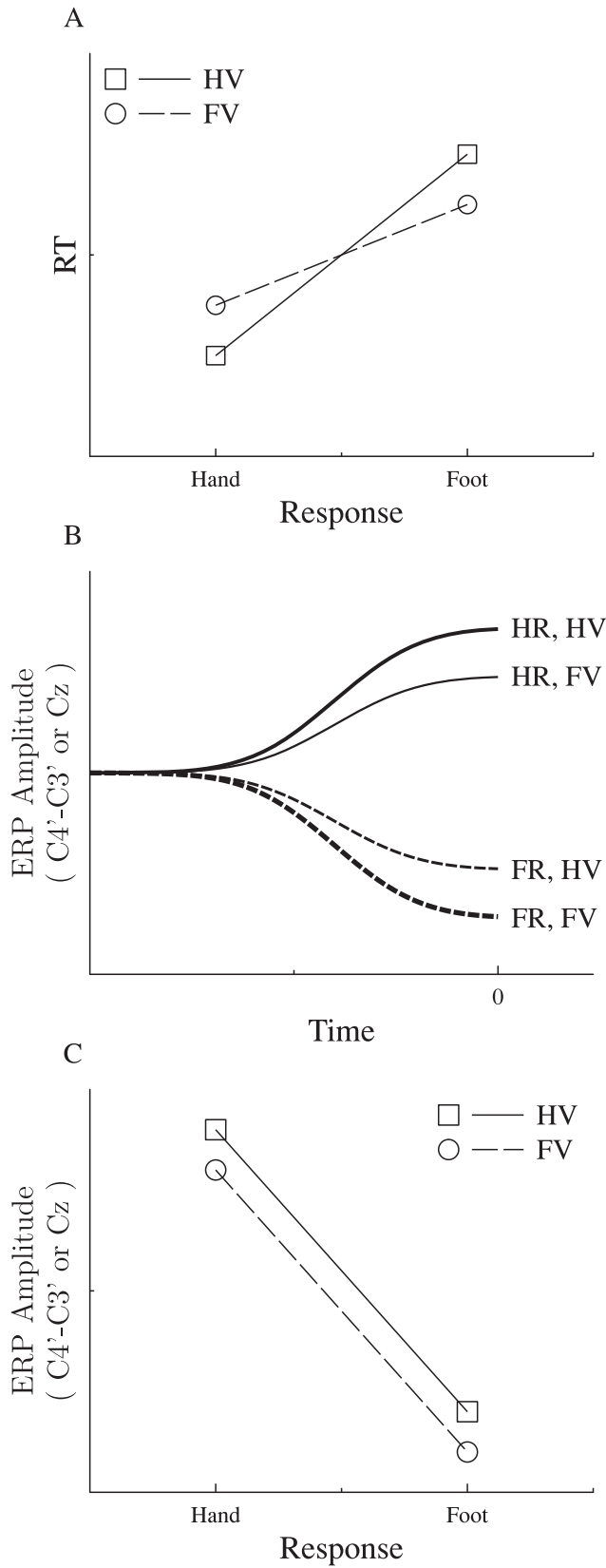
Rationale for the Present Experiments

The present experiments investigated the involvement of the motor areas controlling hand and foot movements in the semantic processing of hand- and foot-associated action verbs using tasks requiring hand versus foot responses. This setup seems to provide an appropriate testing ground for two main reasons. First, various tasks can be constructed so that some trials require responses that are compatible with the linguistic materials (i.e., hand responses to hand-associated verbs or foot responses to foot-associated verbs) whereas other trials require responses that are incompatible (i.e., hand responses to foot-associated verbs or vice versa). The mean RT difference between compatible and incompatible trials directly indexes an ACE on RT, again providing a behavioral measure that should be sensitive to any motor-level activation produced by semantic processing of action verbs. Thus, to the extent that this processing activates the motor structures associated with carrying out those actions, responses should be faster, on average, for compatible trials than for incompatible ones, producing the interaction illustrated in Figure 1A. As was discussed earlier, of course, this ACE on RT could also arise prior to motor activation (e.g., decision-level effects), so it would not by itself provide decisive evidence for motor-level involvement in action verb processing.

Second and more importantly, there exist two clear, functionally defined, event-related potential (ERP) markers of the motor level activation associated with hand versus foot responses. As is discussed in more detail next, these markers are unambiguously associated with differences in hand- versus foot-associated motor activation, because (a) they can be observed when conditions differ only in the response limb used, and (b) they are strongest when the ERPs are time-locked to the motor response. The crucial question examined in the present experiments, then, is whether semantic processing of action verbs also has an influence on these ERP-based markers of motor activation. Such effects would clearly be predicted by embodied cognition models but not traditional ones, so these effects could thus be an important source of evidence for deciding between the two views.

The first of the two ERP markers used in the present experiments is the amount of lateralized sensorimotor EEG activity, measured as the difference between electrodes placed over the left and right sensorimotor cortices, C3' and C4'. Previous studies of the lateralized motor activity at these two sites has focused on the well-known *lateralized readiness potential* (LRP; for a review, see

² The possibility of retrospective activation could also be exacerbated by presenting different verb types in successive trial blocks (e.g., a run of hand-associated verbs followed by a run of foot-associated ones), as is sometimes done (e.g., Aziz-Zadeh et al., 2006). Presenting groups of related verbs together confounds the activation produced by one verb with the residual activation produced by other recently seen verbs of the same type, and it may also foster action imagery for the effector being repeatedly named.



Smulders & Miller, 2012), which is obtained in choice-RT tasks requiring left- versus right-hand responses (e.g., Coles, Gratton, & Donchin, 1988; De Jong, Wierda, Mulder, & Mulder, 1988; Eimer, 1998; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Gratton et al., 1988) or left- versus right-foot responses (e.g., Boschert, Brickett, Weinberg, & Deecke, 1983; Brunia & Vingerhoets, 1981; Jentzsch & Leuthold, 2002; Leuthold & Jentzsch, 2002; Leuthold & Schröter, 2006). Many studies have shown that the ERP produced by the response tends to be more negative over the motor areas contralateral rather than ipsilateral to the responding limb for hand responses, whereas it tends to be more positive contralateral than ipsilateral to the responding foot, as is illustrated in Figure 1B. The opposite lateralizations of the hand and foot actions appear to emerge from the somatotopic mapping of hand versus foot areas of the motor homunculus (Böcker, Brunia, & Cluitmans, 1994a, 1994b; Hari et al., 1983), but the exact reasons for this pattern are not crucial for the present purposes. The important point is that the direction of lateralization provides a sensitive measure of the differences in activation between hand- and foot-associated motor areas. Specifically, with the right hand and foot responses used in the present experiments, these previous results indicate that C4'-C3' would be more positive for hand responses than for foot responses. More critically, C4'-C3' can also be used to assess differential activation of the hand versus foot motor areas by the comprehension of hand- or foot-associated action verbs, as will be discussed in detail after the other psychophysiological marker of motor activation has been described.

The second marker of hand- versus foot-associated motor activation involves a recently identified ERP component known as the *limb selection potential* (LSP; e.g., Miller, 2012, 2016; Miller & Buchlak, 2012; Miller & Gerstner, 2013). In brief, as is also illustrated in Figure 1B, ERPs recorded at Cz tend to be more positive-going for hand responses than for foot responses. The neurophysiological reasons for this difference have not been specifically investigated, but again the important point is that Cz amplitude provides a sensitive measure of the differences in activation between hand- and foot-associated motor areas. With the right-hand and right-foot responses used in the present experiments, the mean Cz amplitude should be larger for hand responses than foot responses, and a corresponding effect of hand- versus foot-associated action verbs on Cz amplitude would reveal the activation of the motor areas by semantic processing.

Previous research strongly suggests that both the mean C4'-C3' and Cz amplitudes are movement-specific and that both are sensitive enough to reveal any motor-level activation produced by action verb comprehension. Their movement-specificity is indicated both by the fact that they differ between hand and foot

Figure 1. Schematic predictions of embodied cognition models for mean reaction time (RT) means (A), for event-related potential (ERP) waveforms (B), and for ERP mean amplitudes (C). In each panel, the four conditions reflect trials in which hand or foot motor responses (HR or FR, respectively) are made in response to hand- or foot-associated action verbs (HV or FV, respectively). The predictions are the same for the two different ERP-based measures of motor activation used here; namely, the mean C4'-C3' and Cz amplitudes (see text). (B) Time zero indicates the moment of the behavioral response.

responses with other factors controlled (e.g., stimulus, task, etc.) and also by the fact that these ERP components are clearest in response-locked waveforms. Their sensitivity is indicated by the fact that these markers can detect partial response activations—not just the final complete motor activation produced by movement execution. For example, motor activation is observed with these markers not only when movements are actually made but also when they are merely prepared, suggested, or imagined (e.g., Leuthold, Sommer, & Ulrich, 1996; Miller, 2012; Miller & Hackley, 1992; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Sommer, Leuthold, & Ulrich, 1994). Thus, partial motor activations produced by semantic processing of action verbs should also be detectable with these measures.

The purpose of the present experiments was to use mean C4'-C3' and Cz amplitudes to check for motor-level activation produced by the semantic processing of action verbs. As is illustrated in Figures 1B and 1C, embodied cognition models predict that both C4'-C3' and Cz should be affected not only by the actual hand or foot response that is made but also by the hand- or foot-association of the action verb being processed. For example, consider trials in which participants make a hand response, which tends to increase C4'-C3' and Cz amplitudes. With a hand-associated (i.e., compatible) action verb, the motor-level hand activation contributed by the semantic processing should add to that produced by activating the overt hand response, leading to larger (i.e., more positive) mean C4'-C3' and Cz amplitudes. With a foot-associated (i.e., incompatible) action verb, in contrast, the motor-level activation of the foot response contributed by the semantic processing should subtract from that produced by the overt response process, leading to smaller (i.e., less positive or more negative) C4'-C3' and Cz amplitudes. Thus, for trials with hand responses, the overall positivity of C4'-C3' and Cz should be greater when the verb is hand-associated than when it is foot-associated.³ The situation is analogous for trials in which participants make a foot response, although the overall C4'-C3' and Cz amplitudes will be smaller or negative on these trials due to the motor activity associated with executing that response. Foot-associated (i.e., compatible) action verbs should contribute extra negativity to the C4'-C3' and Cz activity produced by the motor response process, leading to smaller mean C4'-C3' and Cz amplitudes. Hand-associated (i.e., incompatible) action verbs should contribute some counteracting positivity, on the other hand, making C4'-C3' and Cz less negative or more positive. Considering all conditions together, then, the overall prediction is that there should be a main effect of verb type: C4'-C3' and Cz should be larger with hand-associated verbs than with foot-associated verbs, and this effect should be superimposed on the ERP pattern associated with the responding limb.

In addition to assessing the effect of action verb associations on the motor ERPs produced at the time of responding, several of the present experiments also provided a separate opportunity to assess the effects of action verbs on motor ERPs recorded during a “quiet period”—that is, during a time interval in which participants were not actively making any motor response. For example, during a study phase that was present in Experiments 6 and 7, participants silently read sentences containing action verbs. The instructions for this phase were to study the sentences for a later memory test but not to respond overtly. Crucially, the EEG activity recorded during the study phase could be examined for ERP markers of limb-specific motor activation corresponding to the hand- or foot-

associated action verbs being studied. If the semantic processing of the action verbs activated the motor areas involved in the movements named by the verbs, then this activation should have observable effects on the ERP markers. In principle, the effects of verb-related motor activations on the ERP markers might be especially easy to detect during such response-free quiet periods, because the verb-related activations would not be overshadowed by stronger superimposed movement-related activations (e.g., Klepp et al., 2014).

In summary, to examine the effects of semantic processing of action verbs on motor cortical activation, the present experiments tested for effects of hand- versus foot-associated action verbs on motor-related ERPs. Across the series of experiments summarized in Table 1, we used a variety of different language materials, and the tasks required a variety of different types of stimulus discriminations. Prior results indicate that such stimulus and procedural details can have a strong influence on the extent to which the results support the predictions of embodied cognition models (e.g., Guan, Meng, Yao, & Glenberg, 2013; Hoedemaker & Gordon, 2014; Schuil, Smits, & Zwaan, 2013; Yang, 2014), so it seemed essential to check for effects of semantic processing of action verbs on motor ERPs across a wide range of circumstances to obtain an accurate general picture of the effects of action verb understanding on activation of the motor areas.

Experiment 1

This experiment tested for activation of hand- and foot-associated motor areas by hand- and foot-associated action verbs within a lexical-decision task using single action verbs and nonwords as stimuli. Evidence from previous RT studies indicates that participants process stimuli semantically when discriminating between words and nonwords (e.g., James, 1975; Meyer & Schvaneveldt, 1971; Meyer, Schvaneveldt, & Ruddy, 1975). If the expected semantic processing of action verbs activates the motor areas that would be involved in carrying out the named actions, consistent with embodied cognition models, then an ACE should be observed in mean RTs (i.e., faster responses in the compatible conditions of hand responses to hand-associated verbs and foot

³ This prediction is based on the assumption that the mean C4'-C3' and Cz amplitudes will reflect a combination of motor activations produced by different sources (i.e., word-related as well as movement-related). Empirical tests for exact additivity of ERPs generated from multiple sources can be contaminated in many different ways (e.g., Besle, Fort, & Giard, 2004; Cappe, Thut, Romei, & Murray, 2010; Gondan & Röder, 2006; Schweickert & Mounst, 1998), but near-additivity is sometimes found (e.g., Du et al., 2011; Ossandón, Helo, Montefusco-Siegmund, & Maldonado, 2010). More to the point, the present predictions do not rely on additivity of ERP sources, but merely on the assumption that the overall waveform will show some contribution from each source (e.g., the combination of two positive sources will produce a larger total than the combination of a positive one and a negative one). Miller and Gerstner (2013) found strong evidence for this assumption for both LRP and Cz amplitudes. When participants made different combinations of hand and foot movements, the resulting LRP and Cz waveforms were clearly affected by each of the movements within the combination, although a simple additive model did not provide a complete account of the results (see also Logan, Miller, & Strayer, 2011; Miller & Buchlak, 2012). This shows that the LRP and Cz amplitudes evoked by movements are still subject to further modulation by other influences; they are not all-or-nothing components. Thus, previous evidence supports the assumption that the C4'-C3' and Cz amplitudes could also be modulated by motor activation associated with action verb processing.

Table 1
Summary Across Experiments of the Types of Language Stimuli Used and the Types of Stimulus Discriminations Required

Experiment	Language stimuli	Discrimination(s) required
1	single verbs & nonwords	word/nonword
2	single verbs & nonwords	color & word/nonword
3	single verbs	hand- versus foot-associated action
4	single verbs	old/new recognition memory
5	"HAND" versus "FOOT"	color
6	sentences	old/new recognition memory
7	to-be-visualized phrases	old/new recognition memory
8	sentences	sense/nonsense

responses to foot-associated verbs than in the complementary incompatible conditions). As was described in the Introduction, EEG was also recorded to investigate whether hand- and foot-associated action verbs influence the amplitudes of the motor ERPs (i.e., C4'-C3' and Cz) that are produced when making actual hand and foot movements.

Method

Participants. The reported data were obtained from 16 volunteer participants (19–22 years old, six male) recruited at the University of Otago, who were reimbursed for their time at the rate of \$15 per hour. All participants had normal or corrected-to-normal vision and were right-handed as measured by the Edinburgh Handedness Inventory (EHI; Oldfield, 1971), with a mean handedness score of $M = 80$. Each participant attended one experimental session which lasted approximately two hours, including the preparation time for the physiological recordings. Four additional participants were tested but excluded from analysis due to problems with their EEG recordings (e.g., amplifier failure, excessive blinking).

Apparatus and stimuli. Stimuli were presented and behavioral and psychophysiological responses were recorded with an IBM-PC compatible computer running the DOS operating system. The letters were presented in a light font against the black background of a standard computer monitor. Both words and nonwords varied in length from 3–8 letters and subtended approximately 1.0–2.5 degrees of visual angle. These letter strings, as well as all of the stimuli used in the subsequent experiments, are included in the supplemental online materials.

The words were 190 different English verbs, of which 110 named actions typically performed by the hands or arms and 80 named actions typically performed by the feet or legs. Forty of the hand-associated verbs (e.g., "bash," "carve," "knead," "shoo," "wipe") and 40 of the foot-associated verbs (e.g., "climb," "hike," "kick," "sprint," "trot") were those used by Hauk et al. (2004), who chose them based on participants' ratings on a 1–7 scale of whether words "referred to and reminded them of leg, arm, and face movements" (Hauk et al., 2004, p. 301). To minimize stimulus repetitions and thereby avoid responses based on perceptual familiarity rather than semantic processing, we also included additional verbs that we judged to have clear associations with hand or foot actions (e.g., hand-associated: "bind," "catch," "grab," "press," "sew"; foot-associated: "bound," "dance," "jump," "run,"

"tiptoe"). To validate the hand and foot associations of these verbs, we conducted a pilot RT experiment with 24 participants who were shown the verbs one at a time. In compatible blocks, participants were instructed to make a speeded hand response to hand-associated verbs and a speeded foot response to foot-associated verbs, whereas these S-R assignments were reversed for incompatible blocks. Overall, 90% of participants' responses matched our classification of the verbs as hand- versus foot-associated, validating these associations. In addition, mean RTs were 177 ms faster and 4% more accurate (both $ps < .0001$) in the compatible blocks than in the incompatible blocks, further confirming these associations.

The nonwords were 120 orthographically regular, pronounceable letter strings generated from the ARC database (Rastle, Harrington, & Coltheart, 2002). Hand responses were made with the right index finger by pressing the / (slash) key on a standard English computer keyboard. Foot responses were made by pressing a pedal resting under the ball of the right foot. Participants were tested with their shoes on, and the foot pedal was adjusted so that a response would not be elicited from the resting weight of the foot.

Procedure. Each participant was tested in 15 blocks of 30 randomly ordered trials. Each trial began with the presentation of a fixation cross at the center of the computer screen for 750 ms. A centered letter string stimulus appeared at the offset of this fixation cross, and it remained on screen until the response was made or until 2 s had elapsed, whichever came first. Participants were required to indicate whether each letter string was a word or nonword by making a right hand key press or right foot pedal response, and they were asked to respond to each letter string as quickly and accurately as possible. Response assignments were counterbalanced across participants (i.e., half made hand responses to words and foot responses to nonwords, whereas the other half did the opposite). Accuracy feedback was displayed for 500 ms following a correct response and for 7.5 s following an error, with this difference in feedback duration used to encourage accurate responding. The fixation cross reappeared to begin the next trial approximately 1–2 s after the offset of the accuracy feedback, with the intertrial interval varying randomly according to a uniform distribution.

An initial practice block, not included in the analysis, was used to familiarize participants with the lexical-decision task and the response apparatus, and it used neutral filler words that were not associated with either hand or foot actions. For the remaining experimental blocks, the trials were equally divided among nonwords, hand-associated action verbs, and foot-associated action verbs, with 10 letter strings of each type randomly selected without replacement from the full set of strings of that type, separately for each participant. After multiple blocks, when a participant had seen all of the different letter strings of a given type once, item sampling for that type began again from the full set. On average, each letter string was seen approximately 1.4 times by each participant.

Electrophysiological recording. Electrophysiological activity was amplified with a SA Instrumentation (San Diego, CA) amplifier. Recordings were made with Ag–AgCl electrodes attached to the scalp with EC-2 paste and with disposable self-adhesive electrodes on the face, and electrode impedances were kept below 5 k Ω . On each trial the recording began with a baseline period consisting of the last 200 ms before the onset of the word

stimulus, and it continued for a total of 2.7 s, with a sampling rate of 250 Hz. EEG was recorded at Cz, C3', and C4', with the latter two electrodes positioned 1 cm anterior and superior to positions C3 and C4 of the International 10–20 system (Jasper, 1958), relative to a reference electrode placed on the left ear lobe. Recordings of horizontal electrooculographic activity (HEOG) were made from facial electrodes approximately 2 cm lateral to the left and right outer canthi. Similarly, vertical electrooculographic activity (VEOG) was recorded via electrodes 2 cm above and below the iris of the left eye. EEG and HEOG were recorded with band pass settings of 0.01–100 Hz, whereas VEOG was recorded with settings of 0.1–100 Hz.

Data analysis. For this and all subsequent experiments, preliminary analyses of the RT and PC data were carried out to check for strong practice effects, and the RT distributions were checked for clear outliers. When strong practice effects were present, one or two initial blocks were excluded so that the analysis would include only trials with reasonably stable post-practice performance. Likewise, trials with fast or slow outlier RTs, as identified by visual inspection of the RT distributions pooled across participants, were excluded from further analyses. The exclusions resulting from these analyses, if any, are reported individually for each experiment. It should be emphasized that these preliminary analyses, as well as the identifications of EEG artifacts described next, were carried out only once, blind to the effects of the experimental factors, and they were never revisited after checking factor effects to avoid producing false positive results by taking advantage of “researcher degrees of freedom” (Simmons, Nelson, & Simonsohn, 2011, p. 1359).

Individual-trial EEG and EOG data were checked from the onset of the baseline period to the moment of the trial's behavioral response for artifacts attributable to eye movements, blinks, scalp electromyographic (EMG) activity, and amplifier blocking.⁴ Blocking was defined as a pattern of 20 or more consecutive readings (i.e., at least 80 ms) at a channel's minimum or maximum value on a trial. To identify the other types of artifacts, the peak-to-peak amplitude (PPA) of each channel was scored for each trial individually. The frequency distributions of these scores across trials were visually examined, separately for each channel and participant, and a maximum acceptable PPA for that channel and participant was identified such that trials with larger PPA values were excluded as containing artifacts. Stimulus- and response-locked average ERPs were computed for each participant and condition from the trials remaining after artifact exclusion. Throughout this article, all analyses of mean ERP amplitudes were computed from unfiltered waveforms. The waveforms plotted in all figures were filtered using a finite-impulse response filter with a 12 Hz cutoff (Cook & Miller, 1992).

Two overall summary measures were used to assess the influences of overt responses and action-related words on motor-related ERPs, and both were computed in response-locked waveforms during the last 200 ms preceding the overt key or pedal response based on previous evidence that ballistic motor processes precede overt responses by approximately this amount of time in choice RT tasks (e.g., Hackley & Miller, 1995; Logan, 2015; Miller & Low, 2001; Osman, Moore, & Ulrich, 1995). One measure was mean Cz amplitude. As noted in the Introduction, this measure tends to be larger preceding hand than foot responses (e.g., Miller, 2012; Miller & Buchlak, 2012), and the question of main interest in this

study was whether the hand or foot association of the action verb would also have an effect on Cz amplitude. The second measure was a lateralization score analogous to the LRP, computed as the mean amplitude of the difference C4'-C3'. With the subtraction in this direction, lateralization scores should be larger for hand responses than for foot responses, because the motor lateralization reverses with foot responses for anatomical reasons (Böcker et al., 1994b; Brunia, 1980).⁵

Results and Discussion

Across all participants, six trials with RTs less than 200 ms (0.09%) and 86 trials with RTs greater than 2 s (1.24%) were excluded as outliers.

Behavioral results. Table 2 summarizes the mean correct RT and percentage of correct responses (PC) as a function of the response limb and verb association. Of primary interest in the behavioral results are ANOVAs on RTs and PCs to the action verbs as a function of the within-subject factor of action verb association (i.e., hand- vs. foot-associated) and the between-subjects factor of the response limb used in responding to words. Responses were reliably faster to hand- than to foot-associated verbs, $F(1, 14) = 5.86, p < .05, \eta_p^2 = .30$, and hand responses were reliably faster than foot responses, $F(1, 14) = 9.47, p < .01, \eta_p^2 = .40$. Critically, however, there was no significant effect of the compatibility between the action verb association and the response limb, as indicated by the nonsignificant interaction between these two factors, $F(1, 14) = 0.23, p > .5, \eta_p^2 = .02$. A further ANOVA was conducted to compare the RTs of nonword responses with the average RTs for the word responses, and this factor included the additional between-subjects factor of S-R assignment (i.e., hand responses to words and foot responses to nonwords, or the reverse). This ANOVA indicated that responses were faster to words than to nonwords, $F(1, 14) = 42.11, p < .001, \eta_p^2 = .75$, and that this effect was especially large for participants who responded to words with the hands, $F(1, 14) = 14.68, p < .005, \eta_p^2 = .51$.

The overall average PC was 94.9%. ANOVAs on PC parallel to those computed for RT revealed that responses were significantly more accurate for hand- than foot-associated verbs, $F(1, 14) = 15.99, p < .005, \eta_p^2 = .53$, but the compatibility between the action verb association and the response limb again had no significant effect, $F(1, 14) = 0.09, p > .5, \eta_p^2 = .01$. Overall, responses were more accurate for words than for nonwords, $F(1, 14) = 6.31, p < .05, \eta_p^2 = .31$, especially for those participants who responded to words with the hand and to nonwords with the foot, $F(1, 14) = 11.72, p < .005, \eta_p^2 = .46$.

Psychophysiological results. Across participants, 7%–19% ($M = 12%$) of trials were excluded because of artifacts, and

⁴ Trials with artifacts after the moment of the behavioral response were retained to maximize the number of trials available for estimating the C4'-C3' and Cz mean amplitudes up to the point of those responses.

⁵ For this and all other experiments reported in this article, computations analogous to those carried out on Cz were also carried out on VEOG in order to check for possible contamination by vertical eye movements and blinks, and computations analogous to those on C4'-C3' were carried out using the left- and right-eye HEOG electrodes to check for possible contamination by horizontal eye movements. In no case were condition differences in Cz or C4'-C3' attributable to such eye movement artifacts, so these analyses will not be reported individually.

Table 2
Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μ V, and Mean Cz Amplitude in μ V as a Function of Response Limb and Letter String in Experiment 1

Letter string	Response limb and dependent variable							
	Hand				Foot			
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz
Hand-assoc. verb	696	97.5	2.31	4.72	<i>809</i>	<i>95.6</i>	<i>-.82</i>	<i>-.03</i>
Foot-assoc. verb	708	95.4	2.40	5.09	<i>828</i>	<i>93.2</i>	<i>-.87</i>	<i>-1.02</i>
Nonword	<i>882</i>	<i>95.0</i>	<i>2.66</i>	<i>4.58</i>	947	92.9	.77	-.55

Note. Mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response. The results shown in boldface came from participants instructed to make hand responses to words and foot responses to nonwords, whereas the results shown in italics came from participants with the opposite S-R assignments.

stimulus- and response-locked average ERPs were computed from the remaining trials. Grand-averages of the individual-participant ERPs are plotted in Figure 2.

Table 2 also summarizes the mean C4'-C3' and Cz amplitudes over the 200 ms preceding the overt key or foot pedal response. Consistent with previous results, mean C4'-C3' amplitude was larger for hand responses ($M = 2.51 \mu\text{V}$) than for foot responses ($M = -0.45 \mu\text{V}$), and the statistical reliability of this effect was confirmed in an ANOVA having the within-subjects factor of response limb (i.e., hand vs. foot) and the between-subjects factor of S-R assignment, collapsing across the two verb types within the word response, $F(1, 14) = 98.78, p < .001, \eta_p^2 = .88$. Mean Cz amplitude was also larger for hand responses ($M = 4.74 \mu\text{V}$) than for foot responses ($M = -0.65 \mu\text{V}$), $F(1, 14) = 42.38, p < .001, \eta_p^2 = .75$. There were no corresponding effects of responding limb on VEOG, $F(1, 14) = 2.27, p > .1, \eta_p^2 = .14$, or HEOG, $F(1, 14) = 0.17, p > .5, \eta_p^2 = .01$, indicating that the motor ERP effects were not contaminated by horizontal eye movement or blink artifacts.

Most critically, the response-locked motor ERP amplitudes observed in word trials were basically unaffected by the association of the action verb with hand or foot movements. For both C4'-C3' and Cz, the effect was assessed with an ANOVA having the within-subject factor of action verb association (i.e., hand- vs. foot-associated verbs, with nonword trials excluded) and the between-subjects factor of the response limb used in responding to words. These ANOVAs showed no reliable effects of action verb association for either measure ($p = .87$ and $p = .34$ for C4'-C3' and Cz, respectively). Likewise, the stimulus-locked ERP waveforms in Figures 2A and 2C provide no indication that the verb association affects the motor ERPs.

Discussion. The results provide neither behavioral nor psychophysiological evidence that the hand or foot associations of the action verbs activate the motor areas corresponding to the named actions. First, the latencies of the hand and foot responses were statistically unaffected by their compatibility with the action verb associations. Second, the motor ERPs showed no effect of the hand or foot association of the action verb to which a response was made, although

these ERPs were strongly affected by the actual hand versus foot responding limb, as would be expected based on previous findings. The fact that participants performed the task accurately indicates they did correctly classify the action verbs as words, and such classification is usually thought to involve semantic processing (e.g., James, 1975; Meyer & Schvaneveldt, 1971; Meyer et al., 1975). Thus, the overall picture suggested by these results is that the action verbs were processed semantically without any motor system involvement, contrary to the view that motor system activation is required for semantic processing of action verbs.

The present evidence that action verbs had little or no limb-specific effect on motor activation contrasts with several previous lexical-decision task findings that supported embodied processing of action verbs. For example, Pulvermüller, Härle, and Hummel (2000) and Pulvermüller et al. (2001) found differences in the ERPs evoked by arm-, leg-, and face-related action verbs within a lexical-decision task, and current source density analyses suggested that at least some of the ERP differences arose along the motor strip (also see, de Grauwe, Willems, Rueschemeyer, Lemhöfer, & Schriefers, 2014; Mirabella, Iaconelli, Spadacenta, Federico, & Gallese, 2012; Sato et al., 2008). Those studies included no direct measures of limb-specific motor ERP activity, however, making it impossible to establish a direct correspondence between the activity evoked by the action verbs and that involved in moving specific effectors. In principle, arm- and leg-related action verbs could also have evoked different ERPs in the present study, although such differences would have been unrelated to the limb-specific motor activation studied here. Thus, the present findings weaken previous claims that the understanding of action words in lexical decision tasks necessarily requires activation of the specific motor areas involved in carrying out the named actions.

Experiment 2

Based on the idea that understanding an action verb involves activating the motor areas associated with the action, it is quite surprising that the compatibility of the verb and response limb did not even affect RT in Experiment 1. Perhaps, for some reason, the distinction between hand- and foot-associated verbs was insufficiently salient with the experimental procedure that was used. Although previous results indicate that words are processed semantically in the lexical-decision task, it is conceivable that the action verbs in Experiment 1 were recognized as words based on abstract, effector non-specific representations of their meanings, with little or no semantic processing tied specifically to the effector. In that case, the verb associations would not be expected to influence limb-specific motor activation, and there would thus be no compatibility effect on RT and no effect of action verb association on motor ERPs.

In this experiment, the semantic distinction between hand- and foot-associated actions was emphasized by requiring participants to respond in each trial to the imperative stimulus word "HAND" or "FOOT" with a corresponding key press or foot pedal response. The rationale for requiring this imperative stimulus discrimination was that it would reinforce the hand/foot distinction on every trial, thus increasing that distinction's salience.

The action verbs were presented as Stroop-like stimuli in this experiment, so their meaning was not directly relevant to the choice of hand versus foot response. Specifically, in each trial the action verb appeared at fixation, and the imperative stimulus appeared both above and below it. The fact that Stroop effects are present in many situa-

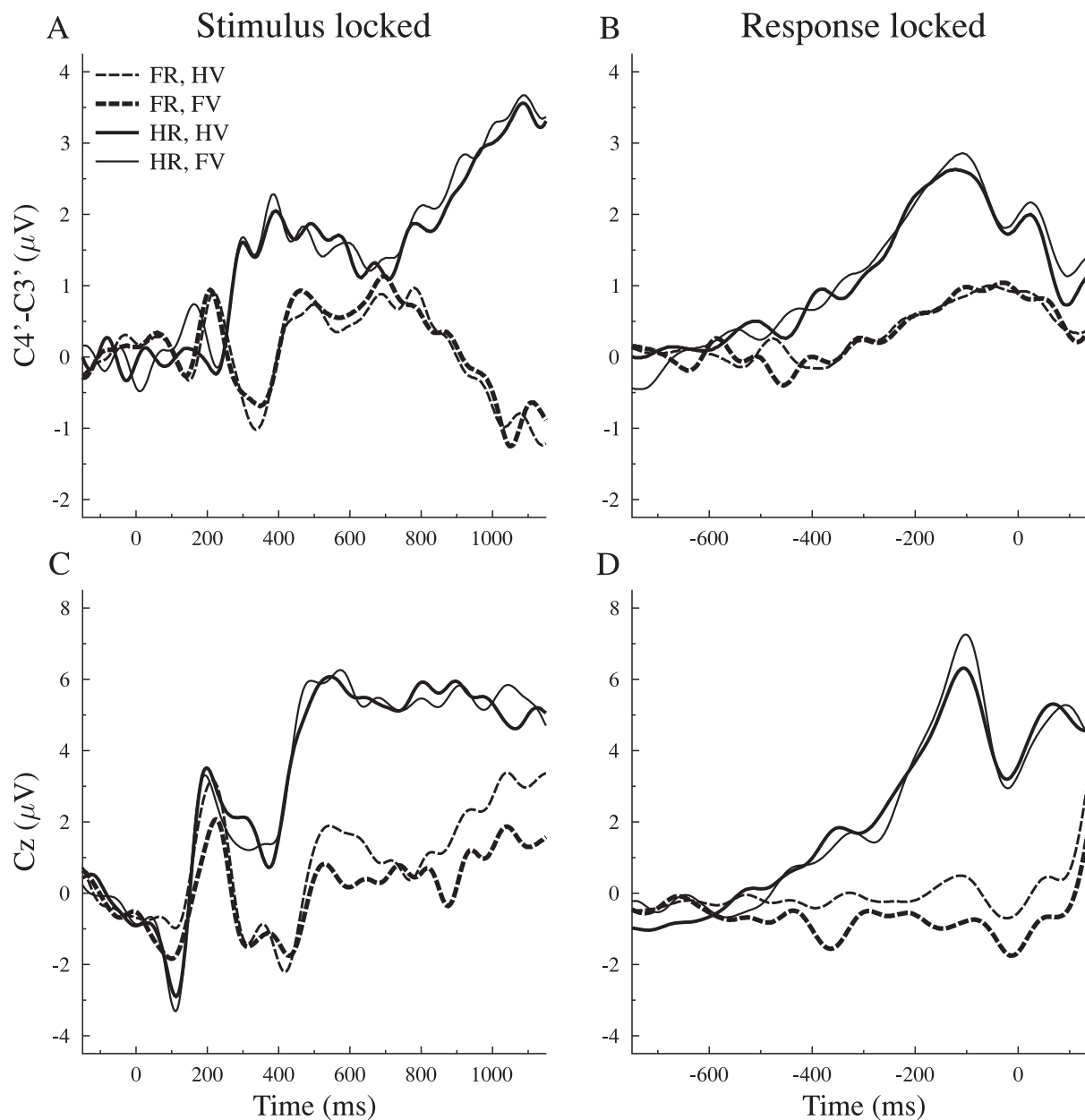


Figure 2. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in Experiment 1 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV).

tions suggests that the action verb would also be processed automatically in this situation (e.g., Ahlberg, Dudschig, & Kaup, 2013; Liepelt et al., 2012; for a review, see MacLeod, 1991). Nonetheless, to encourage verb processing even further, we arranged for verb meaning to be partially task-relevant in order to intensify its semantic processing and thereby increase any motoric effects that it might have. Specifically, the Stroop-like stimulus could be either an action verb or a nonword, and participants were instructed to withhold the response in nonword trials. Thus, in order to perform the task correctly, participants could not completely ignore the action verb—as they can in standard Stroop tasks—but instead they had to assess its lexical status, just as in Experiment 1.

Method

The apparatus, experimental procedure, and recording methods were the same as in Experiment 1 except as noted otherwise. The reported data were obtained from 16 participants (eight females) ranging in age from 19–26 years ($M = 21.5$ years), all of whom were right-handed as measured by the EHI ($M = 85.2$). Two additional participants were excluded because of problems with EEG recordings.

We used a different set of action verbs in this experiment because Experiment 1 produced no evidence of motor activations associated with the semantic processing of action verbs—despite

our best efforts to create a set of strongly associated verbs that would be processed semantically. First, we used a smaller set of 30 hand-associated and 30 foot-associated action verbs, because previous studies finding evidence for motor activations had generally used smaller sets (e.g., Hauk et al., 2004) and we thought this might be an important aspect of the stimulus set. Second, we used subsets of the verbs from Experiment 1 that could be closely matched across hand and foot associations for the number of characters, the number of syllables, and word frequency ($p > .25$ for each of these characteristics), because such matching had also been done in previous studies. Third, we presented the verbs in their present participle forms (e.g., hand-associated: “clapping,” “drawing,” “holding,” “knitting,” “patting,” “rubbing,” “slapping”; foot-associated: “dancing,” “hiking,” “jogging,” “marching,” “pacing,” “running”) in an attempt to emphasize the named actions.

Each trial began with the presentation of a plus sign fixation point for 750 ms. Then, an action verb (e.g., “running”) or a nonword (e.g., “shristing”) appeared at fixation as the Stroop-like stimulus. After a further 200-ms delay, two copies of the imperative stimulus word “HAND” or “FOOT” appeared simultaneously both above and below the Stroop-like stimulus, separated from it by approximately 0.5° . All three stimuli (i.e., one Stroop-like and two imperative) remained on the screen until a response was made or until 2 s had elapsed, whichever came first. Feedback was given for 500 ms following correct responses and for 2.5 s following errors.

Participants were instructed to respond as quickly and accurately as possible if the Stroop-like stimulus was a word but to withhold the response if this stimulus was a nonword. They were told that the imperative stimuli indicated whether the response—if required—should be made with the hand or the foot. Each participant was tested in eight blocks with 60 experimental trials per block, and the trials within each block were divided equally among the six conditions defined by three types of Stroop-like stimulus (i.e., hand-associated verb, foot-associated verb, or nonword) and the two possible imperative stimuli and responses (i.e., “HAND” or “FOOT”).

Results and Discussion

The first block was treated as a practice block and omitted from all analyses. In addition, across all participants, three trials with RTs less than 200 ms (0.05%) were excluded as outliers.

Behavioral results. Table 3 summarizes the mean correct RT and PC as a function of the response limb and action verb association. Of primary interest are ANOVAs on RTs and PCs to word stimuli as a function of the within-subject factors of the Stroop-like stimulus type (i.e., hand- vs. foot-associated) and the response limb (i.e., hand vs. foot). On average, responses were 85 ms faster when the word association was compatible with the response limb, $F(1, 15) = 48.89, p < .001, \eta_p^2 = .76$, and this effect was significantly larger for hand responses than for foot responses, $F(1, 15) = 6.25, p < .025, \eta_p^2 = .29$. Responses were also 4.1% more accurate in compatible trials, $F(1, 15) = 22.84, p < .001, \eta_p^2 = .60$. Both compatibility effects provide evidence that the action verbs had the expected hand or foot associations and that these associations were processed. Responses were correctly withheld on 96.5% of the nonword no-go trials.

Table 3

Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of Stroop-Like Stimulus Type and Response Limb in Experiment 2

Verb assoc.	Response limb and dependent variable							
	Hand				Foot			
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz
Hand	736	98.8	3.00	9.30	851	94.0	1.57	4.50
Foot	840	94.4	3.22	7.56	784	97.9	1.00	5.83

Note. Mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response.

Psychophysiological results. Across participants, 8%–28% ($M = 15\%$) of trials were excluded because of artifacts, and average ERPs were computed from the remaining trials. Grand-averages of the individual-participant ERPs are plotted in Figure 3.

The effects of the response limb and Stroop-like stimuli on motor ERPs were assessed with ANOVAs having the within-subject factors of response limb (i.e., hand vs. foot) and action verb association (i.e., hand- vs. foot-associated). These ANOVAs yielded highly significant effects in the expected direction for response limb on the mean amplitudes of both C4'-C3', $F(1, 15) = 18.58, p < .005, \eta_p^2 = .55$, and Cz, $F(1, 15) = 19.96, p < .001, \eta_p^2 = .57$, but no effect of action verb association on either of these measures (both $p > .5$). The analysis of Cz amplitude revealed a strong interaction of response limb and action verb association, $F(1, 15) = 11.19, p < .005, \eta_p^2 = .43$, such that the tendency for larger Cz amplitude for hand than foot responses was stronger with hand-associated verbs than with foot-associated verbs. This interaction reflects a tendency for larger Cz amplitudes with compatible word/response pairs than with incompatible pairs, a result that is consistent with the common finding of increased positivity for easier task conditions (e.g., Kok, 2001). Note that the interaction does not support embodied cognition models; as outlined in the introduction, these simply predict an action verb main effect (i.e., larger Cz amplitude for hand- than foot-associated verbs). In contrast to this prediction, the interaction reflects a reversal of the expected effect when a foot response was made. No significant effects were found in parallel analyses of mean VEOG and HEOG amplitudes.

Discussion. The conditions used in this experiment produced a large compatibility effect on RT, which demonstrates that the hand or foot associations of the action verbs were processed semantically. Because of the strong contrast with the small compatibility effect in Experiment 1, the present RT results thus support the idea that task-relevance of the hand-foot distinction may have an important influence on the degree to which this aspect of meaning has an effect (for a similar effect of task-relevance, see Mirabella et al., 2017). In addition, compatible-trial RTs could have been facilitated by the semantic association between the action verb (e.g., “kick”) and the imperative stimulus word (e.g., “FOOT”).

More importantly, the motor ERPs C4'-C3' and Cz were unaffected by the association of the verb with hand versus foot actions. Thus, despite the RT-based evidence that limb-specific verb meanings were processed semantically, these ERPs provided no evidence that this processing produced any motor activation of the

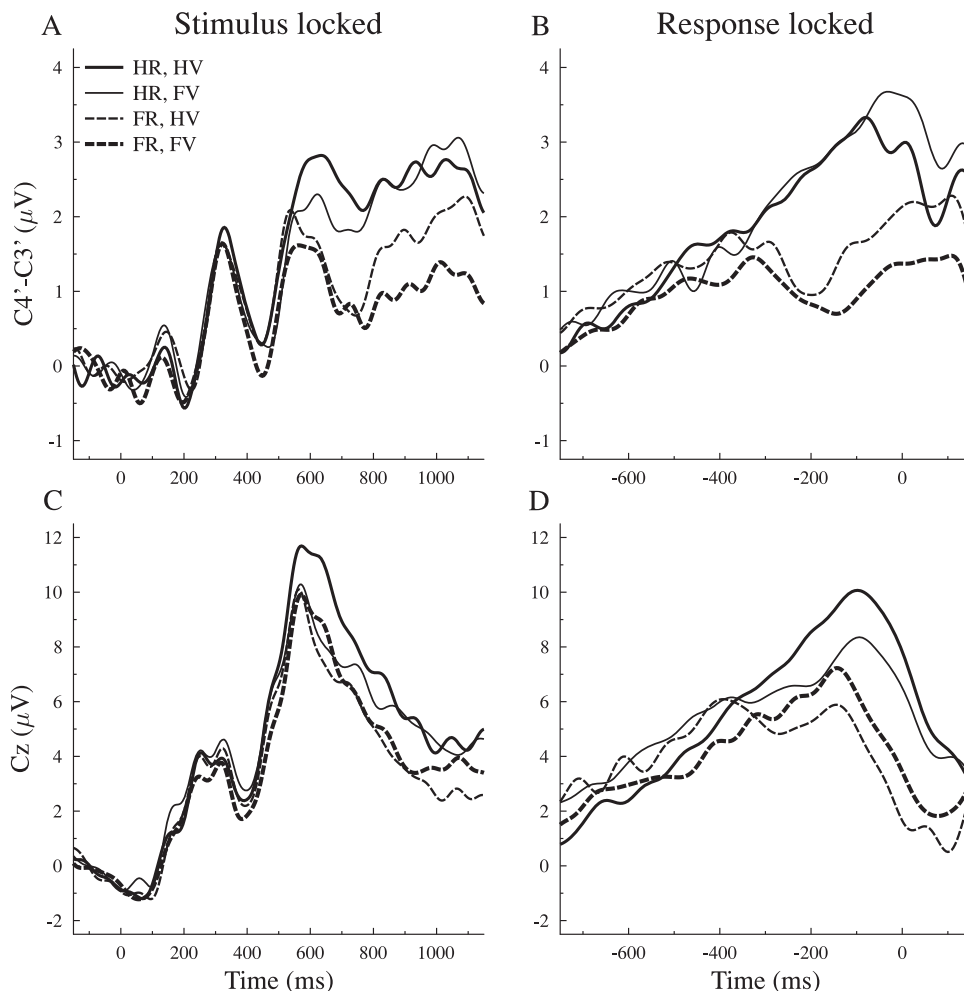


Figure 3. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in Experiment 2 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV). In the stimulus-locked waveforms, Time 0 indicates the point at which the Stroop-like stimulus appeared, and Time 200 indicates the point at which the imperative stimulus appeared.

sort actually involved in generating the associated motor responses. As in Experiment 1, the failure of the verb associations to affect motor ERPs appears inconsistent with the idea that processing the meanings of these verbs necessarily activates the motor areas responsible for carrying out the named hand- or foot-associated actions. In the absence of verb effects on motor ERPs, the most plausible explanation of their compatibility effect on RT is that some premotor process (e.g., deciding which response to make) was carried out more quickly in compatible trials than in incompatible ones.

Experiment 3

Given the larger ACE on RT in Experiment 2 than in Experiment 1, it appears that the ACEs produced by action verbs are enhanced by emphasizing the limb-related aspects and relevance of their meanings, so we sought to strengthen those qualities even further in this experiment. Specifically, in each trial a single action verb was presented, and participants were required to make a hand or foot response to that

verb based explicitly on the verb's association with hand versus foot actions. Thus, participants had to evaluate the meaning of each verb with respect to the exact dimension—hand-associated versus foot-associated—most directly relevant to the verb's putative representation in motor cortex. This requirement would seem to maximize the limb-specific semantic processing of the action verbs and correspondingly enhance any limb-specific motoric representations involved in their understanding.

Measuring an ACE requires testing all four combinations of hand- and foot-associated verbs with hand and foot responses. To achieve that while using hand- versus foot-association as the relevant stimulus dimension, participants were cued in each trial to respond either compatibly or incompatibly to the verb's meaning. Specifically, in each trial the action verb appeared first, and it was followed after 2 s by either a plus sign or a minus sign as an imperative stimulus. Participants were instructed to respond compatibly if the plus sign appeared (i.e., respond to hand-associated verbs with the hand and to foot-associated verbs with the foot), whereas they were to respond

incompatibly if the minus sign appeared. RT was measured from the onset of the imperative stimulus to the key press or foot pedal response.

As in the previous experiments, the critical question in this experiment was whether the hand or foot associations of the action verbs would have an effect on motor ERPs. If understanding the meanings of hand- and foot-associated action verbs activates the motor cortical areas involved in making the corresponding hand or foot movements, then this activation should be reflected in limb-specific movement-related ERPs.

There were two separate opportunities for observing verb-related effects on motor ERPs in this design. First, as in the previous experiments, if the motor activations produced by the action verbs combine with the motor activations involved in executing the motor response, then the verb-related effects could appear in the response-locked motor ERPs. Second, the present design also provides the opportunity to detect effects of action verb meanings on motor-related ERPs during a 2 s quiet period of the sort mentioned in the Introduction. Specifically, participants had 2 s to read and classify each action verb before the plus or minus sign appeared and instructed them to respond compatibly or incompatibly. Because the required key press or foot pedal response is unknown during this period, there should be no ERPs associated with preparation of a motor response. If the understanding of action verbs generates activity in the motor areas responsible for carrying out those actions, however, then observable hand- or foot-associated motor ERPs could be generated during this 2-s period. In fact, even if understanding the limb-associations of the action verbs produces only weak effects on motor ERPs, the absence of any other movement-related ERPs during this quiet period might actually make the effects especially easy to detect during this period.

Method

The apparatus, experimental procedure, and recording methods were the same as in Experiment 1 except as noted otherwise. The reported data were obtained from 19 volunteer participants (11 females) ranging in age from 19–30 years ($M = 21.9$ years), and all were right-handed as measured by the EHI ($M = 70.7$). Two additional participants were excluded from the analyses because of problems with EEG recordings.

Each trial began with the presentation for 750 ms of a lowercase letter “o” approximately 0.4° in height and width in the center of the screen as a combination fixation point and warning signal. A to-be-categorized action verb (e.g., “leap,” “sew”), centered at fixation, was then presented for 2 s. Because there had been no increased evidence for motor effects of the verb associations with the altered stimulus set in Experiment 2, we returned in this experiment to the originally chosen set of action verbs used in Experiment 1. Finally, the action verb was replaced by a plus or minus sign as an imperative stimulus at fixation, and this stimulus remained on the screen until a response was made or until 2 s had elapsed, whichever came first. Accuracy feedback was given for 500 ms following correct responses and for 2.5 s following errors. The fixation point appeared to begin the next trial approximately 2 s after the offset of the feedback.

Participants were instructed that they should categorize each action verb as pertaining to an activity that was more strongly associated with hand (or arm) movements versus foot (or leg) movements. Then, when the imperative plus or minus sign ap-

peared, they were to respond as quickly and as accurately as possible. Specifically, they were instructed to respond to a plus sign with the limb most closely associated with the action verb (“compatible” condition) but to respond to a minus sign with the opposite limb (“incompatible” condition). Each participant was tested in 14 blocks with 24 experimental trials per block, and the trials were approximately equally divided among the four conditions defined by two possible response limbs and two possible action verb associations (i.e., hand vs. foot).

In each trial, EEG was recorded for 4.2 s starting 200 ms prior to the onset of the action verb. Separate stimulus- and response-locked waveforms were computed to examine the effects of action verb associations on motor activity during the quiet period prior to the imperative stimulus onset and prior to the key press or foot pedal response.

Results and Discussion

RTs were measured starting from the onset of the imperative stimuli. Based on their elevated mean RTs compared to the other blocks, the first two blocks were treated as practice blocks and omitted from all analyses. In addition, across all participants, six trials with RTs greater than 2 s (0.12%) were excluded as outliers.

Behavioral results. Table 4 summarizes the mean correct RT and PC as a function of the response limb and action verb association. Overall, participants’ responses were 92.6% correct, validating that they had the expected hand versus foot associations of the action verbs and that these associations influenced responding. In the ANOVA on RT, there were significant effects of both response limb, $F(1, 18) = 44.81, p < .001, \eta_p^2 = .71$, and verb association, $F(1, 18) = 15.37, p < .005, \eta_p^2 = .46$, as well as their interaction, $F(1, 18) = 39.90, p < .001, \eta_p^2 = .69$. The average RTs were 786 ms and 860 ms for compatible and incompatible trials, respectively, so there was an ACE of 74 ms. In the ANOVA on PC, only the main effects of response limb, $F(1, 18) = 9.84, p < .01, \eta_p^2 = .35$, and verb association, $F(1, 18) = 11.13, p < .005, \eta_p^2 = .38$, were significant.

Psychophysiological results. The analyses of stimulus-locked waveforms examined EEGs recorded during the 2 s quiet period preceding the onset of the imperative stimulus; across participants, 5%–17% ($M = 11\%$) of trials were excluded on the basis of EEG artifacts contaminating this period. For the response-locked analyses, trials were checked for artifacts from the onset of the baseline until the key press or foot pedal response; across participants, 5%–27% ($M = 14\%$) of trials were excluded.⁶ Grand-averages of the individual-participant ERPs are plotted in Figure 4.

During the quiet period after the action verb had been presented but before the imperative stimulus had appeared to signal the compatible or incompatible response, there was no sign that the motor-related ERPs were significantly affected by the action verbs

⁶ Response-preceding blinks were more numerous in this experiment than in Experiments 1 and 2, presumably because of the longer-lasting and changing stimulus displays. Exclusion of all trials with blinks would therefore have left too few trials to compute stable ERPs, at least for some participants, so trials with blinks were not excluded when computing the response-locked ERPs. The analyses of VEOG amplitude mentioned in footnote 5 were therefore especially important for this experiment as a check to see whether any of the condition differences in Cz amplitude might have resulted artifactually from differences in the frequency or magnitude of blinks. The same was also true for the later experiments in which temporally extended displays were used (i.e., Experiments 4, 6, and 7).

Table 4
Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of Response Limb and Verb Association in Experiment 3

Verb assoc.	Response limb and dependent variable									
	Hand				Foot				None	
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz	C4'-C3'	Cz
Hand	704	95.7	2.26	2.78	900	92.1	-.68	-3.27	.25	1.12
Foot	821	92.7	2.02	.49	868	89.9	.71	-3.26	.41	.94

Note. Mean C4'-C3' and Cz amplitudes for the "hand" and "foot" responses were measured during the final 200 ms preceding a correct key press or foot pedal response; those for the "none" response were measured during the quiet period from the onset of the action verb to the onset of the imperative stimulus.

($p < .2$). In fact, as can be seen in Table 4, the mean C4'-C3' amplitude during the quiet period was numerically smaller for hand- than foot-associated verbs, so the observed difference was in the direction opposite from that expected if verb understanding activated the motor areas responsible for carrying out the named movements.⁷

Table 4 also shows the mean C4'-C3' and Cz amplitudes in the last 200 ms preceding the hand and foot responses. As usual, ANOVAs with factors of response limb and action verb association showed strong effects of the response limb on both C4'-C3', $F(1, 18) = 30.19, p < .001, \eta_p^2 = .63$, and Cz, $F(1, 18) = 17.60, p < .005, \eta_p^2 = .49$. The action verb association had no significant effects on these motor ERPs (both $p > .2$). On average across hand and foot responses, the effect of the verbs' hand- versus foot-associations was numerically in the same direction seen with actual hand and foot movements for Cz (i.e., more positive with hand- than foot-associated verbs), but the effect was in the opposite direction for C4'-C3' (i.e., more positive with foot- than hand-associated verbs).

Discussion. The hand and foot associations of the action verbs must have been processed semantically in this experiment, because this processing was needed to respond accurately. As expected, mean C4'-C3' and Cz amplitudes once again differentiated clearly between hand and foot movements, verifying their status as measures of motor activation. There were no corresponding effects of the hand or foot associations of the action verbs on these motor ERPs, however. Thus, the results provide no support for the idea that semantic processing of the action verbs resulted in any motor-level activation.

Consistent with embodied cognition models in which action verbs produce motor-level activation, there was a strong effect of compatibility on RT in this experiment (cf. Table 4). As was discussed in the Introduction, however, this effect is not strong evidence for such models, because it could also have arisen at the decision-making level. In fact, a decision-level effect seems especially plausible in this experiment because of the nature of the compatibility manipulation. The effect of compatibility on RT simply means that responses were faster when the imperative stimulus was a plus sign and required the response compatible with the verb's classification than when the imperative stimulus was a minus sign and required the incompatible response. Many previous experiments have shown analogous effects of S-R compatibility on RT (e.g., Fitts & Deininger, 1954), and there is evidence that these

arise at the decision level in many cases (e.g., Proctor, Lu, Van Zandt, & Weeks, 1994).

Experiment 4

Arguably, some aspects of the task used in Experiment 3 may actually have interfered with demonstrating effects of semantic processing on motor ERPs. In particular, the inclusion of trials with incompatible imperative stimuli could conceivably have disrupted the normal semantic processing of hand- and foot-associated action verbs. After all, to the extent that these verbs did activate their corresponding motor areas, this activation would have caused potentially harmful response competition or even induced incorrect responses in incompatible trials. Perhaps, then, participants somehow suppressed the motor activations usually associated with semantic processing to avoid such competition. In short, the interfering effects of the incompatible S-R mapping requirement that was imposed in half of the trials might have distorted the normal semantic processing needed to decide whether each verb named a hand- or foot-associated action.

To avoid any interfering effects of instructed S-R incompatibility while at the same time emphasizing the semantic processing of action verbs, the present study used a recognition memory task in which the responses were categorized as old versus new relative to a previously studied list. Even though the responses were not determined by the limb association of the action verbs, semantic processing of action verb meanings would still be expected, because such processing is known to facilitate memory performance (e.g., Craik, 1981). Indeed, evidence of embodiment effects has been observed in some previous memory tasks (e.g., Liao, Kronecker, Yau, Desmond, & Marvel, 2014; Shebani & Pulvermüller, 2013; Van Dam, Rueschemeyer, Bekkering, & Lindemann, 2013),

⁷ Following the suggestion of an anonymous reviewer, for this and all subsequent experiments with quiet periods (i.e., Experiments 4, 6, and 7), we checked mean C4'-C3' and Cz amplitudes for an effect of action verbs not only on average across the whole quiet period but also within each successive 100 ms window during that period, because these more fine-grained analyses would presumably have greater power to detect brief transient effects. The method of Simes (1986) was used to control for the inflation of Type I error rate associated with multiple testing, because this method has both good power and good control of Type I error rate even when the multiple tests are correlated. These checks of 100 ms windows will be described only for Experiment 7, because they produced no evidence of verb effects in any of the other experiments.

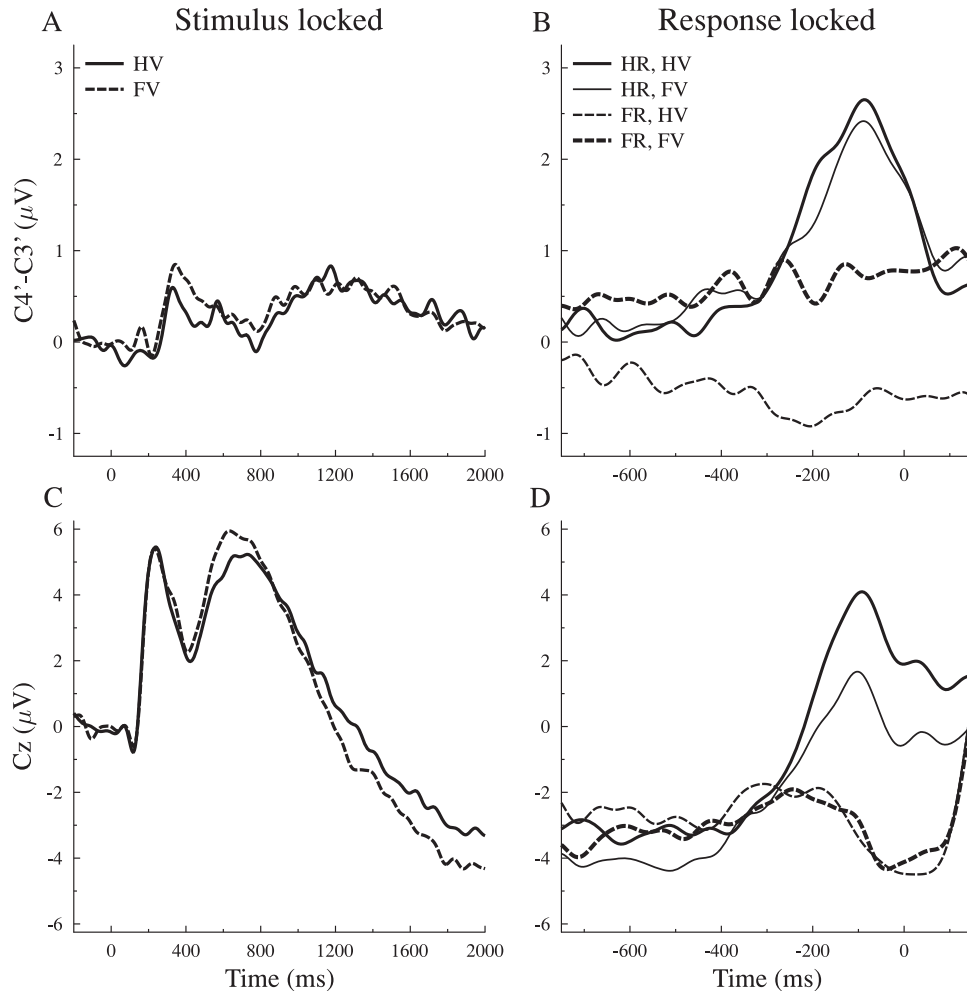


Figure 4. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in Experiment 3 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV). In the stimulus-locked waveforms, Time 0 indicates the onset of the hand- or foot-associated verb and Time 2000 indicates the onset of the imperative signal.

though not in others (e.g., Quak, Pecher, & Zeelenberg, 2014; Zeelenberg & Pecher, 2015).

Study and test phases were interleaved in the current experiment. In each study phase, participants were given a list of three action verbs to memorize. Then, in each trial of the subsequent test phase, they were shown a single action verb that they classified as old or new, relative to the immediately preceding study phase, by making a hand or foot response. Thus, both hand and foot responses were made to hand and foot action verbs, allowing a full factorial design of response limb and action verb association.

As in Experiment 3, it was possible in Experiment 4 to assess the effects of the semantic processing of action verbs on motor activations during quiet periods without overt responses as well as during the active periods immediately preceding such responses. The former were assessed by examining ERPs evoked during presentation of the to-be-memorized verbs in the study phase, since participants made no overt responses to the verbs during this phase. The latter were assessed by examining the

ERPs evoked during the old/new test phase, during which participants responded with one limb or the other to indicate whether each test verb had or had not been presented in the preceding study list.

Method

The apparatus, experimental procedure, and recording methods were the same as in Experiment 1 except as noted otherwise. The reported data were obtained from 23 volunteer participants (11 females) ranging in age from 18–28 years ($M = 21.3$ years), and 21 were right-handed as measured by the EHI ($M = 67.0$). One additional participant was excluded because of excessive blinking.

Each participant was tested in 20 blocks of trials. At the beginning of each block, a memory set of three hand-associated or three foot-associated action verbs was presented sequentially, and these were selected randomly from almost the same set of verbs used in

Experiments 1 and 3.⁸ We used memory sets of all hand-associated or all foot-associated verbs in an effort to maximize the possibility of observing effects of the limb associations during the study phase. It is known that participants tend to rehearse previously seen memory set items during study (e.g., Atkinson & Shiffrin, 1971), so all of the items being rehearsed would contribute to the ERPs observed during the study phase—not just the single item currently being presented. In that case, the largest differences between hand- and foot-associated verbs would be expected when all of the verbs in a given set had the same hand or foot association, so that their limb-specific motor activations would summate during the study phase.

Each memory set verb was presented in red letters, centered at fixation, for 3 s. Participants were instructed to memorize these verbs for a subsequent memory test but not to make overt responses to them. After the memory set had been presented, the remainder of each block consisted of a series of 20 randomly intermixed probe trials, with half old probes (i.e., belonging to the memory set) and half new probes. Each probe trial began with the presentation of a plus sign as a fixation point and warning signal. Then, a single green action verb was presented at fixation, and it remained on the screen for 3 s or until the participant responded, whichever came first. Participants were instructed to respond to each green probe verb with a hand or foot response to indicate whether the probe verb was old (i.e., was one of the memory set verbs previously memorized for the block) or new (i.e., was not one of the memory set verbs). Accuracy feedback lasting 2.5 s was given following errors.

For each participant, the 20 blocks were divided into four sets defined by a 2×2 factorial design with either the hand or the foot response indicating that a probe verb was old and with a memory set of either three hand-associated verbs or three foot-associated verbs. There were five equivalent blocks within each of these four sets. For half of the participants, “old” and “new” probes were assigned to hand and foot responses, respectively, in the first 10 blocks, and these assignments were reversed for the last 10 blocks. For the other half of the participants, these sets of 10 blocks were tested in the reverse order. Within each set of 10 blocks, memory sets of hand- and foot-associated verbs alternated, with the first block’s association counterbalanced across participants. EEG was recorded for 3.2 s starting 200 ms before the onset of each memory set and probe verb.

Results and Discussion

The first two blocks with each S-R assignment (i.e., blocks 1, 2, 11, and 12) were treated as practice blocks and omitted from all analyses. Across all participants, two trials with RTs less than 200 ms (0.03%) and 138 trials with RTs greater than 2 s (1.94%) were excluded as outliers.

Behavioral results. Table 5 summarizes the mean correct RT and PC as a function of the response limb and the action verb’s hand versus foot association. An ANOVA on mean correct RT with these two factors and a third factor of old/new status replicated the usual finding of faster responses with the hands than with the feet, $F(1, 22) = 29.80, p < .001, \eta_p^2 = .57$, as well as the usual finding that responses are faster to old words than to new ones, $F(1, 22) = 14.76, p < .005, \eta_p^2 = .40$.⁹ The only other significant result in this ANOVA was the interaction of response and verb

association, $F(1, 22) = 5.39, p < .05, \eta_p^2 = .20$, with responses 12 ms faster, on average, when the verb association was compatible with the response limb (e.g., hand-associated verb requiring a hand response) than when it was incompatible, once again validating the hand and foot associations of the action verbs. A corresponding analysis of PC yielded no significant effects.

Psychophysiological results. Across participants, 2%–42% ($M = 21\%$) of memory set presentation trials were excluded because of artifacts, and the corresponding percentages for probe trials were 4%–31% ($M = 14\%$). Stimulus-locked grand-averages of the individual-participant ERPs from the memory set presentation trials are plotted in Figure 5, and both stimulus-locked and response-locked averages from the probe trials are shown in Figure 6.

For probe trials, analyses of the mean amplitudes in the last 200 ms before the response were carried out using the same 3-factor ANOVA employed for the RTs and PCs. As expected, mean C4’-C3’ amplitude was larger for hand responses than for foot responses, $F(1, 22) = 92.65, p < .001, \eta_p^2 = .81$. In contrast, it was numerically smaller for hand-associated verbs than for foot-associated verbs, although this difference was not significant, $F(1, 22) = 3.85, p < .1, \eta_p^2 = .15$. The only other significant finding in this analysis was that of slightly greater mean C4’-C3’ amplitude in trials with old words than with new words, $F(1, 22) = 5.05, p < .05, \eta_p^2 = .19$. In essence, the tendency of the right hemisphere to respond more positively than the left hemisphere was larger with old words than with new ones.

The parallel analysis of mean Cz amplitude indicated that this measure was also reliably larger for hand responses than for foot responses, $F(1, 22) = 21.30, p < .001, \eta_p^2 = .49$. Again in contrast, it was numerically smaller for hand-associated verbs than for foot-associated verbs, although this difference was not significant, $F(1, 22) = 0.32, p > .5, \eta_p^2 = .01$. The only other significant result in this analysis was a small but reliable three-way interaction for which we have no explanation, $F(1, 22) = 7.76, p < .025, \eta_p^2 = .26$. Specifically, as can be seen in Table 5, the tendency for mean Cz amplitude to be larger for hand than foot responses was stronger for old hand-associated verbs and for new foot-associated verbs than for the other two combinations of conditions.

Mean C4’-C3’ and Cz amplitudes during presentations of the memory set items (i.e., the quiet period) were also analyzed to check for a motor-related effect of the hand- or foot-associations of the memory set verbs. Neither measure showed a significant effect (both $p > .9$).

Discussion. The reliable—though weak—effect of compatibility on RT replicates previous ACEs and extends them to a speeded old/new recognition memory task. Although the compatibility effect was weaker than in the previous two experiments, its

⁸ Based on participants’ comments about their ambiguous verb status, three foot-associated verbs (i.e., “footstep,” “jig,” and “lame”) were removed from the set used in Experiments 1 and 3, and the new verb “sidestep” was added to partially offset the reduced number of foot-associated verbs. In addition, due to a stimulus file handling error, the verb “clinch” was omitted from the stimulus set for Experiments 4 and 7.

⁹ Among new probe verbs, it is possible to distinguish further between those with the same hand/foot association as the current memory set versus those with the opposite hand/foot association. Preliminary analyses suggested that this factor had little or no effect, however, so we collapsed over it in all reported analyses.

Table 5
Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of the Response Limb and the Probe Verb's Hand Versus Foot Association in Experiment 4

Verb assoc.	Response limb and dependent variable									
	Hand				Foot				None	
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz	C4'-C3'	Cz
Hand	872	97.6	1.42	4.79	976	96.3	-1.49	1.02	.65	.56
Foot	877	96.8	2.03	4.71	957	96.8	-1.30	1.34	.62	.46

Note. For the probe trials with hand and foot responses, mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response. For the memory-set presentation trials with no responses, mean C4'-C3' and Cz amplitudes were measured during the 3-s presentation of the memory set.

presence provides reassurance that there was semantic processing of the limb-related aspects of the action verbs within this task.

The two motor ERP measures once again clearly showed the expected effects of the responding limb, further validating their use as measures of motor activation within this task. Given this validation, it is striking that once again neither measure showed effects of the hand- or foot-association of the action verb—in fact, numerically both effects were in the direction opposite to what would be expected if these verbs activated the motor areas responsible for carrying out the named actions. A parsimonious account of these results is that the semantic processing of action verbs within this task was carried out without the involvement of these motor areas, contrary to the idea that these areas are necessarily activated during the understanding of action verbs.

Experiment 5

It is intriguing that none of the conditions examined in Experiments 1–4 were sufficient for action verbs to produce detectable effects of hand- versus foot-associated verbs on motor ERPs. Although the compatibility effects on RT in Experiments 2–4 demonstrate that the limb-related verb meanings were processed, this processing may only have affected the decision-level representations influencing RT—there was no evidence that it influenced the motoric representations indexed by C4'-C3' and Cz.

One possible explanation for the absence of the motor-level effects is that the hand versus foot associations of the action verbs were not sufficiently salient for semantic processing to activate the limb-specific motor representations of these verbs. That is, the verbs might only have activated abstract, limb-related semantic concepts that were capable of influencing decisions but not capable of activating motor representations. This explanation is supported by arguments that there are many different aspects to the meanings of action verbs (e.g., Mollo, Pulvermüller, & Hauk, 2016). Under some circumstances, the semantic processing of these verbs could conceivably only activate abstract representations that are not closely tied to the hand and foot effectors at a motor level.

Within the context of strong compatibility effects on RT together with null results on motor activation, it seems relevant to ask whether motor activation changes can be seen with even the most direct connection between word meanings and response limbs. For that reason, the present experiment checked for a motor-level influence of compatibility in a version of the Stroop

(1935) paradigm using words chosen to be maximally related to the response effectors. Specifically, in each trial of this experiment the stimulus was the word “HAND” or “FOOT” displayed in one of two colors. Participants were instructed to respond with the right hand when one color was presented and with the right foot when the other color was presented, ignoring the identity of the word.

Based on the strong compatibility effects previously observed in such paradigms (for reviews see, e.g., Hommel, Brown, & Nattkemper, 2016; MacLeod, 1991; Melara & Algom, 2003), it was expected that responses would be faster when the stimulus word named the effector required to respond to the stimulus color (i.e., compatible trials) than when it named the other effector. For example, in a similar color discrimination task with word stimuli, Ahlberg et al. (2013) found a strong effect on RT of the compatibility between hand- versus foot-associated words (e.g., “handball” vs. “football”) and the required hand or foot response, strongly suggesting that “effector-specific information is automatically activated during word processing” (Ahlberg et al., 2013, p. 136) in such Stroop-like tasks. Also, in a color discrimination task requiring a response of either opening or closing the hand, Liepelt et al. (2012) found that RT was affected by the compatibility between the German stimulus word “öffnen” (open) or “schließen” (close) and the hand-opening or -closing response required by the word's color. Under the assumption that analogous compatibility effects on RT would be found in this experiment, then, the question was whether compatibility would also affect the motor ERPs, as would be expected if the effect on RT arises at least partly from automatic activation of limb-specific motor areas.

Method

The apparatus, experimental procedure, and recording methods were the same as in the previous experiments except as noted otherwise. The reported data were obtained from 20 volunteer participants (12 females), and each took part in a single experimental session lasting approximately 2 hr in return for a reimbursement of NZ \$30. Their ages ranged from 20–33 years ($M = 23$ years), and they were all right-handed ($M = 75$) as indexed by the EHI. Two additional participants were excluded because of problems with EEG recordings.

The imperative stimuli were the words “HAND” and “FOOT” displayed as either yellow or light blue upper-case letters against the dark background of the computer screen, and each word subtended approximately $1.4^\circ \times 0.5^\circ$ of visual angle. Half of the

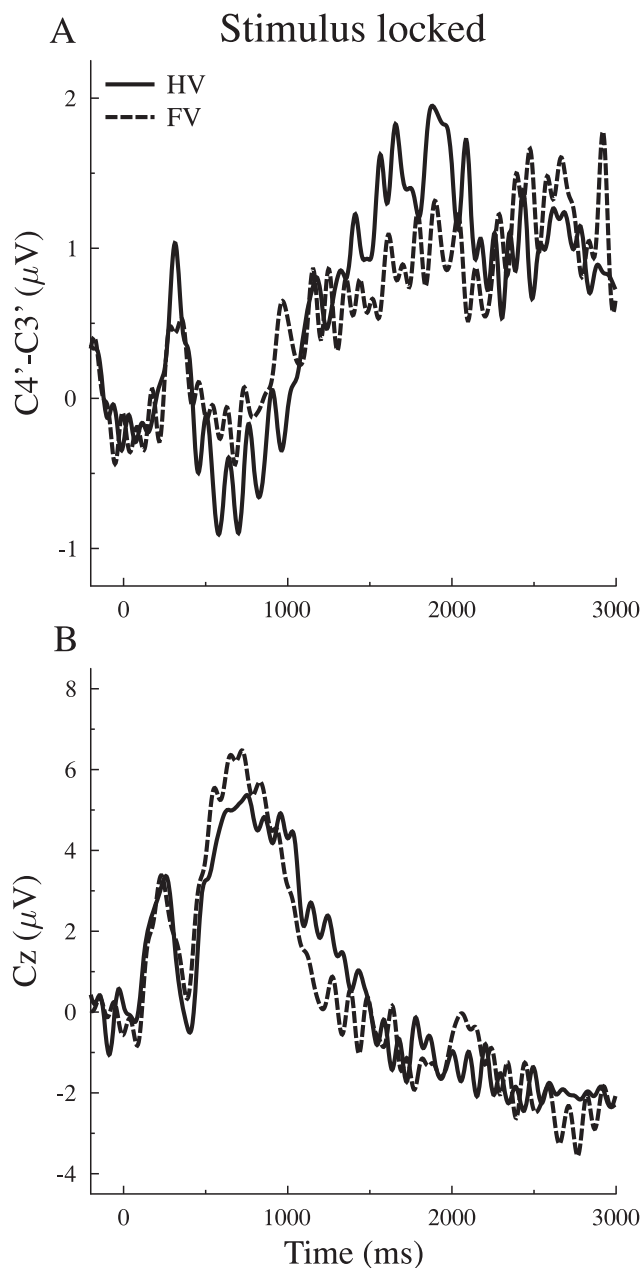


Figure 5. Mean stimulus-locked ERPs, filtered at 12 Hz, in the memory set presentation trials of Experiment 4 as a function of verb type (HV = hand-associated; FV = foot-associated).

participants responded to yellow stimuli with the right hand and to blue stimuli with the right foot, whereas these assignments were reversed for the other half of the participants.

Each participant was tested in eight blocks with 64 experimental trials per block, and each of the four imperative stimuli (i.e., 2 words \times 2 colors) was presented equally often within each block. Participants were instructed to respond as quickly and as accurately as possible with the right hand or foot depending on the stimulus color, ignoring the identity of the word. If an incorrect response was made, error feedback was displayed for 2.5 s. The

fixation point appeared to begin the next trial approximately 2.5 or 5.0 s after the fixation point of the previous trial, depending on whether error feedback was presented.

Results and Discussion

The first block of trials was excluded as practice, and trials with RTs less than 200 ms (0.1%) or greater than 2 s (0.0%) were excluded as fast and slow outliers, respectively.

Behavioral results. Table 6 shows the mean correct RT and PC as a function of the response limb and the Stroop-like word. A repeated-measures ANOVA indicated a highly significant main effect of response limb, $F(1, 19) = 61.87, p < .001, \eta_p^2 = .76$, and a highly significant interaction reflecting 26 ms faster responses, on average, in compatible trials than incompatible ones, $F(1, 19) = 44.46, p < .001, \eta_p^2 = .70$. Numerically, the effect of compatibility was larger for foot responses than for hand responses, but this interaction did not approach significance, $F(1, 19) = 2.05, .2 > p > .1, \eta_p^2 = .10$. In a parallel ANOVA on percentages of correct responses, only the compatibility-based interaction was significant, $F(1, 19) = 4.75, p < .05, \eta_p^2 = .20$, with 98.5% and 97.8% correct responses for compatible and incompatible trials, respectively.

Psychophysiological results. Individual trials were checked for EEG artifacts using the same methods as in the previous experiments. Across participants, 7%–37% ($M = 19\%$) of trials were excluded because of EEG artifacts. Grand-averages of the individual-participant ERPs are plotted in Figure 7.

The amplitudes of the motor ERPs were analyzed with ANOVAs having the within-subject factors of response limb (i.e., hand vs. foot) and Stroop-like word (i.e., “HAND” vs. “FOOT”). These ANOVAs yielded highly significant effects of response limb in the expected direction for both C4'-C3', $F(1, 19) = 31.58, p < .001, \eta_p^2 = .62$, and Cz, $F(1, 19) = 33.49, p < .001, \eta_p^2 = .64$, but no effect of the Stroop-like word on either of these measures (both $p > .15$).

No significant effects were found in parallel analyses of mean VEOG and HEOG amplitudes, although there was a marginally significant tendency for smaller VEOG amplitude in trials with hand rather than foot responses, indicating that blink artifacts—if present—tended to counteract rather than exaggerate the effect of response limb on Cz amplitude.

Discussion. Once again, the compatibility of the word meaning and the response effector influenced RT but had no discernible effect on the amplitudes of motor ERPs. This finding reinforces the contentions that (a) limb-related words can be understood without activating associated limb-specific areas of the motor cortex, and (b) limb-specific compatibility effects on RT do not imply the presence of limb-specific motor activation.

Experiment 6

A potentially important feature of Experiments 1–5 is that they all assessed the effects of single, isolated words on motor ERPs. Although many studies have found evidence for motoric effects with single word stimuli (e.g., Klepp et al., 2014; Mollo et al., 2016; Niccolai et al., 2014; Pulvermüller et al., 2001; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005), reading words within the context of a meaningful sentence might elicit deeper semantic

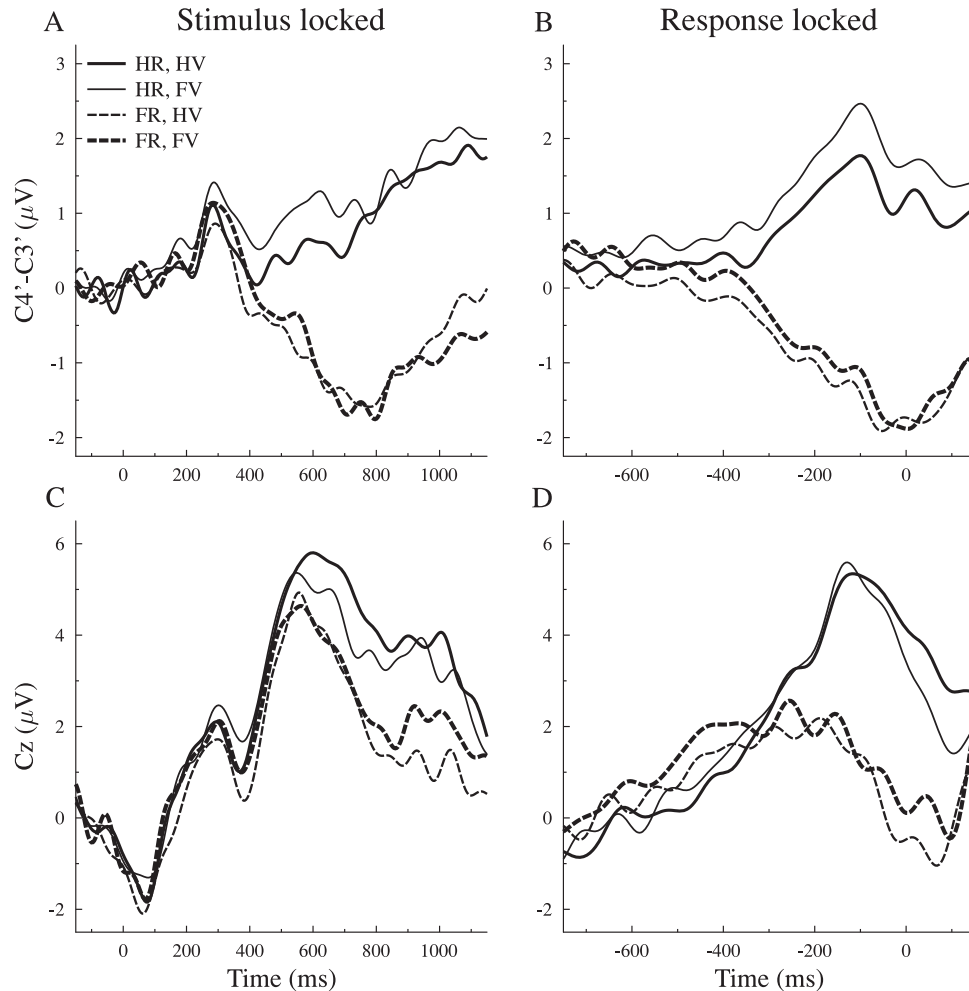


Figure 6. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in the probe trials of Experiment 4 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV).

processing and thus produce stronger activation of the associated motor representations (Glenberg & Kaschak, 2002; Scorilli & Borghi, 2007; Tettamanti et al., 2005). Indeed, in some studies embodiment effects of action verbs were only found when these

words were embedded in sentences describing literal rather than figurative actions (e.g., Cacciari & Pesciarelli, 2013). Thus, the remaining experiments in this article were designed to test for motor-level activation of action verbs in more elaborate contexts involving phrases and sentences.

Table 6
Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of Response Limb and Stroop-Like Word in Experiment 5

Stroop-like word	Response limb and dependent variable							
	Hand				Foot			
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz
"HAND"	549	98.5	2.64	5.55	710	97.3	.00	-1.36
"FOOT"	570	98.3	2.55	5.30	678	98.6	-.19	-1.29

Note. Mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response.

In Experiment 6, each stimulus was a meaningful sentence containing an action verb, and these sentences were presented within the context of an old/new recognition memory task. The experiment was carried out in alternating study and test blocks, with each block consisting of the presentation of 16 sentences. In the study blocks, participants were instructed to read each sentence and remember it for the subsequent recognition memory test, with no motor responses being required. In the subsequent test blocks, the 16 sentences were presented one at a time and participants were required to respond to each with the hand or foot to indicate whether the sentence had been presented in the preceding study block (i.e., "old" vs. "new").

EEG was recorded during both the study blocks and the test blocks, and motor-related ERPs were assessed for both. Note that

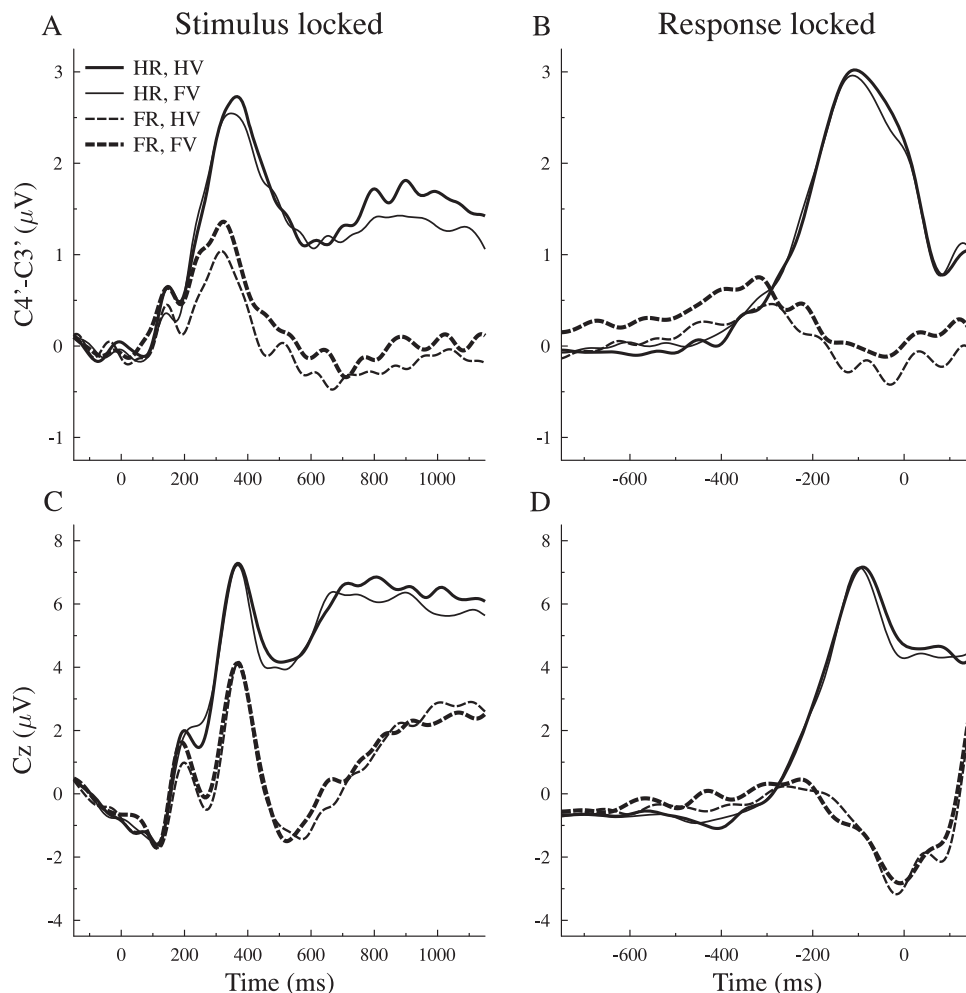


Figure 7. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in Experiment 5 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV).

the ERPs computed from recordings made during the study blocks (i.e., with no overt hand or foot responses) provide an opportunity to observe motor-related ERPs during a quiet period analogous to those examined in Experiments 3 and 4. Any motor-related activity driven by semantic processing of the action verb within its sentence context could be observed during this period, with no possibility of overshadowing by actual movement-related activation of the motor cortex. In contrast, the test-block ERPs allowed measurement of the actual movement-related ERPs and of any effects of action-word processing on these ERPs.

Method

The reported data were obtained from 16 volunteer participants (six females) ranging in age from 19–27 years ($M = 20.4$ years). Three were left-handed as indexed by the EHI, and the overall mean EHI score was $M = 56.6$. Two additional participants were excluded because of problems with EEG recordings, and three were excluded because of unusually high error rates (>35%).

The apparatus and EEG recording methods were the same as those used as in the previous experiments, with the exception of

changes necessary to accommodate the new experimental task. Each participant was presented with 10 blocks of 16 sentences per block, with the instructions for each block presented on the computer screen at the start of the block. Within each block, half of the sentences included hand-associated action verbs and the other half included foot-associated verbs. The odd-numbered blocks were study blocks, and in these blocks participants were simply instructed to read each sentence silently and to remember it for the memory test that would be given in the subsequent block. The even-numbered blocks were test blocks, and in these blocks the participants were required to make either a hand or foot response to each sentence to indicate, as quickly and accurately as possible, whether the sentence was old (i.e., had been presented in the preceding odd-numbered block) or was new. Half of the participants were instructed to respond to old sentences with the hand and to new sentences with the foot, whereas these assignments were reversed for the other half.

The stimuli were three-part sentences constructed from a subject, a verb, and an object phrase or a prepositional phrase (hence-

forth termed simply “object phrase”), and the sentences ranged in length from five to eight words. There were 19 different subjects, each either two or three words in length (e.g., “the nurse,” “the bus driver”), and these are listed in Table A1 of the Appendix. The verbs were the same single-person, present-tense action verbs used in Experiment 4. Two sensical object phrases were generated for each verb (e.g., object phrases of “the wood” or “the onions” for the verb “chops”), and these phrases varied in length from two to four words. Examples of the verbs and their associated object phrases are shown in Table A2 of the Appendix. Each study sentence was a randomly generated combination of one subject, one verb, and one of that verb’s two sensical object phrases. In the test blocks, the “old” sentences were repeated exactly from the preceding study block. For half of the “new” sentences, the original subject was replaced with a different randomly selected subject; for the other half, the object phrase was replaced with the verb’s sensical object phrase that had not been used in the study block.

Each trial started with a fixation point presented for 500 ms followed by a blank screen for 200 ms. Then the three parts of the sentence (subject, verb, and object phrase) were presented successively for 960 ms each, centered at the point of fixation, with a 60 ms gap between the subject/verb and the verb/object. The total time from the start to finish of the sentence display was thus 3 s. An additional 3 s was allowed for rehearsal of the sentence during study blocks or for responding during test blocks. In test blocks, participants responded with the hand or foot to indicate whether the sentence was old or new, with RT measured from the onset of the object phrase. Following each response, accuracy feedback was displayed for 500 or 2,500 ms following correct responses and errors, respectively. In the study blocks, participants did not respond overtly to the sentences, so no RT was recorded and no accuracy feedback was given. The fixation point appeared prior to the next sentence approximately 1–2 s after the end of the 3 s rehearsal period in the study blocks or the feedback in the test blocks. In each trial, EEG was recorded for 6.2 s starting 200 ms before the onset of the subject of the sentence. Because of the longer recording epoch and hardware limitations, the sampling rate was reduced to 100 Hz and a 30-Hz low-pass filter cutoff was used.

Results and Discussion

The first two blocks of trials (i.e., one study block and one test block) were excluded as practice, and test trials with RTs less than

200 ms (0.1%) or greater than 3.5 s (0.7%) were excluded as fast and slow outliers, respectively.

Behavioral results. Table 7 shows the mean correct RT and PC as a function of the response limb and action verb association in the test blocks, and these were analyzed using mixed ANOVAs having the between-subjects factor of response assignment group (“old” to hand and “new” to foot, or vice versa) and the within-subjects factors of response limb and action verb type (i.e., hand- vs. foot-associated). This ANOVA indicated a significant main effect of action verb type, $F(1, 14) = 9.54, p < .01, \eta_p^2 = .40$, with responses 76 ms faster for sentences involving hand-associated action verbs than for those involving foot-associated verbs. Hand responses were 95 ms faster than foot responses on average, but this effect was not statistically reliable, $F(1, 14) = 2.67, p > .1, \eta_p^2 = .16$, nor was the 29 ms compatibility-based interaction significant, $F(1, 14) = 1.10, p > .2, \eta_p^2 = .07$. Given that the hand and foot associations of the action verbs have already been established by the preceding experiments with single-verb stimuli, the nonsignificant compatibility effect in this experiment may well reflect reduced statistical power. RTs are longer and more variable when processing sentences than single verbs, and the action verb influences a smaller proportion of the total processing time.

There was a significant interaction of response limb and group, $F(1, 14) = 7.33, p < .025, \eta_p^2 = .34$, however. Hand responses were 252 ms faster than foot responses for the group making hand responses to old sentences, whereas hand responses were 63 ms slower for the group making hand responses to new sentences. Basically, this interaction emerged because there was a tendency for faster responses to old sentences than to new ones, and this tendency was overlaid on the tendency for hand responses to be faster than foot responses, exaggerating it for one group and counteracting it for the other. No effects were significant in the parallel ANOVA on PC, although the effects on accuracy were generally in the same direction numerically as those on RT (i.e., lower accuracy in the conditions with slower responses).

Psychophysiological results. Study-block trials were checked for EEG artifacts over the entire 6.2 s recording epoch, whereas test-block trials were checked only from the start of the epoch to the moment of the behavioral response. Across participants, 9%–22% ($M = 15\%$) of study-block trials and 6%–27% ($M = 15\%$) of test-block trials were excluded because of EEG artifacts. Grand-averages of the individual-participant ERPs from the study blocks are plotted in Figure 8, and those from the test blocks are plotted in Figure 9.

Table 7

Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of the Response Limb and of the Hand or Foot Association of the Action Verb Used in the Sentence in Experiment 6

Verb assoc.	Response limb and dependent variable									
	Hand				Foot				None	
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz	C4'-C3'	Cz
Hand	1160	90.6	2.43	-.63	1284	85.9	.75	-9.41	-.01	-.43
Foot	1264	87.5	1.71	-.40	1331	78.5	-.27	-8.19	-1.15	.31

Note. For the test-block trials with hand and foot responses, mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response. For the study-block trials with no responses, mean C4'-C3' and Cz amplitudes were measured from the onset of the verb to the end of the 3-s rehearsal period that followed the presentation of the study sentence.

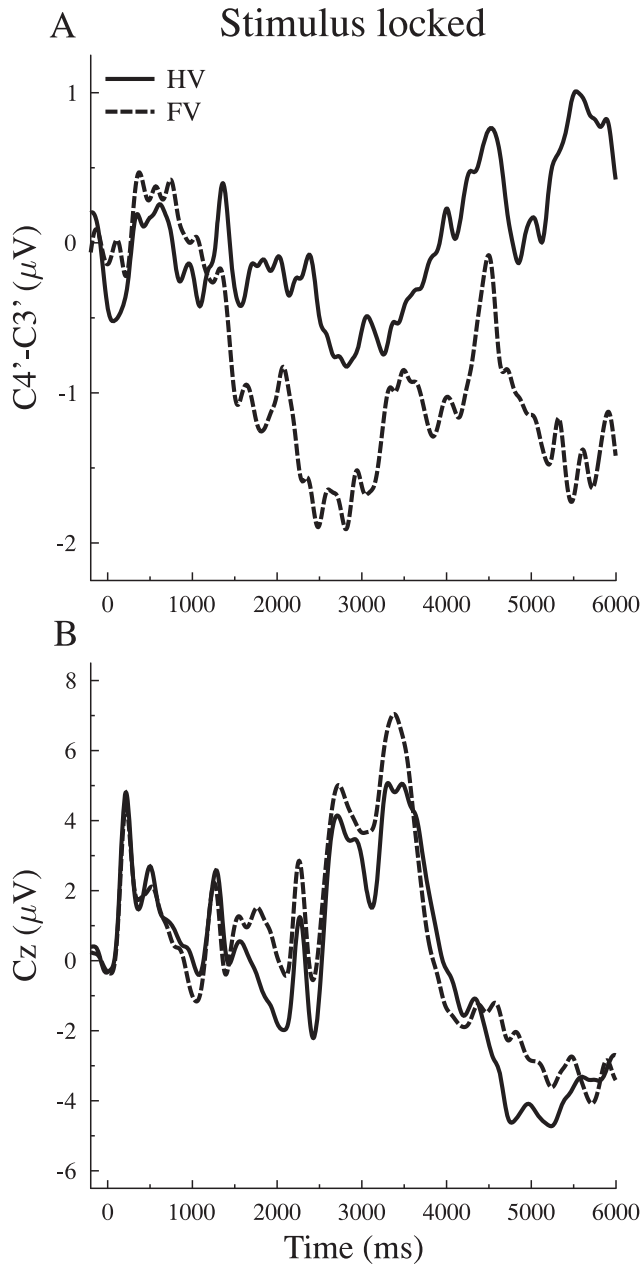


Figure 8. Mean stimulus-locked ERPs, filtered at 12 Hz, in the study blocks of Experiment 6 as a function of verb type (HV = hand-associated; FV = foot-associated). Verb onset was at Time 1,020.

Analyses of mean ERP amplitudes in the last 200 ms before the response in test-block trials were carried out as $2 \times 2 \times 2$ ANOVAs with the same factors used in the ANOVAs of RT and PC. Mean C4'-C3' amplitude was larger for hand responses than for foot responses and for hand-associated verbs than for foot-associated verbs, although neither of these effects approached significance ($p > .1$ for responses and $p > .5$ for verbs). Mean Cz amplitude was reliably larger for hand than foot responses, $F(1, 14) = 15.13$, $p < .005$, $\eta_p^2 = .52$, whereas it was nonsignificantly smaller for hand-than foot-associated action verbs ($p > .5$). There

were no significant interactions in these ANOVAs, nor were there any significant effects in the parallel ANOVAs on VEOG and HEOG.

Mean C4'-C3' and Cz amplitudes were also computed for the study-block trials during the approximately 4 s interval from the onset of each sentence's verb until the end of the presentation-plus-rehearsal interval for that trial (i.e., until the end of the trial's 6.2 s recording epoch). These means were also analyzed to check for motor-related activity produced by understanding sentences involving hand- or foot-associated action verbs during the quiet period of the study-block trials. Neither C4'-C3' nor Cz amplitude showed a significant effect of verb association ($p = .12$ and $p = .68$, respectively). For C4'-C3', the verb association effect was in the direction that would be expected if verbs did activate the motor areas of the limbs that would carry out the named action (i.e., larger for sentences with hand-associated verbs); for Cz, the effect was in the opposite direction (i.e., smaller for sentences with hand-associated verbs).

Discussion. Despite the fact that action verbs were presented in the context of meaningful sentences, there was no evidence that these verbs activated the motor areas that would be involved in carrying out the named actions. There was only a weak compatibility effect on RT, although the reasonably high overall accuracy with which the task was performed suggests that there was semantic processing of the verbs. The small behavioral compatibility effect is consistent with the small effects obtained in the present Experiments 1 and 4, because in all three of these experiments the task could be performed accurately without making any distinction between hand- and foot-associated stimuli. Most importantly, the ERPs again showed no evidence that semantic processing of hand- and foot-associated action verbs differentially activates the motor areas involved in executing hand and foot responses. There were four opportunities to find such evidence, provided by two motor-related ERP measures (i.e., mean C4'-C3' and Cz amplitude) taken during two types of blocks (i.e., study and test), but none showed a reliable effect of the action verb/limb associations.

Experiment 7

A possible problem with the recognition memory task used in Experiment 6 is that participants might not have processed the meanings of the action verbs very deeply. In particular, in that experiment the new sentences always used the same verbs as the study sentences but used different subjects or object phrases. If participants noticed that pattern, they might have focused their study on the subjects and object phrases, thus paying little attention to the action verbs.

To encourage deeper processing of action verb meanings, participants in this experiment were instructed to use "action visualization" as a means of enhancing their performance on the recognition memory test. Visualization instructions seemed promising in the search for effects of verb meaning on motor ERPs, because there is evidence that visualization instructions can enhance embodiment effects by strengthening the processing of motor-related aspects of meaning (e.g., Bergen, Lindsay, Matlock, & Narayanan, 2007; Willems et al., 2010; Yang, 2014; Yu, Abrams, & Zacks, 2014). In addition, there is evidence that action visualization enhances the generation of motor-area neural activity associated with the visualized actions (e.g., Andres et al., 2015; Tomasino,

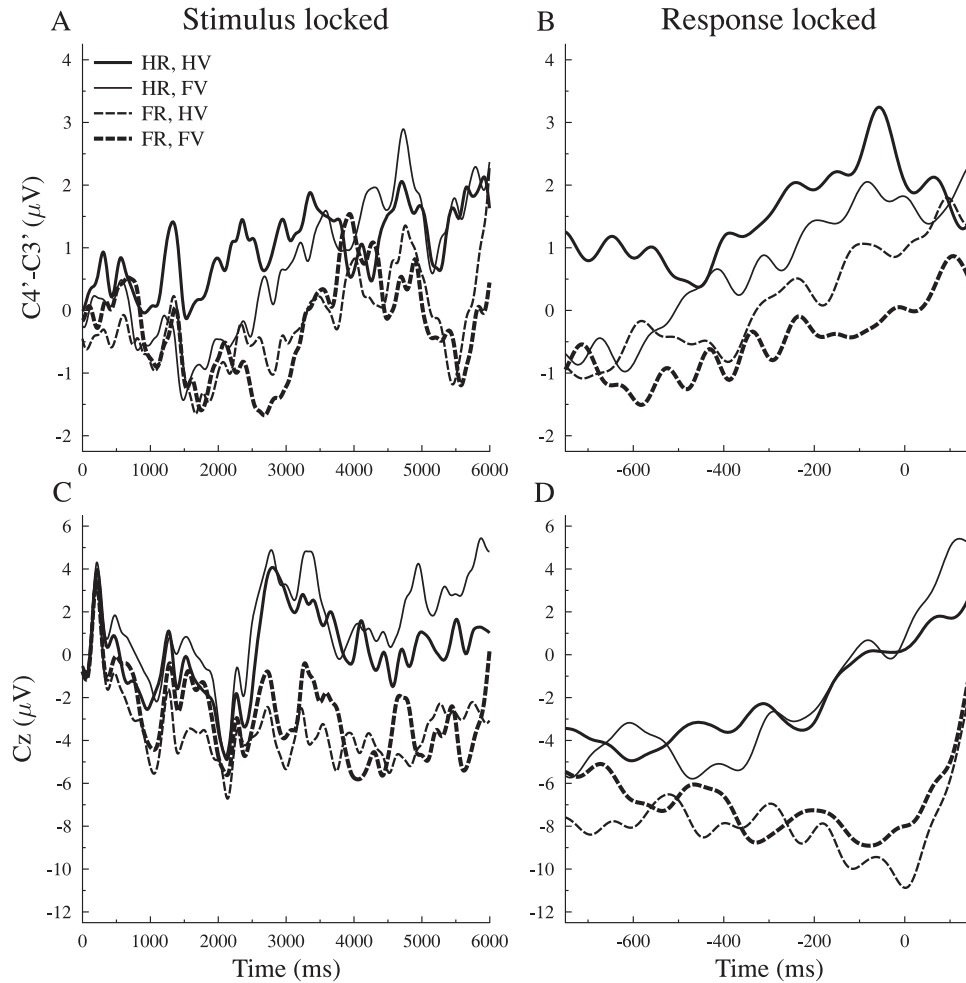


Figure 9. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in the test blocks of Experiment 6 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV). Verb onset was at Time 1,020 in the stimulus-locked waveforms.

Fink, Sparing, Dafotakis, & Weiss, 2008; Tomasino, Werner, Weiss, & Fink, 2007). In this experiment, then, participants were specifically told to visualize the action depicted by each stimulus when it was presented, and they were told that using this strategy would improve their performance on the memory test.

Method

Apart from the new visualization instructions, the stimuli, procedure, and analysis of this experiment were the same as those of Experiment 6 with a few minor exceptions. First, to provide more between-block rest periods and thereby encourage active visualization, the experiment was divided into 22 blocks of 16 trials per block. Second, to encourage first-person visualization, the stimulus was an action phrase consisting of a verb and object phrase but no subject (e.g., “kick the ball”). Because the participants were asked to visualize the actions, we omitted the verb “strangle” from the stimulus set to avoid unpleasantness. These action phrases were presented as a single sequence of words centered at fixation, and they were presented for 4 s in the study blocks or until the response

was made in the test blocks. In each trial, EEG was recorded for 4.2 s starting 200 ms before the onset of the stimulus phrase.

The reported data were obtained from 24 volunteer participants (nine females) ranging in age from 19–28 years ($M = 22.0$ years), and 21 were right-handed as measured by the EHI ($M = 64.8$). Two additional participants were excluded because of unusually high error rates (>25%).

Results and Discussion

Practice effects on RT and PC were minimal, so no initial blocks were excluded, and only 1.4% of trials with RTs greater than 3 s were excluded as slow outliers.

Behavioral results. Table 8 shows the mean correct RT and PC as a function of the response limb and action verb association in the test blocks. An ANOVA on RT with factors of group, response limb, and action verb type revealed that hand responses were faster than foot responses, $F(1, 22) = 9.24, p < .01, \eta_p^2 = .30$, and that responses were faster with hand-associated verbs than with foot-associated verbs, $F(1, 22) = 30.05, p < .001, \eta_p^2 = .58$,

Table 8

Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of the Response Limb and of the Hand or Foot Association of the Action Verb Used in the Action Phrase in Experiment 7

Verb assoc.	Response limb and dependent variable									
	Hand				Foot				None	
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz	C4'-C3'	Cz
Hand	1423	92.4	2.46	.65	1513	89.9	.87	-3.26	.38	.36
Foot	1538	90.2	2.66	1.80	1603	88.3	.29	-1.82	-.18	1.26

Note. For the test-block trials with hand and foot responses, mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response. For the study-block trials with no responses, mean C4'-C3' and Cz amplitudes were measured during the 4-s presentation of the action phrase.

but the small interaction representing the compatibility effect did not approach significance ($p > .4$). Responses were also faster for the group making hand and foot responses to old and new action phrases, respectively, than for the group with the opposite S-R assignment, $F(1, 22) = 7.54, p < .025, \eta_p^2 = .26$. In addition, the advantage for hand responses over foot responses was again larger for the group making the hand response to old action phrases than for the group making the foot response to old action phrases, $F(1, 22) = 50.82, p < .001, \eta_p^2 = .70$. No effects were significant in the parallel ANOVA on PC, but the effects on accuracy were again numerically consistent with those on RT.

Psychophysiological results. Across participants, 11%–38% ($M = 21\%$) of study-block trials and 9%–37% ($M = 20\%$) of test-block trials were excluded because of EEG artifacts. Grand-averages of the individual-participant ERPs from the study blocks are plotted in Figure 10, and those from the test blocks are plotted in Figure 11.

Mean C4'-C3' and Cz amplitudes in the last 200 ms before the test-block responses were larger for hand than foot responses, (C4'-C3': $F(1, 23) = 11.62, p < .005, \eta_p^2 = .34$; Cz: $F(1, 23) = 21.00, p < .001, \eta_p^2 = .48$). These measures were not significantly affected by the hand- versus foot-association of the action verb, although Cz showed a marginally significant 1.3 μV effect in the wrong direction (i.e., larger Cz for foot-associated verbs), $F(1, 23) = 2.97, p < .1, \eta_p^2 = .11$. There were again no significant interactions in these ANOVAs nor any significant effects in the parallel ANOVAs on VEOG and HEOG.

During study blocks, consistent with previous findings of motor imagery effects, mean C4'-C3' amplitude was significantly larger for hand-associated verbs than for foot-associated verbs, $F(1, 23) = 5.16, p < .05, \eta_p^2 = .18$. In contrast, mean Cz amplitude showed a nonsignificant reversal of the predicted effect during the study blocks, in that it was smaller for hand-associated verbs than for foot-associated verbs, $F(1, 23) = 3.14, p < .1, \eta_p^2 = .12$. Both of these results must be interpreted cautiously, however, because different results were obtained in the analyses of 100 ms windows described in footnote 7. In these analyses, the predicted effect of verb association on C4'-C3' was not significant, whereas the reversed effect on Cz was significant.

Discussion. The inclusion of visualization instructions may have slightly strengthened the influence of the action verbs' limb associations on motor ERPs. As in the previous experiment, there was only a numerically weak and statistically nonsignificant effect

of compatibility on RT. There was, however, a significant effect of verb association on the mean amplitude of C4'-C3' during the study period, though the corresponding effect on Cz amplitude was actually slightly reversed. Intriguingly, the response-locked C4'-C3' amplitudes shown in Figure 11B also display the effects of verb association predicted by embodied cognition models (cf. Figure 1B), although they were not significant and there was no hint of the predicted corresponding Cz amplitude effects (Figure 11D).

Experiment 8

Despite the use of meaningful sentences in Experiment 6 and the addition of visualization instructions in Experiment 7, there remains the possibility that participants adopted item-based rather than meaning-based strategies for performing the recognition memory test used in those experiments. To encourage semantic processing of full sentences even further, Experiment 8 used a task in which participants had to make a sensibility judgment (i.e., sense/nonsense) about each presented sentence, responding with the right hand or foot. The sense/nonsense discrimination has often been used to encourage semantic processing of sentence materials (e.g., Cacciari & Pesciarelli, 2013; Glenberg & Kaschak, 2002; Kaup, De Filippis, Lachmair, de la Vega, & Dudschig, 2012; Klatzky, Pellegrino, McCloskey, & Doherty, 1989; Ulrich et al., 2012), because a semantic analysis of sentence meaning is required in order to judge sensibility. If such semantic processing activates the motor areas responsible for hand and foot movements, then this activation should be observable in the amplitudes of the motor ERPs C4'-C3' and Cz.

Method

The apparatus, stimuli, and procedure were the same as those used in Experiments 6 and 7 except as noted otherwise. As in Experiment 6, each stimulus consisted of a simple three-part sentence (i.e., subject, verb, object phrase) with the parts presented sequentially. The sensibility of the sentence was always determined by the relationship between the verb and the object phrase. Some object phrases were sensical (e.g., "kicks the ball"), whereas others were not (e.g., "kicks to the library), and each verb was linked with one sensical and one nonsensical object phrase. Examples are shown in Table A2. Sentences ranged from 5–8 words

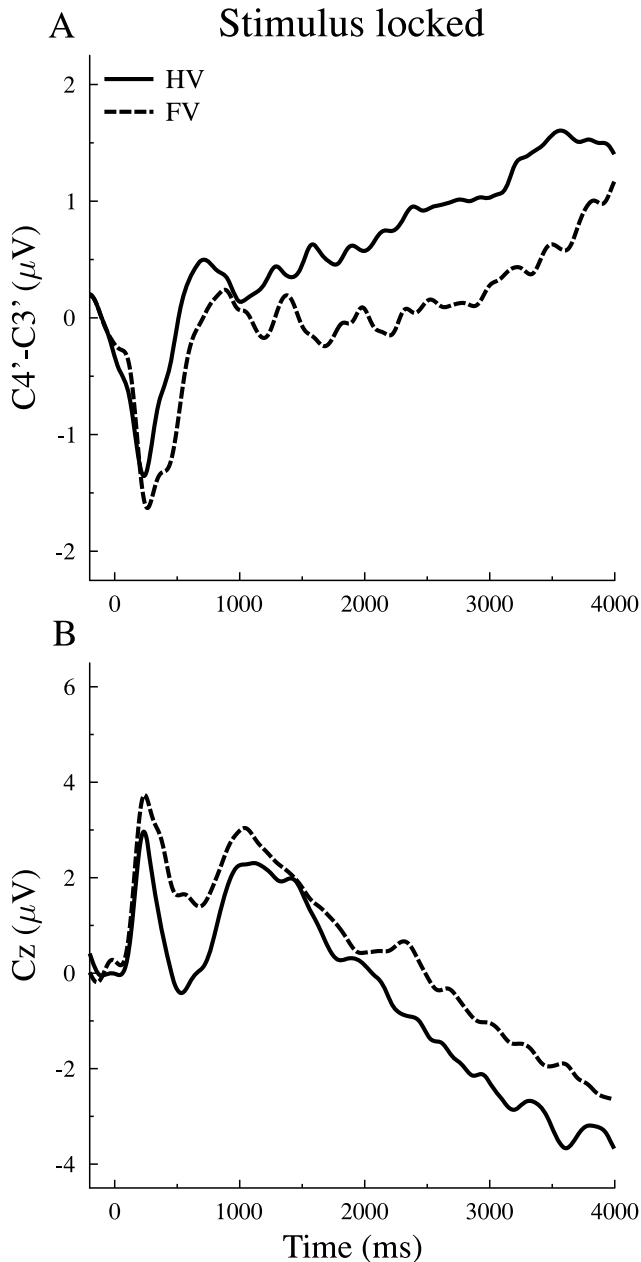


Figure 10. Mean stimulus-locked ERPs, filtered at 12 Hz, in the study blocks of Experiment 7 as a function of verb type (HV = hand-associated; FV = foot-associated). Verb onset was at Time 0.

in length and were generated by randomly selecting the subject (e.g., “the nurse”) and action verb, and then adding the sensical or nonsensical object phrase associated with that verb to make a sentence of the desired sensibility.

Each participant was tested in eight blocks of 40 trials, with instructions appearing on the screen at the beginning of each block. Participants were instructed that they would see a short sentence in each trial and that they should respond according to whether or not the sentence made sense. In the first four blocks, participants were instructed to respond by pressing a key with the right hand if the

sentence made sense and to respond by pressing a foot pedal with the right foot if it did not, or vice versa, counterbalanced across participants. In the last four blocks, each participant’s S-R mapping was reversed. The sequence and timing of trial events was identical to that of Experiment 6. As in Experiment 6, EEG was recorded for 6.2 s starting 200 ms before the onset of the subject of the sentence, with a 100 Hz sampling rate and a 30 Hz low-pass filter cutoff.

The reported data were obtained from 16 volunteer participants (four females) ranging in age from 18–32 years ($M = 27.3$ years), and all were right-handed as measured by the EHI ($M = 72.7$). One additional participant was excluded because of an unusually high error rate (28%), and three were excluded because of amplifier failure.

Results and Discussion

Based on elevated RTs and reduced PCs, the first block with each S-R mapping was omitted. Two (0.06%) and 55 (1.55%) trials were excluded as fast and slow outliers, respectively, based on RT cutoffs of 200 ms and 2.5 s.

Behavioral results. Table 9 shows the mean correct RT and PC as a function of the response limb, the action verb association, and the sense or nonsense status of the sentence. An ANOVA on RT with these factors and including the between-subjects factor of the order of S-R mappings revealed that hand responses ($M = 1,170$ ms) were faster than foot responses ($M = 1,264$ ms), $F(1, 14) = 9.36$, $p < .01$, $\eta_p^2 = .40$, and that responses were faster to sensical sentences ($M = 1,172$ ms) than to nonsensical ones ($M = 1,262$ ms), $F(1, 14) = 17.14$, $p < .005$, $\eta_p^2 = .55$. The tendency for faster responses to sensical sentences than to nonsensical ones was larger for sentences involving hand-rather than foot-associated verbs, leading to a significant two-way interaction of verb association and sense status, $F(1, 14) = 28.86$, $p < .001$, $\eta_p^2 = .67$. The effect of verb-limb compatibility (i.e., interaction of response limb and verb association) did not approach significance, $p < .5$, but there was a highly significant three-way interaction of response limb, verb association, and sense status, $F(1, 14) = 17.85$, $p < .005$, $\eta_p^2 = .56$. As can be seen in Table 9, responses to sensical sentences were on average 41 ms faster with compatible than incompatible response-verb pairs ($M = 1,151$ ms vs. $M = 1,192$ ms). In contrast, responses to nonsensical sentences were on average 45 ms slower with compatible response-verb pairs ($M = 1,285$ ms vs. $M = 1,240$ ms). This three-way interaction can be explained by assuming that the ACE arises during decision making, as is explained in this experiment’s Discussion section. Overall, responses were 92.7% correct, and there were no significant effects or interactions in the parallel ANOVA on PC.

Psychophysiological results. Across participants, 13%–31% ($M = 21\%$) of trials were excluded from the computation of ERPs because of artifacts. Grand-averages of the individual-participant ERPs are plotted in Figure 12.

Analyses of the C4'-C3' and Cz mean amplitudes in the last 200 ms before the response were carried out using ANOVAs with the same factors included in the analyses of RT. Mean C4'-C3' amplitude was larger for hand than foot responses, $F(1, 14) = 8.22$, $p < .025$, $\eta_p^2 = .37$, as was mean Cz amplitude, $F(1, 14) = 5.00$, $p < .05$, $\eta_p^2 = .26$. The hand or foot association of the action verb did not affect either of these amplitudes significantly ($p > .3$). In

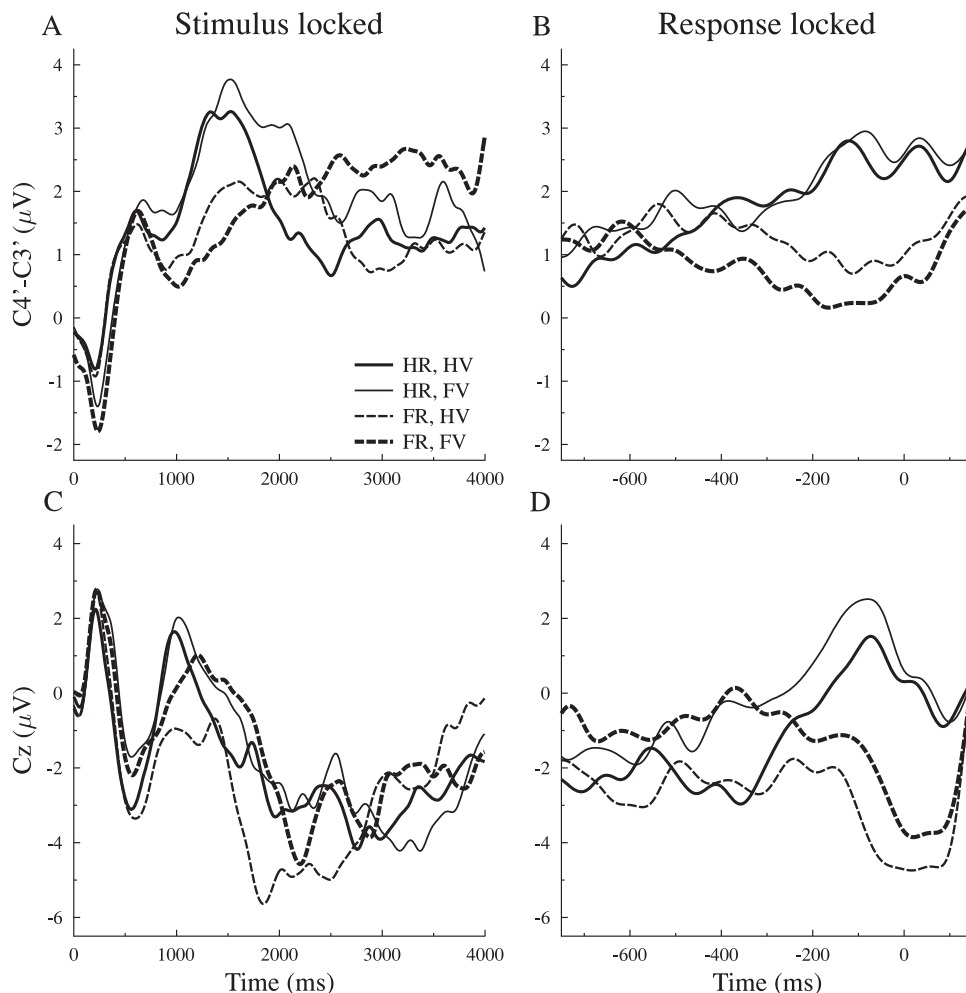


Figure 11. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in the test blocks of Experiment 7 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV). Verb onset was at Time 0 in the stimulus-locked waveforms.

fact, for both measures, mean amplitudes were smaller for hand-associated than for foot-associated verbs, thus going in the direction opposite to the effects seen with actual hand and foot motor responses. The only other significant effect was that Cz amplitude was smaller for sensical sentences than for nonsensical ones, $F(1, 14) = 10.18$, $p < .01$, $\eta_p^2 = .42$, possibly because the nonsensical sentences were easily recognized as impossible but more thorough analysis was needed to be sure that nothing was wrong with the sensical sentences. There were no significant effects in the parallel analyses of VEOG and HEOG amplitude.

A separate set of analyses checked for motor effects of the verb associations during the sentence presentations, prior to the onset of response-related motor activity. Specifically, we compared the sentences using hand- versus foot-associated action verbs during a 1.5 s interval starting with the onset of the verb, with the end of this interval chosen to avoid motor activity. Neither Cz amplitude nor C4'-C3' amplitude was significantly affected by the verb association during this interval (both $p > .1$), and in fact the mean amplitudes of both measures were in the wrong direction (i.e., larger for foot responses than for hand responses).

Discussion. The sensibility task was evidently effective in ensuring semantic processing of the action verbs. This processing was necessary to achieve high overall response accuracy, and it is also implied by the substantial effect of sensibility on RT. Nonetheless, as in the previous experiments, this semantic processing produced no detectable influence of the action verb association on the C4'-C3' and Cz markers of hand and foot motor activations.

There was one unusual finding in this experiment: a three-way interaction of response limb, verb association, and sense status in the analysis of RT. Although responses to sensical sentences were faster with compatible response-verb pairs, as expected, the opposite was true for nonsensical sentences. This pattern clearly cannot be explained by embodied models in which semantic processing of action verbs activates the associated responses, because these models would predict the same compatibility effect regardless of sensibility. The advantage for incompatible responses to nonsensical sentences can be explained as a decision-level effect, however. By definition, nonsensical sentences involve a kind of semantic incompatibility, the presence of which could facilitate the selection of an incompatible verb-response pairing. There are

Table 9

Mean Correct Reaction Time (RT) in Ms, Percentage of Correct Responses (PC), Mean C4'-C3' Amplitude in μV , and Mean Cz Amplitude in μV as a Function of the Response Limb, the Action Verb's Hand Versus Foot Association, and Sentence Sensibility in Experiment 8

Verb assoc.	Response limb and dependent variable							
	Hand				Foot			
	RT	PC	C4'-C3'	Cz	RT	PC	C4'-C3'	Cz
Sensical only								
Hand	1071	94.0	4.53	2.10	1239	92.7	1.36	-4.77
Foot	1145	95.0	3.76	.89	1231	92.5	2.46	-3.72
Nonsensical only								
Hand	1302	91.9	3.19	2.31	1318	90.6	.92	.39
Foot	1161	91.9	4.01	3.94	1268	92.7	1.59	- .90
Average of sensical and nonsensical								
Hand	1187	92.9	3.86	2.20	1278	91.7	1.14	-2.19
Foot	1153	93.4	3.88	2.41	1250	92.6	2.03	-2.31

Note. Mean C4'-C3' and Cz amplitudes were measured in the final 200 ms preceding a correct key press or foot pedal response.

many analogous findings in the literature on S-R compatibility effects, where responses are faster to S-R pairings that are incompatible on both of two dimensions than to pairings that are compatible on one dimension and incompatible on another (e.g., Hedge & Marsh, 1975; Proctor & Pick, 2003; Wühr & Biebl, 2009). Analogously, if sentences are incompatible semantically (i.e., nonsensical), then it would be faster to decide which response to make with incompatible than compatible verb-response pairings.

General Discussion

As summarized in Figure 13, across a variety of paradigms, the present experiments provided negligible evidence that the amplitudes of motor ERPs are affected by the association of an action verb with hand versus foot actions. Consistent with previous findings, C4'-C3' and Cz amplitudes differed significantly for actual hand versus foot movements, indicating that these measures are sensitive to limb-specific motor activations (Figures 13C and 13D). These ERPs were generally unaffected, however, by the semantic processing of verbs naming actions specifically associated with hand versus foot movements (Figures 13E-13H). This pattern of consistently null verb effects on motor ERP amplitudes is inconsistent with embodied cognition models in which the understanding of action verbs necessarily activates the same areas of motor cortex that would be required to carry out the named actions. The null effects are especially diagnostic because in several experiments RT and PC were sensitive to the compatibility between the verb association and the required response. These behavioral effects indicate that participants processed the semantic distinction between hand- and foot-associated action verbs, making it all the more telling that the motor ERPs were unaffected. In short, the present null results add further support to Bottini et al.'s (2016) conclusion that "motor activation is not an automatic and necessary part of semantic processing" (p. 1172) of action verbs.

Potential Problems With the Current Studies

It is natural to consider whether some problematic aspects of the experimental paradigms might have been responsible for the ab-

sence of verb association effects on motor ERPs. It is challenging to identify such problems, though, both because so many different paradigms were used and because several relevant effects were consistently found. Nonetheless, several possibilities can be considered.

First, hand- versus foot-associated action verbs might not have been processed differently, perhaps because they were not processed semantically or because they had very weak limb-specific associations. This problem is ruled out by the presence of compatibility effects on RTs, however, because these effects demonstrate that semantic processing had taken place and that the verb associations were potent. Moreover, in Experiment 3 the hand-versus foot-association of the verb must have been processed because the correct responses were defined by this association.

A second potential problem is that our ERP measures might have been insensitive to the activations of the areas controlling hand and foot movements. This seems unlikely, however, given the consistent differences in C4'-C3' and Cz amplitudes between trials with actual hand and foot responses. Indeed, as was noted in the Introduction, including hand and foot responses in the same experiment with hand- and foot-associated verbs allows the limb-specific sensitivity of the motor ERPs to be validated with the very same data used to check for motoric effects of the action verbs. Moody-Triantis, Humphreys, and Gennari (2014) used equivalent logic in a study assessing the activation of left- versus right-hand-specific motor areas when people either made left versus right hand responses or read sentences describing left- versus right-hand actions, and they also found negative results. The present test for differences in motor activations produced by hand- versus foot-associated action verbs might have been expected to provide an even more powerful test of motor-area involvement in language understanding, because the hand- and foot-specific motor areas are neurophysiologically and functionally more distinct than those of the left versus right hands. Correspondingly, the present findings strengthen and extend Moody-Triantis et al.'s (2014) conclusion that action verbs can be understood without activating the motor areas associated with the named actions.

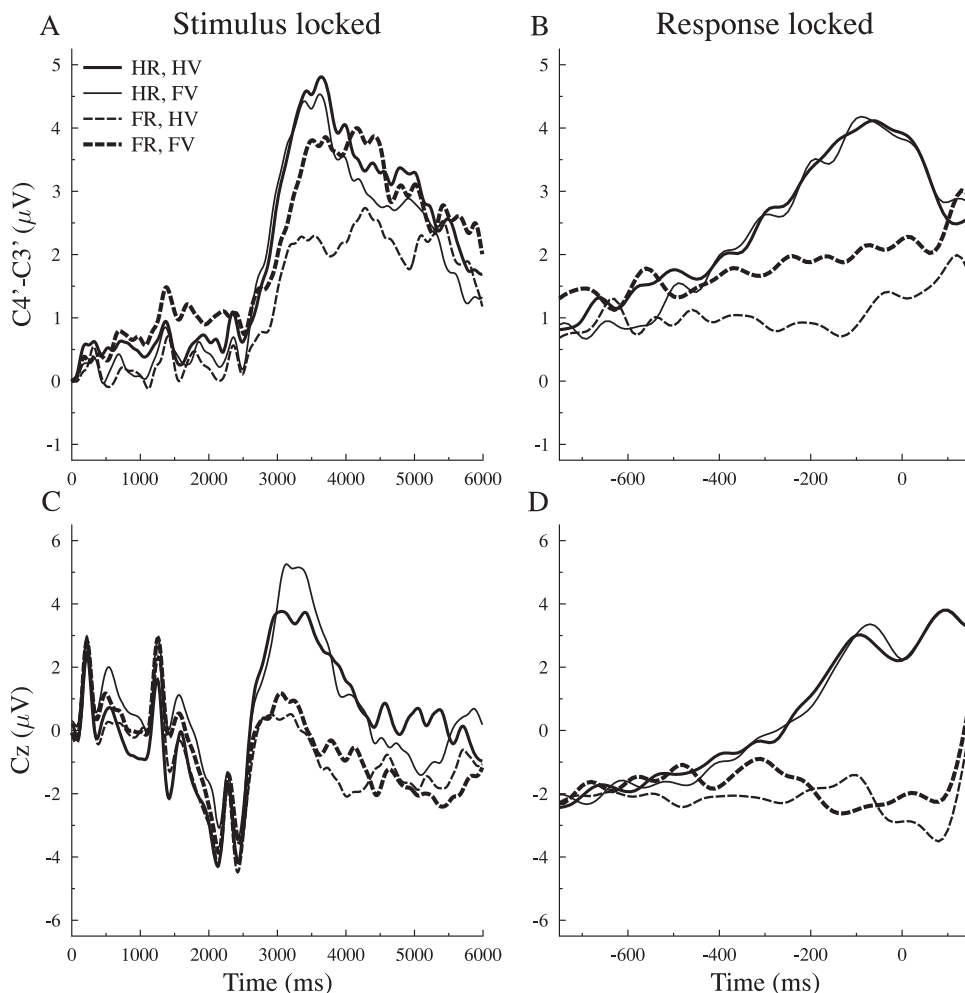


Figure 12. Mean stimulus- and response-locked ERPs, filtered at 12 Hz, in Experiment 8 as a function of hand response (HR) versus foot response (FR) and of hand-associated verb (HV) versus foot-associated verb (FV). Verb onset was at Time 1,020 in the stimulus-locked waveforms.

A third potential problem is that C4'-C3' and Cz amplitudes might have been insensitive to verb effects because these ERPs were saturated by the movement-related activations produced when making overt responses. Pulvermüller et al. (2001) used a version of this argument to explain a null effect of action verb association in the ERPs recorded over central motor sites. They argued that the ERP activity may have been at a ceiling because the task required the preparation and execution of hand responses. This argument would be somewhat strained in the present context, however. As was explained in footnote 3, neither C4'-C3' nor Cz appears to be subject to such ceiling effects, because they can both be affected by multiple superimposed influences (e.g., Miller & Gerstner, 2013). Furthermore, several of the present experiments included a quiet period during which the verbs could have affected ERPs without competition from actual motor activation.

Inferences From Null Results

A distinctive and somewhat unappealing feature of the present experiments is that they document a series of null results with

respect to the (non-)effects of action verbs on motor ERPs. Accepting a null hypothesis is statistically weak (e.g., Grant, 1962; Tryon, 2001), because it is always possible that the null hypothesis was not rejected simply because power was low. Nonetheless, it can be reasonable to entertain the null hypothesis under some circumstances—even based on a single result from a high-power study (e.g., Frick, 1995; Greenwald, 1993). More importantly in the present context, repeated null findings across many statistically independent tests provide much stronger evidence against theories under which the effects should be present. Thus, the fact that the action verb effects shown in Figure 13E–13H are so consistently small—sometimes even reversed—supports the conclusion that the predicted effects are absent.

The point can be quantified using power analyses. Across the present series of experiments, considering that the amplitudes of both C4'-C3' and Cz were checked for effects of verb associations both prior to responding and during quiet periods, there were 24 comparisons capable of revealing such effects. Table 10 shows the estimated power of each comparison, computed assuming that the true effect size was 0.5 μV in each case, which would be a rather

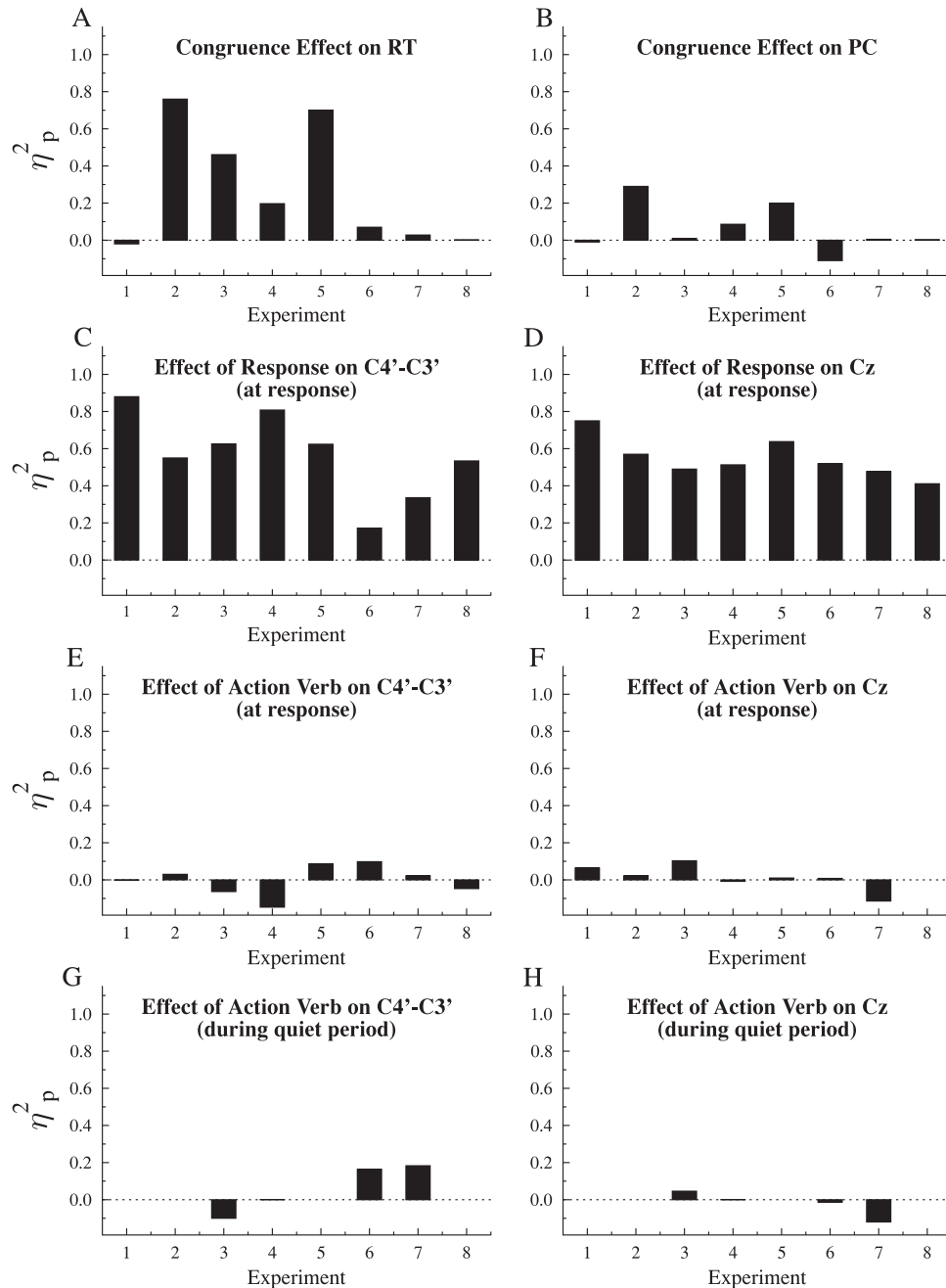


Figure 13. Summary of the key effect sizes, measured with η_p^2 , across all experiments. Negative values of η_p^2 indicate effects in the direction opposite to that predicted by embodied cognition models. A and B: Effects on reaction time (RT) and percent correct (PC), respectively, of the congruence between the hand- or foot-associated action verb and the required hand or foot motor response. C and D: Effects on mean C4'-C3' and Cz amplitude, respectively, of the hand versus foot motor response, with mean amplitudes measured over the 200 ms preceding the overt response. E and F: Effects on mean C4'-C3' and Cz amplitude, respectively, of the hand- versus foot-associated action verb, with mean amplitudes measured over the 200 ms preceding the overt response. G and H: Effects on mean C4'-C3' and Cz amplitude, respectively, of the hand- versus foot-associated action verb, with mean amplitudes measured over the quiet periods included in Experiments 3, 4, 6, and 7.

Table 10
*Estimated Power of Tests for an Effect of Action Verbs on
 Motor Event-Related Potentials (ERPs)*

Time period	ERP	Experiment							
		1	2	3	4	5	6	7	8
At response	C4'-C3'	.99	.45	.13	.64	.99	.10	.46	.13
At response	Cz	.28	.28	.09	.42	.56	.06	.10	.10
Quiet period	C4'-C3'			.74	.18		.10	.49	
Quiet period	Cz			.30	.09		.06	.15	

Note. For each experiment, ERP component, and time period, the observed mean square error was used to estimate the true mean square error for the test, and the true effect size was assumed to be 0.5 μ V.

modest effect relative to the scales of the waveforms shown in Figures 2–12. With these power levels, approximately eight significant results would be expected on average, and there would be an approximately 99.9% chance of obtaining at least three significant results. Analogous computations indicate that there would be an approximately 90% chance of obtaining at least three significant results even with an effect size of only 0.25 μ V. In the actual experiments, however, only one of the comparisons was significant, which is essentially the expected number of Type I errors with this many comparisons. Moreover, the one significant result involved the action verb effect on C4'-C3' during the quiet period in Experiment 7, and this significant result can be explained by motor imagery without resorting to any notions of embodied cognition, as was noted earlier. It is thus difficult to argue that low power is really the explanation of the consistently negative results obtained here.

As has been discussed previously, although negative findings are often regarded as less persuasive—and possibly less informative—than positive ones, ignoring them completely “creates a scientific (and sociological) trap” (Goldinger et al., 2016, p. 974). In the worst case, false positive findings provide support for attractive but incorrect theories (e.g., Ioannidis, 2005; Simmons et al., 2011). The risk of false positives may be quite high for many reasons, including biases toward the publication of positive results (e.g., Francis, 2012; Rosenthal, 1979; Sterling, Rosenbaum, & Weinkam, 1995), *p*-hacking (e.g., Head, Holman, Lanfear, Kahn, & Jennions, 2015), and various statistical complexities in the analyses of psychophysiological data (e.g., Eklund, Nichols, & Knutsson, 2016). Supported but incorrect theories can become entrenched if negative results are suppressed or written off as technically flawed (e.g., Pashler & Harris, 2012). Thus, to ensure that theories are not strongly driven by false positives, it is important to consider negative findings as well as positive ones.

Furthermore, even if the positive results in an area reflect real effects rather than false positives, it is important to consider situations in which predicted effects are absent. Null results can drive theoretical advances by showing how effects depend on particular aspects of the paradigms in which they are obtained and thereby providing a clearer view of the specific mechanisms responsible for the positive results. In the remainder of this discussion, then, we consider how the present null effects of language on C4'-C3' and Cz amplitudes can help to refine the conclusions from previous positive effects of action verbs on motor activation.

Implications Concerning Language Effects on Motor Activation

As was summarized in the Introduction, many prior positive findings suggest that language processing can sometimes affect the activity of motor cortical areas (e.g., Aziz-Zadeh et al., 2006; Boulenger et al., 2009; Hauk et al., 2004; Kemmerer et al., 2008; Raposo et al., 2009; Tettamanti et al., 2005). Despite some reports of negative findings (e.g., Postle, Ashton, McFarland, & de Zubicaray, 2013; for meta-analyses see Crepaldi et al., 2013; Watson et al., 2013), and despite suggestions that these positive findings do not actually provide strong support for the idea of embodied language understanding (e.g., Bedny & Caramazza, 2011; Chatterjee, 2010; Goldinger et al., 2016; Mahon & Caramazza, 2008; Weiskopf, 2010), these positive findings have often been interpreted as support for models in which the understanding of action-related language relies on the motor areas of the brain (e.g., Barsalou, 1999; Glenberg, 1997; Pulvermüller, 2013). According to such models, motor activation should always be generated as part of the process of understanding action verbs.

The present null results weaken these models by showing that language understanding does not necessarily produce activation within the limb-specific motor regions indexed by C4'-C3' and Cz. Broadly speaking, there are two possible interpretations of these findings in conjunction with previous positive effects of language processing on motor activations. One is that the action verbs did produce some motor activation in the present paradigms but that C4'-C3' and Cz were not sensitive to it. The other is that, for one reason or another, the action verbs really did not produce any motor activation in these paradigms. In the following two subsections, we consider the implications of each of these possibilities for embodied cognition models.

What if C4'-C3' and Cz are insensitive to language-related activation? Clearly, the implications of null effects of verb associations on C4'-C3' and Cz amplitude depend critically on the meanings of these two motor ERP measures. For example, the implications would be quite weak if these measures were simply too peripheral to register language-related activations, even though they were clearly sensitive to movement-related activations. As an analogy, there would certainly be differences in neural activity at the spinal level when making hand versus foot movements, but embodied cognition models need not predict the same neural differences for the processing of hand- versus foot-associated action verbs. Spinal differences arise quite late in the motor system and are really only associated with the final ballistic movement execution, so there is no reason to expect that they would be modulated by the semantic processing of action verbs. Could the same be true for C4'-C3' and Cz?

There is very good evidence that C4'-C3' and Cz amplitude are not at all peripheral. As was mentioned in the Introduction, these measures show hand versus foot differences not only for actual movements but also for movements that are merely planned or imagined (e.g., Leuthold et al., 1996; Miller, 2012). This means that they are not exclusively associated with the final stages of movement execution. Furthermore, by comparing direct and mirror viewing of a moving hand, Debnath and Franz (2016) showed that C4'-C3' amplitude is affected not only by the hand that is actually moving but also by the hand that is perceived as moving. Obviously, then, it is not a purely peripheral motor measure.

Of course, the distinction between central and peripheral motor processes is likely to be graded rather than absolute. Thus, embodied cognition theorists might maintain that language understanding involves neural areas that are more central than those driving C4'-C3' and Cz amplitudes and yet are still "motor" areas. Under that view, the present results would be diagnostic in limiting the conclusion of fast, automatic, and somatotopic motor activation to some rather central motor processes (e.g., Hauk et al., 2004; Hauk & Pulvermüller, 2011; Kemmerer et al., 2008; Raposo et al., 2009). Interestingly, this more central and restricted view of language-related motor activation could also help to explain why some patients with damage to the motor cortex have great difficulty moving but seem to have little or no difficulty understanding action-related language (e.g., Arevalo, Baldo, & Dronkers, 2012; Kemmerer et al., 2013; Maieron et al., 2013; Negri et al., 2007)—a finding that seems on the face of it quite inconsistent with embodied cognition models (e.g., Mahon & Hickok, 2016; Masson, 2015; Meteyard et al., 2012). In these patients, the damaged motor areas might be more peripheral than the areas involved in language understanding.

The difficulty with this "relatively central activation" view of embodiment is that it undermines the critical claim that the language-related activation is truly motor. After all, C4'-C3' and Cz are affected by the relatively central processes involved in movement planning and imagining—not just by the peripheral processes responsible for movement execution. If the language-related processes are too central to affect C4'-C3' and Cz, then they would presumably also have to be more central than movement planning and imagining. If they are so central, though, it is difficult to be sure that they are motor. This issue is not unique to C4'-C3' and Cz but has also arisen with many other measures showing effects of language-related activation. Unfortunately, there is often uncertainty about the precise relation between psychophysiological measures and cognitive processes, and this uncertainty tends to be greater for more central measures (e.g., Bedny & Caramazza, 2011; Luck, 2005; Meyer et al., 1988; Rugg & Coles, 1995). As was considered in the Introduction, there have already been suggestions that the other measures shown to be affected by language understanding are associated with decision-level processes as well as motor ones, which implies that language effects on these measures may be caused by something other than motor activation (e.g., Bedny & Caramazza, 2011; Mahon & Hickok, 2016).

What if there is no language-related motor activation in these tasks? An alternative interpretation of the present null effects of action verbs on motor ERPs is that understanding these verbs produced no motor activation *in the present tasks*. This interpretation is consistent with previous evidence that the influence of language on motor activation can be present or absent depending on a variety of poorly understood linguistic and task factors (e.g., Boulenger et al., 2009; Raposo et al., 2009; Willems et al., 2010). It also fits well with the theoretical position that the representation of action word meanings is flexible and task-dependent (e.g., Mahon, 2015b; Mahon & Hickok, 2016).

The present findings provide further evidence against the strong claim that motor activation is an inherent part of—and thus automatically required for—the semantic processing of action verbs (e.g., Barsalou, 1999; Glenberg, 1997; Pulvermüller, 2013). Across eight experiments requiring semantic processing of hand versus foot verbs,

there was very little evidence of limb-specific activation in either C4'-C3' or Cz, despite the fact that these are demonstrably sensitive to such motor activation. Logically, if motor activation is *ever absent* during the semantic processing of action verbs, then it cannot be an integral part of that semantic processing. To advance scientific understanding of the role of motor cortex in semantic processing, then, it will be necessary to delimit the range of conditions under which motor activation is and is not present during such processing (Meteyard et al., 2012). The present results contribute toward that goal by exhibiting a range of conditions under which such activation is not apparent.

One much-discussed and potentially important task factor is that of motor imagery, with a number of findings suggesting that the semantic processing of action verbs only activates motor areas when the task explicitly or implicitly encourages participants to imagine the specified movements (for a recent review, see Andres et al., 2015). For example, Tomasino et al. (2007) found that primary motor cortex activation differed for action versus nonaction verbs (e.g., "jumps" vs. "admires") only in a motor imagery task, not in a control task. Similarly, Tomasino et al. (2008) delivered transcranial magnetic stimulation to the hand area of the primary motor cortex while participants either read verbs related to hand actions, judged the linguistic frequency of those verbs, or imagined themselves performing the named actions. This stimulation had effects only in the motor imagery task, which suggests that "primary motor cortex is critically involved in processing action verbs only when subjects are simulating the corresponding movement" (Tomasino et al., 2008, p. 1915). Participants may engage in motor imagery even when not explicitly instructed to do so, of course, which raises the possibility that other previously observed effects of action verbs on motor activation may have been mediated by imagery in various tasks (Tomasino et al., 2007). If the observed motor activation resulted from motor imagery rather than semantic processing, then that activation would not support embodied cognition models of language understanding (e.g., Andres et al., 2015).

Two aspects of the present experiments fit especially well with the idea that motor activation is only observed when semantic processing is accompanied by motor imagery. First, the present experiments required participants to perform speeded RT tasks, and it is plausible that the demanding nature of these tasks would have prevented participants from engaging in language-related motor imagery. In contrast, many previous studies have used comparatively effortless tasks (e.g., silent reading; Klepp et al., 2014; Schuil et al., 2013) that would have given participants much greater opportunity to engage in motor imagery. Second, it is noteworthy that the one statistically reliable effect of action verbs on motor ERPs, among all 24 of the present tests, was obtained in the study phase of Experiment 7, where participants were explicitly instructed to use imagery. If that study phase effect was not a Type I error, then it clearly supports the view that motor imagery is important in producing language-related motor activations.

Implications for the Action Compatibility Effect

Finally, although the present experiments were designed mainly to examine the effects of action verbs on motor ERPs, two aspects of the results also have important implications concerning the effect of verb-response compatibility on RT and PC. First, even when these

behavioral ACEs were observed, they were not accompanied by verb effects on the amplitudes of C4'-C3' or Cz. This pattern is clearly inconsistent with the idea that the ACE is caused by motor activation produced during the semantic processing of action verbs. Instead, it strengthens claims that the ACE arises at a more conceptual level that precedes the onset of motor activation. Second, there was striking between-experiment variation in the behavioral ACEs (see also Papesh, 2015), and this variation is also problematic for the idea that these effects are caused by automatic motor activation. In particular, we obtained quite large ACEs when the task involved an explicit distinction between hand- versus foot-associated stimuli (i.e., Experiments 2, 3, and 5), whereas it was much smaller (often nonsignificant) when the hand versus foot distinction pertained only to the responses. Thus, the ACE does not seem to have been caused by the processing of verb meaning per se, but rather by the necessity of deciding explicitly between hand- and foot-related stimuli. This suggests that the ACE arises during the decision making process—not as a result of automatic motor activation—as too do the results of Andres et al. (2015) and the present three-way interaction considered in the discussion of Experiment 8. In sum, these two aspects of the present results strongly support claims that the ACE arises prior to motor processes and that it therefore cannot be regarded as a decisive sign of motor activation (e.g., Masson, 2015; Weiskopf, 2010).

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(Appendix follows)

Appendix

Stimulus Materials

Table A1
The Eighteen Subject Phrases Used in Experiments 6 and 8

The artist	The cowboy	The plumber
The astronaut	The doctor	The sailor
The bartender	The firefighter	The scientist
The bus driver	The mechanic	The soldier
The cleaner	The nurse	The student
The cook	The pilot	The teacher

Table A2
Examples of the Verbs and Object Phrases Used as Stimuli in Experiments 6–8

Verb	Sensical 1	Sensical 2	Nonsensical
assembles	the chair	the jigsaw	the long grass
bashes	the wall	the pillow	the heat
binds	the files	the book	on the glass
braids	their hair	the rope	the pen
builds	the house	the deck	into the shower
buries	the coffin	the treasure	to the bus stop
caresses	the silk	their head	the forest
carries	the handbag	the groceries	with their eyelash
carves	the ham	the sculpture	the salt
catches	the frisbee	the cricket ball	with their thumb
boots	the rugby ball	the rubble	across the road
bounces	on the trampoline	off the wall	their shirt
bounds	through the grass	over the wall	the maraca
chases	the thief	the pig	the sand
climbs	the stairs	the hill	their watch
clomps	over the bridge	across the deck	the doughnut
crawls	on the floor	under the desk	the netball
creeps	in the dark	around the corner	their shoelaces
dances	in the ballroom	on stage	the cricket ball
darts	to the shop	to the pool	the baby

Note. In Experiments 6 and 7, each verb was presented with one of the two sensical object phrases, selected randomly. In Experiment 8, a verb was presented with either the first sensical object phrase or the nonsensical object phrase, depending on the condition. Note that the verbs were preceded by one of 16 randomly selected subject phrases in Experiments 6 and 8. In Experiment 7, the verbs were not preceded by subject phrases but were presented as imperatives (e.g., “assemble the chair,” “bash the wall”).

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