

On the Dynamics of Action Representations Evoked by Names of Manipulable Objects

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Two classes of hand action representations are shown to be activated by listening to the name of a manipulable object (e.g., *cell-phone*). The functional action associated with the proper use of an object is evoked very soon after the onset of its name, as indicated by primed execution of that action. Priming is sustained throughout the duration of the word's enunciation. Volumetric actions (those used to simply lift an object) show a negative priming effect at the onset of a word, followed by a short-lived positive priming effect. This time-course pattern is explained by a dual-process mechanism involving frontal and parietal lobes for resolving conflict between candidate motor responses. Both types of action representations are proposed to be part of the conceptual knowledge recruited when the name of a manipulable object is encountered, although functional actions play a more central role in the representation of lexical concepts.

Keywords: action priming, action representations, conflict processing, motor resonance

Language tasks that require the comprehension of action words (verbs like eat, walk, grasp) or nouns denoting manipulable objects (e.g., cup, pencil, cell-phone) activate motor cortical regions, including the premotor and motor cortex (see Willems & Hagoort, 2007, for a concise review). This phenomenon, a kind of motor resonance, has been widely documented using a variety of different methods, including neuroimaging techniques and trans-cranial magnetic stimulation (TMS). These demonstrations raise important questions regarding the computational role of motor representations in the processing of language.

The most straightforward inference – that motor activation is a necessary part of word comprehension (e.g., Gallese & Lakoff, 2005; Glenberg et al., 2008) – is contentious, given traditional linguistic analyses of meaning. These analyses assume a distinction between the abstract conceptual structure of a word (coding for semantic properties like the word's predicate-argument structure and its category membership) and the sensorimotor representations of physical objects (Jackendoff, 1996, 2002). Does motor resonance have anything to do, then, with the constituents of word meaning, or is the phenomenon merely due to the fact that a representation of movement is automatically generated once an action word has been understood?

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In this article, we seek to establish that the action representations evoked by words, far from being mere by-products of comprehension, are directly linked to the structure and organization of lexical concepts. To obtain evidence consistent with this claim, however, one needs a methodology that avoids a number of limitations inherent in current empirical approaches to the evocation of motor representations. We discuss these pitfalls in some detail below. For now, however, we note that two rather different kinds of motor intentions govern the actions we typically associate with manipulable objects. We pick objects up simply to move them from place to place, or we act on objects to implement their proper function. In many cases we apply one kind of grasp for using and another, rather different posture for simply lifting to move an object. Even when similar grasps are used for these two purposes when interacting with certain objects (e.g., a drinking glass), the two goals remain clearly differentiated. The distinction between lifting to move versus grasping to use an object is widely acknowledged in the literature (e.g., Johnson-Frey, 2004; Napier, 1993) and is recapitulated in neuroimaging studies that show different cortical activation patterns for tasks that emphasize one or the other kind of action representation (Buxbaum, Kyle, Tang, & Detre, 2006; Creem-Regehr & Lee, 2005; Culham & Valyear, 2006). In addition, neuropsychological evidence favors the distinction. Patients with apraxia can demonstrate how to pick up and move an object but show impairment when asked to indicate the actions associated with object use (Buxbaum, Sirigu, Schwartz, & Klatzky, 2003). We refer to the action representation consistent with grasping an object to lift and move it as *volumetric* (V), whereas the *functional* (F) action representation concerns the use of an object according to its intended function (Bub, Masson, & Cree, 2008).

In emphasizing the importance of the type of grasp

evoked by words denoting manipulable objects, we distinguish our approach from previous studies that have relied on more generic features of action, like direction of motion, to investigate motor resonance (e.g., Glenberg & Kaschak, 2002; Kaschak & Borregine, 2008; Zwaan & Taylor, 2006). We wish to determine how an internal representation of hand shape associated with an F- or V-grasp is evoked dynamically during auditory word comprehension, thereby leading to insights into their computational role. Hand shape (i.e., the goal posture that determines an F- or V-grasp) is the most crucial element in the planning of an action (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Rosenbaum, Vaughan, Meulenbroek, Jax, & Cohen, 2009), and according to the hierarchical theory of motor programming developed by Rosenbaum et al. (2001, 2009) it is specified in advance of other parameters of action. More generic features, like direction of movement, that have been used as an index of motor resonance do not permit any strong claims about the level of detail that characterize the action representations evoked by language. This constraint applies especially to studies of motor resonance effects that rely on responses entailing a very different goal posture than the one commensurate with the action implied by the meaning of a sentence or word.

Consider, as an example, a recent study by Rueschemeyer, Pfeiffer, and Bekkering (2010), who distinguished between objects typically used by moving the hand towards the body or away from the body (e.g., *cup* vs. *key*). Subjects carried out a go/no-go lexical decision task to individual words denoting one or the other kind of object. The task required lifting a hand to depress a key by means of a movement towards the body for some subjects, or away from the body for others. Responses were faster to words when the movement direction was congruent rather than incongruent with the direction of movement typically afforded by using the object (e.g., on congruent trials, a movement away from the body for *key*). Van Dam, Rueschemeyer, and Bekkering (2010), commenting on this result, inferred that "...very specific information about how an object is manipulated... is activated during lexical retrieval" (p. 1319).

How specific, though, is the information about object manipulation derived from a word given the above evidence? Moving the hand to press a response button or to displace a lever is very different from a reach-and-grasp action afforded by an object, like a toothbrush or cell-phone, that requires fine motor skills. Indeed, the fact that motor resonance occurs despite this difference implies that the obtained effects must be due to shared features between the word and the button-pressing task that are sufficiently generic to influence components of movement that have nothing to do with the particular kind of action needed to lift or use an object.

A further challenge to a straightforward interpretation of the functional role of motor cortical activity in language comprehension is that such activity is elicited even by words that do not entail physical movement. For example, the posterior lateral temporal cortex is involved in the perception of motion, yet Bedny, Caramazza, Grossman, Pascual-Leone, and Saxe (2008) found activation in this region when subjects engaged in semantic-relatedness judgments to words that have nothing to do with physical actions (e.g., *think*). These authors suggest that in addition to sensorimotor representations, parts of the motor system may code for abstract semantic features like changes of state. Glenberg et al. (2008), using TMS, likewise observed modulation of corticospinal motor pathways to hand muscles when subjects read abstract sentences reflecting transfer of information (e.g., *Arthur presents the argument to you*). Given such findings, what steps can be taken to ensure that motor activation to words denoting a physical movement actually reflects a representation of the implied action? One possibility is to rely on the somatotopic organization of primary motor cortex (e.g., the mouth is represented near the Sylvian fissure, the hand and arm are maintained by lateral and dorsolateral sites). A variety of studies have demonstrated that verbs referring to actions carried out by the hand, foot, or mouth activate corresponding somatotopic regions in the primary motor cortex (e.g., Hauk, Johnsrude, & Pulvermüller, 2004; Tettamanti et al., 2005), though the result has not always been obtained (e.g., Postle, McMahon, Ashton, Meredith, & de Zubicaray, 2008).

As a critique of this evidence, we note that the organization of the motor cortex is much more complex than a simple map of distinct regions for different body parts. Different zones appear to emphasize different categories of action, including orchestrated sequences of movements such as closing the hand in a grip while raising the hand and opening the mouth (Graziano, 2009). Many verbs referring to physical actions likewise implicate several body parts. The verb *eat* (often used in the literature on somatotopic activation as an example of an action word specifically invoking the mouth) in fact denotes an action schema involving several body parts, including the arm and hand. Even more problematic is the fact that many verbs by their very nature leave unspecified the parameters of the movement denoted by an action. A word like *grasp* could refer to a power grip (*John grasped the hammer and pounded the nail*), a precision grip (*He grasped the pencil and wrote a reply*), or even a two-handed action (*John grasped the baby and hugged her*). The nature of the parameters of action representations evoked by word concepts is of central relevance to the present article.

A second critical issue is the time course that activation of motor representations follows when

evoked by word concepts. Work using TMS has revealed a changing pattern of effects in response to the auditory presentation of action words or sentences. In these studies, TMS is used to induce in the brain an electrical field of sufficient potency to activate a small area of cortical tissue, yielding an evoked potential in certain muscles such as those of the hand (see Walsh & Cowey, 2000, for a clear introduction to the principles of this technique). The onset of TMS-induced muscle potentials is very rapid, and the effect of a brief pulse that is time-locked to a perceptual or motor event can provide insight into the chronometry of mental processes. The motor effect of presenting a word denoting a physical action carried out with a specific part of the body is determined by looking for modulation of the evoked potential in a muscle group of interest (relative to some baseline condition). For example, if the action word implicates the foot (e.g., *kick*), evoked motor potentials would be recorded from muscles that allow flexing or extending the foot. The comparison (baseline) condition would involve words that do not imply physical actions.

Using this approach, Buccino et al. (2005) compared the effect of TMS on motor evoked potentials when auditory sentences referred to hand actions (e.g., *She sewed the skirt*) or foot actions (e.g., *He kicked the ball*). Abstract sentences (e.g., *He enjoyed the sight*) served as the baseline condition. Single-pulse TMS was delivered to coincide with the second syllable of the verb in each sentence. The results indicated that verbs denoting an action with a hand or foot lowered the amplitude of the evoked potential in the muscles of the corresponding body part (e.g., the response in muscles of the foot given words like *kick* and *march*). The fact that the evoked motor potential was reduced in amplitude rather than enhanced suggests that the language task generated a kind of motor interference. In contrast to this outcome, a number of studies using TMS have observed positive congruency (i.e., facilitating) effects on the motor system induced by verbs denoting physical actions. For example, Papeo, Vallesi, Isaja, and Rumiati (2009) found that evoked potentials were enhanced in muscles of the hand when TMS was applied to the motor cortex, and the language task incorporated verbs denoting hand actions (see also, Oliveri et al., 2004).

The inconsistency between reports may be due to the timing of the interval between the onset of the word and the motor response. Boulenger et al. (2006) found that in a lexical decision task, action verbs interfered with a concurrent reaching task if the cued hand movement was generated shortly after the onset of the word (within 200 ms). The reaching movement was slower for action verbs relative to a control set of nouns referring to concrete but not manipulable objects (see also, Boulenger, Silber, Paulignan, Jeannerod, & Nazir, 2008; Nazir et al., 2008). When enough time was

allowed to elapse between the onset of the word and the initiation of the hand movement – so that the word was processed well before movement onset – facilitation rather than interference was observed, and the hand action was executed more rapidly. Notice that Buccino et al. (2005), who observed interference, applied TMS early during word encoding (coinciding with the second syllable of the word), whereas Oliveri et al. (2004) and Papeo et al. (2009), reporting facilitation, applied TMS somewhat later after word onset. Likewise, in behavioral studies, evidence for interference between action words and a motor task was obtained when the response cue occurred very shortly after word onset (Buccino et al., 2005; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008), whereas facilitation was observed when a longer interval between the onset of the word and the motor response was introduced (Scorolli & Borghi, 2007).

The fact that the processing of an action verb can interfere with a movement generated shortly after word onset, yet facilitate the same movement if word processing is allowed to continue for a slightly longer duration, has led to speculation that motor cortical regions play a role in the comprehension of verbs like *paint* and *throw*, that refer to actions involving the human body. For example, Boulenger et al. (2006) argued that the "...cross-talk between language processes and overt motor behavior provides unambiguous evidence that action words and motor action share common cortical representations and could thus suggest that cortical motor regions are indeed involved in action word retrieval" (p. 1607). Although the short-lived interfering effect of a verb on a hand action may well suggest some kind of competition between motor representations automatically evoked by language and those generated to produce an action (cf., Boulenger et al., 2008), the question remains as to the generality and theoretical implications of this reported phenomenon, especially when we consider that nouns referring to manipulable objects (as opposed to action verbs) are associated with multiple actions (F- and V-grasps), as we have already indicated. Which of these actions might show evidence for the pattern of early interference and later facilitation that has been documented for verbs?

On many accounts, a V-grasp, the motor representation associated with lifting rather than using an object, should not be evoked at all in response to isolated words like *cell-phone* or *pencil*. Buxbaum and Kalénine (2010) argued that V-grasps are not derived from the stored knowledge of object structure but are computed *de novo* from the perceived shape, size, and orientation of an object in relation to the observer (see also, Glover, 2004; Johnson-Frey, 2004; Vingerhoets, Acke, Vandemaele & Achten, 2009). F-grasps, in contrast, are based on a long-term representation of the core features of skilled actions that remain constant

across different instances of the same kind of object. It follows, according to Buxbaum and Kalénine, that "...only function-based (and not structure-based) action is a component of embodied action concepts" (p. 201). If this view is correct, then the meaning of a word may evoke an F-grasp by accessing the stored action representations associated with the use of an object, but no representation in memory is maintained of the grasp required to pick up and move an object, and therefore no V-grasp should be evoked.

In the experiments reported here, we attempt to determine whether motor resonance is confined solely to F-grasps as the meaning of an auditory word unfolds in real time. We also wish to evaluate whether words like *cell-phone* and *pencil* yield both negative and positive congruency effects on evoked action representations at different points in time, consistent with reports in the literature reviewed above. With respect to V-grasps, we re-examine the claim that components of this action – associated with lifting rather than using an object – have no stored representation in long-term memory. We admit that we remain skeptical of this conjecture, and we consider the possibility that given adequate measurement techniques, the presence of this grasp representation may be revealed as part of the motor resonance dynamically evoked by an auditory word. Our reasons for skepticism are as follows. The assumption that invariant core features of an action carried out multiple times are extracted and stored in long-term memory surely applies as much to V-grasps as to F-grasps. Consider, for example, a pocket calculator. The object is a thin rectangular cuboid generally encountered lying flat on a table, and is almost always grasped with the palm downward, and the thumb held in opposition to the other four fingers. True, the orientation of the object can vary, so that there are parameters of the action needed to pick up a calculator that depend on direct perception. It does not follow, though, despite the ubiquity of the claim in the literature, that all aspects of the V-grasp are "constantly updated based on a complex system of spatiomotor transformations of the positions of objects with respect to the retina, eye, head, torso, limb, and hand" (Buxbaum & Kalénine, 2010, p. 207). Indeed, the fact that, without seeing the object, we can immediately indicate the hand posture we would normally use to pick up a calculator in response to the word, renders the claim unlikely that only components of an F- and not a V-grasp are stored in long-term memory. Furthermore, if the imperative sentence *Pick up the calculator* is to have any specific effect on the motor system (consistent with the action denoted by the verb), there must be aspects of the V-grasp available in memory that can be accessed by the meaning of words and sentences (e.g., the shape and general orientation of the hand needed to grasp the object). We seek evidence for the evocation of this kind of action representation to

auditory words, and we compare the waxing and waning of the V-grasp to the time-course of the less contentious F-grasp evoked by the same words.

Tracking F- and V-grasps

Before describing our experiments we provide an explanation of the logic underlying our method of assessing the evocation of specific hand action representations. Consider the response apparatus shown in Figure 1. It comprises six elements, each of which is associated through training with a unique hand action. Subjects learned to produce a given action when cued by a photograph (displayed at the bottom of the figure) representing the goal posture taken by the hand when the element is grasped in the designated way. Speeded responses to the cue were produced by lifting the hand from a button box and carrying out the action on the corresponding element. We measured the total time from cue onset to make contact with a response element by combining the time for both lift-off and transport phases of the movement.

The grasps were carefully chosen to approximate the hand shapes typically used to interact with a range of familiar manipulable objects. The grasp cued by the leftmost hand posture in Figure 1, for example, is applied to the response element on the extreme left of the apparatus, and closely resembles an F-grasp for a cell-phone, remote control, or iPod. The cued grasp posture depicted third from the right in the figure is applied to the large horizontal cylinder and corresponds to the V-grasp required to pick up these objects (all are rectangular cuboid shapes generally lying flat on a surface). Notice that the correspondence between a cued action and the F- or V-grasp associated with a

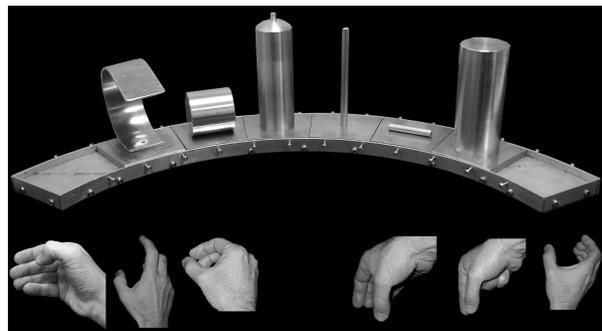


Figure 1. Response apparatus and hand cues used in the experiments. Each element of the apparatus accommodated one hand action (from left to right: thumb press, horizontal grasp, aerosol grip, writing grip, horizontal pinch, and vertical grasp). The three hand cues on the left correspond to the cues used to denote the three functional grasps (thumb press, aerosol grip, and writing grip, respectively) and the three cues on the right were used to cue the volumetric grasps (horizontal grasp, horizontal pinch, and vertical grasp, respectively).

particular object is not necessarily exact (for example, the curvature and aperture of the fingers is not quite the same to lift a cell-phone and to grasp the horizontal cylinder). For our purposes, it suffices that the grasp applied to a response element matches an F- or V-grasp in critical features that clearly distinguish the grasp from the actions applied to the remaining F- or V-elements in the display. Take, for example, the horizontal cylinder matching the V-grasp to a cell-phone. The power grasp with palm facing downward, when applied to this element, is closer to the V-grasp for a cell-phone than the precision grasp assigned to the thin horizontal cylinder (which corresponds to the V-grasp we normally use to lift a slender object like a pencil), and also differs from the action assigned to the thick, flat-top upright cylinder, which matches the V-grasp for lifting an object like a spray can.

The apparatus in Figure 1 could be thought of as a device that instantiates a small "vocabulary" of hand actions (in our experiments, a maximum of six), each action resembling the F- or V-grasp associated with a kind of manipulable object. To determine whether an auditory word like *cell-phone* automatically evokes an F- or V-grasp, we simply present the word at some point in time that overlaps with the visual cue that instructs the subject to reach and grasp one of the six response elements. Let us assume that the word automatically gives rise to an F- or V-grasp, just as a consequence of attending to its meaning, even though the subject is not asked explicitly to associate or imagine any action connected with the word as part of the motor task. On some trials, the action representation evoked by the word will overlap with the cued action the subject must actually plan and execute on a response element (e.g., the cued action on the leftmost element of the apparatus in Figure 1, given the word *cell-phone*). If hearing *cell-phone* automatically evokes an F-grasp and this representation is active when the subject produces a reach-and-grasp action applied to the element shown on the extreme left, then the movement should be primed relative to another action that does not correspond to the F-grasp associated with *cell-phone*. It follows that the speed of the cued reach-and-grasp action should be altered as a result of the direct motor influence of the word.

Experiment 1

In Experiment 1, we assessed which grasp representations were evoked when listeners attended to isolated auditory words: an F-grasp, a V-grasp, or both. The time course of these action representations is of special interest, as we have already noted. Very rapid evocation would be consistent with the claim that F- and/or V-grasps emerge as a dynamic and immediate consequence of word processing. A slower evocation would imply these action representations play a less

automatic role in comprehension. To evaluate the time course of F- and V-grasps, we chose four temporal locations for the response cue relative to the auditory context word: shortly before the onset of the word, at word onset, halfway through the word, and at the end of the word. The more rapidly a grasp representation accrues, the earlier in this time sequence we should find a reliable effect of the word on the cued reach-and-grasp action. In addition, presenting the action cue at early as well as later time points allows us to verify whether the remarkable pattern of negative-then-positive congruency effects, documented in previous studies with verbs, extends to the temporal dynamics of action representations evoked by nouns. As we have seen, reversed congruency effects between language and cued actions have been taken as evidence that motor representations play a crucial role in the meaning of a word (e.g., Boulenger et al., 2006). A word like *grasp*, on this account, might interfere with the programming and execution of a hand movement because the movement requires features that have been enlisted to compute the meaning of the action word. Later, once the meaning is fully retrieved, the motor system is no longer recruited for language processing, and the word sharing features with a cued movement can now exert a positive impact on performance. Our methodology tests for motor priming effects at different points in time throughout the word, and so allows us to further examine this hypothesis.

Method

Subjects. Forty-eight undergraduate students at the University of Victoria were tested, with half randomly assigned to each of two cue-position conditions. All subjects were native or fluent speakers of English and received extra credit in a psychology course for their participation.

Materials and apparatus. Three functional and three volumetric hand actions (F- and V-grasps) were selected for use in the experiments we report. These actions were chosen so that each F-grasp was paired with one of the V-grasps, and each such pair would represent grasps typically used with a set of manipulable objects with which subjects would be familiar. Four objects were selected as matching each pair of F- and V-grasps. The list of actions and corresponding objects is shown in Table 1. An audio recording was made of a female native English speaker enunciating each object name in isolation. A digital sound editing program was used to determine the onset, middle, and end of each recorded word and these word-specific time points were used to control the timing of the presentation of the visual hand cues during the experiment. The mean length of the utterance across the six object names was 821 ms. Photographs of a hand making each of the six actions were rendered as

Table 1
*Grasp Pairs and Corresponding Object Names Used
 in the Experiments*

F-grasp	V-grasp	Object names
Aerosol grip	Vertical grasp	Hairspray, insect spray, room spray, spray paint
Thumb press	Horizontal grasp	Cell-phone, game boy, iPod, TV remote
Writing grip	Horizontal pinch	Crayon, marker, pen, pencil

Note. See Figure 1 for visual depictions of the listed actions.

grayscale digital images and used as cues to signal which grasp was to be produced on each trial. Both right-handed and left-handed versions of these photographs were generated. Responses were made by grasping an element of a response apparatus designed to accommodate the designated hand action. The apparatus contained six elements, one for each of the six grasps. The apparatus and the hand cues are shown in Figure 1. The response elements were mounted on a curved base that was positioned in front of the subject. Elements could be positioned in any order on the base and the relative locations of the elements was varied across subjects. The apparatus was made of aluminum and a weak electrical field was passed through it so when the subject's hand made contact, the circuit was broken and a signal was relayed to a computer indicating that the response had been completed. Stimuli were presented using a Macintosh desktop computer equipped with two monitors and a set of headphones that was worn by the subject. One monitor was used to display task instructions and visual stimuli to the subject. The other monitor was visible only to the experimenter and was used to indicate the target response expected of the subject on each trial.

Design. Related and unrelated prime conditions were defined by the relationship between the object name presented on a trial and the cued hand action. Table 1 shows which object names were designated as being related to each of the F- and V-grasps. All of the other object names, of course, were deemed unrelated. Over the course of 288 critical trials given to a subject, each object name was presented equally often and was followed equally often by each of the six actions. Thus, each of the six actions was related to the object name on 1/3 of its presentations and unrelated to the object on 2/3 of its presentations. This arrangement ensured that the object name was not predictive of the action to be performed on a given trial. Priming was defined as the difference in average response time for these two conditions and was computed separately for F- and V-grasps. Four different time points related to the presentation of the auditory word prime were tested. To keep the number of trials required of each subject

within reasonable bounds, subjects were randomly divided into two groups, with each group tested on two of the time points, as described below.

Procedure. Subjects were tested individually in a quiet room, seated with a button box within easy reach. Just beyond the button box was the response apparatus, and beyond that, at a distance of about 50 cm from the subject, was the computer monitor. The subject began a trial with the index finger of his or her dominant hand resting one of the buttons on the button box. When a hand cue appeared on the monitor, the subject made a speeded reach-and-grasp response by lifting the dominant hand from the button box and grasping the appropriate element of the response apparatus using the hand posture indicated by the cue. The response apparatus was outfitted with six response elements, corresponding to the six actions listed in Table 1.

Subjects were first shown what action to make and which response element to contact in response to each hand cue. During this demonstration the experimenter simply pointed to the relevant element and no mention was made of object names. This instruction was followed by 42 training trials on which a visual hand cue was given with no accompanying auditory stimulus. Each grasp action was cued seven times in a random order. Subjects were instructed to make the cued grasp as quickly and as accurately as possible. Subjects were able to respond fluently before the end of this period of training.

After the training phase, subjects were told that they would hear a word, presented binaurally over headphones, on each trial as well as having to respond to the hand cue. To ensure that subjects attended to the auditory word primes, they were prompted on 25% of the trials to report the identity of the word that had been presented on that trial. At the beginning of each trial, a fixation cross was presented until the subject depressed a button on the response box with his or her response hand. The cross was erased and after a blank 500-ms interval the next trial event occurred (either the onset of the auditory word or the hand cue or both, depending on the cue-presentation location for that trial). The visual presentation of the hand cue occurred at one of four possible time points relative to the onset of the auditory word prime: 150 ms before onset, at the onset of the word, half way through the word's enunciation, or as soon as the enunciation of the word had ended. Figure 2 illustrates the sequence of events on a trial. For half of the subjects, the -150 ms and the middle cue positions were used, and for the remaining subjects, the onset and end positions were used. On trials in which subjects were prompted to report the word's identity, a message requesting that report appeared on the computer monitor and the subject responded orally. The experimenter made key presses to classify the reach-and-grasp response as correct, incorrect (wrong hand action was completed), or spoiled (e.g., raising the

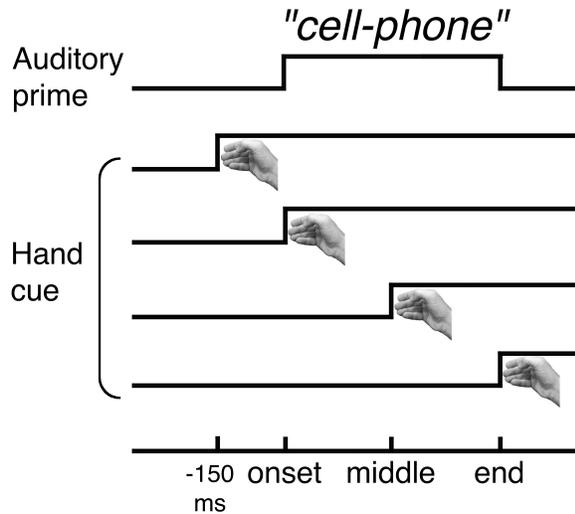


Figure 2. Illustration of events on a critical trial. The presentation of the hand cue was timed relative to the onset of the auditory prime. The hand cue appeared 150 ms in advance of the auditory prime, at the onset of the prime, at the middle of the prime, or end of the prime, and remained in view until the subject initiated a response.

response hand before the hand cue appeared caused the trial to be aborted), and to classify the report of the prime as correct or incorrect.

Each subject completed 24 practice trials followed by 288 critical trials on which a grasp response was made while listening to the auditory prime. The 288 critical trials were constructed by presenting each of the 72 possible combinations of six hand actions and 12 objects twice at each of two cue presentation positions (-150 ms and middle for half of the subjects; onset and end for the other half). Thus, the object name presented as a prime on a given trial was not predictive of the hand action that would have to be made (each of the trained actions was equally likely to be cued). Two different random orders of presentation of the critical trials were constructed for each version of the experiment, with equal numbers of subjects tested using each order. The ordering of trials was constrained so that neither the grasp response nor the object name was repeated on consecutive trials.

Results

Errors and spoils were very rare, with a mean error rate of 0.2% and a mean spoil rate of 0.5%. For both measures, a majority of subjects made no faults of that type. Therefore, we report no inferential analysis of either error rates or spoil rates. The mean percent correct on the prime-report task was 99.9%, indicating that subjects succeeded in attending to the auditory prime words as they were presented.

The response time measure we report is the total

time taken to complete the reach-and-grasp response. This time is measured from the onset of the visual hand cue to the instant the response hand made contact with the response apparatus. Initially, we examined time to initiate hand movement (i.e., lift-off time) and reach time separately, but we found that the effects that are apparent in the total response time measure often are present in a weaker form in each of the two component measures or only in lift-off time. At present, we attach no theoretical importance to the distinction between effects on lift-off time and on reach time in this priming task, so we report only analyses of total response time. Outliers at the upper end of the response time distribution were defined so as to eliminate no more than 0.5% of the responses (Ulrich & Miller, 1994). To meet this constraint, the cutoff was placed at 2,600 ms.

Mean response time is shown in Figure 3 as a function of cue presentation position, grasp type (functional or volumetric), and relatedness between the

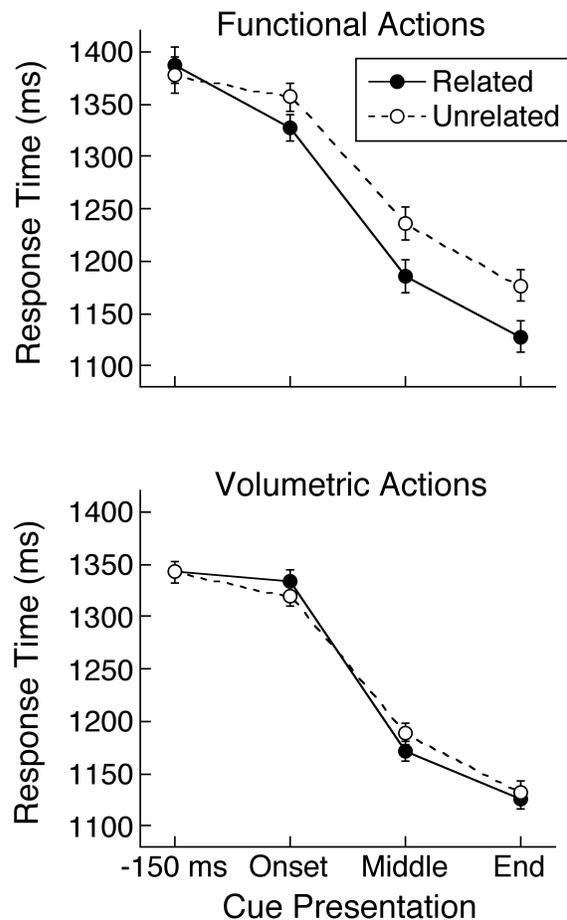


Figure 3. Mean response time in Experiment 1 as a function of grasp type, prime relatedness, and cue presentation position. Error bars are 95% within-subjects confidence intervals appropriate for comparing means in related and unrelated conditions (Loftus & Masson, 1994; Masson & Loftus, 2003).

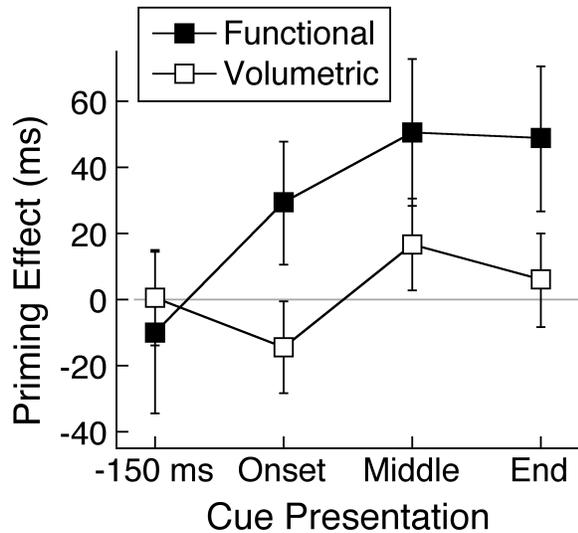


Figure 4. Mean priming effect in Experiment 1 as a function of grasp type and cue presentation position. Error bars are 95% confidence intervals appropriate for comparing the mean priming effect to zero.

cued action and the spoken object name. Inspection of that figure reveals that subjects generally responded faster when the cue was placed at a later position relative to the word prime and that V-grasps were made faster than F-grasps. Our primary interest, however, lies in the pattern of priming effects, defined as the difference between unrelated and related conditions, shown in Figure 4. It is apparent that no priming was found when the hand cue was presented 150 ms in advance of the prime's onset. Beginning at the prime onset, however, a clear priming effect was present for F-grasps. For V-grasps, in contrast, a reverse priming effect was observed when the hand cue coincided with the onset of the prime, whereas a positive priming effect was found when the cue occurred at the midpoint of the prime's duration. Finally, the priming effect for V-grasps was no longer present when the cue appeared at the offset of the prime. These inferences about the pattern of priming effects are supported by the confidence intervals shown in Figure 4.

Additional inferential analyses were conducted using the Bayesian analysis procedure proposed by Wagenmakers (2007; see also Masson, 2011). This procedure entails estimating the Bayesian posterior probability that one model rather than another is valid, given the observed data. Models being tested may correspond to the standard forms of null and alternative hypotheses used in null-hypothesis significance testing. For example, the null model, which assumes that no real effect is present (null hypothesis), may be compared to a model that assumes a real effect of an unspecified size is present (alternative hypothesis). Wagenmakers showed that when it is assumed that errors of measurement are normally distributed, as is

assumed in the standard analysis of variance (ANOVA), the posterior odds may be estimated using sums of squares from the ANOVA. These odds may readily be converted to conditional probabilities, which we designate as p_{BIC} , that quantify the support in favor of either the null (no effect is present) or the alternative hypothesis (an effect is present), given the obtained data. Further, the conditional probabilities for the two hypotheses are complementary in that they sum to 1.0. Raftery (1995) provided verbal labels to characterize the strength of evidence associated with ranges of values of these probabilities (.50-.75: weak; .75-.95: positive; .95-.99: strong; > .99: very strong) and we adopt that terminology here. For those who wish to have familiar benchmarks, priming effects reported here as being supported by the data were significant at least at the .05 level and more typically at the .01 level, when standard hypothesis testing methods were applied.

The relative size of the priming effect for F- and V-grasps was compared separately for each of the three later cue positions, given that that factor was partially nested within the two different groups of subjects and that no priming effect was apparent at the -150 ms position. The Bayesian analysis indicated that priming was clearly larger for F-grasps than for V-grasps at each of the three later cue positions. The posterior probabilities favoring the alternative hypothesis over the null hypothesis were substantial for all three positions: onset, $p_{BIC} = .974$; middle, $p_{BIC} = .888$; and end, $p_{BIC} = .929$. In addition, for V-grasps, a model assuming different priming effects at the onset and middle positions (where reverse and positive priming effects, respectively, were found) was strongly preferred to a model that assumed no difference in priming at those two cue positions, $p_{BIC} = .959$.

Discussion

Priming effects can reliably be observed when the cue is presented as soon as word onset. An examination of lift-off time (one of the two components of the total response times that we report here) indicated that grasp actions were launched on average about 600 ms following onset of the response cue. The F-grasp elicited by the word cue must evolve within this time window to exert an effect on lift-off time. It follows that an F-grasp must be generated quite rapidly after word onset, given that priming effects can be seen for cues time-locked to the initial segment of a word. We will later discuss hidden evidence that further confirms the relatively fast evocation of the F-grasp; its influence can be detected on reach-and-grasp actions cued 150 ms prior to word onset.

The results also establish that an F-grasp is sustained over the word once it has been evoked. Priming of an action is clearly apparent when the cue is

delayed until the middle and even until the final segment of the word. It is remarkable that the F-grasp – a complex action representation having to do with the knowledge of how to use an object – is retrieved under conditions that require only attention to an auditory word while subjects carry out an F-related or F-unrelated reach-and-grasp action. Since the proportion of F-related cued actions is very low (on 83% of trials, the grasp is unrelated to the functional action associated with the word), we have good evidence that F-grasps are evoked as an automatic consequence of word recognition.

An equally remarkable outcome is that V-grasps, and not just F-grasps, are elicited by auditory words, although these action representations evince a strikingly distinctive time-course. Unexpectedly, it is only the V-grasp, not the F-grasp, that produces a small but reliable negative congruency effect when the cue is presented at word onset, consistent with previous observations in the literature on negative congruency effects induced by action words (verbs). This reverse congruency effect for V-grasps quickly changes to a positive congruency effect when the cue is presented a short time later, to coincide with the middle of the word. The V-grasp then dissipates rapidly and, unlike the F-grasp, has no influence by the time a reach-and-grasp action is cued at the end of the word.

The very short-lived evocation of the V-grasp, and the unusual form of the negative-then-positive congruency effects induced by this motor representation, explains why its presence has been difficult to detect in our previous work on auditory words. In Masson, Bub, and Warren (2008), we presented the response cue only in the middle and at the end of the word, and averaged across these time points to obtain an overall estimate of the priming effect. Given the rapid and abbreviated temporal dynamics of the V-grasp documented here, it is clear that we could not have detected the evocation of this action representation without a more fine-grained and systematic analysis.

The qualitatively distinct time courses for F- and V-grasps lead to a number of theoretically important considerations. First, the fact that auditory words automatically generate both V- and F-grasps is not consistent with the widely held view that a conceptually-driven representation of action is associated with only the functional knowledge of an object, and not with its overall shape. Buxbaum and Kalénine (2010) articulated this view, which is shared by many other investigators (e.g., Fridman et al. 2006; Glover, 2004; Johnson-Frey, 2004; Pisella, Binkofski, Lasek, Toni, & Rossetti, 2006; Vingerhoets et al., 2009). They posit two computationally and neuro-anatomically separate systems, one responsible for actions based on object structure (in our terminology, the V-grasp) and the other governing actions driven by

knowledge of an object's function (the F-grasp). The system representing a V-grasp, on the Buxbaum and Kalénine account, is activated only by the perceived form of an object, and generates "...a rapidly decaying sensory-motor memory, consistent with specialization for online processing" (p. 207). By contrast, the system generating F-grasps relies on long-term conceptual representations of the core action features associated with the skilled use of the object.

We have already raised objections to this two-system framework on a priori grounds (see also Masson, Bub, & Breuer, in press). But Experiment 1 also yields strong behavioral evidence against this view of action representations. A V-grasp is the power or precision grasp normally applied to lifting a given object like a cell-phone or pencil. Simply attending to words denoting such objects immediately and automatically evokes this action representation. Clearly, aspects of the grasp for lifting, and not just using an object, must be stored as part of a word's conceptual representation, though the evanescent time-course indicates that the V-grasp is subject to rapid decay (as argued by Buxbaum & Kalénine, 2010), at least under certain task conditions.

An additional point emerges given the very different temporal dynamics of F- and V-grasps. The early negative congruency effect we observed, apparently restricted to V-grasps, raises doubts about the standard interpretation of such effects in the literature. A negative or reverse congruency effect occurs when a cued response is slower rather than faster when presented in conjunction with a word evoking a similar action representation (e.g., the word *cell-phone* delays the production of an inverted closed grasp, the V-grasp associated with this object, relative to some other grasp, say a horizontal pinch, that bears no similarity to an action for *cell-phone*). If the delay is occasioned by conscription of the motor system for word processing, our results, taken at face value, would imply that only a representation of the action for grasping and lifting an object is enlisted during language comprehension, whereas there is no equivalent demand placed on action representations dealing with the function of an object. It seems hardly plausible to argue that V-grasps play a more central role than F-grasps in word recognition, though the evidence –without further ado–would seem to invite this conjecture.

But how believable, actually, are the results we have obtained? At the very least, replication of the negative congruency effect for a V-grasp is needed, given the modest size and brief duration of the phenomenon. But an additional concern is that the effect, even if genuine, may be the result of local competition between F- and V-grasps, both of which were repeatedly evoked by the same words during the course of Experiment 1. Jax and Buxbaum (2010) have

reported that production of a V-grasp is slowed if the grasp occurs after an F-grasp has been made to the same object. The reverse effect does not occur – an F-grasp is not delayed by a previously executed V-grasp. Furthermore, the interference caused by the F-grasp in the Jax and Buxbaum study was long-lasting, such that the V-grasp was delayed minutes after subjects applied an F-grasp to the same object.

Conceivably, the negative congruency effect we observed in Experiment 1 may have occurred because an F-grasp evoked by a word delayed the subsequent evocation of a V-grasp, even though some time had elapsed between the two priming events. To be sure, there is nothing in the Jax and Buxbaum (2010) account of the interference generated by a prior F-grasp on a V-grasp that would explain why the negative congruency effect is restricted to a very brief time window after word onset, switching to positive congruency when the cue is presented in the middle of the word. Nevertheless, the remarkably different temporal dynamics of F- and V-grasps need confirmation if we are to proceed with any confidence, and their different time courses would be most convincingly revealed in an experimental context that does not entail a mixture of both action representations as priming events.

Experiment 2

In Experiment 2, we measured the evocation of F- and V-grasps separately for different groups of subjects. One group produced cued reach-and-grasp actions that were either V-related or V-unrelated to the words acting as primes. These subjects used just three response elements (the remaining elements in Figure 1 were removed from the apparatus), requiring either precision or power grasps. Another group of subjects used only the three response elements designed to assess the evocation of F-grasps. Thus, any negative congruency effects observed for a V-grasp could no longer be due to possible interference from the prior execution of an F-grasp.

Method

Subjects. Sixty students drawn from the same population as in Experiment 1 participated in Experiment 2. Half of the subjects were randomly assigned to be tested on F-grasps and the other half were tested on V-grasps.

Procedure. The materials and apparatus were the same as in Experiment 1, except that only three response elements were mounted on the base of the apparatus, corresponding to the three actions that a subject was to make. For subjects tested with F-grasps, the elements accommodating the aerosol grip, thumb press, and writing grip were provided. In the V-grasp condition, only the three elements corresponding to the

volumetric actions were available. In the training phase, where subjects learned to associate pictures of hand cues with reach-and-grasp actions, trials were presented as in Experiment 1. Each of the three target actions was performed 14 times. Priming trials were also presented using the same procedure as in Experiment 1, except that each subject was tested with all four cue positions (150 ms prior to word onset, word onset, middle of word, and end of word). Each of the 36 combinations of three actions and 12 objects was presented twice at each of the four cue presentation positions. This arrangement ensured that the auditory prime was not predictive of the hand action that would be cued on any particular trial.

Results

Once again, error and spoil rates were very low (means were 0.1% and 0.5%, respectively), with most subjects making no errors or spoils. Mean accuracy at reporting the prime word when cued to do so was 99.8%. Response time was again measured from the onset of the visual cue to completion of the response. Outliers were defined as response times that exceeded 1,800 ms for subjects tested with functional actions and 1,700 ms for subjects tested with volumetric actions. These thresholds ensured that no more than 0.5% of observations were excluded as outliers.

The mean response time and priming effects for Experiment 2 are shown in Figures 5 and 6, respectively. These figures reveal the same patterns of effects as were found in Experiment 1. In particular, no priming was found when the cue appeared 150 ms in advance of the prime word, large priming effects emerged over time for F-grasps, and smaller priming effects, swinging from negative to positive priming were found for V-grasps. These impressions were confirmed by Bayesian analyses of the priming effects. First, priming was substantially greater for F-grasps than for V-grasps at the later three cue positions, $p_{BIC} = .999$.¹ The fact that we manipulated cue position fully within each subject allowed us to examine models based on specific trends. We assessed linear and cubic trends for both action types. For F-grasps, a model

¹A reviewer of a draft of this article observed that two of the three F-grasps appeared to be visually similar to the V-grasps. For example, it was suggested that the V-grasp for a pencil (a vertical pinch) was superficially similar to the F-grasp for writing. One F-grasp, the thumb press for an iPod, cell-phone, etc., however, is noticeably different from its corresponding V-grasp (horizontal grasp). The question of interest for this reviewer was whether the priming advantage for F-grasps over V-grasps at the three later cue positions would remain if the thumb press F-grasp were removed from the analyses. For both Experiments 1 and 2, this was indeed the case, all $p_{BIC} s > .999$. This result clearly establishes that the priming differences between F- and V-grasps is not being carried by one idiosyncratic goal posture.

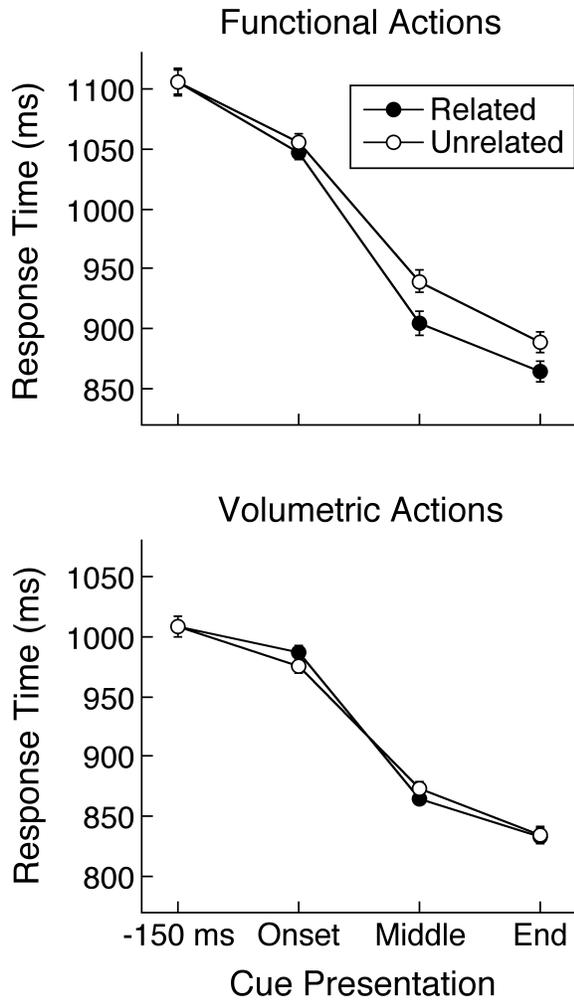


Figure 5. Mean response time in Experiment 2 as a function of grasp type, prime relatedness, and cue presentation position. Error bars are 95% within-subjects confidence intervals appropriate for comparing means in related and unrelated conditions. Some error bars are smaller than the symbols.

based on a linear trend in mean priming as a function of all four cue positions was very strongly preferred over a null model, $p_{BIC} = .992$, and also over a model based on a cubic trend in the means, $p_{BIC} = .999$. In contrast, the analysis of priming of V-grasps indicated that a cubic trend model was preferred over a null model, $p_{BIC} = .911$, and strongly preferred over a linear trend model, $p_{BIC} = .987$.

Discussion

The striking discrepancy in the time-course of V- and F-grasps seen in Experiment 1 was fully replicated in Experiment 2. F-grasps emerged rapidly and were sustained over the duration of the word. We again found that V-grasps showed a brief negative congruency effect when the response cue was presented

at word onset, which then quickly resolved into positive congruency by the middle of the word. This grasp representation after being evoked, dissipated quickly as V-grasps cued at the end of the word no longer yielded any priming effect.

The consistency of the overall pattern of results for F- and V-grasps provides strong evidence that both action representations are automatically evoked by the meaning of a word like *cell-phone*. Furthermore, the different patterns of priming effects for these two types of action would seem to be a genuine aspect of their dynamic expression. The F-grasp is activated quickly and endures, whereas the activation of a V-grasp is fleeting.

An issue to be resolved, though, is the unexplained negative congruency effect for V-grasps briefly seen in both Experiments 1 and 2. What accounts for the effect, and why does it apply to V-grasps but apparently not to F-grasps? We can reject one explanation immediately. It is not the case that the negative congruency effect is simply a consequence of switching between F- and V-grasps as priming events. Testing for V-grasps alone in one group of subjects yielded the same negative congruency effect that we observed in another group who experienced a random mix of both F- and V-grasp representations. The effect is therefore intrinsic to the temporal dynamics of the V-grasp, and is not merely the outcome of local interference caused by the priming of an F-grasp that delays the subsequent evocation of a V-grasp.

We also reject as implausible the argument that the negative congruency effect occurs because the V-grasp

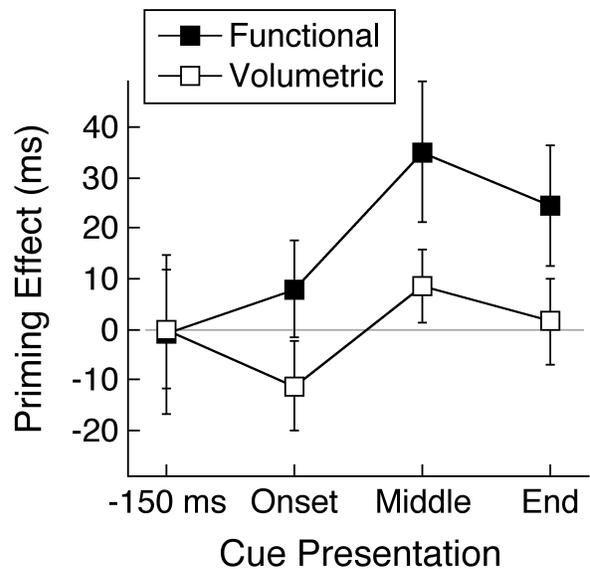


Figure 6. Mean priming effect in Experiment 2 as a function of action type and cue presentation position. Error bars are 95% confidence intervals appropriate for comparing the mean priming effect to zero.

plays some crucial role in language processing. This account holds that a fundamental dependency exists between language and action that would render a V-grasp temporarily unavailable for the production of a cued reach-and-grasp action at some critical stage of word comprehension. It seems unlikely that only a representation of grasping and lifting an object, but not using an object, would be conscripted to derive the meaning of a word, given the core role that functional knowledge seems to play in semantic classification (e.g., Greif, Kemler Nelson, Keil, & Gutierrez, 2006; Jackendoff, 2002).

In seeking an account of the negative congruency effect, we conjecture that the phenomenon is most likely a subtle outcome of the way competition is dynamically resolved between the V-grasp generated automatically to the word and the action representation for the cued response. Previous research suggests that two cortical mechanisms work interactively to resolve such competition (Coulthard, Nachev, & Husain, 2008). The parietal lobe generates a set of possible actions to a stimulus ensemble evoking multiple affordances (in our case, the ensemble of an auditory word in combination with the visual response cue), and selects among them to produce the desired response. The ease with which a particular action is selected depends on the relative strengths of competing affordances. Weak competition between active response options is more quickly resolved than stronger competition. Concurrently with parietal lobe activity, a frontal system monitors for response conflict and speeds the resolution of competition by enhancing the activation of the intended action and reducing the activation of competitors.

These two mechanisms operate independently to resolve competition in the following sense. The frontal system anticipates conflict on the basis of experience given repeated events. The more often conflict occurs, the more active is its engagement. The parietal lobe, by contrast, does not function as a predictive mechanism, but deals only with strong or weak stimulus-driven competition as currently experienced.

This dual-system architecture was invoked by Coulthard et al. (2008) to explain a remarkable form of negative congruency effect observed in a group of patients with right parietal damage. These patients (whose symptoms included motor neglect) were required to move a joystick left or right in response to a central arrow. A pair of distracting (flanker) arrows displayed above and below the target pointed either in the same (congruent) or opposite (incongruent) direction as the target. Control subjects demonstrated the expected result, widely reported in the literature, whereby incongruent trials yielded slower performance than congruent and neutral trials (the flankers in this latter condition were a pair of squares above and below the central target). Performance was delayed on incongruent trials by the conflict between the flanker

arrows pointing in one direction and the target arrow demanding a response in the opposite direction. The same result was found in patients with right parietal damage when the target entailed a leftward movement.

Surprisingly, however, the patients showed a paradoxical negative congruency effect when cued to make rightward movements. Their responses were actually faster to targets on incongruent trials than on congruent or neutral trials. What accounts for this remarkable outcome? In what follows, we explain how the seemingly anomalous negative congruency effect emerges as a natural consequence of the different roles that frontal and parietal systems play in the selection and control of competing action representations. We argue that the interpretation proposed by Coulthard et al. (2008) applies equally to the negative-then-positive congruency effect we have documented for V-grasps. We bolster this novel interpretation by deriving two predictions which we then test and successfully confirm.

Consider the nature of the interaction between the frontal and parietal systems on an incongruent trial with the target requiring a leftward movement and the flankers generating a rightward competing response. In patients with right parietal damage, there is relatively weak activation of a movement to the contralesional (left) side of space because of motor neglect, and competition is strong from the flankers pointing in the opposite direction, which invite a movement to the right. The frontal control system helps to resolve this competition by enhancing the response to the target and suppressing the flankers. Thus, the cost of an incongruent trial is reduced.

Now consider the situation when the target demands a rightward movement of the joystick and the flankers compete by evoking a response to the left. Since a leftward movement is weakly activated in motor neglect, the competition generated by the flankers is quickly resolved in favor of the rightward movement demanded by the target. The frontal control mechanism, however, operating independently of the parietal system, continues to exert its modulatory influence on incongruent trials, and boosts the activation of the rightward movement. Because conflict was only weak on trials requiring a rightward movement, the outcome of the boost from the frontal system is a net facilitation of performance under conditions of response conflict, yielding a reverse congruency effect (see Cisek, 2008, for a detailed exposition).

Application of this account to the negative congruency effect observed for V-grasps is straightforward. The V-grasp evolves over the duration of the word. At an early stage in its evocation, this motor representation is weakly activated and generates little competition with the cued reach-and-grasp action. Nevertheless, on incongruent trials the contribution of

the frontal control system is to augment the intended motor response (i.e., to the visual cue). Because this enhancement is applied only when conflict is detected (incongruent trials), the outcome is the reverse congruency effect observed when the response cue coincides with the beginning of the word. As the activation of the V-grasp builds in strength, competition increases between this motor representation and the cued action, delaying responses on incongruent trials. The frontal system continues to boost the activation of the cued response, but the increased competition from the V-grasp (when the action is cued in the middle of the word) results in the typical pattern of a performance advantage on congruent trials.

If we are correct in suggesting that the reverse priming of volumetric actions in the word-onset cue position is a result of weak activation of those action representations, then it might be possible to show that weak activation of functional action representations produces a similar result. Although functional actions yielded a positive congruency effect when the hand cue was presented at the onset of the context word (see Figures 4 and 6), we considered the possibility that when the hand cue was presented 150 ms prior to word onset, preparation to respond to that cue may have overlapped, at least on some trials, with weak evocation of functional action representations initiated by the context word. If there were weak activation of functional action representations in this early cue condition, we might expect that activation to be particularly weak when relatively little processing has been applied to the context word. That is, on trials where subjects responded especially fast to the hand cue, preparation and execution of the cued response would occur alongside particularly early, and presumably weak, activation of functional action representations generated by the context word. On trials where subjects were slower to respond, activation of functional action representations would be stronger because, on average, more processing of the context word would have been carried out before the required response was made. Thus, we anticipated that an analysis of response time distributions in the -150 ms cue position might reveal a signature of weak activation of functional action representations, namely, a reversed priming effect, for fast responses. The reverse priming effect in this condition should dissipate and perhaps turn positive as response times lengthen (a result of increasingly strong activation of functional action representations).

We tested this prediction by segregating each subject's response time data into four ordered, equal-sized bins (quartiles) for each condition. The response time observations in each quartile were averaged to produce a series of response time means across quartiles for each subject. At each quartile, a priming effect was computed, resulting in an assessment of

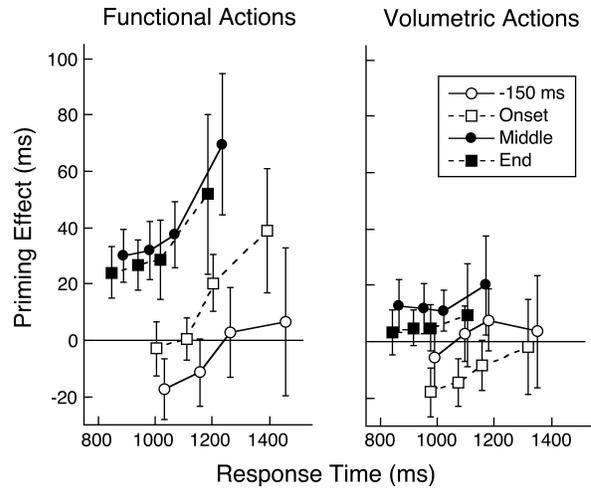


Figure 7. Delta plots for priming effects in Experiments 1 and 2 combined. Each function shows the mean priming effect across response time quartiles (see text for explanation). Error bars are the 95% confidence interval for the priming effect at each quartile. Horizontal placement of data points corresponds to mean response time within a quartile, averaging across related and unrelated conditions.

priming across the response time distribution (from fast to slow responses). Averaging these priming effect functions across subjects, and aggregating the data across Experiments 1 and 2, yielded a delta plot (Ridderinkhof, 2002) for each condition defined by cue position and action type. These plots are shown in Figure 7. The delta plot for functional actions tested in the -150 ms cue position indeed showed evidence of reverse priming restricted to the shortest quartiles. As a statistical test of the prediction for the first quartile, we contrasted a model that assumed a reverse priming effect with a null effect model. The analysis indicated that the reverse priming effect model was more strongly supported by the data, $p_{BIC} = .948$. Moreover, the only other condition whose delta plot showed evidence of reverse priming in any quartile was the plot for volumetric actions in the onset cue condition. Thus, as we had anticipated, there is evidence that a reverse priming effect emerges in conjunction with relatively weak evocation of a functional action representation.

Experiment 3

We have argued that the negative congruency effect for V-grasps (and, within a very small time window, for F-grasps as well) is linked to weak activation of this motor representation at an early stage in its evocation, generating correspondingly weak competition with the cued response. A parietal mechanism quickly resolves this competition, while an independent frontal mechanism, triggered by initial detection of competition, continues to enhance the

activation of the intended response, producing a faster reach-and-grasp action on incongruent than congruent trials. As support for this claim, we established that even the F-grasp can be shown to yield a reversed effect of congruency at a point in time when this action representation is expected to be weak, that is, for very fast responses cued just before the onset of the word.

A second piece of evidence would lend further support to our account of the negative congruency effect. Presumably, the V-grasp is weak at the same time as the F-grasp yields a positive congruency effect because the F-grasp comes to dominate over the course of the word. In the absence of direct visual information about the shape of an object, the V-grasp accrues slowly and is fleeting, whereas the activation of the F-grasp is more rapid and sustained. Note that we have previously shown both action representations are equally potent when visual objects rather than words are presented as stimuli (Bub et al., 2008). Can we increase the activation strength of the V-grasp in the domain of auditory language? If so, the negative congruency effect observed in Experiments 1 and 2 (when the cue is presented at word onset) should no longer be observed, giving way instead to a positive congruency effect, both at this early time point and at later points in time.

We might increase the strength of a V-grasp as follows. Adding a verb like *lift*, *move*, or *pick up* to the object noun should enhance the V-grasp because the meaning of the phrase as a whole is now more consistent with a volumetric than a functional action. The choice of verb in combination with a noun strongly favors a V-grasp, boosting the weak activation that yielded a negative congruency effect at word onset. In Experiment 3, the noun was therefore combined with a verb to produce an imperative phrase (e.g., *lift the cell-phone*) designed to augment the activation of a V-grasp. We examined the time course of this action representation when the cue for a reach-and-grasp action occurred at three critical temporal locations in the noun: time-locked to word onset, the middle of the word, or its termination.

We should point out that the evidence we seek is also a strong test of an alternative interpretation of the negative congruency effect, one which we have already discussed and rejected. Previous accounts of the phenomenon (e.g., Boulenger et al., 2006) assume that motor representations are conscripted to derive the meaning of words associated with physical actions, and so are briefly unavailable to the motor system for executing other tasks (in this instance, the production of a cued reach-and-grasp response). On this view, if the V-grasp is momentarily enlisted for word comprehension, then adding a verb to a noun would surely not alter these language-incurred demands on the motor system. If anything, the emphasis on the V-grasp generated by the verb phrase should absorb more

processing resources during comprehension, producing a robust negative congruency effect.

Method

Subjects. Twenty-four students from the same source as in Experiments 1 and 2 were tested.

Materials. Each of the 12 object names used in the earlier experiments was included in a new audio recording in which a female speaker uttered a brief imperative sentence. The sentence described a volumetric action applied to one of the objects using one of three verb phrases, *lift*, *pick up*, or *move* (e.g., *Lift the pencil*; *Pick up the iPod*). Thirty-six such sentences were recorded, consisting of each possible combination of verb (3) and object name (12). A digital sound editing program was used to identify the time points corresponding to the onset, middle, and end of the critical noun within each sentence. The same three hand cues and response elements for V-grasps as in the earlier experiments were used.

Procedure. The same procedure as in Experiment 2 was used, except for the following changes. First, only three cue presentation positions were used, corresponding to the onset, middle, and end of the pronunciation of the object name. Second, there were 324 critical trials, consisting of all pairs of 36 sentence primes and three volumetric actions being presented three times at each of the cue-presentation locations. As in the earlier experiments, two different random orders of presentation of the critical trials were used, one for each half of the subjects. The orders were constrained so that no object name or action was repeated across two consecutive trials.

Results

Across all 24 subjects only four errors and 26 spoils (less than 0.5% in each case) were made, so no inferential analysis of those data was conducted. Mean performance on the object reporting task was 90.4%. Response times greater than 1,800 ms were excluded from the analyses as outliers (less than 0.5% of observations).

Mean response times and mean priming effects are shown in Figure 8. Although the familiar pattern of shorter latencies with longer delay before cuing the hand action was obtained, the pattern of priming for volumetric actions here was radically different from what was seen in Experiments 1 and 2. Rather than reverse priming when the response cue was presented at the onset of the prime object's name, a clear positive priming effect was found. Moreover, this effect was sustained across the subsequent cue positions. A Bayesian analysis testing the overall priming effect very strongly preferred a model that included a parameter for priming over a null effect model, $p_{\text{BIC}} >$

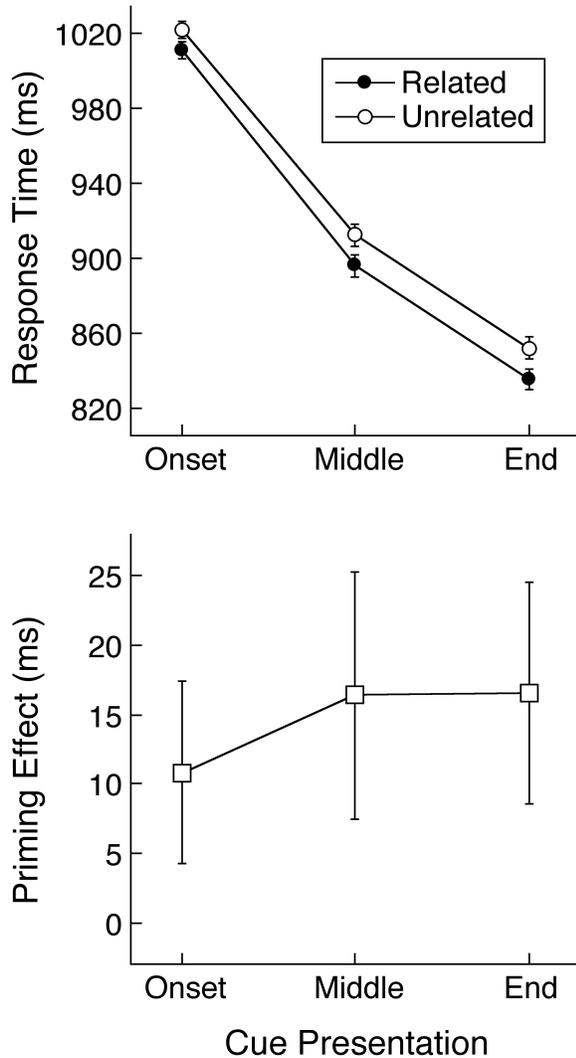


Figure 8. Mean response time and priming effect in Experiment 3 as a function of cue presentation position. Only volumetric grasps were tested. Error bars for response time are 95% within-subjects confidence intervals appropriate for comparing means in related and unrelated conditions. Error bars for priming are 95% confidence intervals.

.999. A model assuming no change in amount of priming across cue position (null interaction model) was preferred over a model that allowed for such a change (i.e., an interaction between cue presentation and priming), $p_{\text{BIC}} = .929$.

Discussion

We have obtained further evidence that supports our interpretation of the negative congruency effect. Embedding the noun in a phrase like *Pick up the cell-phone* altered the time course of the V-grasp in two ways. The negative congruency effect previously observed when the response cue was time-locked to word onset was no longer apparent. We found instead a

robust positive congruency effect. In addition, the V-grasp was no longer fleeting. Instead, a positive congruency was sustained over the duration of the word. We infer that the unusual time course of the V-grasp to a single auditory word is not an ineluctable feature of its temporal dynamic. The distinctive pattern – negative congruency, followed by a positive congruency effect that quickly dissipates – is due to the fact that the V-grasp is weakly present in comparison to an F-grasp. The addition of a verb, like *pick up*, to the noun generates a change in the evocation of a V-grasp. Under these circumstances, the volumetric action representation is rapidly evoked, generating stronger competition with the cued response on incongruent trials and a lasting positive congruency effect ensues.

General Discussion

Motor resonance is a widely documented phenomenon that raises important questions about the role of action representations in language comprehension. In the present article, we sought to clarify the nature of the relationship between motor resonance and the conceptual content of a single word denoting a manipulable object, like *cell-phone*.

For many manipulable objects, we typically use one goal posture to lift or move it (a V-grasp) and another distinct grasp posture to implement the object's proper function (an F-grasp). Our approach places a special emphasis on these hand postures, allowing us to track the dynamic evocation of an F- or V-grasp while an auditory word is processed in real time. The temporal dynamics we demonstrated support a number of inferences. First, we argue that the evidence is not consistent with the view that these action representations must be consulted in order to determine the meaning of a word like *cell-phone*. The claim that "...language-related activity in cortical motor regions might contribute to the understanding of action words that refer to parts of the human body" (Boulenger et al. 2006, p. 1613) has been made in regard to the effect of verbs on cued movement. At an early stage of processing, the verb generally interferes with a related action, at a later stage facilitation occurs. This pattern has been taken to imply that execution of an action is initially delayed because the motor system is recruited for word comprehension, and thus becomes momentarily unavailable for the production of an overt response. Once the meaning of the word is determined, resources are no longer shared between language and action, and the verb exerts a positive rather than a negative influence on performance.

We found, remarkably, the same pattern of negative followed by positive congruency effects for V-grasps to nouns denoting manipulable objects. In addition, a careful analysis of the reaction time distribution for F-grasps disclosed a similar though less

obvious negative congruency: on trials with particularly short response times, responses were slower on congruent than incongruent trials when the cue occurred slightly (150 ms) in advance of word onset. It is difficult to argue that these negative congruency effects occurred because word comprehension enlisted motor resources on which actions also depend. This presumed sharing of common resources would have to involve the two grasp representations at different points in time (an F-grasp before the V-grasp), requiring the implausible assumption that each is engaged separately and in sequence to derive the meaning of the word.

In our view, the theoretical challenge of the unusual temporal dynamics of the V-grasp (recapitulated to a lesser degree in the F-grasp) requires a different form of argument, one that: (a) is linked to principles and phenomena already extant in the burgeoning literature on motor priming effects, and (b) generates novel predictions that can be tested to develop a better understanding of the connection between word processing and motor representations. The account we invoke rests on claims about the nature of two cortical mechanisms working together to resolve the motor competition between the word and the intended (cued) action. A parietal mechanism generates multiple action representations (in this instance, to the word and the visual cue), and resolves the competition between them in favor of the intended response (Cisek & Kalaska, 2010). In addition, a frontal system is separately triggered on incongruent trials to minimize the effect of response conflict on performance by enhancing the intended action representation over competing alternatives. Under conditions of strong conflict, the two mechanisms acting in concert reduce but do not eliminate the slowing in performance on incongruent relative to congruent trials. When the competition between the evoked and intended responses is weak, though, the parietal lobe quickly resolves the conflict in favor of the cued action. The frontal lobe, enlisted on trials where an incongruency is detected, nonetheless continues to exert its modulatory influence, amplifying the activation of the target response. Under these circumstances, the combined effect of parietal and frontal mechanisms is a net advantage for incongruent over congruent trials, producing a reverse congruency effect (Coulthard et al., 2008).

The same theoretical argument elucidates the negative congruency effects we see for V- and F-grasps. At a sufficiently early stage of processing, the auditory word generates only weak motor competition with the cued response, which is quickly resolved by the parietal system in favor of the target action. The frontal system nevertheless works to boost the activation of the cued response on incongruent trials, producing a reverse congruency effect. As the strength of the V- or F-grasp primed by the object noun grows,

the resulting increase in competition on incongruent trials delays selection of the cued response. The parietal mechanism takes longer to resolve the conflict, and the modulating influence of the frontal system now serves to reduce but not eliminate the competition. Thus, the rapid transition from a negative to a positive congruency effect is due to a corresponding change in the strength of the grasp representation evoked by the word. The switch takes place at different points in time for F- and V-grasps because of their different temporal dynamics. The F-grasp dominates the V-grasp because it accrues more rapidly and is more strongly evoked. Thus, a much smaller time window is available during which to observe any weak activation of the F-grasp.

The V-grasp is more slowly (and in general, more weakly) activated by language than the F-grasp. Accordingly, we observed a negative congruency effect at a later point in time for V-grasps, and the effect was more visible, persisting within a larger temporal window that encompassed both faster and slower responses. To obtain further evidence supporting our account, we argued that enhancing the strength of the V-grasp should eliminate the negative congruency effect and indeed, this was exactly what was found. The addition of an imperative verb phrase to the noun, denoting an action more consistent with a V- rather than an F-grasp resulted in a robust positive congruency effect with a faster build-up (appearing even for responses cued at the onset of the word), that persisted over the time course of the word.

We turn now to further theoretical implications suggested by our results, specifically in regard to action representations and the conceptual content of everyday object names like *cell-phone* or *spray can*. The fact that a V-grasp, no less than the F-grasp, is an ineluctable correlate of the meaning of a word is crucially relevant to any argument that the word's conceptual content must be independent of action representations connected with the object. One such argument hinges on the performance of apraxic cases who are impaired in their ability to use a manipulable object like a hammer, yet show intact performance when asked to name the object, describe its origin or intended purpose, and understand or produce sentences referring to the object. It is inferred, on the basis of this dissociation, that "...the concept HAMMER is 'symbolic', 'abstract', and 'qualitatively different' from the motor 'knowledge' that is compromised in the patient" (Mahon & Caramazza, 2008; p. 68).

Can we infer that the ability of an apraxic patient to correctly use the word *hammer* in a sentence is truly dissociated from action concepts linked to the object's identity? The impairment concerns the accurate representation of an F-grasp, but the patient can readily invoke a V-grasp, both to an object (Buxbaum et al., 2003) and, presumably, to a word denoting the object. The conceptual knowledge retained by the patient that

is adequate for tasks like naming or sentence comprehension includes details of an object's shape and weight, as well as its surface and inertial properties, all of which are encapsulated in the V-grasp. The impairment in apraxia, then, concerns a particular kind of motor representation, but other forms of action concepts (e.g., a V-grasp) linked to the identity of an object remain intact. Embodied human agents, we argue, are in possession of multiple action representations inextricably associated with the meaning of a word. Indeed, it seems to us unlikely that a patient suffering neurological damage that impairs the knowledge of both an F- and a V-grasp would be able to identify a manipulable object like a hammer.

We need not confine ourselves to the neuropsychological literature, however, to realize that the action representations we normally associate with an object as part of its identity are not merely limited to F-grasps. Neither of us has the vaguest idea how to use an abacus, but we can identify the object if asked and we can understand a sentence like *John expertly used his abacus to find the cube root of 129* to mean something like: John manipulated a sequence of beads on wires in some way (that we cannot determine), so as to carry out a particular numerical operation.

Can we say that we really understand the meaning of *abacus* if we do not know how to physically use the object? This question brings us to a second tacit assumption prevalent in the literature that, we argue, might profitably be revised. In particular, the notion of an "abstract conceptual structure" that constitutes the meaning of a word, divorced from sensori-motor representations, generally presupposes an undifferentiated list of features in propositional form. But recent work has pointed to a richer conceptual system underlying the compositional semantics of nouns like *cell-phone* and *pencil* that includes an explicit representation of motor and perceptual properties of an object. The properties of a lexical concept like *abacus* can be partitioned into a number of different subtypes referred to as *qualia* by Pustejovsky (1995). These properties are not basic features like *<made of wood>* but rather involve a highly organized system that plays a fundamental role in linking together the combined meaning of different words. The *formal quale* for the word *abacus* describes the object from a taxonomic standpoint; it is a kind of calculating or counting device. The *constitutive quale* includes details of the dimensions, shape, size, texture, and weight of an abacus, the materials from which it is fashioned, and its part structure. The *agentive quale* represents information about the origins of this object; that the abacus is fashioned by human beings and was invented a long time ago, before the advent of modern calculating machines. Finally, the *telic quale* encodes the object's purpose in both general and specific terms. The abacus is used for diverse arithmetic operations and

to carry out the proper function of this tool, we need to know in detail how moving the parts (beads on a wire frame) can produce different numerical computations.

It should be clear from this brief overview of the conceptual structures underlying the generative power of the lexicon (Pustejovsky, 1995) that we cannot reasonably divorce abstract semantic representations from action concepts. Knowing about the weight, shape, and size of an abacus immediately entails that, as embodied agents, we can directly represent ways of manually interacting with and lifting the object. Thus, there is no way to dissociate a V-grasp from the constitutive quale of the word *abacus*. Likewise, we cannot divorce the F-grasp from the telic properties of an object. The actions associated with the proper function of an object may be distinct from other semantic features concerning the purpose of an object, but in combination with these features, they fill out the meaning of a word (Jackendoff, 2002).

What is lacking, though, in our conceptual representation of *abacus* if we do not know how to use the device? The answer surely depends on what we as embodied conceptual agents are being asked to do with the object. We can understand, reason, and act on a request such as *Can you pack my abacus in your suitcase?* because though we know nothing about the details of the object's proper function, we possess information concerning the typical shape, size, and weight of the object. But like apraxic cases who fail to evoke an F-grasp, we do not have a demonstrative action concept associated with the telic properties of an abacus, in that we are incapable of representing the correct sequence of movements needed to perform calculations on the device. So we can reach some understanding of the sentence *John quickly extracted the cube root of 49 on his abacus* by contacting the knowledge we do possess of this object (including any descriptive information regarding its function, such as the general purpose for which an abacus is designed), but we cannot determine the specifics of the actions implied by the sentence. Motor representations evoked during comprehension will surely reflect this fact, and will differ in crucial ways from those available to an expert abacist. Motor resonance, far from being an epiphenomenon, is rooted in the conceptual organization of our lexicon.

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