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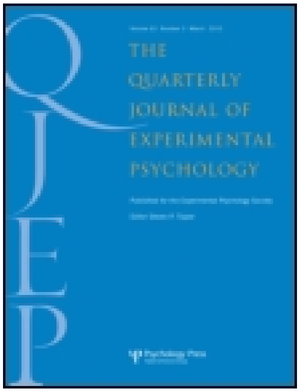

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Mountain high, valley low: Direction-specific effects of articulation on reaching

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Representations underpinning action and language overlap and interact very closely. There are bidirectional interactions between word and action comprehension, semantic processing of language, and response selection. This study extends our understanding of the influence of speech on concurrent motor execution. Participants reached-to-grasp the top or bottom of a vertically oriented bar in response to the location of a word on a computer screen (top/bottom). Words were synonyms for “up” or “down”, and participants were required to articulate the word during movement. We were particularly interested in the influence of articulated word semantics on the transport component of the reach. Using motion capture to analyse action kinematics, we show that irrespective of reach direction, saying “up” synonyms led to greater height of the hand, while saying “down” synonyms was associated with reduced height. This direction-specific influence of articulation on the spatial parameters of the hand supports the idea that linguistic systems are tightly integrated and influence each other.

Keywords: Semantics; Speech; Reaching; Embodied cognition.

The human hands and speech organs solve intricate problems relating to our interaction with the physical and social environment. Hand movements and speech may appear to have separate roles but the neural systems that support them are overlapping and reciprocally connected (e.g., Arbib, 2008; Pulvermüller, 2005). Language processing and manual actions can interfere with or facilitate one another, as indicated by behavioural measures such as reaction time (RT) as well as kinematics (e.g., Kühn & Brass, 2008; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008). Indeed, there are suggestions that the two systems may have co-evolved (Arbib, 2008; Corballis, 2003), with common coding of meaning (semantics) in speech and action bridging a transitional period, during which manual gestures were the primary means of communication. The migration of communicative motor signals to the vocal chords, tongue, and other structures came later, but in this way semantics can be said to be integrated or embodied into action and body states. In this paper, we are

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interested specifically in response parameters of the hand during speech and what they tell us about the links between gestures and language.

The concept of "embodied cognition" suggests that there are overlapping representations that "leak" into overt behaviour after activation of certain semantic codes. Crucially, body states support and reinforce these codes: There are bidirectional interactions between language comprehension, speech, and action production (see Fischer & Zwaan, 2008, for review) that can modulate behaviour.

There is a neural foundation for embodied cognition. Action word meaning activates somatotopically the motor regions associated with that action. In early work conducted by Pulvermüller, Härle, and Hummel (2001) using evoked response potentials (ERPs), activation was evident over the frontal lobe 400–500 ms after stimulus presentation during a lexical button-press decision task ("is this a word or a nonword?"). Activation was topographically specific—that is, greater over the leg area for leg-related verbs and greater over the face area for face-related verbs. Functional magnetic resonance imaging (fMRI) paradigms indicate that when participants view action words related to face, arm, and leg, the activation overlaps with areas activated by the actual movement (Hauk, Johnsrude, & Pulvemüller, 2004). That there is somatotopic activation within premotor and primary motor areas shows that the effects are not simply due to generalized motor activation. Buccino et al. (2005) recorded motor evoked potentials (MEPs) from hand and foot muscles while participants listened to hand- and foot-related sentences (for example, "he took the cup", "he kicked the ball") or abstract sentences ("he loved his land") and received single-pulse transcranial magnetic stimulation (TMS) to the hand or foot motor area, respectively. MEPs for hands decreased when listening to hand-related actions, and similarly for feet when listening to foot-related actions. This did not occur when listening to the abstract sentences.

Semantic modulation of behaviour is crucial in the argument for embodied cognition: the impact of meaning on how we interact with the environment. In fact, there is substantial evidence for this impact. Glenberg and Kaschak (2002) demonstrated this using a reaction time action–sentence compatibility paradigm. They presented participants with sensible sentences that implied action either moving away ("Close the drawer") or moving towards the body ("Open the drawer"), or with nonsense sentences that did not imply direction ("Boil the air"). Participants were asked to judge whether the sentence was sensible, never the direction of the action. Three buttons were aligned such that they were near, middle, and far from the body. Participants initiated each trial by depressing the middle button to view the sentence. If the sentence was sensible, they released the middle button and pressed the far one. The button assignment was then reversed, such that they pressed the near button to respond yes. Sentences implied action either away from or towards the body, such that participants were moving their hand either congruently or incongruently with the sentence direction. The crucial timing measure was from onset of the sentence on the monitor to release of the middle button. Responses were faster when participants moved in the direction congruent to that implied by the action (toward–near, away–far) than when they moved in an incongruent direction (toward–far, away–near). Glenberg and Kaschak reasoned that this "action–sentence compatibility" effect emerged because the meaning of action sentences is action based. Hence, reading the sentence leads to the activation of affordances (in this case direction away or towards the body), which influences efficiency of task performance.

Similarly and again using response time, sentences that imply hand actions (such as "unwrap the sweet") facilitate manual responses, while sentences that describe foot actions (such as "pedalling a bicycle") potentiate foot actions (Scorolli & Borghi, 2007). Stimuli in the Scorolli and Borghi study were short sentences of verb–noun pairs. In one block they related to either the mouth or the hand. In another block they related to either the foot or the hand. In a decision-making task, participants determined whether the sentence made sense. They recorded either verbal (Group 1) or foot pedal (Group 2) responses for "yes". Responses were withheld when the sentence made no sense. Verbal responses were faster for the mouth- than for the hand-related sentences. Similarly, foot pedal responses were faster for foot- than for hand-related sentences. Scorolli and Borghi argue that simply reading the sentences automatically leads to the simulation of the action contained in the sentences. These data support the idea that meaning carried in linguistic information is embodied and therefore affects action execution.

This semantic influence extends to object-directed action—that is, performing a prehensile action rather than pressing a button (Bub, Masson, & Cree, 2008; Masson, Bub, & Warren, 2008). Moreover, it affects kinematic parameters of the action (velocity of movement and grasp width), as well as response times. Scorolli, Borghi, and Glenberg (2009) showed that processing sentences containing references to weight altered the lifting of visually identical light and heavy objects. Participants lifted one of two boxes of the same shape but different mass (12 kg or 3 kg) while they heard a sentence referring to a heavy or a light object. “Heavy” sentences increased peak velocity latencies to heavy objects while “light” sentences reduced it. Dalla Volta, Gianelli, Campione, and Gentilucci (2009) showed that listening to effector-relevant words affected both object-directed and non-object-directed actions. Interestingly, effector-compatible words facilitated response times, but the speed of movements was slowed under these conditions (see also Boulenger et al., 2006). Words indicating size also influence the grasp component of a reach. They presented acoustically 10 verbs of hand actions, 10 foot actions, and 10 abstract actions (for example, to sign, to walk, to love). Participants executed an internally driven action when the verbs were concrete: They were asked to open their thumb and forefinger by an arbitrary amount but maintain this throughout the experiment. They withheld the response when verbs were abstract. Peak opening velocity was slower to hand- than to foot-related words. Action words referring to one of multiple effectors, therefore, alter the kinematics of those effectors.

There is also evidence that semantics differentially alter the kinematics of single effectors. Gentilucci and Gangitano (1998) showed that the linguistic context of the action affected the transport component of the hand. They presented the Italian words for “long” and “short” on a uniformly sized block. When reaching towards the block with “long” printed on it, participants tended to attain higher peak velocity and acceleration than when reaching for the block with “short”. Presumably, “long” activates the semantic representation of greater distance, which leaks into the programming of the reach. Because longer reaches attain a higher peak velocity, the impact of this semantic processing can be seen in the temporal parameters of the reach kinematics (see also Gentilucci, 2003).

Thus far, the evidence appears convincing. RT measures tell us about readiness to respond, and the electroencephalography (EEG) and MEP recordings and fMRI tell us about coactivation. But the spatial kinematics can tell us whether there is indeed a functional connection between symbolic gesture and language. Recall that one of the claims of the embodied language proposition is that action (gesture) represents meaningful speech, and that articulate language may have co-evolved with manual gestures. Specifically, we argue that the *position* of the hands and fingers should change systematically with the spatial meaning of the word. This goes beyond showing dissociation between hand and foot response times to hand- and foot-based words. In other words, the evidence for this connection will come from spatial parameters. To gesture “my son is this tall”, it does not matter whether I move my hand quickly or not: What matters is that I position my hand at specific distance from a referent, such as the ground. The importance of spatial precision is clear in sign languages, in which gestures are imbued with meaning from their using spatial parameters. Spatial precision, moreover, is absolutely crucial in sign languages.

Some previous work has investigated the spatial parameters of actions during language processing. Focusing upon grasping actions, Glover, Rosenbaum, Graham, and Dixon (2004) had participants reach to rectangular wooden blocks 40, 50, or 60 mm wide. Concurrently, they presented in the centre of a monitor 1 of 10 object words, 5 of which required small grip, and 5 large grip (e.g., "grape" vs. "apple"). Participants opened their eyes to a first tone and read the word. Then 1,000 ms later, they reached to grasp the block to a second tone. After reading large-object words, participants had larger grips (the distance between finger and thumb) during the early stages of the reach, before online correction modified the grip to a target-appropriate width. Bach, Griffiths, Weigelt, and Tipper (2010) showed that shapes of mentally represented objects activate iconic movements that capture the object's shape. Importantly, the stimuli were words (for example, "window"). Using a Stimulus-Response Compatibility (SRC) paradigm, participants "drew" in the air either square or round actions in response to a colour cue, or performed square movements to the word representing an object found inside the house and a round one to an object found outside the house (or vice versa). When the shape to be "drawn" was incongruent to the shape of the presented object (for example, circle to "billboard"), initiation and task completion times were slowed. Relevant to our series of experiments, using this paradigm Bach et al. also showed that in these incongruent conditions the trajectories of the hands through space altered. For example, when making round drawings but seeing "billboard", trajectories were wider than when making and seeing round shapes.

In this paper, we aim to demonstrate that semantics have a *directional* and systematic impact on the spatial kinematic parameters of effectors. Showing this would indeed indicate a strong connection between action, gesture, and language. We also need to show that semantics influence ongoing action independently of attributes of the object to be acted upon: In Gentilucci and Gangitano (1998), the semantic information was on the object itself and thus possibly encoded together with the object as one entity. In other words, Gentilucci and Gangitano showed systematic modulation of kinematics when semantics form a physical part of the object. We aim to show that this modulation can also happen when semantic information and the object are distinct. The experiments described below investigate interactions between language and action, but instead of looking at the object-related grasp (as in Glover et al., 2004) or the velocity profiles of the transport component of a reach (Gentilucci & Gangitano, 1998), we investigate the spatial component of the transport of the hand towards its target while the participant concurrently engages in a language task. In doing so, we would demonstrate evidence of language–action interactions at a more abstract level than in the work most closely related to the current study.

EXPERIMENT 1

It is clear that kinematic analysis of human action is an incredibly nuanced tool for describing the links between the motor system and other cognitive mechanisms (Gentilucci & Gangitano, 1998; Glover et al., 2004). In this study, we investigated whether a trace of semantic encoding can be detected in the spatial parameters of the transport component of reach-to-grasp actions even when the to-be-grasped object does not provide the semantic information. This would demonstrate that activation of linguistic representations penetrate the manual motor system at a deeper, more abstract level than current evidence suggests. We asked participants to make natural reach-to-grasp actions to the top or bottom of a vertically oriented metal bar (Experiment 1) or to pantomime reaches to the top or bottom (Experiment 2) in response to the location of a word on a computer screen. During their reach, participants read aloud the word on the screen. Words were synonyms of "up" or "down", thus compatible or incompatible with their reach direction. We analysed the spatial and temporal parameters of the hand in-flight towards the bar. The data demonstrate that the direction of the spoken word systematically affects the height of the reach, suggesting that semantic information penetrates action execution.

Method

Participants

Nineteen individuals volunteered for the experiment (mean age = 22.4 years; 8 were males). All were right-handed, had normal or corrected-to-normal vision, and gave informed consent.

Stimuli and apparatus

We generated 18 words from the English Lexicon Project (Balota et al., 2007). The words were composed of two syllables and were fewer than 10 characters, and they were matched for lexical frequency. Nine words were synonyms for "up" and 9 for "down". For each word group, 3 are primarily used as verbs, 3 as nouns, and 3 as adjectives, though several of the words can be multiple parts of speech in the English language. In addition, 10 nonwords were generated, and 15 independent individuals volunteered a definition. We selected 3 words whose definition never involved reference to the vertical dimension. The stimuli were as follows:

Synonyms of up: Climbing, flying, increase, higher, rising, upward, top, ascent, upper.

Synonyms of down: Decline, decrease, falling, downhill, lower, sinking, dropping, bottom, descent

Nonwords: Bomary, hiruff, linark

"XXXX" served as the no-articulation stimulus and as baseline condition. We presented the words in white on black Calibri 46 point font, either at the top or at the bottom of a computer monitor placed 70 cm away from the participant (see Figure 1).

A vertical black metal bar (20 cm height, 1 cm width) was placed in front of the participant. It was suspended 12 cm from the table-top by a bar fixed to the table. A mark on the table indicated starting hand position such that the distance from the wrist was 48 cm and 38 cm to the top and bottom of the bar, respectively (see Figure 1 for a depiction of the experimental set-up). We tracked movements with a three-camera ProReflex (Qualisys; 100-Hz sample rate, measurement error <0.3 mm) infrared motion capture system. We placed spherical reflecting markers (12 mm diameter) on the index finger, thumb, and wrist (one marker on the distal process of the radius and one on the ulna) of the right hand of the participant (see Figure 1). The x, y, and z position of each marker was recorded across the duration of each reach movement and was processed with QTM (Qualisys) and in-house analysis software implemented in the Matlab (Mathworks, 2001) platform.

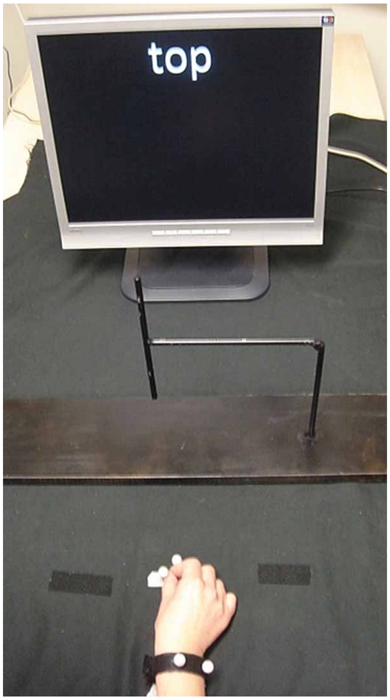

Figure 1. *An illustration of the equipment (vertical bar and monitor with word) set-up with resting hand with attached reflective markers. To view a colour version of this figure, please see the online issue of the Journal.*

Design

The critical variables were "reach direction" (two levels, "up" or "down") and "word meaning" (two levels, also "up" or "down"). Seventy-two reaches contributed to cell means for these conditions (18 reaches/condition). Thus each word was presented four times, twice at the top of the screen and twice at the bottom. Additional trials were included in the design to provide baseline measures of reach performance when not processing directional words (nonwords, 12 trials) and when not processing linguistic stimuli (XXXX, 24 trials). As such, these conditions are included in post hoc comparisons only. There were a total of 318 experimental trials, run in three randomized blocks.

Procedure

Participants placed their hands with their wrist resting on the table surface at the start position, and their thumb and index finger in gentle opposition and touching the surface of the table. After each reach, they returned to this initial posture waiting for the next trial. This ensured that the initial position of the markers was always identical. We asked participants to reach for and grasp the bar between their thumb and index finger in response to the location of the stimulus—the upper end if the word appeared at the top of the screen, and the lower end if it appeared at the bottom. The location-based task renders the semantics of the letter string irrelevant to the participants' task. Each trial started with the presentation of the letter string (duration 500 ms); subsequently, a blank black screen appeared for 2,500 ms. Thereafter, the next trial began, with the presentation of another letter string. Each testing session took approximately 40 minutes, including debrief, and included 24 practice trials. Participants were instructed to execute a non-speeded reach on seeing the letter string. In addition to the reach-to-grasp action, we asked participants to articulate concurrently the word on the screen during their reach; they were to synchronize the onset of movement with onset of articulation. If the stimulus was XXXX (baseline), participants were asked to reach in silence.

Data processing

Trials with errors (i.e., wrong reach direction in initial or final part of the trial, failure to initiate speech at onset of reach) were removed. Further, trials on which marker trajectories were lost were removed prior to statistical analysis (10.3% of trials). Initial reaches in the wrong direction and errors in the final position were in fact few (four or fewer trials per participant), but tended to occur in incongruent trials. Marker trajectories were submitted to a second-order, dual-pass Butterworth filter (10-Hz cut-off). The critical temporal (initiation time, IT) and spatial parameters (maximum z or vertical deviation from a straight reach, and maximum reach height, as well as the height of the hand at the point of gripping the bar) were extracted in Matlab and analysed in SPSS. The maximum vertical deviation from a straight reach is a measure of deviation from a straight trajectory. The straight trajectory of a given reach was calculated on a trial-by-trial basis, with the height (i.e., z-plane position) of the radial marker at the start of the trial and z at grip (i.e., end of the reach) as start and end points. The natural parabolic nature of a reach deviates above this straight line—we measured the maximum z deviation in this paradigm to investigate influences of semantics on these spatial parameters (see Figure 2 for a depiction of maximum vertical deviation).

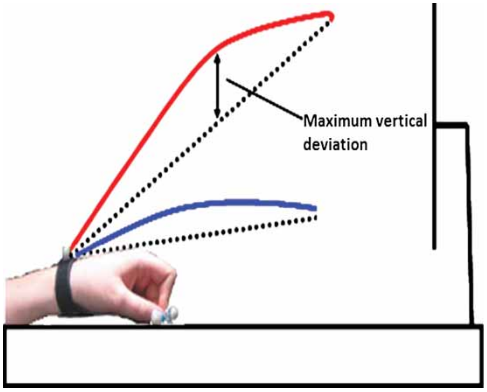

Figure 2. *An illustration of the calculation of maximum z deviation. Dashed lines are putative straight lines between start point of radial marker along the vertical (z) axis in depth (from right to left) as the participant reaches for either the top or the bottom of the frame. The dark and light grey lines illustrate the general parabolic nature of the reach—note that they are not to scale and solely demonstrate how we obtained the data represented in Figures 3 and 5A. This figure shows that the measure of maximum z deviation is the point at which z-plane is maximal between the putative straight line and the data. To view a colour version of this figure, please see the online issue of the Journal.*

Results

Initiation time

A 2 (reach direction) × 2 (word direction) repeated measures analysis of variance (ANOVA) performed on the mean initiation times (ITs) for each condition revealed a significant main effect of reach direction, F(1, 18) = 24.3, *MSE* = 267, $p < .001$, $\eta_p^2 = .57$; initiation times were faster for upward than for downward reaches (975 ms and 994 ms, respectively). The main effect of word direction was nonsignificant, $F(1, 18) < 1$. The interaction, however, was significant, $F(1, 18) = 5.26$, *MSE* = 421, $p = .034$, $\eta_p^2 = .27$, reflecting a congruency effect: Participants were faster to initiate a reach when the word they articulated was congruent with the location of the stimulus/reach direction (see Table 1).

While participants were not required to initiate their actions in a speeded manner, it is interesting that this paradigm nevertheless reveals an action–language congruency effect that has been observed in several previous reports (Fischer & Zwaan, 2008).

Supplemental analysis showed that ITs for nonarticulatory and nonword trials were not significantly different to ITs on word trials, $t\text{s} < 1.6$, $p\text{s} > .12$, though the trend was for faster ITs on nonarticulatory trials (982 ms) and slower ITs when participants were asked to say a nonword (993 ms).

Spatial measures

Maximum reach height. The maximal *z*-plane value of the radial marker was analysed in the same way as initiation time. Of course, when reaching to the top of the bar, a significantly higher reach is made than when reaching to the lower portion of the bar, $F(1, 18) = 98.0$, *MSE* = 2,203, $p < .001$, $\eta_p^2 = .85$ (248 mm vs. 142 mm). However, the more interesting "word direction" main effect, $F(1, 18) = 2.42$, *MSE* = 61.2, $p = .14$, $\eta_p^2 = .12$, and the interaction between the two factors both failed to reach significance, $F(1, 18) = 2.36$, *MSE* = 5.16, $p = .14$, $\eta_p^2 = .12$. It is noteworthy that the trend in these data is in line with our hypothesis that the spatial characteristics of a reach will reflect the directional semantics of concurrently spoken words (see Table 1). The post hoc contrast revealed no significant differences between articulation word, nonword, and nonarticulatory trials ($t\text{s} < 1$, $p\text{s} > .4$).

Maximum vertical deviation. This measure is the extent to which a reach trajectory curves away from a straight line between the start and end points. If saying, for example, an "up" word leaks into the action production system, then this measure should show this influence. On average, the maximal deviation above a straight line was 44 mm across all conditions. The ANOVA results revealed a main effect of "reach direction", $F(1, 18) = 85.2$, *MSE* = 123, $p < .001$, $\eta_p^2 = .83$, again due to the natural tendency for more "curvy" upward reaches (55 mm) than downward reaches (32 mm). Critically for the evaluation of our hypothesis, the "word direction" main effect was also significant, $F(1, 18) = 8.64$, *MSE* = 2.51, $p = .009$, $\eta_p^2 = .32$ (see Table 1 and

Table 1. *Means for each analysed parameter for each condition for Experiment 1*

	Measure					
	Initiation time (ms)		*Maximum height (mm)*		*Maximum vertical deviation (mm)*	
Articulation condition	*Reach direction upwards*	*Reach direction downwards*	*Reach direction upwards*	*Reach direction downwards*	*Reach direction upwards*	*Reach direction downwards*
"Up" synonym	969 (95)	998 (112)	249 (26)	144 (27)	56.2 (11.1)	32.5 (7.3)
"Down" synonym	982 (106)	990 (96)	247 (29)	140 (22)	54.9 (11.2)	31.6 (7.0)
Nonword	984 (112)	1001 (108)	249 (25)	144 (31)	54.6 (10.6)	32.1 (7.7)
No articulation	977 (82)	986 (96)	250 (24)	141 (25)	58.2 (12.2)	32.4 (7.5)

Note: Standard deviations in parentheses.

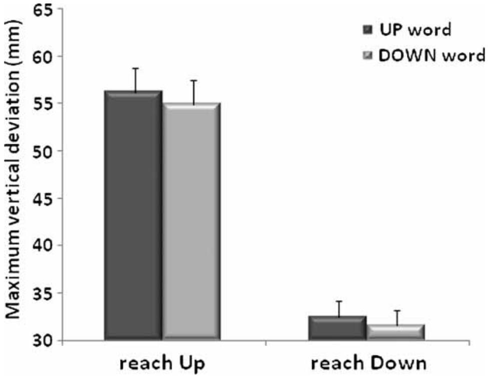

Figure 3. *Maximum z deviation means (with standard error bars) for the critical directional word articulation conditions in Experiment 1. The effect of articulation on z deviation was significant both when reaching towards the bottom and when reaching towards the top of the bar.*

Figure 3). This was due to greater *z* deviation when saying words related to "up" (44.3 mm) than when articulating synonyms for "down" (43.3 mm). The interaction was nonsignificant, $F < 1$. The post hoc *t* tests did reveal significant effects, however—trials on which no articulation was required (stimulus = XXXX) were associated with larger maximal deviations in the *z*-plane (45.3 mm). This was revealed when comparing no articulation with articulating real words (43.8 mm), $t(18) = 3.24$, $p = .005$, and nonwords (43.3 mm), $t\,(18) = 2.81$, $p = .012$.

We conclude, therefore, that word meaning/semantics systematically modulates the position of the hand. We speculate, moreover, that the activation needs to be a relevant speech programme (either compatible or incompatible with the action), rather than generalized speech activation: In Experiment 1, articulating a nonsense word while making a reach was insufficient to modulate the spatial parameters of the reach. We explored this further in a follow-up experiment.

Eleven volunteers (6 females) who were friends or colleagues of the investigators gave informed consent to participate. They had normal or corrected-to-normal vision. The same design, apparatus, and words were used. We made two important alterations, however. First, participants were not required to articulate the words appearing at the top or bottom of the screen, but simply reach to the top or bottom of the bar according to word position. Second, we introduced no-go trials to ensure that participants encoded the word meaning, rather than simply its location. Specifically, we instructed participants to withhold their response in trials where the word was an animal name (monkey, camel, rabbit, tiger, hamster, parrot). This time we administered two randomized blocks of trials, a total of 262 including the no-go trials.

Initiation time

A 2 (reach direction) × 2 (word direction) repeated measures ANOVA performed on the mean initiation times for each condition revealed a significant main effect of reach direction, $F(1, 10) = 9.46$, $MSE = 367$, $p < .01$, $\eta_p^2 = .48$, such that initiation times were faster for upward than for downward reaches (1,106 ms, $SD = 152$, and 1,121 ms, $SD = 166$, respectively). The main effect of word direction was nonsignificant, as was the interaction $F(1, 10) < 1$. This was consistent with post hoc comparisons showing a trend for faster reaches to the top than to the bottom of the bar during baseline (XXXX and nonsense word) trials (1,088 ms, $SD = 93$, and 1,106 ms, $SD = 87$, respectively), $t(10) = 2.378$, $p < .05$. Participants, therefore, were initiating the reach faster for upward than downward reaches, as in Experiment 1. Unlike Experiment 1, there was no effect of word direction.

Maximum vertical deviation

A 2 (reach direction) × 2 (word direction) repeated measures ANOVA performed on the mean vertical deviation again showed a significant main effect of reach direction, such that peak deviation of the hand was greater when reaching to the top than when reaching to the bottom of the bar (68.73 mm, $SD = 3.33$, and 39.17 mm, $SD = 3.26$, respectively), $F(1, 10) = 83.38$, $MSE = 437$, $p < .0001$, $\eta_p^2 = .89$. That is, as in Experiment 1, trajectories were more "curved" in the vertical plane in upwards than in downward reaches. This was consistent with post hoc comparisons showing a greater curvature in reaches to the top than in reaches to the bottom of the bar during baseline trials $t(10) = 9.389$, $p < .0001$. Word direction again did not modulate this effect.

The findings of this follow-up experiment show that articulation is a crucial component of the modulation of action by semantic codes. We speculate that this modulation is task dependent; specifically, it relies on deep processing of spatial representations achieved here through articulation. This is explored further below.

It is noteworthy that these reliable effects of reach curvature emerged despite our arrangement of our stimuli to the top and bottom of the screen. Placing the words at the top and bottom of the screen afforded us a strong test of the null hypothesis because deep semantic processing of the word is unnecessary in our task. The participant needs to process the phonology of the word to articulate it. Moreover, in our task, the only information that the action system needed was to determine the location of the visual stimulus (up or down). Hence, it is impossible to attribute this pattern of results to a Simon effect (e.g., Simon, 1969), such that the spatial differences were driven by the location of the word on the monitor. Rather, the data provide stronger evidence for an automatic effect of language on action than if we had placed the words in a neutral location and used a different task. Moreover, the faster initiation (and greater vertical deviation for up words) when reach and word location were congruent were abolished in this experiment. This would indicate that the effect is not simply due to the location of the word on the screen, and that semantic coding (during articulation) influences action.

In Experiment 2, we set out to replicate the effect and also to clarify whether it is restricted to goal-directed actions and the spatial (volumetric) properties of physically present objects. The presence of the bar in Experiment 1 may have attenuated the effects of language, because it provided a precise goal or point in space (though see Arbib, 2008). If so, then absence of the bar should be associated with greater modulations of the z-plane parameters than would the presence of the bar (there should be an interaction with bar presence).

EXPERIMENT 2

In Experiment 2, we addressed this issue with the simple expedient of removing the bar in the second half of the trials.

Method

Eleven participants (8 females) performed the same task as that in Experiment 1, with the following changes: After 24 practice trials, they performed one block of trials in which they reached for the top or bottom of the bar, as indicated by the location of the word in either the top or the bottom of the monitor. They pronounced the word (real or nonsense) concurrently with starting the reach, or said nothing when they saw XXXX. In the next experimental block, we removed the bar and instructed participants to reach to where the bar end-points *would have been*, again saying the word aloud or saying nothing to XXXX. We always administered this order of blocks to ensure that participants had a stable internal representation of the spatial properties of the extent of the bar before performing the pantomimed actions—otherwise, individual differences in initial interpretation of the extent of the bar may have washed out the effect of interest. This time the critical variables were “bar” “present” or “absent”), “reach direction” (“up” or “down”), and “word direction” (“up” or “down”). This paradigm has the advantage of replication, as well as testing the issue of goal-directed versus gestural (pantomimed) action. The experiment was run in two blocks, with a total of 216 trials.

Results

Initiation time

A 2 (bar present/absent) × 2 (reach direction: up/down) × 2 (word direction: up/down) repeated measures ANOVA revealed a significant main effect of word direction, $F(1, 10) = 6.40$, $MSE =$

655, $p = .03$, $\eta_p^2 = .39$, due to faster initiation times when articulating an "up" (985 ms) than when articulating a "down" (999 ms) synonym. This effect was larger when the bar was present than when it was absent, leading to a significant "bar presence" by "word direction" interaction, $F(1, 10) = 7.67$, $MSE = 403$, $p = .02$, $\eta_p^2 = .43$. Replicating Experiment 1, a congruency effect was revealed through a word direction by reach direction interaction, $F(1, 10) = 7.50$, $MSE = 2{,}551$, $p = .021$, $\eta_p^2 = .43$; initiation times were quicker when reaching was in a direction congruent with that of the concurrently articulated word (see Figure 4). No other main effects or interactions reached significance (ps > .12). See Table 2 for a breakdown of the means in each condition for IT and spatial measures.

Supplemental analyses showed that initiation times were not significantly different on articulated word trials (992 ms) than on nonword (1,000 ms) and no-articulation trials (990 ms), ps > .08.

Spatial measures

Maximum reach height. Note that due to technical problems, maximum reach height could not be calculated for one participant, hence $n = 10$ for this parameter. Again in this experiment we replicated the pattern for maximum reach height obtained in Experiment 1. The reach direction main effect was significant, $F(1, 9) = 1{,}078$, $p < .001$, $MSE = 1{,}072$, $\eta_p^2 = .992$, such that the hand's maximum height was higher when reaching to the top than when reaching to the bottom of the bar (up = 276 mm, down = 137 mm). There was also a significant word direction main effect, such that, averaged over bar presence and reach direction, the hand's maximum height was greater for "up" words than for "down" words (211 vs. 201 mm), $F(1, 9) = 61.0$, $p < .01$, $MSE = 32.5$, $\eta_p^2 = .871$. Note that the bar main effect was not significant, and neither did it interact with the other factors, (ps > .05), indicating that the presence or absence of a physical goal (the bar) did not modulate the impact of semantics on spatial parameters of the reach. As regards interactions indicating congruency effects, there was a significant Reach Direction × Word Direction interaction, $F(1, 9) = 12.2$, $p = .007$, $MSE = 45.8$, $\eta_p^2 = .576$ (see Figure 5A). For this parameter, however, the effect of word direction was significant for both reach directions; participants reached higher when saying an "up" word than when saying a "down" word both when reaching up, $F(1, 9) = 36.0$, $MSE = 64.6$, $p < .001$, $\eta = .80$, and when reaching down, $F(1, 9) = 16.0$, $MSE = 13.7$, $p = .003$, $\eta = .64$. Thus, word direction altered systematically the maximum height reached by the hand, depending on cued reach direction. The presence/absence of a physical reach target (the bar) had no effect on maximal reach height, as this factor did not reach significance as a main effect nor as part of an interaction (ps > .05). Post hoc contrasts comparing reach height on nonarticulatory (206 mm) and articulatory (208 mm) control conditions with the experimental articulation trials (206 mm) revealed no significant differences (ps > .12).

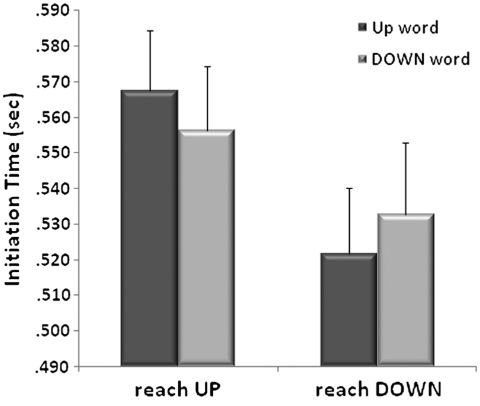

Figure 4. *Initiation time means (with standard error bars) for the critical directional word articulation conditions in Experiment 2. The effect of articulation on initiation time was significant both when reaching towards the bottom and when reaching towards the top of the bar.*

Maximum vertical deviation. There was a reach direction main effect, $F(1, 10) = 24.2$, $MSE = 3{,}369$, $p < .001$, $\eta_p^2 = .707$, such that the hand's vertical deviation from a hypothetical straight line was greater when reaching to the top than when reaching to the bottom of the bar (76.8 and 41.7 mm, respectively). The word direction main

Table 2. *Means for each analysed parameter for each condition for Experiment 2*

		Measure							
		Initiation time (ms)		*Maximum height (mm)*		*Maximum vertical deviation (mm)*		*Height at grip (mm)*	
Bar	*Articulation condition*	*Reach direction upwards*	*Reach direction downwards*	*Reach direction upwards*	*Reach direction downwardss*	*Reach direction upwards*	*Reach direction downwards*	*Reach direction upwards*	*Reach direction downwards*
Bar present	"Up" synonym	939 (172)	965 (212)	271 (14)	140 (16)	69 (14)	38 (13)	268 (26)	137 (14)
	"Down" synonym	997 (216)	972 (210)	261 (14)	136 (14)	64 (17)	40 (11)	249 (25)	128 (13)
	Nonword	959 (171)	959 (214)	277 (11)	133 (18)	69 (17)	38 (10)	266 (22)	126 (14)
	No articulation	984 (196)	990 (230)	271 (12)	133 (15)	69 (22)	40 (12)	262 (27)	131 (17)
Bar absent	"Up" synonym	992 (84)	1036 (111)	291 (24)	131 (34)	90 (55)	45 (21)	260 (57)	123 (32)
	"Down" synonym	1,021 (111)	1,012 (90)	275 (20)	139 (36)	84 (47)	44 (18)	246 (55)	121 (34)
	Nonword	1,013 (111)	1,030 (83)	284 (29)	138 (35)	85 (50)	445 (25)	260 (51)	118 (33)
	No articulation	1,007 (103)	1,035 (113)	283 (22)	131 (37)	92 (62)	51 (27)	251 (69)	116 (34)

Note: Standard deviations in parentheses.

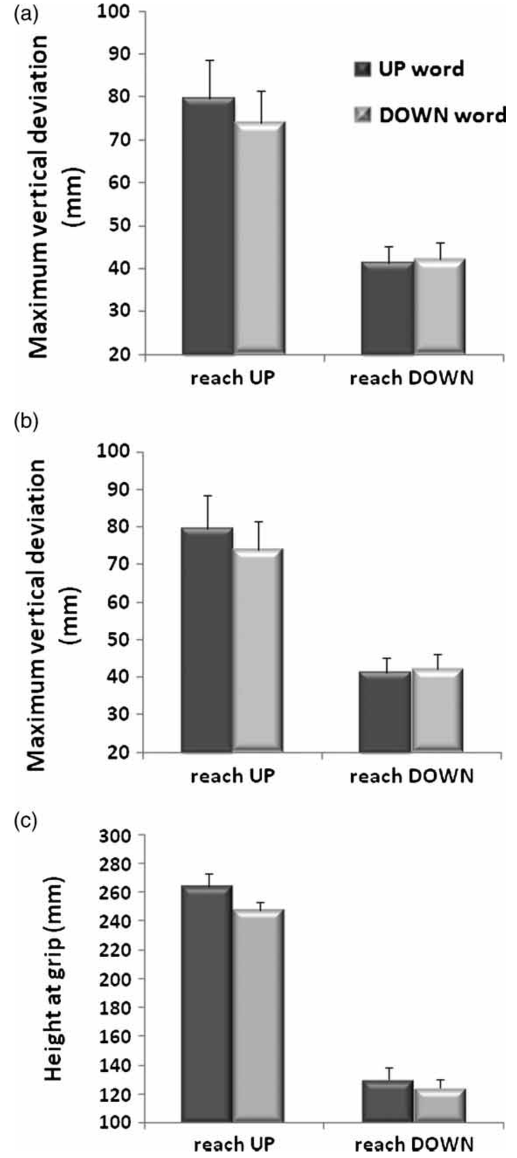

Figure 5. *Means (with standard error bars) for maximum reach height (Panel A), maximum z deviation (Panel B), and height at grip (Panel C) for the critical directional word articulation conditions in Experiment 2.*

effect was significant due to greater vertical deviation when articulating "up" synonyms than "down" synonyms (60.5 vs. 58.0 mm, respectively), $F(1, 10) = 5.28$, $MSE = 24.9$, $p = .044$. $\eta_p^2 = .346$. The Reach Direction × Word Direction interaction approached significance, $F(1, 10) = 4.84$, $MSE = 52.7$, $p = .06$, $\eta_p^2 = .31$ (see Figure 5B). This was because the effect of "word direction" on z deviation was only consistent for upward reaches, $F(1, 10) = 6.37$, $MSE = 56.6$, $p = .03$, $\eta = .39$, but not for downward reaches, $F(1, 10) < 1$.

Post hoc contrasts showed that there were no significant (ps $> .1$) differences between z deviation on experimental trials (59 mm) and nonarticulatory (59 mm) and nonword baseline trials (63 mm).

Height at grip. Because in this experiment we were interested specifically in whether the presence of a goal (bar) altered reaches compared with an absence of a goal (no bar), we include this measure. It denotes the height, from the table-top at which the finger and thumb were at their minimum distance from one another, denoting either a real or a pantomimed grip. Reach direction was significant, $F(1, 10) = 234$, $MSE = 1{,}550$, $p < .0001$, $\eta_p^2 = .96$, such that the height of the grip was greater when reaching up (256 mm) than when reaching down (127 mm). Word direction was also significant, $F(1, 10) = 57.0$, $MSE = 46.3$, $p < .0001$, $\eta_p^2 = .85$: Height of grip was higher when articulating "up" synonyms than "down" synonyms (197 mm vs. 186 mm). Again, the Reach Direction × Word Direction interaction was significant, $F(1, 10) = 25.9$, $MSE = 25.3$, $p < .001$, $\eta_p^2 = .72$ (see Figure 5C). This interaction was due to a stronger effect of word direction on grip height when reaching up than down, but the effect of word direction nevertheless reached significance for both "up", $F(1, 10) = 58.3$, $MSE = 52.6$, $p < .001$, $\eta = .85$, and "down" reaches, $F(1, 10) = 17.5$, $MSE = 19.0$, $p = .002$, $\eta = .84$. No other main effects or interactions were significant ($p > .05$).

Post hoc contrasts again demonstrated no consistent differences between the height of the hand at grip on our experimental (191 mm) trials compared with baseline (nonword articulation = 190 mm; nonarticulation = 192 mm).

In summary, the findings of Experiment 2 replicate and extend those of Experiment

1. Consistently and across several spatial measures, the implied spatial direction of the words (semantics) modified the extent of the reach direction—that is, the height in space attained by the hand. Direction-congruent words extend the height of the reach (in this paradigm, in the vertical plane), and direction-incongruent ones contract it. That is, we show for the first time that embodied semantic codes have a spatial as well as a temporal dimension.

It is worth noting several issues. First, the obtained IT pattern is consistent with the timing and speed measures reported previously (Glenberg & Kaschak, 2002; Kühn & Brass, 2008). Second, the lack of bar main effects and interactions indicates that the presence of a bar does not dilute the effect by providing a constant goal point: Participants' hands reached higher or lower on the bar to the same extent as they did to corresponding points in space. This is important because it means that the embodiment effects can actually override the rapid and automatic perception–action programming by the dorsal visual steam (Goodale & Milner, 1992; Kritikos, Bennett, Dunai, & Castiello, 2000). Recall that in Experiment 2, participants always reached to a physically present bar first and thus learned the volumetric properties of it. They then pantomimed the action, and in so doing they were probably able to retrieve the internal representation of the volumetrics of the bar. We may thus speculate that the semantic codes influence actions to physically present objects as well as well-established internal representations of objects. The final point is that the effects are not due to dual-task interference (articulation disrupting reach execution), because they are systematic and not seen in the "neutral" trials of nonsense words where there was meaningless articulation. This is in fact consistent with the postulations about embodied language set out by Arbib (2008). He views pantomimed actions as transitions between evolutionary stages of language development, with contracted pantomimes of extended action sequences being "shorthand" or "protosign" language. In this context, indeed it is not surprising that we show no differences in the action parameters between goal-directed and pantomimed reaches.

Our work establishes clearly that embodiment is evident in spatial motor programming and execution, not simply timing parameters. In other words, the spatial parameters of the hand's flight are altered by semantic codes of concurrently articulated words. We make the point that, if any, it is these features that will be associated with symbolic language: You wave your hand palm down somewhere above your head to signal someone is "this tall!".

GENERAL DISCUSSION

Along with previous workers, we suggest that semantic codes "leak" into behaviour. This is manifest in temporal measures (this series of experiments; Bub et al., 2008; Glenberg & Kaschak, 2002; Kühn & Brass, 2008; Masson et al., 2008). One of the most important tenets of the embodied language perspective is that action and gesture preceded language. If so, meaningful actions need to be spatially precise to both physically present objects and the internal representations of those objects.

In this series of experiments, we show that semantics systematically modulate spatial action parameters. There is, of course, already evidence for modulation of temporal parameters (Gentilucci & Gangitano, 1998), as well as directional effects in grasp parameters (Glover et al., 2004). Here, however, we advance the literature in three ways. First, in the incongruence between word and reach direction we show a bidirectional effect in the transport component of the action, with the word direction (word meaning) changing the intended location of the hand. Second, we also show clearly that the effect is not a confound of cross-interference from concurrent speech motor programming, because the effect was not apparent in reaches during articulation of pronounceable nonwords. Finally, the effect is not restricted to non-goal-directed (pantomimed) actions because it was evident regardless of bar presence or absence.

We argue, therefore, that this is strong indication for common mechanism in language and action. Before discussing the height of the hand during coarticulation, we note, first, that the design as well as the pattern of response time results replicates previous literature. Performing word direction congruent reaches was associated with faster ITs than performing incongruent reaches (Glenberg & Kaschak, 2002). Second, the effects are not attributable to dual-task interference (reaching and talking), because the semantic modulation was systematic for incongruent reach–articulation pairs: Up words were associated with increased height of the hand while reaching down, and vice versa. Moreover, articulating nonword did not cause any change in the height of the reach or the IT. Finally, the modulation does depend on articulating the words.

The task requirement to prepare and execute a (motor) verbal response appears a necessary factor, however, because the effect was eliminated when no articulation was required. This is consistent with Bub and Masson's (2006) findings. When participants had to mimic a gesture presented on the screen, responses were faster when the prime was an object related to that gesture—but only when they had to name the prime. In contrast, other studies have shown the effect without concurrent articulation (e.g., Glenberg & Kaschak, 2002; Scorolli & Borghi, 2007). We speculate that the clue to this apparent inconsistency is in the design. Glenberg and Kaschak had participants decode a sentence and decide whether the implied action was moving toward or away from the body and then respond yes/no by pressing a button. Similarly, Scorolli and Borghi had participants decide whether the sentence made sense. That is, they had to reconstruct an action and represent it internally before they could reply. In other words, deep semantic coding (processing) was achieved. Similarly, in our task, participants had to process the word to articulate it, thus activating semantic codes. We argue that it is this deep processing and activation of internal representations that is crucial, rather than simply activating the speech apparatus: Indeed the effect was not evident with nonwords. In the viewpoint of Arbib (2008), acting, imagining (in our terminology, internally representing), and understanding action are closely related and perhaps use the same neural structures.

Other features of our results are noteworthy. In IT, participants initiated their reaches faster when the meaning of the word matched the direction of the reach, replicating prior work (Glenberg & Kaschak, 2002) and confirming that semantic processing of the word has been completed before reach initiation. Strictly, semantic processing was unnecessary to select action direction, because the *location* of the word indicated reach direction. This pattern demonstrates that this is not the case: The semantics of prepared speech influenced response selection.

What this study demonstrates beyond response times is that semantic processing modulates systematically the transport component of simple reaches. Specifically, participants deviate upwards away from a straight line while uttering a word related to “up” compared with “down”, and vice versa. Hence, the spatial aspect of the word directly influences the nature of the reach trajectory.

Our main interest was the path of the hand from the starting position to the bar. Three key measures demonstrated clear directional effects of semantic processing during articulation on reaching. First, the hand deviated more in the vertical dimension from a hypothetical straight line when saying “up” than when saying “down” words, and vice versa in Experiment 2. This suggests that articulated semantic information influences the parabola of the reach. Second, the maximum height attained by the hand when reaching up was greater when saying “up” than when saying “down” words; it was lower for downward reaches when saying “down” than when saying “up” words. This pattern was identical for the height at which the real or pantomimed grip occurred. This suggests that semantic information affects not just the parabola but also the end-point of the reach. It does so, moreover, regardless of the presence of an actual end-point, the tip of the bar. Crucially, these are not simply interference effects indicating greater or lesser reach efficiency depending on word compatibility. Instead, the meaning of the word affects the quality of the reach in a systematic manner, lending support to Arbib's (2008) suggestion that pantomimes are precise "shorthand" for (goal-directed) action meaning.

Our data support the notion that language and action co-evolved. One interpretation of the embodiment of language within action is that is reflects a transition from action and gestures to language (Arbib, 2008). But gestures are not arbitrary; they are spatially precise ("this high"). In support of that interpretation, we demonstrate that semantic codes modulate spatial kinematic parameters of the hand. Importantly, we show that the modulation depends on verbal motor action that is specific to the spatial parameters: The effect was eliminated when no verbal response was required. In this case, there is a *direct* link between motor-activated semantic codes and action execution. Processing the word is insufficient to activate these links.

While we cannot speculate specifically about the neural substrates underlying this interaction, we suggest that the nexus between semantics and action points to a more complex interaction of the dorsal (action precision) and ventral (semantics) pathways than previously described (Arbib, 2008; Milner & Goodale, 2008). Specifically, we suggest that there is a bidirectional link, between motor language areas and the semantic coding areas of the ventral stream, and also a unidirectional link from motor language areas to the dorsal (action execution) stream. Activation of semantic codes alone does not seem sufficient to influence the dorsal action stream. Motor speech apparatus activation without semantic content is also insufficient, as indicated by the lack of modulation by nonsense words. Again, as Bub and Masson (2006) suggest, the task that participants undertake matters a great deal in the manifestation of these effects. Future work could plot how the link between language motor control and semantic codes becomes established, by giving a spatial meaning to novel words and then training participants in using them and then in saying and making congruent and incongruent reaches. Prior to training, there ought to be no effect evident. But over time it should become evident, compared with novel words that are never associated with spatial meaning.

Our findings fit well into the broad concept of embodied cognition—the internal cognitive representations of semantic categories of the vertical dimension leak into the motor programs controlling overt action (Fischer & Zwaan, 2008; Masson et al., 2008). That the meaning of articulated words affects the spatial component of a reach towards a static object as well as one that is imagined demonstrates the depth to which language and the sensorimotor systems are integrated. More than this, we suggest that these findings indicate that language indeed may have evolved from action, because the semantic and spatial codes are linked. Future work will further elucidate how we represent language within actions towards our environment.

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