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RESEARCH ARTICLE

Language-induced motor activity in bi-manual object lifting

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Abstract Language comprehension requires a simulation process that taps perception and action systems. How specific is this simulation? To address this question, participants listened to sentences referring to the lifting of light or heavy objects (e.g., pillow or chest, respectively). Then they lifted one of two boxes that were visually identical, but one was light and the other heavy. We focused on the kinematics of the initial lift (rather than reaching) because it is mostly shaped by proprioceptive features derived from weight that cannot be visually determined. Participants were slower when the weight suggested by the sentence and the weight of the box corresponded. This effect indicates that language can activate a simulation which is sensitive to intrinsic properties such as weight.

Keywords Language · Weight · Intrinsic objects properties · Movement

All human studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

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Introduction

The simulation theory of language (e.g., Barsalou 1999; Glenberg and Kaschak 2002; Gallese 2007; Gallese and Goldman 1998; Jeannerod 2007) proposes that language comprehension requires a simulation of the situation described using the same neural systems that contribute to perception, action, and emotion within that situation. In the last 15 years, many studies have shown that simulating implies recruiting these systems without necessity of a transduction process from the sensorimotor experience to an amodal and astract representation (Pecher et al. 2003; Saffran et al. 2003; for recent reviews see Barsalou 2008a, b; Fischer and Zwaan 2008; Gallese 2008; Martin 2007). An important question within this framework concerns the detail of the simulation. For example, must the simulation match the temporal course of the situation? Are lifting forces simulated? We investigate these questions by examining the effects of language comprehension on the kinematics of bimanual lifting. We begin with a brief review of the literature relating language and kinematics, and we develop the case for focusing on the interaction of language and actual weight being lifted. We then present the results of an experiment demonstrating that interaction.

Many recent studies provide evidence of language-induced effects in motor areas of the brain (Wise et al. 1991; Martin et al. 1996; Lafuente de and Romo 2004; Hauk et al. 2004; Kemmerer 2006; Kemmerer et al. 2008) and also on overt motor behavior (Glover et al. 2004; Gentilucci et al. 2000; Gentilucci and Gangitano 1998). In particular, kinematics studies have examined the effect of different syntactic (adjectives, adverbs and verbs) and semantic (e.g., 'long' vs. 'short') categories of words on the mono-manual reaching and grasping movements (Gentilucci et al. 2000; Glover and Dixon 2002; Boulanger et al.

2006). The experiments have demonstrated interactions of language and both intrinsic properties, i.e. invariant object features, such as size and shape, and extrinsic (visual) object properties, such as orientation (Gentilucci et al. 2000; Glover and Dixon 2002). Given that the point of these studies was to test whether language affects the visuo-motor transformations during the programming of movement, kinematics analyses focused on mono-manual object grasping. In particular, analyses concentrated on the prehension movement, from the beginning of the reaching until object grasping. The parameters which are typically considered are the thumb–index finger distance and the wrist velocity, both relying on object visual analysis. The thumb–index finger distance in shaping the suitable grasp depends on the object intrinsic properties. The wrist velocity in reaching the object is mostly a function of object extrinsic properties, such as orientation, thus it is sensitive to subject's observation conditions. Evidence reveals that both the reach and the grasp components of the movement are modulated by words. For example, linguistic labels such as "far" and "near" printed on a target object affect the reach kinematics, whereas labels such as "large" and "small" influence the initial grasp kinematics (Gentilucci and Gangitano 1998; Gentilucci et al. 2000; Glover and Dixon 2002). Evidence shows that not only the meaning but also the class of word has a different influence on kinematics: for example, verbs influence the action kinematics more than adjectives (e.g., "lift" vs. "high") (Gentilucci 2003a). The class of words has an influence on timing as well: for example, adverbs (e.g. "up" vs. "down") influence more the grasping action, whereas semantically equivalent adjectives (e.g. "high" and "low") affect more the movement planning phases (Gentilucci et al. 2000).

After grasping an object, the movement is shaped more by proprioceptive than by visual features. Object weight is a kind of proprioceptive feature, as it cannot be visually predicted. In summary, even though an increasing number of kinematics studies deal with language, to our knowledge all of them focus on object properties that can be visually detected. None of these studies focuses on the influence of language on properties that cannot be visually detected, such as object weight.

The panorama is similar if we consider, more generally, kinematics evidence concerning prehension. The majority of the studies have shown that the manipulation of intrinsic object properties influences the grasp component of the movement, and that manipulation of extrinsic object properties mainly affects the reaching component of the movement (Jeannerod 1981; Gentilucci et al. 1992; Jeannerod et al. 1995). As previously noted, size and shape are properties that can be visually detected, so the studied movement phase is the one that precedes the interaction with the object.

Studies focusing on the effects on movement of object mass[1] are scarce. Nonetheless, it is clear that the heavier the weight, the more lifting time increases, due to the applications of larger lifting forces (Brouwer et al. 2006; Johansson and Westling 1984, 1988; Westling and Johansson 1984).

Most of the studies of weight manipulate both visual cues for the estimation of weight (e.g., size, illusory size, color, object identity), and/or learning and participants' expectancies—for example by presenting participants with a heavy object in a 'light block' of trials, or, vice versa, by presenting a light object in a 'heavy block' of trials. For example, Eastough and Edwards (2007) recently found that the weight of the object significantly influences prior-to-contact grasp kinematics. The effect of participants' expectations about weight is detectable not only in the lifting phase of the movement, but also during the reaching phase. In particular, some studies provide evidence of longer lifting time for objects that were unexpectedly heavy, and shorter lifting time for objects that were unexpectedly light (Brouwer et al. 2006; Johansson and Westling 1988; Weir et al. 1991; Jenmalm et al. 2006). Some of the issues addressed by these studies are whether online control of movement is specialized for features such as size and shape, and whether it can be extended to non-visual features such as weight. Different studies addressed the mono-manual lifting movement to directly investigate whether people can adjust their movement plan to visually indicated sudden changes in weight. In contrast with previous evidence (Glover 2004; Goodale 1998; Milner and Goodale 1993), recent results argue against visual online control specialized only for low-level features, such as size and shape. Instead, there is some evidence that visual online control is also extended to weight (Brouwer et al. 2006).

Compared with previous studies, our work is novel in at least two respects. First, we examine the effects of language on a property that cannot be visually detected (in our experiment), namely, object weight. Whereas the effects of language on visually detectable properties such as size and shape have been demonstrated in a variety of experiments, this is not the case for a property such as weight. Finding a result with weight would contribute to enhancing the role of simulation by showing that it takes into account more than visuo-motor transformations. As shown in our review, participants' expectations about weight can be influenced both by visual features such as object size (size-weight illusion, see, for example, Brenner and Smeets 1996) and shape, and by memory and learning. But in the current experiment, we

[1] Objects mass is an intrinsic object property that does not depend on the object spatial position, whereas object weight is the gravitational field effect on this mass. However, from here on, we will refer to mass as 'weight', following the literature mainstream.

ruled out possible influences of object size and shape by keeping them constant, and we randomly changed object weight in order to analyse the effects on kinematics parameters of sentences referring to different weighted objects.

To investigate the effect of language on an intrinsic proprioceptive feature such as weight, it is necessary to focus on the placing phase, i.e. on the movement phase in which participants interact with the object. Therefore, the second novel aspect of our work is investigating effects of language on the motor system after grasping, in the early phase of the placing movement. During this phase, participants interact with the object, and their movement is shaped by the proprioceptive information which constrains the movement very quickly. Our analysis focused mainly on lift delay defined as the time immediately after the object is grasped. It has been demonstrated that this parameter is the most sensitive to weight manipulation (Weir et al. 1991; Johansson and Westling 1988).

Thus the aim of the present study is to test whether the simulation activated by language takes into account weight, and thereby influences action production. To investigate this issue, we presented participants with sentences describing the lifting of differently weighted objects (e.g., light objects such as pillows, and heavy objects such as tool chests). After listening to the sentence, participants were required to lift with both hands (bimanual lifting) a heavy or a light box placed in front of them.

We can derive predictions based on two contrasting hypotheses. The first hypothesis begins with the assertion that language comprehension does not involve a simulation. However, people may use the content of the language to control their behaviour. Thus, when participants hear a sentence describing the lift of a light object, they may take that as a hint that the box they are about to lift is in fact light, and the converse for sentences describing heavy objects. This hypothesis predicts a main effect of sentence content on lift kinematics: hearing about heavy objects will result in the application of more force, and hence faster lifting times, than hearing about light objects. Here and henceforth, we define faster lifting times in terms of the early occurrence of the first peak velocity, rather than in terms of an overall faster movement. As noted by an anonymous reviewer, this hypothesis makes predictions substantially similar to a priming hypothesis in which language inputs prime motor outputs.

The second hypothesis is based on the MOSAIC model of action control discussed by Hamilton et al. (2004). According to MOSAIC, the force used in an action arises from integrating the force parameters from several modules that might apply in the situation (e.g., modules for lifting a light box and modules for lifting a heavy box). The integration is based on the estimated probability that a module applies in the situation. Furthermore, Hamilton et al. (2004) demonstrated that modules may be rendered temporarily unavailable by simultaneous use in another task, and that this produces a type of repulsion effect. That is, when a module for producing a light force is being used in Task 1 and hence it is unavailable for Task 2, the integration of forces from the remaining modules produce too much force in Task 2; similarly, when a module for producing a heavy force is being used in Task 1, the integration of forces from the remaining modules produce too little force in Task 2. As discussed later, Scorolli et al. (2007) demonstrated that language comprehension could serve as Task 1 and render modules unavailable when Task 2 consists of judging the weight lifted by another.

Consider how such a repulsion effect would be revealed in the current experiment. (One caveat is important, however: movements are complex, and thus the MOSAIC for actually generating and controlling such a movement would need to be complex. Here we consider just one parameter, namely, the amount of force used in lifting a box.) The upper section of Table 1 illustrates the force parameters for six MOSAIC modules. For illustrative purposes, we suppose that the force required to lift the Light Box (force = 2) is generated by Module 2 and the force required to lift the Heavy Box (force = 5) is generated by Module 5.

In our experiment, participants experience only two boxes, and thus these modules are weighted more than the others. Nonetheless, in the absence of any visual information about which box is the one that will be lifted on the current trial, the average force (3.5) is generated for every

Table 1 Computation of forces according to the MOSAIC model

	Light			Heavy		
	Box and Sentence			Box and Sentence		
	Mod1	Mod2	Mod3	Mod4	Mod5	Mod6
Force	1	2	3	4	5	6
Prob.	0.1	0.3	0.1	0.1	0.3	0.1
Force no Sentence = (1 × 0.1 + 2 × 0.3 + 3 × 0.1 + 4 × 0.1 + 5 × 0.3 + 6 × 0.1)/1 = 3.5						
Force Light Sentence = (1 × 0.1 + 3 × 0.1 + 4 × 0.1 + 5 × 0.3 + 6 × 0.1)/0.7 = 4.14						
Force Heavy Sentence = (1 × 0.1 + 2 × 0.3 + 3 × 0.1 + 4 × 0.1 + 6 × 0.1)/0.7 = 2.86						

lift (bottom section of Table 1). We will also assume that simulating a light sentence requires (most often) Module 2 and simulating a heavy sentence requires (most often) Module 5. When these modules are removed from consideration (because of the simulation) and the contributions of the remaining modules renormed, the force generated after comprehending a light sentence is 4.14 and the force generated after comprehending a heavy sentence is 2.86 (note the repulsion effect).

Table 2 illustrates the relation between the force generated after listening to a sentence relative to the force required to lift the boxes. For the Light Box, the force generated after the light sentence is further from the required force than the force generated after reading a heavy sentence. Just the opposite obtains for the Heavy Box. That is, the force generated after the heavy sentence is further from the required force than the force generated after a light sentence.

Once the participant begins to lift a box, she will receive feedback from proprioception. Thus the bottom section of Table 1 can also be read as the discrepancy between generated force and the required force revealed by feedback. When the discrepancy is large, we presume that more time will be needed to recompute and apply the new force. Hence, based on the Table 2, we derive the following prediction: when lifting a Light Box, listening to a Light Sentence will slow attainment of some kinematics benchmarks (such as latency to peak velocity) compared to listening to a heavy sentence. In contrast, when lifting a Heavy Box, listening to a Heavy Sentence will slow attainment of the benchmarks relative to listening to a light sentence.

The present study

Method

Participants

Eighteen students of the University of Bologna (mean age 20 years) were recruited and were given credit for research participation. Their height ranged from 1.62 to 1.80 m and their hand spans[2] ranged from 17 to 19 cm. All the participants were right handed and were free from pathologies that could affect their motor behavior. All subjects gave informed consent to participate in the study and were naïve as to the purpose of the experiment. The study was carried out along the principles of the Helsinki Declaration and was approved by the local ethics committee.

Table 2 Predictions for the MOSAIC model

	Generated force relative to required force	
	Light Box Req. (2)	Heavy Box Req. (5)
Force after Light Sentence (4.14)	Further from required	Closer to required
Force after Heavy Sentence (2.86)	Closer to required	Further from required

Stimuli

Linguistic materials An independent group of 12 participants evaluated a set of 18 object words on a seven-point scale in order to assess whether their weights better matched the weight of a box with polystyrene (3 kg weighted box) or a box with gold ingots (12 kg weighted box). All words referred to bi-manually graspable objects, with about the same size and shape. From the original set, 12 words were selected. We chose words whose average weight ratings were less than 3.5 points for Light Sentences and words whose average weight ratings were greater than 4.5 for Heavy Sentences. Then we built 12 sentences using the selected object words and embedded them in the same context, "move xxx from the ground to the table". Thus the linguistic stimuli were constituted by six sentences referring to the lifting of 'light' objects (e.g. "move the pillow from the ground to the table") and by six sentences referring to the lifting of 'heavy' objects (e.g. "Move the tool chest from the ground to the table"). Each sentence was presented only once. For each sentence we constructed a comprehension question (e.g., "Is the object on the table edible?"; "Does the object that was on the ground contain drinks?"). To make the experimental purpose opaque to subjects, we selected comprehension questions that did not explicitly refer to weight. Unlike other studies of language effects on kinematics, this semantic task allowed us to be sure that the sentence had been comprehended (see Boulanger et al. 2006).

Object materials Two boxes, one 'heavy' (mass of 12 kg) and one 'light' (mass of 3 kg) were created. Both boxes had exactly the same rectangular shape (40 cm wide × 30 cm high × 24 cm deep), were white coloured, and smooth textured. Each box had two handles, to allow an easy grasp of the object and to constrain the movement both across subjects and across experimental conditions. We examined bimanual rather than mono-manual object placing. Using large boxes that required bimanual lifting enabled us to introduce a large difference between object weights, thus allowing for easy detection of differences in overt motor behavior.

[2] Span: the distance between the tip of the thumb and the tip of the little finger, when the hand is fully extended.

Procedure

At the beginning of the experiment, the experimenter showed the lifting movement to the participants. Participants stood with their feet on a fixed point 40 cm from the box they would lift. Participants were encouraged to execute the movement in a relaxed and natural way. Each trial began with an acoustically presented sentence referring to the lifting of a light object or of a heavy object. After listening to the sentence, participants were required to lift the box and place it on a pedestal (high 30 cm; 100 cm far from the starting point) (see Fig. 1). After the execution of the motor task, participants were required to return in the erect starting position. Finally, they were asked a yes/no question about the sentence to verify that they had comprehended it. The 12 experimental trials were preceded by two practice trials which allowed subjects to familiarize themselves with the procedure. To minimize possible effects in weight estimating due to the involvement of memory, learning processes (Brouwer et al. 2006), or expectations, the presentation order of both linguistic and object stimuli was randomised.

Movement recordings

A BTS Smart system, constituted by a vision system, three cameras, and a control unit, was used in recording the movements. Capture and Tracker software were used to record and to track the spatial positions of five markers (infrared light-emitting diodes), at a frequency of 60 Hz and with a spatial resolution of 768 × 576 pixel. Markers were taped on the hand (third metacarpal bone), on the external wrist (carpus), on the elbow (humeral lateral epicondyle), on the shoulder (scapular acromion) and on the ankle (talus bone).

Data analysis

Movements were visualized and analyzed using Smart Analyzer software. Raw data were smoothed using a rectangular window filter. Kinematics parameters were assessed for each individual movement. The choice to use kinematics parameters as dependent variables is based on evidence showing that using force metrics (dynamics) confirms results obtained with kinematics measures on lifting movement (Jackson and Shaw 2000).

Our major concern is with the *lifting phase* (Brenner and Smith 1996; Brouwer et al. 2006), as it reflects the time in which the grasp and the lift forces are accumulating. The *lifting phase* onset was calculated as the end of the reaching movement, that is as the last value of a sequence of nine decreasing points on the basis of ankle and wrist velocity profile (both ankle and wrist velocity at zero-crossings). The end of the lifting phase, when the object is placed on the pedestal, was defined as the last value of a sequence of nine decreasing points on the basis of wrist velocity (starting from wrist velocity zero-crossing). We did not consider the latency of the object motion per se because this measure was included in the duration of the *lifting phase*.

Within the *lifting phase*, we analysed latencies of hand velocity peak and elbow angular velocity peak. The elbow angle is formed by wrist–elbow ray and shoulder–elbow ray. Positive velocity values determine the extension movement, whereas negative ones define the muscular contraction, i.e. the bending movement. As outlined in the introduction, we considered only the *first* velocity peaks recorded in the *lifting phase* of the movement. Velocity peak latencies were defined as the time elapsed between *lifting phase* onset and the first maximum value of the hand velocity and the elbow angular velocity. We decided to

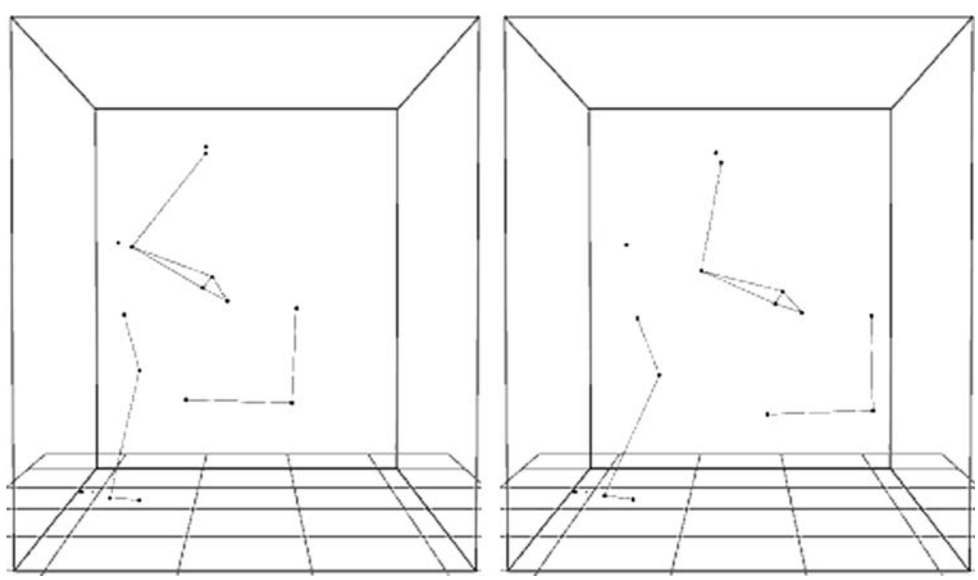

Fig. 1 *Left* subject bimanually grasps the handles of the box; *right* subject rests the box on the pedestal

focus on hand and arm movement as they are the first body parts that interact with the object. Our choice to focus on velocity rather than on acceleration, as in other studies (Gentilucci 2003a, b; Glover et al. 2004; Lindemann et al. 2006; Zoia et al. 2006), is based on the fact we are interested in the change of position in time. In addition, in our study we focused on the *first* velocity peak, which is correlated with acceleration.

Moreover, we focused on the latencies of velocity peaks rather than on the velocity values. The latter measure is sometimes used to study mono-manual grasping. Nonetheless, latencies of velocity peaks appear to be a more reliable measure in a motor performance characterized (as in our task) by strong individual differences between participants as far as force and various bodily characteristics are concerned. All kinematics parameters were determined for each individual trial and were averaged for each participant as a function of (light/heavy) sentence category.

Results

We excluded from the analysis trials when (a) the marker movement was not captured correctly, and (b) the comprehension question was not answered correctly. Removed items accounted for 9.53% (1.17% for wrong answers to the comprehension questions) of kinematics recordings. All analyses were performed with both kind of Sentence and kind of Box as within-subject factors.

Analyses of 'lifting'

To specifically investigate if the simulation activated by sentences influences movement production, we performed analyses on latencies of hand velocity peak and elbow angular velocity peak during the '*lifting*' phase. For both the parameters we considered the first peak immediately after having grasped the box to move it onto the pedestal. From this point forward, we will discuss only significant results, taking 0.05 as our level of significance.

Hand We analyzed the hand movement focusing on the absolute value of the third metacarpal bone velocity. Data from two participants were removed as the hand marker was not accurately captured in more than 50% of the trials. We performed a 2 (kind of Sentence: Heavy vs. Light) × 2 (kind of Box: Heavy vs. Light) analysis of variance on velocity latencies with both variables as within participants variables. Results showed a main effect of the kind of box, as participants achieved velocity peaks earlier during lifting of Light Boxes ($M = 0.43$ s) than during lifting of Heavy ones ($M = 0.58$ s), F (1, 15) = 19.68, $MSe = 0.02$, $P < 0.001$. This is consistent with previous evidence on mono-manual lifting movement showing that the lifting time increases with the application of larger lifting forces required for larger weights (Johansson and Westling 1984, 1988; Westling and Johansson 1984; Smeets and Brenner 1999).

Crucially, we found a significant interaction between the kind of Sentence and the kind of Box, F (1, 15) = 4.35, $MSe = 0.01$, $P < 0.05$ (see Figs. 2, 3 top): while lifting a light box participants reached the velocity peak later ($M = 0.44$ s) after listening to a light sentence than after listening to a heavy one ($M = 0.42$ s). Symmetrically, during lifting of a heavy box, participants were slower in reaching the hand velocity peak after a heavy sentence ($M = 0.61$ s) than after a light one ($M = 0.55$ s). Newman–Keuls post hoc analysis indicates that this effect is mainly due to the effect of the Light vs. Heavy Sentences during lifting of the Heavy Boxes ($P < 0.04$). These results indicate that the simulation activated by the sentence affects the lifting movement, and they are substantially in agreement with the predictions derived from Hypothesis 2: when a MOSAIC module is occupied by an ancillary task (in this case, simulation in the service of language comprehension), integration of force across the remaining relevant modules will be biased.

Arm extension We analysed the arm extension and bending focusing on the elbow angular velocity. We used the velocity vector, instead of the scalar absolute value of velocity, as it maintains the information on the specific kind of performed movement: the positive sign of the angular velocity vector accounts for the arm extension movement, and the negative sign accounts for the arm bending movement. We analysed the two kinds of movements separately.

We submitted the latency to the elbow positive velocity peaks to a 2 (kind of Sentence: Heavy vs. Light) × 2 (kind of Box: Heavy vs. Light) ANOVA, with both factors as within subjects variables. Neither of the main effects was statistically significant. Crucially, the interactions between kind of Sentence and kind of Box was significant, F (1, 17) = 4.74, $MSe = 0.04$, $P < 0.04$ (see Fig. 3 bottom). When lifting Light Boxes participants were significantly slower in reaching the velocity peak when they previously listened to Light Sentences ($M = 0.56$ s) than Heavy Sentences ($M = 0.37$ s). Symmetrically, after listening to Light Sentences they were faster ($M = 0.47$ s) in extending the arm to lift the Heavy Box than after listening with Heavy Sentences ($M = 0.49$ s). Newman–Keuls post hoc analysis indicates that the interaction is mainly due to angular velocity peak differences between the Light Sentence and Heavy Sentence conditions during the Light Boxes lifting ($P < 0.04$). Once again, these results indicate that the simulation activated by the sentence affects the lifting movement, and they are substantially in agreement with the predictions derived from Hypothesis 2, that is, when the

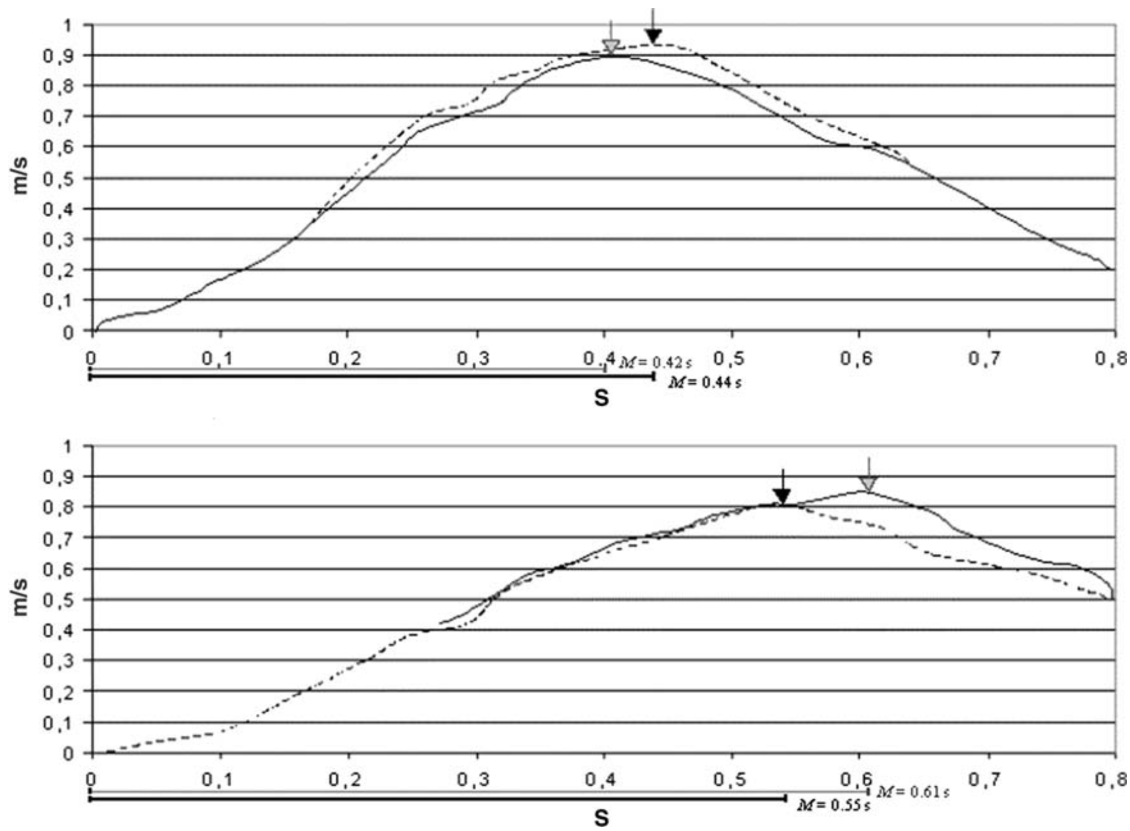

Fig. 2 *Diagrams* examples of hand velocity profiles during the *lifting phase*. Single movements are represented. Latencies of velocity peak are defined as the time elapsed between *lifting phase* onset and the first maximum value of the hand velocity. *Top* Light Box lifting; *bottom* Heavy Box lifting. *Continuous lines* refer to the movement after listening to a Heavy Sentence; *grey arrows* refer to the first velocity peaks; *grey segments* (below the *X* axis) refer to the first velocity peaks latencies. *Dashed lines* refer to the movement after listening to a Light Sentence; *black arrows* refer to the first velocity peaks; *black segments* refer to the first velocity peaks latencies. From the figure it might appear that the latencies are measured from the moment in which the object starts to move rather than when the hand velocity is at zero-crossing. However, this is not the case: the erroneous impression is due to the very brief delay occurring between hand velocity zero-crossings and hand movement onset

weight implied by the sentence and the weight of the box to be lifted are similar the time delay is larger compared to when they do not match at all.

Arm bending The latency to negative velocity peaks were submitted to the same ANOVA. The factor kind of Box was significant, as the velocity peaks were faster when lifting the Light Boxes ($M = 0.26$ s) compared to the Heavy ones ($M = 0.37$ s), $F\ (1,\ 17) = 46.93$, $MSe = 0.01$, $P < 0.001$. Results showed also a significant main effect of the kind of Sentence: participants were slower with the Light Sentences ($M = 0.33$ s) than with the Heavy ones ($M = 0.30$ s), $F\ (1,\ 17) = 7.41$, $MSe = 0.04$, $P < 0.01$. The two factors did not interact, however.

Analyses by halves of the experiment

To understand why the effect of language did not emerge as clearly as for the other two parameters, we analyzed the elbow negative velocity peaks separately for trials from first half (see Fig. 4 top) and second half (see Fig. 4 bottom) of the experiment. In the first half of the experiment, the participants may have taken the sentences as providing information about the weights of the boxes, as suggested by Hypothesis 1. After experiencing the lack of correlation between the weight of the object mentioned in the sentence and the weight of the box that was lifted, it is less likely that the participants would consider the sentences as providing information about the boxes.

In the analysis performed in the first half of trials, the factor kind of Box was significant, as the velocity peaks were faster when lifting the Light Boxes ($M = 0.30$ s) compared to the Heavy ones ($M = 0.39$ s), $F\ (1,\ 14) = 7.50$, $MSe = 0.02$, $P < 0.02$. Results showed also a significant main effect of the kind of Sentence: participants were slower with the Light Sentences ($M = 0.37$ s) than with the Heavy ones ($M = 0.32$ s), $F\ (1,\ 14) = 7.38$, $MSe = 0.007$, $P < 0.02$. The two factors did not interact (see Fig. 4 top). Nevertheless, the pattern was interesting, as participants were slower to lift a Heavy box after listening to a Light

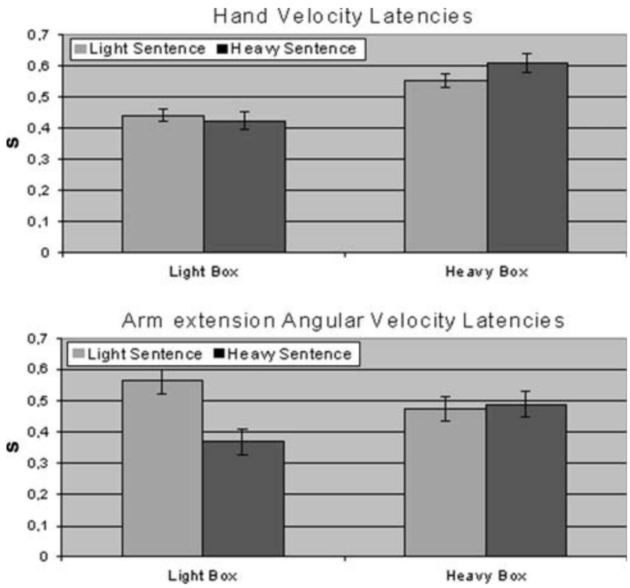

Fig. 3 *Top* Hand: the interaction between the kind of Sentence and the kind of Box; *bottom* Arm extension: the interaction between the kind of Sentence and the kind of Box. *Bars* indicate SEs

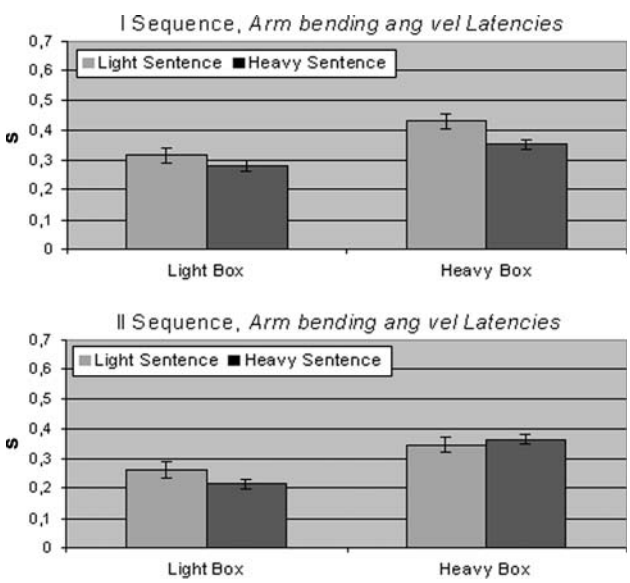

Fig. 4 *Top* Arm bending: first half of trials; (*bottom*) Arm bending: second half of trials. *Bars* indicate SEs

sentence ($M = 0.43$ s) than after a Heavy one ($M = 0.35$ s). In contrast, they were faster to lift a Light box after listening to a Heavy sentence ($M = 0.28$ s) than after a Light one ($M = 0.32$ s).

These results are similar to expectation effects about weight (Johansson and Westling 1988; Jenmalm et al. 2006). For example, if one expects to lift a light object and instead one lifts a heavy object, the loading phase requires more time. These results are consistent with Hypothesis 1.

In the analysis performed on the second half of the trials the factor kind of Box was significant, as the velocity peaks were faster when lifting the Light Boxes ($M = 0.24$ s) compared to the Heavy ones ($M = 0.36$ s), $F(1, 13) = 15.98$, $MSe = 0.01$, $P < 0.02$. The main effect of kind of Sentence was not significant. The interaction between the kind of Sentence and the kind of Box almost reached significance, $F(1, 13) = 2.79$, $MSe = 0.01$, $P < 0.11$ (see Fig. 4 bottom). Most interestingly, the pattern is changed: participants were faster to lift a Light box after listening to a Heavy sentence ($M = 0.21$ s) than after a Light one ($M = 0.26$ s), but they were faster to lift a Heavy box after listening to a Light sentence ($M = 0.35$ s) than after a Heavy one ($M = 0.37$ s).

Dividing the experiment into two halves greatly reduced statistical power, which is the likely reason for the interaction failing to reach statistical significance. Nonetheless, the pattern of the means in the second half is similar to the patterns obtained for Hand and Arm extension movement, and all of those patterns are consistent with Hypothesis 2.

To understand if the same change of pattern found in the arm bending parameter for the lifting of Heavy boxes occurred also for the other kinematics parameters, we also performed analyses by halves of the experiment on hand and arm extension movement.

Concerning the hand movement, in the analysis performed in the first half of trials, the factor kind of Box was significant, as the velocity peaks were faster when lifting the Light Boxes ($M = 0.45$ s) compared to the Heavy ones ($M = 0.67$ s), $F(1, 12) = 61.56$, $MSe = 0.01$, $P < 0.02$. The factors kind of Box and kind of Sentence did not interact. In the analysis performed in the second half of trials, the factor kind of Box was significant, as the velocity peaks were faster when lifting the Light Boxes ($M = 0.43$ s) compared to the Heavy ones ($M = 0.59$ s), $F(1, 13) = 38.92$, $MSe = 0.01$, $P < 0.02$. Crucially, the interaction between the kind of Sentence and the kind of Box almost reached significance, $F(1, 13) = 3.83$, $MSe = 0.02$, $P < 0.07$, and the pattern of the means was consistent with Hypothesis 2: in the second half of the experiment participants were faster to lift a Heavy box after listening to a Light sentence ($M = 0.50$ s) than after a listening to a Heavy one ($M = 0.67$ s).

As to the arm extension movement, in the analysis performed in the first half of trials we did not find significant effects. Also in the analysis performed in the second half of trials we did not find the interaction, but again the pattern switched over. In fact, while in the first half of the experiment participants were faster to lift a Heavy box after listening to a Heavy sentence ($M = 0.39$ s) than after a Light one ($M = 0.46$ s), in the analyses performed on the second half of trials we found that participants were faster to lift a Heavy box after listening to a Light sentence ($M = 0.55$ s) than after a Heavy one ($M = 0.57$ s).

These results of these analyses, although only tentative given the reduced statistical power, are consistent with the following summary: in the first half of the experiment, participants may have been using the sentences to form conscious expectancies about the weights of the boxes, and then they used those expectancies to modify their lifting. After experiencing the independence of the weights of objects mentioned in the sentences and the weights of the boxes, these expectancies were weakened. At this point, effects of language simulation, as described by Hypothesis 2, were more evident.

General discussion

We have shown that the comprehension of sentences referring to the lifting of differently weighted objects effects the production of action. We asked participants to lift heavy or light boxes after listening to sentences referring to the lifting of heavy objects (e.g., a tool chest) or light objects (e.g., a pillow). Unlike other kinematics studies of language, we used a bimanual rather than a mono-manual lifting task. In addition, we focused on sentences rather than on single word processing. Finally, we added a semantic comprehension task to make sure that participants comprehended the sentences. Most importantly, we focused on an object property that cannot (in our experiment) be visually inferred, namely weight.

The data provide support to our primary hypothesis that language affects the motor system. Importantly, the data speak in favour of the embodied view, according to which during sentence comprehension we internally simulate the actions and situations described by the sentence (Jeannerod 2007; Gallese and Goldman 1998; Zwaan 2004). In addition, the data suggest that simulations can, in at least some situations, consider aspects such as object weights.

There are at least three results that could be offered in support of the claim that simulation can be quite specific. The two most important results are based on analyses of hand and arm delay (latencies of first peak velocities) immediately after grasping the box. We found that participants' time delay was larger when the weight implied by the sentence and the weight of the box they lifted were similar compared to when they were dissimilar. These results are consistent with the operation of the MOSAIC model as outlined in Hypothesis 2.

Third, the effects obtained in the current experiment are consistent with other findings obtained in our lab (Scorolli et al. 2007). In that experiment, some participants first practiced lifting boxes of various sizes, shapes, and weights to familiarize themselves with the kinematics appropriate for those boxes; other participants did not have this practice. Then, for all participants, on each trial they read a sentence describing the lift of a Heavy Weight or a Light Weight, and the sentence was followed by a video (Bosbach et al. 1996) depicting the lift of a Large Box or a Small Box. Finally, the participant estimated the weight of the box observed in the video. When observers were required to practice lifting large and small boxes before the reading and judgment tasks, there was a dramatic increase in the correlation between judged and observed weight. Crucially, for the Light Videos (depicting lifts of light objects), the Light Sentences (describing the lifting of light objects) produced the lowest correlations between judged and observed weight, whereas for the Heavy Videos, Heavy Sentences produced the lowest correlations.

The results just described can also be accommodated by the MOSAIC model described as part of Hypothesis 2. First, comprehending the sentence describing a lift requires a simulation using the motor system. This simulation temporarily occupies a particular module (e.g., the module for lifting a 250 g weight) rendering it unavailable for use in the judging the weight of the box observed in the video. Variability of the weights simulated (and consequently, variability in the modules used in the judgment task) reduces the correlation between judged weight and observed weight. Because the modules used in simulating the light sentences are unlikely to be used in judging the heavy weights (and vice versa), the correlation is most reduced when the sentence is about lifting objects similar to those observed.

Evidence is rapidly accumulating that simulations during language comprehension are rather specific (e.g. Buccino et al. 2005; Glenberg and Kaschak 2002; Scorolli and Borghi 2007). The novelty of our study is that it shows for the first time that the simulation activated during language comprehension can entail information on object weight. As noted in the introduction, weight information cannot be inferred from visual stimuli in our experiment; instead it must be based on proprioceptive and kinaesthetic information. Thus, we have demonstrated through observations of kinematics parameters how language can have another type of specific effect on the motor system.

It can be objected that our results, which are in keeping with the MOSAIC model, conflict with results of other studies examining language effects on action. The reason why this difference appears might lie in the design of the studies. Namely, our study was explicitly designed to produce a contrast effect between the modules used during the ancillary task, the language processing task, and the modules used during the task directly involving the motor system, that is the lifting task. That is, detecting the effect requires that the ancillary task uses a MOSAIC module that is likely to be needed during the motor task, and that this ancillary task be compared to one that does not use that MOSAIC. Consider, for example, evidence by Gentilucci et al. (2000) showing that the kinematics of the initial reaching/grasping phase was modulated by the labels “LARGE” and “SMALL” written on a cube to be grasped. It is possible that in these experiments the MOSAIC required to process a word is not required to set reach kinematics. So, these experiments probably reflect a type of priming (e.g., Hypothesis 1).

One last issue is worth discussion and further exploration. It seems that language can have a different effect than expectations. As outlined in the introduction, it has been demonstrated with mono-manual lifting (Johansson and Westling 1988; Jenmalm et al. 2006) that when an unexpected heavy weight is lifted after a light weight, then the duration of the loading phase is longer than when a heavy weight is lifted after another heavy object. Differently, the lifting of an unpredictable light weight after a heavy weight results in an early lift off.

Our results partially differ from those obtained in studies on expectations. Namely, we found that participants were faster in the case of heavy box lifting preceded by light sentences. Similar to those studies, however, we found that the time delay of a light box lifting preceded by a heavy box was shorter. Even though these discrepancies might be accounted for by differences in method (e.g., mono- vs. bi-manual lifting), they raise the interesting possibility that language and expectations might tap different mechanisms. In keeping with these speculations, in an fMRI study, Jenmalm et al. (2006) found activity in the right inferior parietal cortex regardless of whether the weight was heavier or lighter than predicted, as well as differences in brain activity (left primary sensory motor cortex and right cerebellum) specific to the direction of the weight change. Unfortunately, research on differences between language effects and expectancy effects are likely to be complicated because language can also be used to change expectancies. Indeed, our analyses of arm bending latencies are consistent with the claim that language can produce both expectancy effects (as in the first half of the experiment) as well as more subtle effects on action control (as in the second half of the experiment). Further research should be conducted to investigate whether language affects different brain circuitries than the ones activated by an unpredictable weight change, and whether module/modules engaged in the comparison between the predicted and the actual sensory feedback are different from that ones engaged during language comprehension.

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