Abstract and Concrete Phrases Processing Differentially Modulates Cortico-Spinal Excitability

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Abstract

An important challenge of embodied theories is to explain the comprehension of abstract sentences. The aim of the present study was to scrutinize the role of the motor cortex in this process. We developed a new paradigm to study the abstract-concrete dimension by combining concrete (i.e. action-related) and abstract (i.e. non-action-related) verbs with nouns of graspable and non-graspable objects. Using these verb-noun combinations we performed a Transcranial Magnetic Stimulation (TMS) on the left primary motor cortex while participants performed a sentence sensibility task. Single-TMS pulses were delivered 250 ms after verb or noun presentation in each of four combinations of Abstract and Concrete verbs and nouns. To evaluate cortico-spinal excitability we registered the electromyographic activity of the right first dorsal interosseous muscle. As to verb-noun integration, analysis of motor evoked potentials (MEPs) after TMS pulse during noun presentation revealed greater peak-to-peak amplitude in phrases containing Abstract rather than Concrete Verbs. Response times were also collected and showed that compatible (Concrete-Concrete and Abstract-Abstract) combinations were processed faster than mixed ones; moreover in combinations containing concrete verbs, participants were faster when the pulse was delivered on the first word (verb) than on the second one (noun). Results support previous findings showing early activation of hand-related areas after concrete verbs processing. The prolonged or delayed activation of the same areas by abstract verbs will be discussed in the framework of recent embodied theories based on multiple types of representation, particularly theories emphasizing the role of different acquisition mechanisms for concrete and abstract words (Borghi & Cimatti, 2009;2012).

1. INTRODUCTION

The ability to understand and use abstract words is an important part of the human capacity to interact with the environment and with others. While many studies have been devoted to this important topic, the issue of how abstract concepts and words are represented is still unsolved (for a recent review, see Pecher et al., 2011). It is well known that abstract words are remembered and recognized more slowly than concrete ones (Schwanenflugel, 1991). Their processing can engage mental imagery, but at a lower rate and with a greater variability compared to concrete words (Paivio, et al., 1968; Paivio, 1991). It is also well established that abstract words are acquired later than concrete and generally highly imaginable words (Bird et al., 2001). Finally, the double dissociations found between the understanding of abstract and concrete words (Shallice & Warrington, 1975; Warrington, 1975) further suggest that, even if the domain of 'abstract concepts' is not homogeneous, there must be some common features that link its variegated members. In recent years many neuroimaging and meta-analyses have investigated the differing neural correlates involved in abstract and concrete concepts (for a recent quantitative meta-analysis see Wang et al., 2010; see also Kiefer & Pulvermüller, 2012). In addition, several brain imaging studies have recently investigated the difference between figurative and literal actions (e.g., Aziz-Zadeh et al., 2006; Boulenger et al., 2009; Boulenger et al., 2012; Desai et al., 2011). For example, Boulenger et al. (2009) have shown that semantic somatotopy of the motor system characterizes not only literal but also sentences with a figurative meaning (e.g., "kick the ball" vs. "kick the habit"). Other studies suggest an involvement of both the sensory-motor system and the semantic one. For example, Desai, Binder, Conant, Mano and Seidenberg (2011) found with fMRI some similarities between abstract and metaphoric sentences in the activation of left superior temporal regions suggesting that abstract words as well as action metaphor comprehension is based both on sensory-motor simulations and on lexical-semantic codes.

On one hand the concern for the difference between abstract (and figurative) and concrete concepts is due to a genuine interest in the specific topic, on the other hand this interest is strongly related to the theoretical implications of this issue for embodied and grounded theories of cognition (for a review on different kinds of embodied views, see Goldman & De Vignemont, 2009). Embodied theories vary in their details, but most of them maintain that all concepts and words activate a simulation mechanism that recruits the same action, perception and emotional networks activated during actual experience with their referents (e.g. Barsalou, 1999; 2003; Glenberg & Robertson, 2000; Zwaan, 2004). Notice that different versions of the notion of simulation have been proposed (for reviews, see Borghi, in press; Decety & Grezes, 2006). The term "simulation" as we intend it here involves two aspects: it implies the re-enactment of past experiences (Barsalou, 1999) and it is predictive. It refers to a process that is embodied, unconscious, not deliberate, and it is aimed at action preparation (Gallese, 2009). In contrast with other views (e.g., Decety & Ingvar, 1990) simulating does not imply a deliberate reactivation of previously performed actions, and it does not consist in a posteriori forms of motor imagery. Empirical evidence on simulation is compelling with respect to concrete concepts and words. For example, Pulvermüller et al. (2005) found a specific and early (150 ms) facilitatory effect of TMS sub-threshold stimulation of the motor cortex on the action words processing. In their study, participants were presented with single words referring to leg (e.g., to kick) or hand-arm actions (e.g., to pick) and were asked to perform a lexical decision task. Leg words recognition was faster when TMS targeted the leg area than when TMS was delivered over upper limb representation; symmetrical results were obtained for hand-arm verbs. The results showed that the activation of motor and premotor areas modulates the processing of specific kinds of words, semantically related to the arm or the leg (see also Scorolli & Borghi, 2007; Scorolli, Borghi, & Glenberg, 2009).

Nevertheless the challenge embodied theories have to face with is to clarify whether abstract concepts and words are also represented via embodied simulations. Mental metaphors could represent a potential solution, as they import the image-schemas derived from the source domain of sensorimotor experience (Lakoff, 1987; Gibbs & Steen, 1999). Compelling evidence has been collected in favor of this approach (e.g., Casasanto, 2009), but it is hard to foresee how it can be generalized to all varieties of abstract words.

Recently, some scholars have addressed the issue by getting to the root of the problem: embodied accounts of language have focused largely on language grounded in bodily experiences but have neglected that language also plays a role in shaping our experience (Borghi & Cimatti, 2009; 2012; Borghi & Pecher, 2011). In their proposal (Words as Tools, WAT) Borghi and Cimatti (2009; 2012), similarly to other authors (Dove, 2009, 2010; Louwerse & Jeauniaux, 2009; Barsalou et al., 2008; Kiefer & Barsalou, 2011; Simmons et al., 2008), try to integrate linguistic and modal approaches. The unique quality of the WAT proposal maintains that the linguistic system does not simply involve a form of superficial processing and that words cannot be conceived of as mere signals of something. Words are also tools that allow us to operate in the world (Clark, 2007; Gianelli et al., 2012; Mirolli & Parisi, 2011; Tylèn et al., 2010). The WAT proposal has direct implications for the explanation of abstract word meanings. Indeed, Borghi and Cimatti (2009; 2012) proposed that, probably due to their different acquisition mechanisms, abstract word meanings rely more than concrete word ones on the social experience of language. With concrete words, such as "phone", the word's referent can be indicated and tagged using linguistic labels. With abstract words, instead, there is not a specific referent to be indicated. In this case, the word used by others, such as "freedom", plays a major role, as it helps assemble a set of diverse sensorimotor experiences (e.g., we put together different experiences of freedom once we have learned the word "freedom"). In addition, since there is no referent to indicate, in the case of abstract words the contribution of other members of the linguistic community becomes crucial, as they can provide useful explanations of the word meaning. For example, as argued by Prinz (2002), to learn the word "democracy" we may visualize a series of scenes, but also rely on the opinion of authoritative members of our community. In support of this proposal, Borghi et al. (2011) have shown that the acquisition modality of novel concrete and abstract words (manipulation of their referents vs. simply visualization of scenes with interacting objects) has an impact on their representation: in a verification task participants responded faster to abstract words when using the microphone, and to concrete words when using the keyboard. The results indicate that concrete words evoke more manual information, whereas abstract words evoke more linguistic information; importantly, the advantage of the microphone with abstract words was more pronounced when the meaning of the word was linguistically explained, and it was not present when the linguistic information contrasted the perceptual information. These results clearly show the similarities but also the differences between embodied accounts (Barsalou et al., 2008; Borghi & Cimatti, 2009; 2012; Simmons et al., 2008; for recent brain imaging evidence consistent with this view see Rodríguez-Ferreiro, et al., 2010) and Paivio's dual coding theory (e.g, Paivio, 1986; Binder et al., 2005; Desai et al., 2010). Both accounts share the idea that multiple types of representation underlie knowledge, but embodied proposals differ from Paivio's view as they hypothesize that not only concrete, but also abstract words are grounded in perception and action.

The aim of the present study is to test the WAT proposal (Borghi & Cimatti, 2009; 2010; 2012) through scrutinizing the possible modulation of the left primary motor cortex (M1) activity during abstract and concrete phrase processing (for a study on positive and negative abstract and concrete phrases see also Liuzza et al 2011). We used an innovative paradigm recently developed by Scorolli et al. (2011), in which the same Concrete Verb (CV) was combined with a Concrete Noun (CN) and with an Abstract Noun (AN), the same Abstract Verb (AV) was combined with the nouns previously used. One of the advantages of this design is the possibility to study abstractness along a continuum - that is, to study combinations in which abstract and concrete verbs and nouns are put together. This paradigm was adapted to the use of single-pulse transcranial magnetic stimulation (TMS) technique, with the aim to explore the modulation of M1 activity during the processing of concrete (i.e. action-related) and abstract (i.e. non-action-related) verbs, combined with nouns of graspable and non-graspable objects.

Resting on the predictions of the WAT proposal, we hypothesized that the processing of language is different within the motor cortex for concrete and abstract language content. Specifically concrete phrases or words should be associated with sensori-motor and/or somatic experience, and, as such, encoded within brain areas (e.g. M1) composing the human motor system. Because of the sensori-motor and somatic nature of the encoding, concrete phrases and words should be much better and deeper stored in the brain (see Desai et al. 2011). Therefore, concrete phrases and words should be more easily accessible than abstract ones when areas of the primary motor cortex representing body parts (e.g. the hand) involved in motor acts they refer to are stimulated.

On the basis of the assumption that the mode and age of acquisition of concrete and abstract words differ, we expected to also find clues for different roots of processing. Specifically, our predictions are:

I. Given that according to embodied theories both concrete and abstract words are grounded in the motor system, we predict that concrete and abstract words differentially recruit neurons of the hand areas in M1 (detectable on the modulation of motor evoked potentials, MEPs, analyses).

II. If concrete words, and concrete *verbs* in particular, evoke motor information related to the hand more directly than abstract words, we predict:

IIa. an earlier activation of hand representation areas in concrete verb processing over abstract verb processing, detectable on MEPs collected after a pulse delivered on the first word, and a later modulation due to abstract verb processing, detectable on MEPs collected after a pulse delivered on the second word;

IIb. faster phrase processing when the pulse is delivered on concrete verbs than on abstract verbs (detectable on response times, RTs, analyses).

III. Finally a. if linguistic information is more relevant for abstract words, and perception and action information for concrete ones, we predict costs in mixed combinations (regardless of the TMS pulse); b. due to different acquisition modality between concrete and abstract words, within the mixed combinations we also predict an advantage when the concrete word precedes the abstract one, consistently with Scorolli et al., 2011 (both the effects are detectable on response times, RTs, analyses).

These effects should be present only when the phrases are sensible, otherwise no simulation should occur, or the simulation should be interrupted when the first word (verb) has to be combined with the second one (the noun).

2. RESULTS

Our dependent variables were reaction times (RTs) and motor evoked potentials (MEPs). It is worth noting that, due to the fact that we used phrases instead of single words and that for each phrase we stimulated either the verb or the noun, results from these two measurements cannot be completely matched. To clarify: I. MEPs recorded after the stimulation on the first word (verb) provide information concerning the first part of phrase processing (the processing of a verb that has later to be integrated with a specific noun); II. MEPs recorded after stimulation on the second word (noun) provide us with information on the integration between the verb and the noun (whole phrase processing) ; III. RTs provide information on the whole phrase processing.

2.1 Analyses on MEPs

One participant was eliminated from analyses as, due to reported high levels of anxiety, we stopped the experimental session before finishing the overall experiment. As predicted in the Sham condition we did not record any MEPs, so we will not further discuss the non-active condition. Peak-to-peak amplitude (mV) of each MEP was computed by an automatic Excel script prior to normalization by means of a logarithmic transformation [log10 (mean MEPs amplitude value)]. MEP amplitudes inferior to 0.05 mV were excluded from analyses. One participant was excluded from further analyses due to the high percentage of unrecorded

MEPs (25.45 %). We eliminated MEPs for which participants gave an incorrect response on the phrase sensibility task.

Normalized MEPs recorded after TMS stimulation on the first word (verb) were submitted to a *t-test*, with Verb (Concrete vs. Abstract) working as the within participant variable. MEPs peak-to-peak amplitudes recorded from the right FDI muscle during TMS delivery did not differ in the case of Concrete Verbs or Abstract Verbs ($p = 0.19$).

Normalized MEPs recorded from the right FDI muscle after the stimulation on the second word (noun) provided information on the verb and noun integration. This allowed for a 2 (Verb: Concrete vs. Abstract) X 2 (Noun: Concrete vs. Abstract) ANOVA, with all variables manipulated *within* participants. We eliminated MEPs for which participants gave an incorrect response on the phrase sensibility task. We found a significant main effect of the Verb, F (1, 13) = 13.21, $MSe = 0.002$, $p < .005$: in case of active pulse, peak-to-peak MEPs amplitude was greater for phrases containing Abstract Verbs ($M = 2.71$) than for phrases containing Concrete Verbs ($M = 2.67$, *see* Fig. 1). The last result obtained when the pulse was delivered on 2nd word (the noun) shows that the primary motor cortex activity is specifically modulated by the processing of Abstract Verbs. Overall, this result gives an additional hint as to the recruitment of the motor system during Abstract Verbs processing.

To understand if this recruitment occurs later or lasts longer than with Concrete Verbs, we contrasted the kind of verb and the pulse delivered timings. As we found no effect of the kind of noun, we were entitled to perform a 2 (pulse delivered timing: at verb vs. at noun) X 2 (Verb: Concrete vs. Abstract) ANOVA. We found a significant interaction between the Pulse Delivered Timing and the Verb, F (1, 27) = 13.78, $MSe = 0.001$, $p < .001$: abstract verbs obtained greater peak-to-peak MEPs amplitude when the pulse was delivered at noun

(400+250 ms), *M* = 2.71, rather than at verb (250 ms), *M* = 2.67, after the verb presentation, post hoc LSD: $p < .005$. (650 ms after stimulus onset might appear very late in the semantic processing according to Event Related Potential (ERP) findings, since the N400 was found to occur at the 300-350 ms time window after presentation of motor vs. abstract words (Kellenbach, Wijers, Hovius, Mulder, & Mulder, 2002). Notice however that 650 ms after the verb presentation is equal to 250 ms after the noun presentation, and that the noun meaning needs to be integrated with the meaning of the verb).

Symmetrically we found that concrete verbs obtained greater peak-to-peak MEPs amplitude for the pulse delivered timing at verb, *M* = 2.69, than at noun (650 ms), *M* = 2.67, post hoc LSD: $p = .055$. Interestingly the activation of the motor system for concrete verb after an early pulse did not differ from the one obtained for abstract verb after a delayed pulse (*M* = 2.69 vs. *M* = 2.71, $p = .07$).

Insert Figure 1 about here

2.2 Analyses on MEPs after a pulse on 2nd word for both sensible and non-sensible phrases

As we found no effect of the kind of noun (abstract vs. concrete), in order to disambiguate the role of the pulse delivered timing (at verb *vs.* at noun) and the kind of subsequent noun (determining a sensible vs. non-sensible combination) on the verb, in a further analysis we considered also the MEPs recorded from the FDI during non-sensible phrase processing (see Kocha et al., 2010; see also Graves et al 2010). Normalized MEPs (after a pulse on 2nd word) were submitted to a 2 (Phrase: Sensible vs. Non-sensible) X 2 (Verb: Concrete vs. Abstract) X 2 (Noun: Concrete vs. Abstract) ANOVA. We conducted the analysis with participants as a random factor. We found a significant interaction between the Phrase and the Verb, F (1, 13) = 27.47, MSe = 0.001, $p < .001$: sensible phrases containing abstract verbs obtained greater peak-to-peak MEPs amplitude, M = 2.71, than sensible phrases containing concrete verbs, M = 2.67, post hoc LSD: $p < .0005$, *see* Fig. 2. Crucially, in the case of meaningless context we found an opposite pattern, that is greater peak-to-peak MEPs amplitude with Non-sensible Phrases containing Concrete (M = 2.69) rather than Abstract Verbs (M = 2.67, post hoc LSD: $p < .05$). Finally we found a three way interaction between the Phrase, the Verb and the Noun, F (1, 13) = 11.24, MSe = 0.001, $p < .005$: sensible phrases containing abstract verbs followed by abstract nouns obtained greater MEPs, M = 2.73, than sensible phrases formed by an abstract verbs plus a concrete noun, M = 2.69, post hoc LSD: $p < .05$; we did not find an analogous modulation for non-sensible phrases (p = .44). Interestingly the effect was also due to great MEPs amplitude for Non-sensible phrases containing concrete verbs followed by abstract nouns, M = 2.71, if compared to all other Non-sensible phrases (ps = .01), as well as to sensible phrases composed by concrete nouns (ps = .01).

Insert Figure 2 about here

2.3 Analyses on accuracy and RTs

One participant was excluded from behavioral analyses due to the high percentage of unrecorded data (35.6%) because of difficulties with the response device. Percentages of errors were submitted to a 2 (Pulse: Active vs. Sham) X 2 (Verb: Concrete vs. Abstract) X 2 (Noun: Concrete vs. Abstract) X 2 (Pulse Delivered Timing: at verb vs. at noun) ANOVA; we manipulated all variables *within* participants. We will first focus on results involving the Pulse and the Pulse Delivered Timing variables: results showed an interaction between the Pulse, the Pulse Delivered Timing and the Verb, F (1, 12) = 7.44, MSe = 0.060, $p < .05$: in the Active Pulse condition with Phrases containing Abstract Verbs participants made more errors (M = 0.78%) when the pulse was delivered on the second word than on the first one (M = 0.56%, post hoc LSD: $p < .01$; the effect was not replicated for the control-sham condition, p = .12); we found no effect of the Pulse Delivered Timing for Phrases containing Concrete Verbs (post hoc LSD: p = .28; control-sham condition, p = .58).

Moreover we found a main effect of the Verb: participants made more errors with phrases containing Abstract Verbs (M = 0.59%) compared to phrases containing Concrete Verbs (M = 0.37%), F (1, 12) = 18.97, MSe = 0.141, $p < .001$. Analyses also showed a significant interaction between the Verb and the Noun, F (1, 12) = 19.71, MSe = 0.286, $p < .001$, basically due to the high number of errors in Abstract Verbs followed by Concrete Nouns (M = 0.81%) condition, that significantly differed from Abstract Verbs followed by Abstract Nouns (M = 0.38%, post hoc LSD: $p < .001$), Concrete Verbs followed by Concrete Nouns (M = 0.26%, post hoc LSD: $p < .001$) and Concrete Verbs followed by Abstract Nouns (M = 0.48%, post hoc LSD: $p < .01$) conditions.

Before performing analyses on response times all incorrect responses were eliminated (3.57 %). Response times (ms) were submitted to a 2 (Pulse: Active vs. Sham) X 2 (Verb: Concrete vs. Abstract) X 2 (Noun: Concrete vs. Abstract) X 2 (kind of Pulse Delivered Timing: at verb vs. at noun) ANOVA, with all variables *within* participants. We will first report results involving the Pulse and the Pulse Delivered Timing variables. We found a three way interaction between the Pulse, the Pulse Delivered Timing and the Verb, F (1, 12) = 4.77, MSe = 3012.27, p < .05: when the pulse was delivered on the 1st word (verb), phrases containing Concrete Verbs (M = 538.55 ms) were processed faster than phrases containing Abstract Verbs (M = 576.11 ms, post hoc LSD: p < .05); in the control-sham condition we found no effect of the Verb (p = .64). The time latencies for phrases containing concrete verbs (M = 561.46 ms) and phrases containing abstract verbs (M = 565.65 ms) did not differ when the pulse was delivered on the 2nd word (noun, p = .10); not effect of the kind of verb was found for the sham condition (p = .16). This result clearly argues in favor of a greater activation of the motor system during Concrete Verbs processing in case of TMS pulse.

Finally we found a main effect of the kind of Noun, F (1, 12) = 5.05, MSe = 3966.197, p < .05: phrases containing Abstract Nouns (M = 556.32 ms) were processed faster than phrases containing Concrete Nouns (M = 575.94 ms). (This result appears to be due to the very slow response times obtained with Abstract Verbs plus Concrete Nouns combinations. Indeed, due to our particular paradigm, we collapsed verb and noun RTs focusing on phrases. As a result Concrete Noun processing turned out to be slower than Abstract Noun processing because the timing reflected not only the process of noun comprehension, but also the process of previous verb comprehension, as well as a possible delay caused by the switching cost.) We will not discuss this result as it is partially explained by the interaction between the Verb and the Noun, F (1, 12) = 36.86, MSe = 1740.424, p < .0001: participants were faster with congruent combinations (AA: *M* = 546.29 ms; CC: *M* = 550.84 ms) than with the mixed ones (AC: *M* = 601.04 ms; CA: *M* = 566.34 ms, post hoc LSD: $p < .05$). The advantage of congruent over mixed combinations replicates results found by Scorolli et al (2011) in a behavioral task employing the same paradigm. Additionally, post hoc LSD showed that participants employed the slowest response times with Abstract Verbs combined with Concrete Nouns: the modality switching (from concrete to abstract, or vice-versa) determines a delay; this delay is larger in case of phrases containing Abstract rather than Concrete Verbs.

To better understand our results we performed two further separated analyses focusing on the Active pulse condition and on the Sham condition: for both the analyses, response times (ms) were submitted to a 2 (Verb: Concrete vs. Abstract) X 2 (Noun: Concrete vs. Abstract) X 2 (Pulse Delivered Timing: at verb vs. at noun) ANOVA, with all variables manipulated within participants. In the analysis on Active Stimulation Condition we found a significant interaction between the Verb and the kind of Pulse Delivered Timing, F (1, 12) = 4.90, MSe = 1477.771, $p < .05$: phrases containing Concrete Verbs were processed faster when the pulse was delivered on the 1^{st} word (verb, *M* = 538.55 ms) than on the 2^{nd} one (noun, *M* = 561.46 ms, post hoc LSD: $p < .05$, *see* Fig. 3); conversely with phrases containing Abstract Verbs we found no effect of the Pulse Delivered Timing (p = .35). Finally we found an interaction between the Verb and the Noun, F (1, 12) = 6.50, MSe = 4121.074, $p < .05$: participants were faster with congruent combinations (AA: *M* = 541.52 ms; CC: *M* = 547.26 ms) than with the mixed ones (AC: *M* = 600.24 ms; CA: *M* = 552.75 ms).

The interaction between the Verb and the Noun was significant also in the separated analysis on the Sham Condition, F (1, 12) = 15.28, MSe = 2476.217, $p < .005$: participants were faster with congruent combinations (AA: M = 551.06 ms; CC: M = 554.52 ms) than with the mixed ones (AC: M = 601.85 ms; CA: M = 579.93 ms).

Insert Figure 3 about here

3. DISCUSSION

An important challenge of embodied theories is to explain the comprehension of abstract phrases. We performed a transcranial magnetic stimulation (TMS) study to explore the role of the left primary motor cortex during the processing of concrete and abstract verbs with nouns of graspable and non-graspable objects. Participants performed a sentence sensibility task. Single TMS pulses were delivered 250 ms after verbs vs. nouns presentation.

The first important result is that both concrete and abstract words modulate the activity of the motor system, as indicated by analyses on MEPs and suggested by results on RTs. This result supports the embodied view that there is a strict relationship between words and actions. Embodied views would be falsified and standard propositional view would be supported if no modulation of the motor system for concrete words, for abstract words or for both occurred. However, we found that this modulation involves different temporal windows (for a study on single verb processing using different temporal windows see Papeo et al., 2009). In addition, as predicted, our results suggest that concrete words activate the hand-related motor system in a more direct and straightforward way. These results does not support standard embodied theories (for a review see Pecher et al., 2011), according to which processing and representation of concrete and abstract words do not differ, since both kinds of words are grounded in action. In contrast, results are in line with a subset of theories that, even if maintaining an embodied and grounded stance, highlight possible differences in grounding and representation of concrete and abstract words, posing that multiple kinds of representation underlie knowledge. These multiple representation views are compatible with the WAT proposal. We will now discuss the results that led us to this conclusion.

1. Early simulation with concrete verbs. Our study extends results by Pulvermüller et al. (2005) showing the temporal evolution of the language and action systems linkage in case of whole phrase processing, using a language comprehension task (see Turken et al., 2011). Analyses of MEPs after the pulse only on the first word do not allow us to draw any conclusion on Concrete Verbs processing. Nevertheless the separate analysis we performed to contrast the kind of verb and the pulse delivered timings showed that abstract verbs elicited greater peak-to-peak MEPs amplitude with a delayed pulse (650 ms) than with an early one (250 ms); crucially concrete verbs presented an opposite pattern (see also Candidi, Leone-Fernandez, Barber, Carreira and Aglioti, 2010).

Moreover our data on non-sensible phrases (pulse on the second word) are informative (for studies contrasting meaningful versus reversed, non-meaningful, phrases see Graves, Binder, Desai, Conant & Seidenberg, 2010 and Borghi & Scorolli, 2009). Indeed, we found that in case of meaningless context, that is when the whole phrase processing is broken as it is impossible to integrate the noun with the previous verb, motor activation is stronger for verbs referring to physical actions performed with the hand (greater peak-to-peak amplitudes with concrete than abstract verbs). It seems that when participants have to evaluate the sensibility of a phrase, as in the present task, they do not process the single words sequentially; rather the meaning emerges from the combination of words in phrases (see Pulvermüller, 2011), consistently with recent findings on single words formed by different morphological components (Rueschemeyer, Brass and Friederici, 2007). If the integration cannot be accomplished due to semantic constraints the comprehension process stops at the verb level.

Together with the results on MEPs for sensible phrases, these results on both meaningless vs. meaningful phrases help us rule out a possible alternative explanation, that motor activity may increase merely as a function of task difficulty (e.g., Davis and Johnsrude, 2003; Fridriksson, et al., 2008). Analysis on the sentence sensibility judgment task (response latencies) showed consistent findings, as we found an advantage for phrases containing concrete rather than abstract verbs only when the pulse was delivered on the 1st word. Interestingly this effect seems to be very early, as the first pulse was delivered just 250 ms after the word presentation.

2. Verb-noun integration: late simulation with abstract verbs. As we presented verb-noun combinations, instead of single words, it is crucial to understand how the integration process of verbs and nouns takes place.

2a. Our results show that MEPs peak to peak amplitudes after a 'delayed' pulse (pulse on the second word, the noun) were greater with phrases containing abstract verbs than phrases containing concrete verbs. This result favors the hypothesis that abstract words (verbs) also activate the motor system (specifically, in our study, the motor system related to manual action; see Jirak et al, 2010). The unexpected result that the MEPs peak are larger with abstract than with concrete words is not in keeping with one influential embodied theory, the Conceptual Metaphor one, that we briefly illustrated in the introduction. According to this view concrete concepts are used as metaphor to represent abstract concepts, providing them structure and grounding. The fact that the MEPs peaks are higher with abstract words can be due to the fact that, because abstract sentences are less embodied in M1 hand motor cortex, the effort to process abstract words in M1 is higher. A further, more probable explanation is that the effort to process abstract words in the premotor cortex or other secondary areas is higher and therefore determines a stronger modulatory influence on M1. This could also explain the larger delay of the peak activation.

More crucial to our hypotheses, which are not based on the idea that abstract concepts are metaphorically grounded on concrete ones but that multiple representations are activated in both cases, is that the motor system activation is delayed with abstract words compared to concrete words. As said, this can be due to the fact that the effort to process abstract words in secondary areas is higher. Alternatively, it can be due to a delayed activation of hand areas due to an early activation of mouth areas in the case of abstract words (this account will be discussed later in a more detailed way). This delay is suggested by separate analysis contrasting the kind of verb and pulse delivered timings, regardless of the noun (as it did not modulate the MEPs). The role of the early or delayed pulse and the context is disambiguated by further analysis we performed on both sensible and non-sensible phrases: crucially, this greater delayed involvement of the motor system in the case of phrases containing abstract verbs disappears with non sensible phrases (for which presumably the noun is not integrated with the verb). This suggests that simulation related to the semantic meaning of the phrase only occurs when the content makes sense and that this process leads to activation of the motor system.

Actually in the case of meaningless context we also found greater MEPs amplitude with phrases containing concrete verbs followed by abstract nouns than for both the other non-sensible phrases and sensible-phrases composed by concrete verbs. Consider that our concrete plus abstract combinations result on phrases having a metaphorical meaning that can often be grasped also for non-sensible combinations (e.g. "to smoke a shade": the noun can be integrated with the previous verb), that can be intended as less familiar metaphors. Moreover our CC, CA and AA combinations roughly match the literal action sentences (e.g. "The daughter grasped the flowers"), the metaphoric action sentences (e.g. "The public grasped the idea") and the abstract sentences (e.g. "The public understood the idea"), respectively, used by Desai et al. (2011). In this recent work authors found that activation in a number of sensory-motor regions was negatively correlated with familiarity for sentences containing concrete verbs (i.e. for both literal and metaphoric action sentences). Therefore the activation of M1 hand-related areas for meaningless phrases composed by a concrete verb followed by an abstract noun seems to be due to the negative correlation of primary motor areas with metaphor familiarity (Desai et al, 2011). We are aware that during processing of non sensible phrases normal comprehension processes are disrupted, thus strong conclusions are typically not drawn based on results on non sensible phrases (but see Graves, Binder, Desai, Conant & Seidenberg 2010). Consider, however, the specificity of our paradigm, in which the phrase is not presented in its whole, but each word that composed it is presented separately. This allows us to capture the effects of the first word and of the integration of its meaning with that of the second word.

We propose two possible explanations for the delayed activation with abstract words compared to concrete words, relying on two different embodied views: (a) the motor simulation is also evoked by phrases containing abstract verbs, but this simulation occurs later than with phrases containing concrete verbs. This interpretation is consistent with a recent embodied theory that, similarly to WAT, proposes that multiple kinds of representation underlie knowledge, the Language and Situated Simulation Theory, LASS (Barsalou et al., 2008). According to LASS linguistic forms and situated simulations interact continuously, but while the linguistic system is mainly involved during early superficial linguistic processing, a deeper conceptual processing would be necessary for the operation of the simulation system (e.g., sensorimotor system activation; for consistent results, see also Louwerse & Connell, 2011). This proposal can account for the delayed activation of phrases containing abstract as opposed to concrete verbs, but LASS would predict a modulation of MEPs by the kind of noun. We found greater activation of the motor system for abstract verbs than concrete ones in MEPs *after a pulse on the noun* (400+250 ms). From 250 ms after the noun onset participants should have already processed the noun (Pulvermüller et al., 2005); so LASS would predict greater MEPs for graspable than for non-graspable objects combined with abstract verbs. Instead, we did not find any modulation of the noun; moreover, in the analyses of both sensible and non-sensible phrase we found an opposite pattern.

The second possible explanation (b) of this result supports the WAT proposal (Borghi and Cimatti, 2009; 2012). As anticipated in the introduction, the role played by socially transmitted linguistic information should be more important for abstract than for concrete words, due to the fact that for their acquisition the use of labels and of explanations of the word meaning provided by others is particularly crucial. Due to their acquisition modality, concrete words evoke more manual information, while abstract words elicit more verbal information (Borghi et al., 2011). We can account for these results through arguing that concrete verbs activate early motor areas related to the hand, while abstract verbs activate earlier motor areas related to the mouth, as data on acquisition modality suggest (Borghi et al., 2011). The early activation of motor areas related to the mouth would have a delayed effect on motor areas related to the hand, due to their topological contiguity. The reason why MEPs modulation should be similar for both a direct effect (hand) and an indirect effect (mouth) might not seem straightforward. However, one could speculate that, in the temporal window of 250 ms, we might detect the hand related curve in its *decreasing* phase, while in the temporal window of 650 ms we might detect the curve describing the effect of the mouth on the hand areas during its *increasing* phase. On this basis, the signal that we detect at 650 ms could be a compound of mouth induced activation (abstract verbs) plus the activation determined by noun processing, that - resting in our measures - we cannot estimate, but that is reasonably different from zero (null activation). This interpretation is consistent with a study on visual, motor and abstract words by Kellenbach et al (2002): measuring event related potentials (ERPs). They found greater anterior positivity (lateral sites) activation with abstract words than with motor words starting from 300 ms; the effect lasted until 500 ms (centro-anterior sites). Later the effect became left lateralized (550-750 ms). Further results in line with our perspective have been found by Desai et al. (2010) with fMRI. Participants were presented with sentences of the form ‘‘I/You/We/They <verb > the <noun >’’ (e.g., “I throw the ball”) and had to evaluate their sensibility by pressing a key; they had to respond only to non sensible sentences. The sentences included either a motor (e.g., “grasp”), visual (e.g., “read”) or an abstract verb (e.g., “explain”, “allow”) combined with concrete and abstract nouns (e.g., “ball” vs. “method”). The results showed that abstract sentences, differently from motor and visual ones, strongly activated the superior/anterior temporal and inferior frontal areas. In line with WAT, this study on sentence processing suggests that the meaning of abstract words may be represented primarily through verbal associations with other words. The difference between Paivio’s view and embodied multiple representation views such as WAT is that, according to the last, both sensorimotor and linguistic information are crucial for both concrete and abstract words, even if the distribution of the two information sources is different. In our study the analysis on MEPs when the pulse was delivered on the second word indicates that also abstract verbs activated the manual motor system, even if it is unclear from the present study whether this activation of the manual system is the cascade effect of the involvement of the mouth areas (see below).

2b. Beyond the analysis on MEPs, the second main result on verb-noun integration is from reaction times analyses. We found an interaction between the Verb and the pulse delivered timing: phrases containing concrete verbs were processed faster than phrases containing abstract verbs when the TMS pulse was delivered on the presentation of the verb. We did not find any difference when the pulse was delivered on the noun. Consistently with our interpretation of MEPs, reaction times were faster when the hand related motor areas were directly involved (concrete verbs). The *supposed* indirect activation of hand areas by abstract verbs affected the MEPs but it did not last long enough, and probably was not strong enough, to affect response times. Finally, the interaction between the Verb and the kind of Noun is consistent with a recent cross-linguistic study (Scorolli et al., 2011) in which we found the same advantage a. for compatible combinations, and, b. within the mixed combinations, when the concrete word preceded the abstract word, regardless of its grammatical class (*see* Paivio, 1965).

Overall our results seem to indicate that while phrases containing concrete verbs imply a direct early activation of the hand related motor system, the activation of the same system is delayed in the case of phrases containing abstract verbs. The processing of abstract verbs could early engage mouth related motor areas, that later affect the contiguous areas (hand areas).However, the present evidence does not allow for disambiguation between two alternative explanations: (1) abstract words have a weaker grounding in the sensorimotor system; (2) abstract words are processed in an alternative route, maybe in the premotor cortex, with involvement from mouth related motor areas. Integrating these results with those recently obtained in a study on novel words acquisition (Borghi et al., 2011) we lean towards the second hypothesis. Whether this indirect or "cascade" effect of the mouth-related neural network on the hand related motor areas plays a functional role in meaning or is an effect of cortical connectivity cannot be determined on the basis of our current study. Integrating the current results with previous behavioural results on concrete and abstract words acquisition we are inclined to think that the mouth areas activation is not simply a by-product of cortical connectivity but contributes to the process of meaning formation. However, further research is needed to clarify this issue, and particularly studies aimed at directly stimulating the motor cortex mouth areas.

As hypothesized by the WAT proposal, mouth areas could be crucial for abstract word processing. In thinking about the acquisition of a concrete word, such as "pencil": the acquisition simply requires a person to use the label while indicating the right referent. The acquisition of a concept-word like "democracy", instead, implies the presence of somebody explaining the word meaning, using language. This experience is still a bodily experience but the contribution of the social dimension is more relevant to acquisition. In addition, in this experience language is not *only* the counter part of an external referent but is a tool that allows us to acquire more complex meanings, a powerful means of collecting a variety of bodily and situational experiences.

4. EXPERIMENTAL METHOD

4.1 Participants

16 students (7 men and 9 women; mean age = 27.44 years; s.d. = 1.93) attending the University of Bologna took part in the study. All were native Italian speakers, right-handed and all had normal or corrected-to-normal vision. Before starting the experimental session, the experimenters assessed their general health status with a brief interview: none of them were reported evidence for neither neurological or psychiatric diseases, nor contraindications related to single-pulse TMS procedure. Then participants were provided with a detailed explanation about the procedure, contraindications and risks of the experiment (Wessermann, 1998). To begin the experiment participants had to confirm their voluntary participation by written consent. The study was approved by the local ethics committee (Department of Psychology, University of Bologna). All participants received compensation for their participation.

4.2 Transcranial Magnetic Stimulation and EMG recording

As an index of cortico-spinal excitability, we recorded motor-evoked potential (MEPs). MEPs induced by TMS were recorded from the right first dorsal interosseus muscle (FDI, in the region of the index finger) by means of a Biopac Student Lab MP36 electromyograph (Biopac Systems, Inc, U.S.A.). EMG signals were band-pass filtered (20 Hz–2.5 kHz, sampling rate fixed at 10 kHz), digitized and stored on a computer for off-line analysis. Pairs of silver/silver chloride surface electrodes were placed over the muscle belly (active electrode) and over the associated joint or tendon of the muscle (reference electrode). A circular ground electrode with a diameter of 30 mm was placed on the internal bone of the right elbow. Single-pulse TMS was applied to the left M1, using a Magstim Rapid 2 stimulator (Magstim, Whitland, Dyfed, U.K.) connected to a figure-of-eight coil (70 mm in diameter). The coil was moved over the left hemisphere to determine the optimal position from which maximal amplitude MEPs were elicited in the FDI muscle. The optimal scalp position for the induction of MEPs with the maximum amplitude in the right FDI muscle was individuated for each participant. The coil rested tangential to the scalp with the handle pointing backwards and laterally at a 45° angle away from the midline. The target site was marked with a drawing pen on a cap applied on participants' head, and the coil was maintained in position by the experimenters. The intensity of magnetic pulses was set at 120% of the resting motor threshold (rMT), which is the minimum intensity of output required to produce MEPs with amplitude of at least 50 μV in the FDI muscle with 50% of probability (Rossini et al., 1994). The absence of voluntary contraction was continuously verified visually and, prior to the recording session, through auditory monitoring of the EMG signal.

4.3 Linguistic materials

Stimulus materials consisted of word pairs composed of a transitive verb and a concept noun. We used 28 quadruplets, thus 112 sensible phrases. Each quadruplet was constructed by pairing a concrete verb (e.g. *to grasp*) with a concrete noun (e.g. *a flower*) or an abstract noun (e.g. *a concept*); and by pairing an abstract verb (e.g. *to describe*) with the previously used concrete and abstract noun. We defined Concrete Nouns as nouns referring to graspable objects and Concrete Verbs as verbs referring to physical actions (Taylor, 1977; Vendler, 1957) performed with the hand. We defined Abstract Nouns as nouns that do not refer to graspable objects and Abstract Verbs as verbs expressing mental processes, with no reference to a physical object (Taylor, 1977; Vendler, 1957). To select the 28 critical quadruples from 48 ones, we asked twenty Italian students to judge the familiarity of each phrase (verb + noun) and with what degree of probability they would use each phrase. We then selected the quadruples with highest scores in both ratings and with lowest scores in the standard deviations (for a detailed description of the materials' selection *see* Scorolli et al., 2011).

In order to further test if the selected pairs differed in written frequency of use we utilized the research engine “Google”: we checked the number of occurrences of each verb-noun pair, by using quotations marks (Page et al., 1998; Griffiths et al., 2007; Sha, 2010). The obtained frequencies were submitted to a 2 (Noun: Concrete vs. Abstract) X 2 (Verb: Concrete vs. Abstract) ANOVA. Crucially, we did not find any significant effect (all $p_s \geq .41$). The establishment of control on written frequency allowed us to exclude that processing differences rest on different degrees of association between the words pairs used in the quadruples. Finally we selected 112 non-sensible phrases, that is phrases in which the actions described by the abstract (e.g. *to suspect*) or concrete (e.g. *to eat*) verbs were not suitable for the abstract (e.g. *the freedom*) or concrete (e.g. *a pen*) nouns that followed the verb (non-sensible phrases). Due to the particular kind of paradigm it was impossible to balance phrases for word length and number of syllables. However, this should not represent a problem, given that our main hypotheses pertain to the interactions.

4.4 Procedure

The experiment was programmed using the EPrime (Psychology Software Tools, Inc, U.S.A) software to control sequence and duration of the presentation of the linguistic material, and to trigger TMS and EMG recording. Participants were asked to perform a sentence sensibility task: they were required to judge if phrases made sense or not. Participants focused on a fixation cross; after 1000 ms a verb appeared on the screen; after 400 ms the verb was substituted by a noun. The cut-off was set at 2500 ms from the noun onset. On conclusion of this cycle there was a pause; then the next trial began. Each trial lasted 8000 ms from start to finish, i.e. long enough to prevent interaction between consecutive TMS-pulses (Robertson et al., 2003). Participants were instructed to use the left foot – homolateral side with respect to TMS stimulation site – to respond. They were randomly assigned to one of two groups. Participants in the first group were asked to respond "yes" (= the combination makes sense) pressing the right pedal and "no" (= the combination doesn't make sense) pressing the left pedal; participants in the other group were assigned the opposite mapping. Participants were instructed to keep their right arm/hand and head motionless and muscle relaxation was monitored throughout the entire experiment to check for involuntary movements. Response times and errors were recorded using EPrime; the timer started from the noun presentation.

Experimental Design

The experiment consisted of four blocks of 112 items (verb + noun) each: 56 sensible phrases and 56 non-sensible phrases. The phrases of the quadruplets were constructed by combining a Concrete Verb with a Concrete Noun or with an Abstract Noun, and an Abstract Verb with the nouns previously used. For two blocks participants were delivered a TMS stimulation at verb or at noun: in both cases there was a delay of 250 ms after the word onset. For the remaining two blocks they were delivered with a sham stimulation (at verb vs. at noun).

Each phrase was presented twice, so we collected 14 observations for each experimental condition. 224 motor evoked potentials (MEPs) were obtained from each participant, one magnetic stimulus being applied for each item (the pulses delivered during the two sham-blocks did not elicit MEPs). The four kinds of phrases were presented in random order within each block, with a short pause after 28 items

The choice of the temporal window was motivated by electrophysiological evidence showing that starting from 250 ms motor words elicited greater negativity than both visual and abstract words (Kellenbach, Wijers, Hovius, Mulder, & Mulder, 2002). The order of the two stimulation conditions (TMS and sham) was counterbalanced across subjects. To mimic the TMS conditions (Robertson et al., 2003), in the sham stimulation conditions the same intensity of magnetic pulse was used, but a cylinder made of insulating material was located between the coil and the scalp surface.

At the end of the experiment participants were debriefed. Since none of them was previously exposed to TMS, they reported that they had attributed the differences in the peripheral effects intensity in the sham and TMS conditions to different pressures applied on the scalp by the two experimenters.

Insert Figure 4 about here

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FIGURE CAPTIONS

Figure 1. Normalized MEPs recorded after the TMS stimulation on the 2nd word. Peak-to-peak MEPs amplitude was greater for phrases containing Abstract Verbs than for phrases containing Concrete Verbs.

Figure 2. The interaction between the kind of Sentence and the Verb: Sensible phrases containing Abstract Verbs obtained greater MEPs amplitudes than Sensible phrases containing Concrete Verbs. We found an opposite pattern for Non-sensible phrases.

Figure 3. The interaction between the Verb and the kind of Pulse Delivered Timing: phrases containing Concrete Verbs were processed faster when the pulse was delivered on the 1st word than on the 2nd; with phrases containing abstract verbs no effect was found.

Figure 4. The figure shows the experimental paradigm. The coil was moved over the left hemisphere to determine the FDI representation in the primary motor cortex.