Understanding action language modulates oscillatory mu and beta rhythms in the same way as observing actions

Iván Moreno *, Manuel de Vega, Inmaculada León

Department of Cognitive Psychology, University of La Laguna, Spain

ARTICLE INFO

ABSTRACT

The mu rhythms (8–13 Hz) and the beta rhythms (15 up to 30 Hz) of the EEG are observed in the central electrodes (C3, Cz and C4) in resting states, and become suppressed when participants perform a manual action or when they observe another's action. This has led researchers to consider that these rhythms are electrophysiological markers of the motor neuron activity in humans. This study tested whether the comprehension of action language, unlike abstract language, modulates mu and low beta rhythms (15–20 Hz) in a similar way as the observation of real actions. The log-ratios were calculated for each oscillatory band between each condition and baseline resting periods. The results indicated that both action language and action videos caused mu and beta suppression (negative log-ratios), whereas abstract language did not, confirming the hypothesis that understanding action language activates motor networks in the brain. In other words, the resonance of motor areas associated with action language is compatible with the embodiment approach to linguistic meaning.

© 2013 Elsevier Inc. All rights reserved.

1. Introduction

The notion that meaning is grounded in embodied representations is becoming popular in cognitive psychology and the neuroscience of language, as opposed to the traditional notion that meaning is represented conceptually and denoted by arbitrary symbols (Barsalou, 2008; De Vega, Glenberg, & Graesser, 2008; Fischer & Zwaan, 2008; Glenberg & Gallese, 2011). The embodiment approach to language claims that understanding words and sentences involves a mental simulation of the objects, events and actions described in the sentences. That is, linguistic meaning has a perceptual-motor character, emulating the experience that occurs when performing and observing an action. From a neurological point of view, the notion of embodied meaning implies that language comprehension elicits activity in brain areas that partially overlap those responsible for processing the action, perception or emotion.

The motor activity associated with action language has been extensively investigated with neuroimaging methods, especially functional magnetic resonance imaging (fMRI). For example, understanding action verbs, in comparison with nouns referring to perceptual objects, elicited activations in fronto-central regions, including the premotor and motor cortex (Pulvermüller, 1996), demonstrating that the meaning of action words is associated with

the activity of motor networks in the brain. Other neuroimaging studies have shown that processing verbs referring to face, arm, and leg actions elicited activations in somatotopic regions of the cortex that partially overlap those involved in the execution of these actions (Hauk & Pulvermüller, 2004; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005; Rizzolatti & Luppino, 2001). Furthermore, these motor activations were even reported when the participants focused their attention on a distractor task, indicating that such brain processes "are to a large degree automatic" (Pulvermüller et al., 2005; although see Raposo, Moss, Stamatakis, & Tyler, 2009, for a non-automatic context-dependent proposal). In the same vein, motor activations in the brain have been reported not only when these words occur in isolation but also in some types of sentential contexts. For example, action words occurring in sentences such as *I kick the ball* activate the fronto-parietal-motor network with respect to sentences with an abstract content (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Tettamanti et al., 2005). Even sentences referring to actions that imply varying degrees of physical effort (e.g., pushing the *piano*, vs. pushing the *chair*) modulate activity in pre-motor regions differently, thus suggesting that language recruits action representations as a function of fine-grained action properties (Moody & Gennari, 2010). Taken together, these findings indicate that the processing of action verbs either presented in isolation or in the context of sentences activates highly specific and detailed neural representations of actions that are partially shared with those engaged in performing actions.

The above neuroimaging studies have provided some evidence that motor processes underlie the comprehension of action lan-

* Corresponding author. Address: Department of Cognitive Psychology, University of La Laguna, Campus de Guajara, s/n, La Laguna, Tenerife 38205, Spain.
   E-mail address: ivanzevzui@hotmail.com (I. Moreno).

guage. However, the fMRI technique they employed does not record proper neural activity but rather only hemodynamic changes, which are supposedly correlated with neural activity. An interesting alternative is to explore the mu rhythms observed in the EEG, which directly reflect one aspect of brain dynamics. Mu rhythms spontaneously occur at rest, in the frequency band between 8 and 13 Hz, over the sensorimotor cortex, equivalent to a central distribution in the brain mapping (Gastaut, 1952; Muthukumaraswamy, Johnson, & McNair, 2004; for a review see Pineda, 2005). Mu rhythms show maximal synchronization at rest and become desynchronized during the execution, observation or even imagination of an action, especially if this action is manual (McFarland, Miner, Vaughan, & Wolpaw, 2000; Pfurtscheller, Brunner, Schlögl, & Lopes da Silva, 2006; Pineda, 2005). These observed modulations of mu rhythms are consistent with the idea that these rhythms are markers of motor neuron activity in the premotor and motor cortex (Pfurtscheller, Neuper, Andrew, & Edlinger, 1997). Some authors, employing EEG and MEG source estimation, even propose that the suppression of mu rhythms could reflect downstream premotor cortex modulation of primary sensorimotor areas (Hari, Salmelin, Mäkelä, Salenius, & Helle, 1997; Muthukumaraswamy et al., 2004; Taniguchi et al., 2000), and activity in the supplementary motor area (SMA), which is anterior to the primary motor cortex (Babiloni et al., 1999).

Most remarkably, given the fact that mu rhythms are also modulated by action observation, they have been associated with the activity of the human mirror neuron system (Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010; Rizzolatti & Craighero, 2004). According to some researchers, the mirror neuron system includes perceptual-motor neurons mainly located at the frontal, motor and parietal cortex, which are activated both when an individual performs an action and when he/she observes another's action, especially if the action is manual (Mukamel et al., 2010; Muthukumaraswamy et al., 2004; Perry & Bentin, 2009; Pfurtscheller et al., 1997; Rizzolatti & Craighero, 2004; Ulloa & Pineda, 2007).

From the above evidence, it is reasonable to think that sentences describing manual actions will also modulate mu rhythms, because they may also activate the premotor and motor cortex. Recently, van Elk, van Schie, Zwaan, and Bekkering (2010) analyzed the synchronicity of mu and beta rhythms while participants read action sentences with a human agent ("The woman is swimming in the pool") or an animal agent ("The duck is swimming in the pond"). They found EEG desynchronization in the mu and beta frequency rhythms, with respect to the resting baseline periods, associated with the action verbs. Notice, however, that the absence of non-action sentences as contrasting condition, does not allow concluding that mu and beta rhythms are exclusively modulated by action language. On the other hand, they found larger desynchronization in the context of animal agents than in the context of human agents. According to the authors a possible reason for this is that action verbs have higher cloze probability in animal contexts than in human contexts; for instance, "swimming" can be predicted more easily given "ducks" than given "woman". Still it remains intriguing why the modulation of mu and beta occurs for sentences describing animal actions, which do not belong to the human motor repertoire.

One goal of the current study is precisely to test whether mu suppression is restricted to the comprehension of action language or whether it is a general phenomenon associated with language processing. The main hypothesis is that action language, but not abstract language, will modulate mu and perhaps beta activity. We also checked beta activity because, as mentioned before, these rhythms could also be sensitive to motor processes. A second goal of this study is to contrast action language with the observation of real actions. Assuming that the modulation of mu rhythms is a marker of motor neuron activity in the premotor and motor cortex, we hypothesize that mu and beta suppression might be similar for the understanding of action language and the observation of real actions. To accomplish these goals, we presented participants with blocks of action sentences, abstract sentences and action video clips while their EEG was recorded for mu and beta analyses. Following each block of stimuli, participants performed a recognition task, and the resulting accuracy scores were also analyzed.

2. Material and method

2.1. Participants

Thirty undergraduate students of Psychology at the University of La Laguna participated in this study. All were women with an age range between 18 and 22, and they were right-handed according to the Edinburgh Handedness Inventory, with a mean coefficient of lateralization of 77 ($SD = 19.4$). We chose woman as participants because they show stronger mu suppression than males when watching hand actions (Cheng et al., 2008), and we assume that this could also be the case when they understand action language. All had Spanish as their mother tongue, and reported no neurological diseases, visual problems or intake of medication. In addition, all received credit for volunteering.

2.2. Material and design

A pool of 56 action sentences and 56 abstract sentences in Spanish was initially created. Action sentences referred to concrete manual actions, such as "Ahora corto el pan" ("Now I cut the bread"), and abstract sentences referred to mental states or processes, such as "Ahora dudo del plan" ("Now, I doubt of the plan"). These sentences were then submitted to a normative study with 41 participants, none of whom participated in the main experiment. Each participant in the normative study received a booklet with 28 abstract and 28 action sentences in random order, and were asked to judge their degree of imageability using a 5-point Likert scale: 1 as very difficult to imagine and 5 as very easy to imagine. The goal was to select the most imaginable action sentences and the least imaginable abstract sentences. Thus, four action items with scores less than 3, and four abstract sentences with scores larger than 3 were discarded. A final set of 104 experimental sentences was selected for the experiment: 52 action sentences (imageability: $M = 3.96$ and $SD = 0.73$) and 52 abstract sentences (imageability: $M = 2.01$ and $SD = 0.50$). All sentences had the following sequence: the adverb "ahora" ("now"); a verb in first person; a function word; and a noun. Verbs and nouns of the two experimental conditions were controlled in the number of syllables (2 or 3) and full-word frequency per million, which was checked in the Spanish frequency dictionary BUSCAPALABRAS (Davis & Perea, 2005). Given that Levené's test for inequality of variances was not significant, we applied t-tests assuming equal variances. The results showed no significant differences in lexical frequency between abstract verbs ($M = 8.53$, $SD = 19.09$) and action verbs ($M = 15.85$, $SD = 15.87$; $t(38) = -1.31$, $p > .05$), or between abstract nouns ($M = 43.91$, $SD = 73.33$) and action nouns ($M = 72.40$, $SD = 74.83$; $t(78) = -1.71$, $p > .05$). The sentences were tape recorded for the experiment using a female voice. The duration of the recorded sentences ranged between 1164 and 1749 ms ($M = 1436$; $SD = 155$), and each was followed by a variable silence period to complete the total duration of 2.5 s for each voice file. In addition to the linguistic material, we used 34 video clips, each lasting 2.5 s, showing an actress' hands performing simple manual actions with familiar objects, similar although not identical to the actions described in the action sentences. The videos involved an

external, rather than internal or egocentric perspective. Although the nominal duration of the verbal stimuli and the video stimuli were the same, the videos were exposed the whole 2.5 s temporal slot, whereas the sentences only lasted about 1.5 s of the temporal slot. To compensate for this modality-based bias, we employed more sentence trials than video trials.

A block design was used, in which sentences (or videos) of the same type were presented together, alternating with resting baseline periods. With this design, cumulative effects of mu modulation may be expected, offering a better signal-to-noise ratio than a randomized presentation of stimuli. Four blocks with action sentences and 4 blocks with abstract sentences were generated, with each block including 26 sentences and lasting about 65 s. Each sentence was presented twice, in two different blocks. Thus, the total duration of the 8 sentence blocks was almost 9 min. For the action observation condition, 4 blocks of 17 video clips each were generated, with each video clip shown twice in two different blocks. Each video clip block lasted 42.5 s, which meant that the total duration for the action observation condition was 3 min and 23 s. The baseline condition, in which participants remained motionless watching a fixation point, consisted of three blocks of 65 s each, the duration of this condition being therefore 3 min and 25 s.

2.3. Procedure

Participants were seated in a comfortable chair with instructions to remain relaxed and to minimize blinking during the experiment. First, they received blocks of action and abstract sentences, counterbalanced across participants, and then they received blocks of video clips also counterbalanced. Sentences and videos were randomized within each block. Sentences were presented aurally, by means of the E-Prime 2 software, through two bilaterally located speakers, while participants directed their attention to a fixed black point placed in the center of the computer screen over a light grey background to minimize eye movements. After listening to each block of sentences, participants received a set of three recognition sentences (presented in Arial font, and 26 points size) with instructions to judge whether they were "old" or "new" by pressing with the left hand middle and index fingers the keys "1" or "2" in the keyboard, respectively. Each recognition sentence remained on the screen until the participant responded or for a maximum of 3 s. After watching each block of video clips, the participant also performed a recognition test in which three frames, either "old" or "new", were presented. Each frame was presented until the participant responded or for a maximum of 3 s. Thus, a total of 12 recognition probes (6 old and 6 new) were performed for each condition: action language, abstract language, and action observation. After each recognition test in both the language and video clip blocks, a period of inactivity followed lasting 15 s, aiming to restore mu rhythms after the modulation caused by the motor responses. During this time the participants simply directed their attention to a fixation point. The total duration of the experiment was about 20 min.

2.4. Data acquisition and analysis

2.4.1. EEG recording
Participants' EEGs were recorded continuously by a Compumedics Neuroscan (version 4.5) system from 30 tin electrodes mounted on a Quick-Cap elastic cap, following the 10/20 system. Mastoids were used as references, and the ground was set in AFz. The signal was amplified (SynAmps^2), digitized at a sampling rate of 1000 Hz, band-pass filtered from 0.1 to 30 Hz and 50 Hz notch filtered (to isolate the electrical recording from any environmental contamination), and re-referenced off line to the average of two mastoids. Blinks and eye movements were monitored using bipolar horizontal and vertical EOG derivations via two pairs of electrodes, one pair attached to the external canthi, and the other to the infra-orbital and supraorbital regions of the right eye.

2.4.2. Data processing
Data were segmented into epochs of 2 s, each starting at the onset of a segment (a sentence verb or a video clip). Epochs with blinks and eye movements identified by abrupt changes in the EOG waves were submitted to an artifact reduction algorithm, which subtracted the eye movement from the ongoing EEG, improving it before averaging. Data from one participant were excluded from the analysis due to the excessive number of blinks and motor artifacts (facial muscle activity) identified during the session. After the automatic correction of blinks, the remaining data were carefully inspected and trials with artifacts, other than movements were rejected. The total rejection rates were: action language: $M = 24.13\%$, $SD = 19.48$; abstract language: $M = 30.43\%$, $SD = 19.55$; and action observation: $M = 23.08\%$, $SD = 15.46$). These rejections were unbiased by conditions, as none of the pairwise comparisons reached statistical significance: action language–abstract language: $t(56) = 1.23$, $p > .05$); action language–action observation: $t(56) = 0.22$, $p > .05$); and abstract language–action observation $t(56) = 1.59$, $p > .05$). Our main interest was on mu and beta rhythms defined as oscillatory measures over the sensorimotor cortex, represented by the C3, Cz and C4 electrodes on the scalp (Cochin, Barthelemy, Roux, & Martineau, 1998; Muthukumaraswamy et al., 2004; Oberman et al., 2005). However, to avoid theoretical-driven biases in the statistical analysis we tested samples of electrodes in three representative regions: frontal (F7, F3, Fz, F4, F8), fronto-central (C3, FC1, Cz, FC2, C4) and parieto-occipital (PO7, O1, Pz, O2, PO8). The fronto-central region of interest included the target electrodes C3, Cz, and C4 but also FC1 and FC2, which could be considered within the topography of motor related mu oscillatory rhythms (e.g., McFarland et al., 2000; Quin & He, 2005). Given the fact that the frequency in the mu band overlaps with the frequency in the alpha band in posterior sites, it is possible that recordings from the critical fronto-central region might be contaminated by the posterior alpha activity associated with expectancy. To reduce this influence, and following recommendations by Oberman et al. (2005), Oberman, Pineda, and Ramachandran (2007), the first and last 7.5 s of each block of data were removed (and discarded from the analysis) for all subjects. Additionally, the data from the parieto-occipital region (PO7, O1, Pz, O2, and PO8) also included in the analyses provided a test of remaining alpha activity.

Beta rhythms were also analyzed because, according to the literature, they could also be modulated at central sites during action performance and observation (e.g., McFarland et al., 2000; Pfurtscheller et al., 2006; Pineda, 2005). For each 2-s epoch the integrated power in the 8–13 Hz range (mu band) and in the 15–20 Hz range (low beta band) were computed using Fast Fourier Transforms (FFT) on the cleaned and epoched data (based on 1024 points per segment, using Hanning window). A spectral power analysis, performed on the FFT coefficients, was carried out on the EEG to identify changes in spectral amplitude of the mu and beta frequency bands. A ratio (as opposed to a simple subtraction) was used to control for variability in absolute mu or beta power derived from individual differences such as scalp thickness and electrode impedance (Pineda & Oberman, 2006). Following Oberman et al. (2005), log-ratio values were calculated between each experimental condition and the baseline in the mu and beta frequency bands. Values smaller than 0 correspond to power reduction and values larger than 0 imply increased power of the mu rhythm.

To explore the scalp topography of mu (8–13 Hz) and beta (15–20 Hz) rhythms, data were first grand-averaged across trials for

each experimental condition in the whole scalp, and were subtracted from the baseline. Thereafter, the plots corresponding to pairs of conditions were subtracted (action language – abstract language; action observation – abstract language; and action language – action observation) to obtain the differential topography of mu and beta.

3. Results

3.1. Behavioral performance

The recognition scores were computed as the number of correct responses, ranging from 0 to 12 for each condition. Recognition was higher for the action observation condition ($M = 11.27$), followed by action language ($M = 9.44$), and abstract language ($M = 7.10$). The contrast between action language and abstract language ($t(28) = 6.59$, $p < .01$), and the contrast between action observation and abstract language ($t(28) = 7.2$, $p < .01$) were both statistically significant.

3.2. Electrophysiological effects

Fig. 1 shows the spectral power in the 5–30 Hz range for the five fronto-central electrodes, showing modulations in the mu oscillatory rhythms band (8–13 Hz approximately), namely, clear mu suppression in the action observation task and also in the action language, in comparison with the abstract language condition. There was also some modulation in the low beta oscillatory rhythms band (15–20 Hz) for the action observation and the action language conditions.

Fig. 2 depicts the log-ratio scores for the frequency band 8–13 Hz in the five fronto-central electrodes for the experimental conditions, showing clear mu suppression, especially in the electrodes C3, Cz and C4, for action observation and action language, but not for abstract language. To statistically explore these effects, a 3 Region (frontal, fronto-central, and parieto-occipital) x Condi-
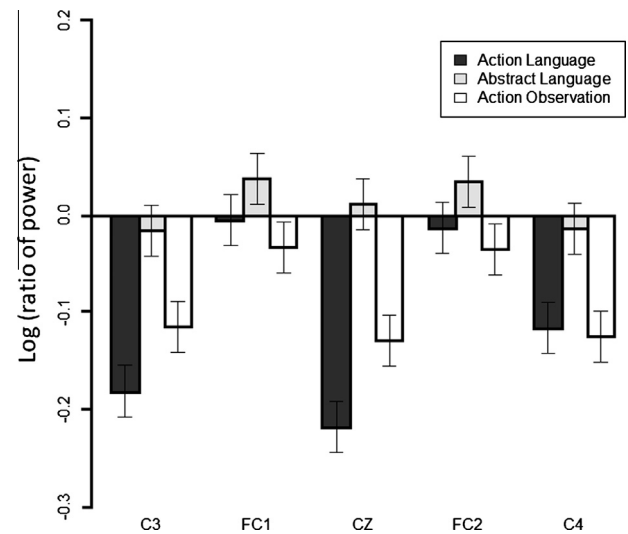

Fig. 2. Mean log-ratio (condition/baseline) values and confidence intervals in the mu rhythms band (8–13 Hz) in electrodes C3, FC1, Cz, FC2 and C4, as a function of action language, abstract language and action observation. Log-ratio values above 0 indicate increased spectral power, while values below 0 indicate reduction in spectral power.

tion (action language, abstract language, action observation) Analysis of Variance (ANOVA) was performed on the log-ratio of mu power by means of the ULLtoolbox implemented by Hernández (2012). Greenhouse–Geisser correction for sphericity was applied when necessary. There was a main effect of Region ($F(1,28) = 7.87$; $p < .003$; $\varepsilon = 0.78$, qualified by the Region × Condition interaction: ($F(1,28) = 3.89$; $p < .02$; $\varepsilon = 0.21$). To explore this interaction, separate ANOVAs were performed for each region, and significant differences among conditions only were found in the fronto-central region ($F(1,28) = 7.91$, $p < .001$). The simple effect test for this region showed that, in comparison with abstract
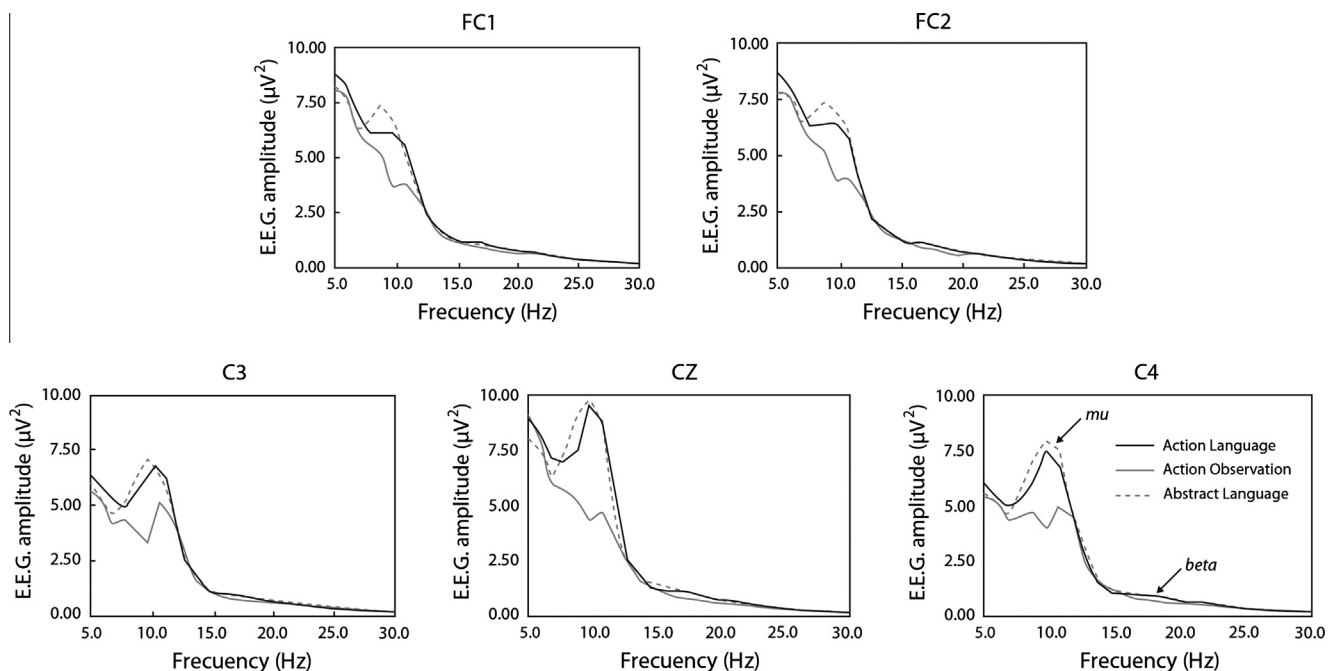

Fig. 1. Spectra power in electrodes C3, FC1, Cz, FC2, and C4. The average normalized power across the 5–30 Hz frequency range was calculated during action language (black solid line), abstract language (dash line) and action observation condition (gray solid line). Modulations occur in the mu frequency band (8–13 Hz) and in the beta lower frequency band (15–20 Hz).

language, action language ($t(28) = 3.29$, $p < .02$), and action observation ($t(28) = 3.59$, $p < .01$) showed mu power reduction. Fig. 2 suggests that the effects in the fronto-central region are clearer in the critical central electrodes. Therefore, a new 3 Electrode (C3, Cz, C4) × 3 Condition ANOVA was performed. Only a main effect of Condition was obtained ($F(1,28) = 6.90$; $p < .005$), indicating that the conditions differ in similar ways in these three electrodes. Notably, no significant differences were found between action language and action observation either in the fronto-central region or in any other. It is also remarkable that alpha log-ratio scores at the parieto-occipital region were negligible in the action ($M = -.032$) and the abstract language ($M = -.002$), and small in the action observation task ($M = -.22$). Most important, none of the pairwise comparisons in this region reached statistical significance, indicating that the experimental design succeeded in avoiding relevant alpha activity. The general pattern is straightforward: when participants observe real actions and when they understand action sentences, there is a reduction of oscillatory mu rhythms exclusively in the target fronto-central electrodes. By contrast, processing abstract language does not produce any reduction in these oscillatory rhythms.

The analyses performed on the log-ratio of lower oscillatory beta rhythms (15–20 Hz) only showed a main effect of Condition ($F(1,28) = 3.93$, $p < .04$; $\varepsilon = 0.71$). The simple effect tests showed that, compared to abstract language, only action observation showed significant beta power reduction ($t(28) = 2.41$, $p < .023$), whereas the contrast between action language and abstract language was just marginally significant ($t(28) = 1.86$, $p < .07$). Nonetheless, when the three regions were analyzed separately, differences emerged only in the fronto-central region ($F(1,28) = 4.96$, $p < .023$). The simple effect tests for this region confirmed that in comparison with abstract language, both action observation ($t(28) = 2.55$, $p < .016$) and action language ($t(28) = 2.05$, $p < .05$) exhibited significant beta power reduction.

The average beta power values in the fronto-central region were: action observation $M = -.60$, $SD = 1.05$; action language $M = -.29$, $SD = .87$; and abstract language $M = -.11$, $SD = .63$. Notably, no significant difference in beta power reduction was obtained in any contrast between action language and action observation confirming similar modulations in both action-related conditions.

Fig. 3 shows the topographies of the oscillatory rhythms in the frequency bands of mu (8–13 Hz) and beta (15–20 Hz), resulting from subtracting pairs of conditions. As expected, a strong mu around the central electrodes for the action language and for the action observation conditions remained after subtracting abstract language. A similar, although weaker, beta pattern can be also observed for action observation and, to lesser extent, for action language. By contrast, the mu and beta topographies after subtracting action observation from action language did not show any differential trend in these oscillatory rhythms.

4. Discussion

This EEG study explored whether mu and beta rhythms, generally considered as electrophysiological markers of motor processes in the brain, are modulated by the comprehension of action language. Complementary to the EEG data, behavioral data (recognition task) were also collected and analyzed. The recognition task showed better performance both in action observation, and in action language than in abstract language. These findings are compatible with some well-known results described in the classical literature on verbal learning (Kounios & Holcomb, 1994; Paivio, 1971, 1986). In these studies, memory for concrete words has been reported as being better than memory for abstract words, and memory for pictorial materials is sometimes better than memory for verbal materials (Paivio, 1971, 1986). Several theories consider these results as evidence of two kinds of mental representations: sensorimotor and linguistic (Barsalou, 2008; Paivio, 1971, 1986).
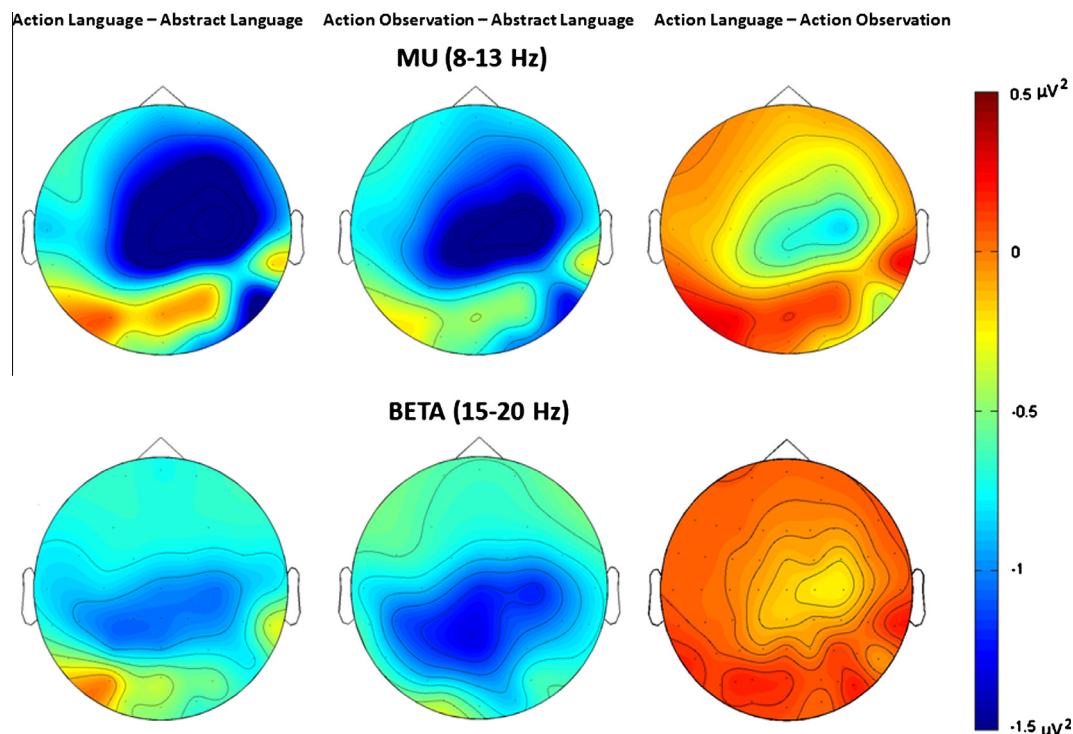

Fig. 3. Scalp distribution of the oscillatory rhythms in the 8–13 Hz frequency band, and in the 15–20 Hz frequency band, calculated by subtracting the mean EEG power between pairs of conditions. The differences between Action language and Abstract language (leftward plots), and between Action observation and Abstract language (central plots), indicate that both action conditions show similar activity in the mu -and beta- related electrodes. Instead, Action language and Action observation (rightward plot) do not show any difference in these oscillatory bands.

Paivio's dual coding hypothesis, for instance, proposes that concrete words (usually referring to visual perceptual objects) are better remembered than abstract words, because the former are encoded by both the mental imagery (a sensorimotor code) and the verbal system, whereas the latter are encoded only by the verbal system. In the same vein, Barsalou's (2008) LASS theory consider that encoding concrete concepts involves modal simulations, including motoric simulations of actions, whereas abstract concepts are mainly encoded by the linguistic system. Modal simulations produce deeper representations than linguistic encoding, resulting in better memory. The current experiment differs, however, from these classical studies in that we employed action or abstract verbs embedded in sentences, rather than lists of concrete and abstract nouns. Moreover, the analysis of oscillatory rhythms of the EEG suggests that we are not dealing here with general concreteness effects, because we observed an electrophysiological phenomenon specifically associated with the motor rather than the perceptual quality of action language.

As Figs. 1 and 2 illustrate, the spectral analysis of the EEG showed a clear suppression of mu oscillatory rhythms for the action observation condition and, most remarkably, also for action language. By contrast, mu rhythms were not modulated by abstract language, ruling out the possibility that mu suppression was a general phenomenon associated with language processing. Mu rhythms modulation was virtually identical in action language and action observation, despite the fact that the action and abstract sentences used in the study shared the same linguistic code, and even had identical syntactic structure and similar word frequency, whereas the action sentences and the action video clips differ in many respects, such as the input modality (auditory vs. visual) and the coding system (verbal vs. perceptual). As mentioned in the Introduction, the modulation of mu has been associated with downstream premotor cortex modulation of primary sensorimotor areas (Hari et al., 1997; Muthukumaraswamy et al., 2004; Taniguchi et al., 2000), and with activity in the SMA (Babiloni et al., 1999). However, we cannot entirely assume these interpretations for the current experiment, because oscillatory rhythms recorded from individual electrodes in the scalp do not allow dissociating specific cortical sources. In any case, the fact that mu suppression caused by action language was similar to mu suppression caused by action observation suggests that understanding action language involves the activation of *motoric* brain areas. Furthermore, action language did not differentially modulate oscillatory rhythms at the parieto-occipital electrodes, suggesting that alpha occipital activity played a minor role (if any) in the observed modulation of mu rhythms, thus reinforcing the idea that this modulation was a genuine product of motor processes in the brain. To conclude, these results are consistent with the idea that understanding action language is embodied, in the sense that it engages sensorimotor brain substrates.

In the last few years, mu suppression has been associated with activity in the mirror neuron system (Muthukumaraswamy et al., 2004; Perry & Bentin, 2009; Pfurtscheller et al., 1997; Ulloa & Pineda, 2007). One reason to believe this is that mu rhythms are modulated not only by performing actions but also by observing another's actions (Mukamel et al., 2010; Rizzolatti & Craighero, 2004). In this study we have replicated this phenomenon, as we obtained mu suppression while participants observed video clips of manual actions recorded from an external "onlooker" perspective. Most remarkably, we also obtained mu suppression while participants listened to action sentences. This could be considered evidence that mirror neurons are also involved in action language. But a more conservative interpretation is possible: mu suppression could be due to the activity of ordinary motor neurons rather than mirror neurons. The linguistic perspective was marked here by the first person of verbs (e.g., *I cut the bread*), which may induce the

participant to take an actor's point of view. Namely, the participant would simulate the action as performed by herself rather than as performed by another person. If this were the case, mirror neurons, which by definition react to another's actions, would not be directly involved. However, it has recently been reported that readers could adopt an external perspective when first person sentences are embedded in short discourse context (Brunyé, Ditman, Mahoney, Augustyn, & Taylor, 2009). In this experiment there was no discourse context, but the first person sentences were presented aurally, which could induce participants to simulate the action as performed by another person (the speaker), and therefore mirror neurons could be involved to some extent.

We do not have enough information in this experiment to distinguish between the two aforementioned hypotheses: mu as reflecting ordinary motor neuron activation, or mu as a marker of mirror neuron activation. To reveal the role eventually played by mirror neurons in action language, new studies will be necessary, in which the external and the egocentric perspectives of language are more neatly manipulated. For instance, including third person (*she* cut the bread) and second person sentences (*you* cut the bread), would unambiguously induce external or internal agency, respectively (Brunyé et al., 2009; Ditman, Brunyé, Mahoney, & Taylor, 2010). Another important issue not covered in this study is the determination of the temporal course of motor resonance associated with action language by means of time–frequency analysis of mu oscillatory rhythms. In this study we chose women as participants, because they show clearer mu suppression than men (Cheng et al., 2008). This was convenient for an exploratory study on language-related mu suppression, but this decision puts some limits to the generality of our findings. Finally, we cannot establish from this study whether the motor activity underlying action language, revealed by modulations in oscillatory mu rhythms, plays any functional role in linguistic meaning or is just an epiphenomenon, as some authors argue (e.g., Mahon & Caramazza, 2008). Further researches might be required to solve all these issues.

There was also a weaker suppression in lower beta rhythms, which was similar in the action observation condition and in the action language condition. This is not strange, as beta desynchronization has been reported as occurring in parallel to mu desynchronization in the same central electrodes during motor tasks (Pfurtscheller & Lopes da Silva, 1999), action observation tasks (Orgs, Dombrowski, Heil, & Jansen-Osmann, 2008), and motor imagery tasks (McFarland et al., 2000). The only beta modulation reported in the literature of action language was the aforementioned study by van Elk et al. (2010). They found a parallel mu and beta desynchronization, especially strong when the action verbs appeared in sentences with an animal agent, compared to verbs in sentences with a human agent. Also beta, but not mu, was sensitive to the sentences cloze probability. However, van Elk et al.' study is not directly comparable to the current one, because both studies markedly differ in their materials and designs. Furthermore, they found higher beta modulation (20–30 Hz), whereas here we only found modulation for the lower beta band (15–20 Hz). The functional role of beta rhythms in action processes is not yet well understood, nor is their functional relation with the mu rhythms that occur in parallel. It has been proposed that lower beta oscillation (around 20 Hz) may be a first harmonic of the mu rhythm although their topographical distributions sometimes slightly differs, suggesting that different neural populations are involved (Pineda, 2005). In any case, according to the literature, we can consider that both the mu and beta desynchronization obtained here are typical of motor processes in the brain.

In spite of the manual character of the actions and the fact that participants were right-handed, bilateral suppression in both action language and action observation was found in this study. This is consistent with other results reported in the literature, which

also showed similar mu and beta suppression in both hemispheres (e.g., Muthukumaraswamy et al., 2004; Pineda, 2005). A possible account for this hemispheric symmetry is that most of our manual actions require combining movements of the two hands, even though the right hand usually has a more active role than the left hand (e.g., in cutting the bread, the right hand moves the knife while the left hand holds the bread still).

5. Conclusions

To summarize, the present study highlights similarities of mu modulations and, to lesser extent, of beta modulations during the processing of action language and nonlinguistic action stimuli. Such modulations of mu and beta rhythms (suppression), not observed in abstract language, are compatible with the idea that understanding action language involves motor simulations in the brain. This lends support to neurological embodiment theories, which defend that linguistic meaning goes beyond the activation of the classical perisylvian areas (Broca and Wernicke), involving the activation or "resonance" of other regions in the sensorimotor cortex that overlap those involved in processing real world experience.

Acknowledgments

References

Aziz-Zadeh, L., Wilson, S. M., Rizzolatti, G., & Iacoboni, M. (2006). Congruent embodied representations for visually presented actions and linguistic phrases describing actions. *Current Biology, 16*, 1–6.

Babiloni, C., Carducci, F., Cincotti, F., Rossini, P. M., Neuper, C., Pfurtscheller, G., et al. (1999). Human movement-related potentials vs desynchronization of EEG alpha rhythm: a high-resolution EEG study. *Neuroimage, 10*, 658–665.

Barsalou, L. M. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645.

Brunyé, T. T., Ditman, T., Mahoney, C. R., Augustyn, J. S., & Taylor, H. A. (2009). When you and I share perspectives: Pronouns modulate perspective-taking during narrative comprehension. *Psychological Science, 20*, 27–32.

Cheng, Y., Lee, P. L., Yang, Ch. Y., Lin, Ch. P., Hung, D., & Decety, J. (2008). Gender differences in the mu rhythm of the human mirror-neuron system. *PLos ONE, 3*, 1–7.

Cochin, S., Barthelemy, C., Roux, S., & Martineau, J. (1998). Perception of emotion and EEG activity in human adults. *Electroencephalography Clinical Neurophysiology, 107*, 287–295.

Davis, C. J., & Perea, M. (2005). BuscaPalabras: A program for deriving orthographic and phonological neighborhood statistics and other psycholinguistic indices in Spanish. *Behavior Research Methods, 37*, 665–671.

De Vega, M., Glenberg, A. M., & Graesser, A. C. (2008). *Symbols, embodiment, and meaning*. Oxford, UK: University Press.

Ditman, T., Brunyé, T. T., Mahoney, C. R., & Taylor, H. A. (2010). Simulating an enactment effect: Pronouns guide action simulation during narrative comprehension. *Cognition, 115*, 172–178.

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *The Quarterly Journal of Experimental Psychology., 61*, 825–850.

Gastaut, H. (1952). Etude électrocorticographique de la réactivité des rythmes rolandiques. *Revue Neurologique, 87*, 176–182.

Glenberg, A. M., & Gallese, V. (2011). Action-based language: A theory of language acquisition, comprehension, and production. *Cortex.* http://dx.doi.org/10.1016/j.cortex.2011.04.010.

Hari, R., Salmelin, R., Mäkelä, J. P., Salenius, S., & Helle, M. (1997). Magnetoencephalographic cortical rhythms. *International Journal of Psychophysiology, 26*, 51–62.

Hauk, O., & Pulvermüller, F. (2004). Neurophysiological distinction of action words in the fronto-central cortex. *Human Brain Mapping, 21*, 191–201.

Hernández, J. A. 2012. ULLToolbox. <https://sites.google.com/site/ullrtoolbox/>.

Kounios, J., & Holcomb, P. (1994). Concreteness effects in semantic processing: ERP evidence supporting dual–coding theory. *Journal of Experimental Psychology: Learning, Memory, and Cognition., 20*, 804–823.

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology – Paris, 102*, 59–70.

McFarland, D. J., Miner, L. A., Vaughan, T. M., & Wolpaw, J. R. (2000). Mu and Beta rhythm topographies during motor imagery and actual movements. *Brain Topography, 12*, 177–186.

Moody, C. L., & Gennari, S. P. (2010). Effects of implied physical effort in sensory-motor and pre-frontal cortex during language comprehension. *NeuroImage, 49*, 782–793.

Mukamel, R., Ekstrom, A. D., Kaplan, J., Iacoboni, M., & Fried, I. (2010). Single-neuron responses in humans during execution and observation of actions. *Current Biology, 20*, 1–7.

Muthukumaraswamy, S. D., Johnson, B. W., & McNair, N. A. (2004). Mu rhythm modulation during observation of an object-directed grasp. *Cognitive Brain Research, 19*, 195–201.

Oberman, L. M., Hubbard, E. M., McCleery, J. P., Altschuler, E. L., Ramachandran, V. S., & Pineda, J. A. (2005). EEG evidence for mirror neuron dysfunction in autism spectrum disorders. *Cognitive Brain Research, 24*, 190–198.

Oberman, L. M., Pineda, J. A., & Ramachandran, V. S. (2007). The human mirror neuron system: A link between action observation and social skills. *Social Cognitive and Affective Neuroscience, 2*, 62–66.

Orgs, G., Dombrowski, J. H., Heil, M., & Jansen-Osmann, P. (2008). Expertise in dance modulates alpha/beta event-related desynchronization during action observation. *European Journal of Neuroscience, 27*, 3380–3384.

Paivio, A. (1971). *Imagery and verbal processes*. New York: Holt, Rinehart & Winston.

Paivio, A. (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.

Perry, A., & Bentin, S. (2009). Mirror activity in the human brain while observing hand movements: A comparison between EEG desynchronization in the mu-range and previous fMRI results. *Brain Research, 1282*, 126–132.

Pfurtscheller, G., Brunner, C., Schlögl, A., & Lopes da Silva, F. H. (2006). Mu rhythm (de)synchronization and EEG single-trial classification of different motor imagery tasks. *Neuroimage, 31*, 153–159.

Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology, 110*, 1842–1857.

Pfurtscheller, G., Neuper, C., Andrew, C., & Edlinger, G. (1997). Foot and hand area mu rhythms. *International Journal Psychophysiol, 26*, 121–135.

Pineda, J. A. (2005). The functional significance of mu rhythms: Translating "seeing" and "hearing" into "doing". *Brain Research Reviews, 50*, 57–68.

Pineda, J. A., & Oberman, L. M. (2006). What goads cigarette smokers to smoke? Neural adaptation and the mirror neuron system. *Brain Research, 1121*, 128–135.

Pulvermüller, F. (1996). Hebb's concept of cell assemblies and the psychophysiology of word processing. *Psychophysiology, 33*, 317–333.

Pulvermüller, F., Hauk, O., Nikulin, V. V., & Ilmoniemi, R. J. (2005). Functional links between motor and language systems. *European Journal of Neuroscience, 21*, 793–797.

Quin, L., & He, B. (2005). A wavelet-based time–frequency analysis approach for classification of motor imagery for brain–computer interface applications. *Journal of Neural Engineering, 2*, 65–72.

Raposo, A., Moss, H. E., Stamatakis, E. A., & Tyler, L. K. (2009). Modulation of motor and premotor cortices, by actions, actions words and action sentences. *Neuropsychologia, 47*, 388–396.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review Neuroscience, 27*, 169–192.

Rizzolatti, G., & Luppino, G. (2001). The cortical motor system. *Neuron, 31*, 889–901.

Taniguchi, M., Kato, A., Fujita, N., Hirata, M., Tanaka, H., Kihara, T., et al. (2000). Movement-related desynchronization of the cerebral cortex studied with spatially filtered magnetoencephalography. *Neuroimage, 12*, 298–306.

Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo, P., et al. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *Journal of Cognitive Neuroscience, 17*, 273–281.

Ulloa, E. R., & Pineda, J. A. (2007). Recognition of point-light biological motion: Mu rhythms and mirror neuron activity. *Behavioural Brain Research, 183*, 188–194.

van Elk, M., van Schie, H. T., Zwaan, R. A., & Bekkering, H. (2010). The functional role of motor activation in language processing: Motor cortical oscillations support lexical-semantic retrieval. *Neuroimage, 50*, 665–677.