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Muscle activation in semantic processing: An electromyography approach

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ABSTRACT

In this study, we focus on the spontaneous activity related to manual verbs to determine the extent to which semantic processing of manual verbs affects spontaneous arm muscle activity. For this purpose, we recorded the arm's electromyographic activity while participants read manual and non-manual verbs, focusing their attention on the semantic content or a specific letter. In addition, we manipulated the arm position (in front of the body or behind the back) to observe postural priming effects for spontaneous muscle activity. Our results show that when arms were placed forward and the attention was directed to the semantic content, there was an enhanced spontaneous activation. Our results suggest that spontaneous motor responses are related to the involvement of the motor system in action language comprehension as suggested by language embodiment theories.

1. Introduction

Embodied cognition (e.g., Gallese & Lakoff, 2005) highlights the relevance of the person's body to explain cognition, which depends on the sensorimotor experiences of the entire body (Shapiro, 2014; Varela, Thompson, & Rosch, 1991). In this sense, cognition is distributed across the body, brain and environment. The evidence from behavioral experiments, neuroimaging, motor pathologies and spontaneous motor activity shows that language processing involves sensorimotor systems, suggesting that language is embodied (Buccino, Colagè, Gobbi, & Bonaccorso, 2016; Ellis, 2019). Here we summarize some of this evidence.

First, behavioral experiments have supported that people respond faster when the direction of the motor response is congruent with the direction of an action described in an action sentence, in comparison with incongruent conditions (Ambrosini, Scorolli, Borghi, & Costantini, 2012; Glenberg & Kaschak, 2002; van Dam, Brazil, Bekkering, & Rueschemeyer, 2014).

Second, neuroimaging studies have shown that the presentation of verbs activates different motor brain structures (Horoufchin, Bzdok, Buccino, Borghi, & Binkofski, 2018; Pulvermüller, Härle, & Hummel, 2001; van Dam, Rueschemeyer, & Bekkering, 2010). For example, with functional magnetic resonance imaging (fMRI) recordings, Hauk, Johnsrude, and Pulvermüller (2004) found that presenting action words (e.g., kick) enhanced the activation of the motor and premotor cortex (apart from left inferior cortex), and the same occurred when movements related to an action word were performed.

Third, patients with motor pathologies such as Parkinson's disease suffer impairment in the production of action verbs (Bocanegra et al., 2015) as well as processing (Fernandino et al., 2013), with this delay in processing of action verbs being stronger for words with higher motion content (Bocanegra et al., 2017).

The most recent evidence in spontaneous motor activity studies has been related to the study of the action sentence processing. For example, sentences related to high physical effort lead to higher postural sway than low physical effort sentences (Stins, Marmolejo-Ramos, Hulzinga, Wenker, & Cañal-Bruland, 2017), suggesting that motor periphery is intertwined with semantic processing (and thus causes increased postural activity). Research into the role of facial muscles and their relationship with linguistic material related to affective content has reached similar conclusions. For example, Niedenthal, Winkielman, Mondillon, and Vermeulen (2009) asked their participants to focus on the emotional content of the word, while a control group had to indicate the word's typeface. Only the first group showed spontaneous electromyography activity in the facial muscles related to emotion (e.g., elevator muscle was activated for words related to disgust).

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Importantly, this study pointed out that spontaneous elevation from the muscle resting state was present only when words were actively attended to, similarly to other findings (e.g., Fino, Menegatti, Avenanti, & Rubini, 2016). However, the research on the effect of language processing on spontaneous muscle activation has not reached the same conclusion as the aforementioned emotional studies.

To our knowledge, only one study has addressed this issue. In the study of Stins and Beek (2013), participants were lying supine on a massage table in a relaxed position; they had to read a sequence of action verbs related to arm or leg movements (e.g., throw and walk, respectively) and abstract verbs unrelated with body actions (e.g., hate). Following previous research, deep semantic processing of the verb has been considered fundamental to obtaining spontaneous muscle activity for emotion (Niedenthal et al., 2009). In this vein, for superficial semantic processing, Stins and Beek (2013) instructed participants to say "yes" if the verb contained the letter 'R' and "no" when the letter 'R' was absent. For deep semantic processing, verbs related to arm and leg movements were presented in two blocks. For example, in a "manual" block, the participants had to say "yes" when the verb contained a manual action and "no" when it did not (i.e., leg or abstract verbs). In the "leg" block, the participants had to say "yes" when the verb contained a foot action, and so on respectively. Right muscles for arm and leg were measured (anterior deltoid and biceps brachii, and tibialis anterior and vastus medialis for arm and leg, respectively). They hypothesized that verb processing related to arm and leg actions would increase the electromyographic activity of the aforementioned muscles due to the involvement of motor somatotopy in semantic processing (i.e., deep semantic processing). Contrary to the expected results, the authors found that semantic processing had little (and unexpected) effect on a muscular level. The authors observed an electromyographic activity reduction for the congruent conditions, such as arm words with arm muscles, only when there was deep semantic processing of the word. Therefore, this evidence suggests that semantic processing modulates spontaneous muscle activity. However, this effect was only found when data from the four measured muscles were collapsed. Thus, these data are not consistent at all. More importantly, the decrease in activation was unexpected. The authors offered a tentative explanation for these results where the supine and relaxed position could suppress the motor activity related to semantic processing. In fact, recent research confirms this hypothesis. In a more recent study, Stins et al. (2017) found an effect on body sway when the participants were standing. Specifically, they observed greater postural sway for high physical effort sentences compared to low or absent physical effort sentences (considering that changes in body sway are necessarily accompanied by changes in muscle activity). These results suggest that language processing might indeed produce spontaneous muscle activation when the body position primes the motor action, as in previous studies where arm posture was manipulated. For example, Yasuda, Stins, and Higuchi (2017) found delayed responses for manual action verbs and non-manual action verbs when the arm posture was constrained.

1.1. Present study

Arms and manual actions are inherent in human communication and language processing, and this is more evident when it is observed that hand gestures are relevant information integrated into language processing (Cornejo et al., 2009; Hostetter & Alibali, 2008; Kelly, Healey, Özyürek, & Holler, 2015). For example, it has been shown that gestures and speech interact to enhance language comprehension (Kelly, Özyürek, & Maris, 2010). In this respect, figurative language is said to be influenced by gestures in non-native speakers (Ibáñez et al., 2010) (See also Cevasco and Marmolejo Ramos (2013) to know more about psycholinguistic embodiment models where hand gestures have been highlighted in language comprehension and production). Here we propose that there is a link between body dynamics and language processing that could be reflected in arm actions (García & Ibáñez, 2016).

The aim of the present research was to determine the extent to which semantic processing of manual verbs affects spontaneous arm muscle activity, reflecting a simulation of the action. The current study was directly motivated by the study performed by Stins and Beek (2013). We used a similar design, but manipulating the participant's posture to prime the motor action. In this context, a similar manipulation of Yasuda et al. (2017) is proposed. Specifically, arms were placed forward on a resting table or both kept behind the participants' back. We hypothesized an enhanced muscle activation when there was postural priming for the action (i.e., arms forward) and when words were actively processed to do so, in line with previous literature on emotional processing (e.g., Niedenthal et al., 2009). The results of this study will aid in understanding the processing of semantic information and its relationship with spontaneous motor activity. Additionally, these results provide evidence to support the notion that action language processing is enacted in the body according to the embodied language theory.

2. Material and methods

2.1. Participants

The sample consisted of 36 participants (18 women; M age = 21.5, SD = 2.2). We calculated this sample size using a statistical power analysis (G*power 3.1.9.2) for a repeated measures ANOVA (within factors) with a medium effect size, setting statistical significance at $\alpha = .05$ and a power of 0.8. All participants had normal or corrected to normal vision. All were right-handed as assessed with the Edinburgh Handedness Inventory (Oldfield, 1971) with a cutoff score of 70 (following Schachter, 2002). They were Spanish native speakers. All participants provided written informed consent prior to their participation. All procedures were conducted in accordance with the Declaration of Helsinki and the ethical guidelines of the Human Research Advisory Committee at the Universidad de La Frontera.

2.2. Stimuli

A set of 52 verbs was presented in the experimental task: 26 verbs were manual actions, while the other 26 verbs were non-actions. The experimental set of stimuli was previously supported by the procedure employed by Yasuda et al. (2017). A total of 30 participants (women = 15; M age = 20.2, SD = 1.1) completed a questionnaire to rate 70 verbs according to whether they considered the verb a manual or a non-manual action. Participants were instructed to rate each verb on an ordinal scale, where zero is 'not related to a manual action at all', and 5 is 'strongly related to a manual action'. The manual verbs were rated much higher than the chosen non-manual verbs. We chose the 26 manual verbs with a higher rating (M = 4.62, SD = 0.15) and the 26 non-manual verbs with a lower rating (M = 1.38, SD = 0.22) for the current experiment. Similar ratings were obtained from the participants of this study (M = 4.82, SD = 0.26 for manual verbs and M = 1.26, SD = 0.35 for non-manual action). See Appendix 1 for further details.

2.3. Procedure

The stimuli were presented on a PC (Intel Core i5), controlled by the E-prime software (Schneider, Eschman, & Zuccolotto, 2002). The vowel data collection was measured by a Chronos multifunctional response device controlled by E-Prime. Verbs were presented randomly for 3 s and followed by a 3-second black screen. Four different blocks counterbalanced following a Latin square design were presented to the participants. In two conditions, participants had to solve the task with superficial processing of the words (superficial processing condition). For this, half of the participants were instructed to say "yes" when the letter "O" appeared and "no" when it did not. The other half were instructed to say "no" when the letter "O" appeared and "yes" when it did not. In another two conditions, participants had to solve the task with deep processing of the words owing to their semantic category (deep processing condition). For this, half of the participants were instructed to say "yes" when the word was a verb involving an arm action and "no" when it was a non-action verb. The other half was instructed to say "yes" when it was a non-action verb word and "no" when the word was a verb involving an arm action. Importantly, we did not emphasize speed in the response.

While participants solved the task, their arms could be placed in front or behind the back. These conditions involve the hypothesized postural priming for spontaneous muscle activity. For arms forward and to maintain the same posture for all the participants, they were seated on a chair adjusted to a 90-degree angle of elbow flexion in the sagittal plane and the forearms with a 30-degree angle in the horizontal plane, placing their hands on two hand silhouettes. For arms behind the back, participants placed the dorsal area of extended hands about the height of the lumbar muscles with a 90-degree angle at the elbow (similar to Yasuda et al., 2017). After the subject placed their arms in the aforementioned postures, the screen was individually adjusted to be placed 40 cm from the participants at eye level (see Fig. 1). Participants were instructed to stay relaxed and not move their limbs, while watching the sequence of verbs presented on the screen. Prior to each block, it was verified that participants were relaxed in both positions and that muscles did not maintain an isometric contraction.

All subjects were given 12 practice trials followed by four blocks of 52 experimental trials. In each of the four blocks, the same set of 52 verbs (26 manual and 26 non-manual with the letter O included in the half of them) were presented in random order. Participants had 1 min of rest between blocks. The experiment took about 30 min.

2.4. Electromyography recording

Electromyography (EMG) was recorded with a wireless EMG measurement module from BIOPAC Inc., with active Ag/AgCl electrodes, using a sampling frequency of 2000 Hz and a gain of 1000. The electrical activity from the anterior deltoid, biceps brachialis and extensor common muscle of the fingers on the right hand were measured (See Fig. 2). We placed two disposable bipolar electrodes per muscle, 1 cm in diameter and 2 cm between them, according to the recommendations of the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) project (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Thus, after completing each experimental session, additional EMG data were recorded during maximum voluntary isometric contractions (MVIC) of each muscle to assess the relative magnitude of muscle activation. It should be noted that the EMG signal must be individually normalized per muscle and participant (Halaki & Ginn, 2012) to compare EMG activity in the same muscle on different days or in different individuals, or to compare EMG activity between muscles. For this, a trained physiotherapist applied manual resistance according to the standard muscle test protocol (Kendall, McCreary, & Provance, 1993). Importantly, EMG recording encompasses the interval between the presentation of the verb and 2000 ms after the verbal response. Thus, a time window detection algorithm associated with the presentation of the stimulus and its respective response was generated. This procedure was chosen to ensure that the recorded muscle activity was related to the time associated with the presentation of the stimulus and its respective response.

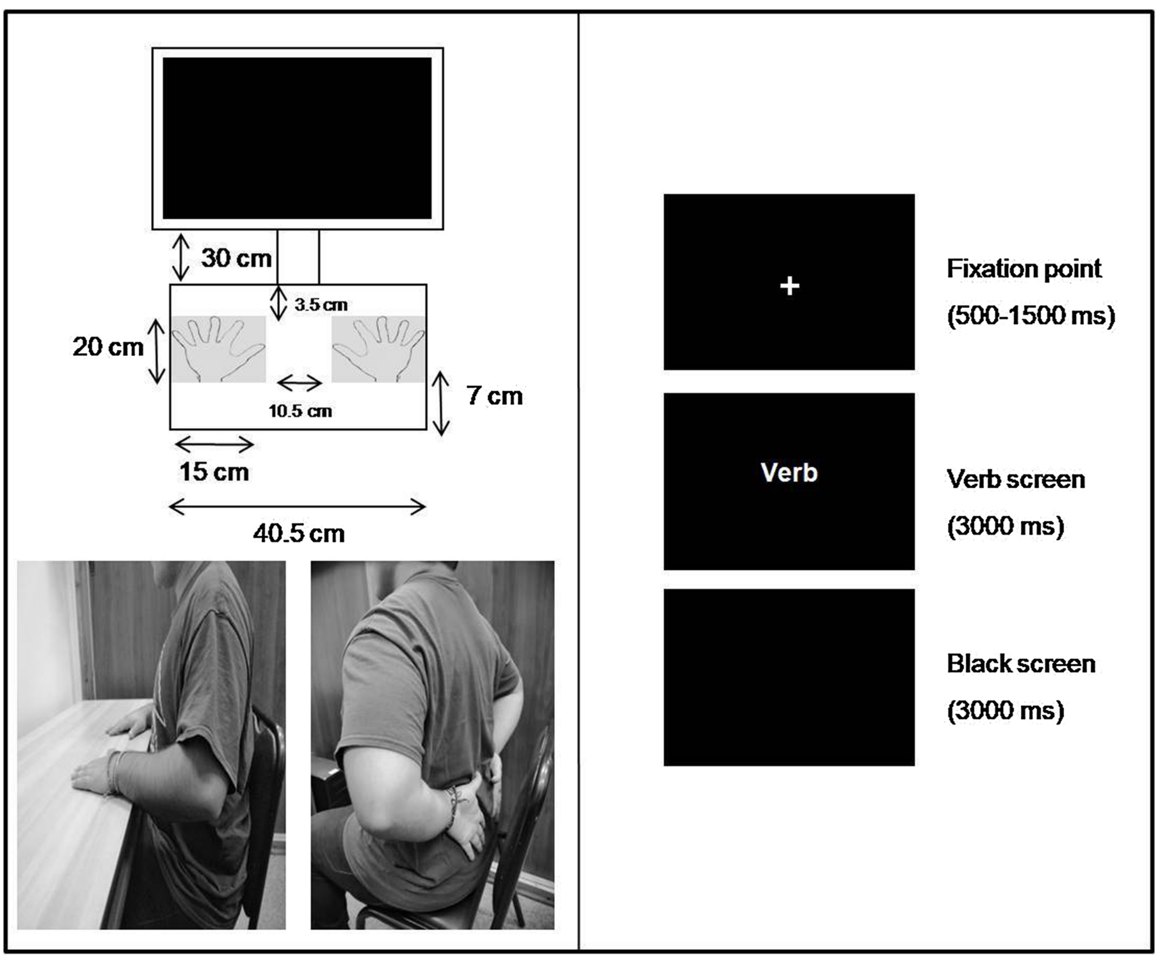

Fig. 1. Left panel: Experimental setup, Right panel: Sequence of events in an experimental trial.

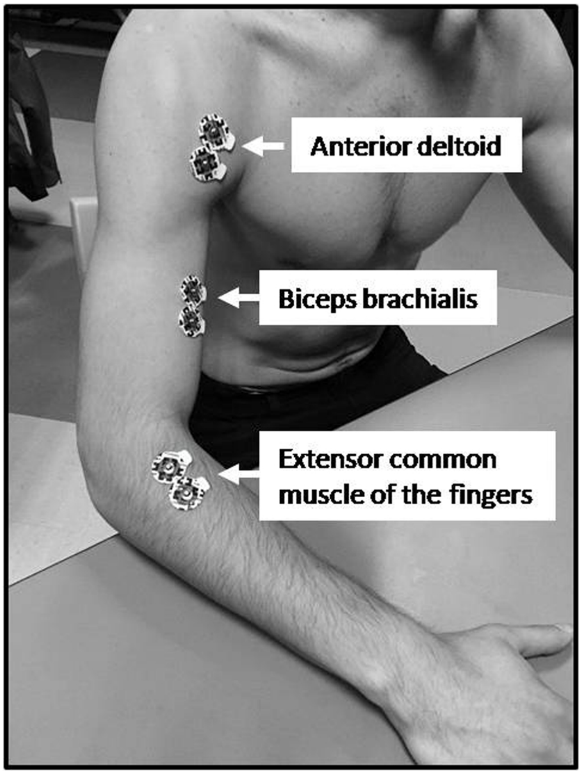

Fig. 2. Location of the surface electrodes and measured muscles.

2.5. Data analysis

Mean muscle activation (defined as the percentage of muscle activation related to MVIC) was recorded for each of the three measured muscles. Although we did not emphasize speed in the verbal response, the vocal reaction time and vocal errors (trials where the participant responded incorrectly) were measured. Prior to conducting analyses, vocal errors (4.84 %) were excluded and analyzed separately.

Factorial repeated measures ANOVAs (SPSS 25 and R Core Team, 2019) and robust ANOVAs (with the corresponding all pairwise post hoc comparisons; R Package WRS2 of Mair & Wilcox, 2016) were carried out on: (a) arms posture (arms in front of the body vs. arms behind the back), (b) semantic processing (superficial vs. deep) and (c) type of verb (manual vs. non-manual). For the mean of muscle activity and in order to reduce the overall likelihood of Type I errors, we configured Bonferroni corrections on the *p* values. Results were therefore considered significant at $p < 0.05/3$, i.e., $p < 0.017$ (three ANOVAs were carried out; one per measured muscle).

Data processing of the surface EMG signal was performed using an algorithm in the MatlabR2016a software (The MathWorks, 2012). The signal was digitally corrected by subtracting the mean of the signal from a zero-centered mean. We used a Notch filter to remove the 50 Hz component and a Butterworth filter with cut frequencies between 10 Hz and 450 Hz. The International Society of Electrophysiology and Kinesiology proposes the use of low pass filters between 5 − 100 Hz for smoothing through the linear envelope (Merletti & Di Torino, 1999), highlighting that a very low-cut filter could eventually remove signal components that effectively correspond to muscle activity and could skew the results. Then, the amplitude normalization with respect to the maximum voluntary contraction (MVIC) was performed and the root mean square (RMS) of the signal was calculated with a sliding window technique 20 samples wide. Every EMG burst was isolated by calculating the mean and the maximum amplitude of the signal.

3. Results

3.1. %MVIC for anterior deltoid

For %MVIC for the anterior deltoid (ANOVA arms posture × semantic processing × type of verb, see Panel A of Fig. 3), the robust test was significant, $F(1.09, 22.87) = 92.07$, $p < 0.001$. The main effect of arms posture was significant, $F(1, 35) = 82.02$, $p < 0.001$, $\eta_p^2 = 0.70$. The main effect of semantic processing was marginally significant, $F(1, 35) = 5.84$, $p = 0.021$, $\eta_p^2 = 0.14$, with more activation for the deep semantic processing condition than the superficial semantic processing condition (0.59 % vs. 0.54 %). The main effect of type of verb was significant, $F(1, 35) = 72.08$, $p < 0.001$, $\eta_p^2 = 0.67$. All interaction within-subject effects were significant (η_p^2 ranged from 0.40 to 0.73, e.g., the interaction between all main effects was: $F(1, 35) = 66.24$, $p < 0.001$, $\eta_p^2 = 0.65$). Regarding this last interaction, planned comparisons showed that for the arms behind the back condition there was no interaction between semantic processing and type of verb ($p = 0.666$), whereas for the arms in front of the body condition this interaction was significant ($p < 0.001$). Thus, for the arms in front of the body condition, the effect of type of verb was not significant for the superficial semantic processing condition ($p = 0.905$), but was significant for the deep semantic processing condition ($p < 0.001$), with more activation for the manual verbs condition than for the non-manual verbs condition ($\eta_p^2 = 0.77$; 0.48 % vs. 0.27 % respectively).

3.2. %MVIC for biceps brachialis

For %MVIC for biceps brachialis (ANOVA arms posture × semantic processing × type of verb, see Panel B of Fig. 3), the robust test was significant, $F(1.09, 22.81) = 42.46$, $p < 0.001$. The main effect of arms posture was significant, $F(1, 35) = 32{,}49$, $p < 0.001$, $\eta_p^2 = 0.48$, with more activation in the arms behind the back condition than the arms in front of the body condition (0.88 % vs. 0.28 %, respectively). The main effects of semantic processing and type of verb were not significant ($F(1, 35) = 2.10$, $p = 0.156$, $\eta_p^2 = 0.06$ and $F(1, 35) = 0.004$, $p = 0.952$, $\eta_p^2 = 0.00$, respectively). No other interaction for this muscle was significant.

3.3. %MVIC for extensor common muscle of the fingers

For %MVIC for extensor common muscle of the fingers (ANOVA arms posture × semantic processing × type of verb, see Panel A of Fig. 3), the robust test was significant, $F(1.76, 37.04) = 100.73$, $p < 0.001$. The main effect of arms posture was significant, $F(1, 35) = 98.65$, $p < 0.001$, $\eta_p^2 = 0.74$. The main effect of semantic processing was marginally significant, $F(1, 35) = 5.24$, $p = 0.028$, $\eta_p^2 = 0.13$ The main effect of type of verb was significant, $F(1, 35) = 166.10$, $p < 0.001$, $\eta_p^2 = 0.83$. Except the arm posture x semantic processing interaction, the rest of the within-subject effects were significant (η_p^2 ranged from 0.74 to 0.81, e.g., the interaction between all the main effects was: $F(1, 35) = 128.20$, $p < 0.001$, $\eta_p^2 = 0.79$. Regarding this last interaction, planned comparisons showed that for the arms behind the back condition there was no interaction between semantic processing and type of verb ($p = 0.291$), whereas for the arms in front of the body condition this interaction was significant ($\eta_p^2 = 0.91$, $p < 0.001$). For the in front of the body condition, the effect of type of verb was not significant for the superficial semantic processing condition ($p = 0.909$), but it was significant for the deep semantic processing condition ($p < 0.001$), with more activation for manual verbs than for non-manual verbs ($\eta_p^2 = 0.95$; 0.54 % vs. 0.31 % respectively)

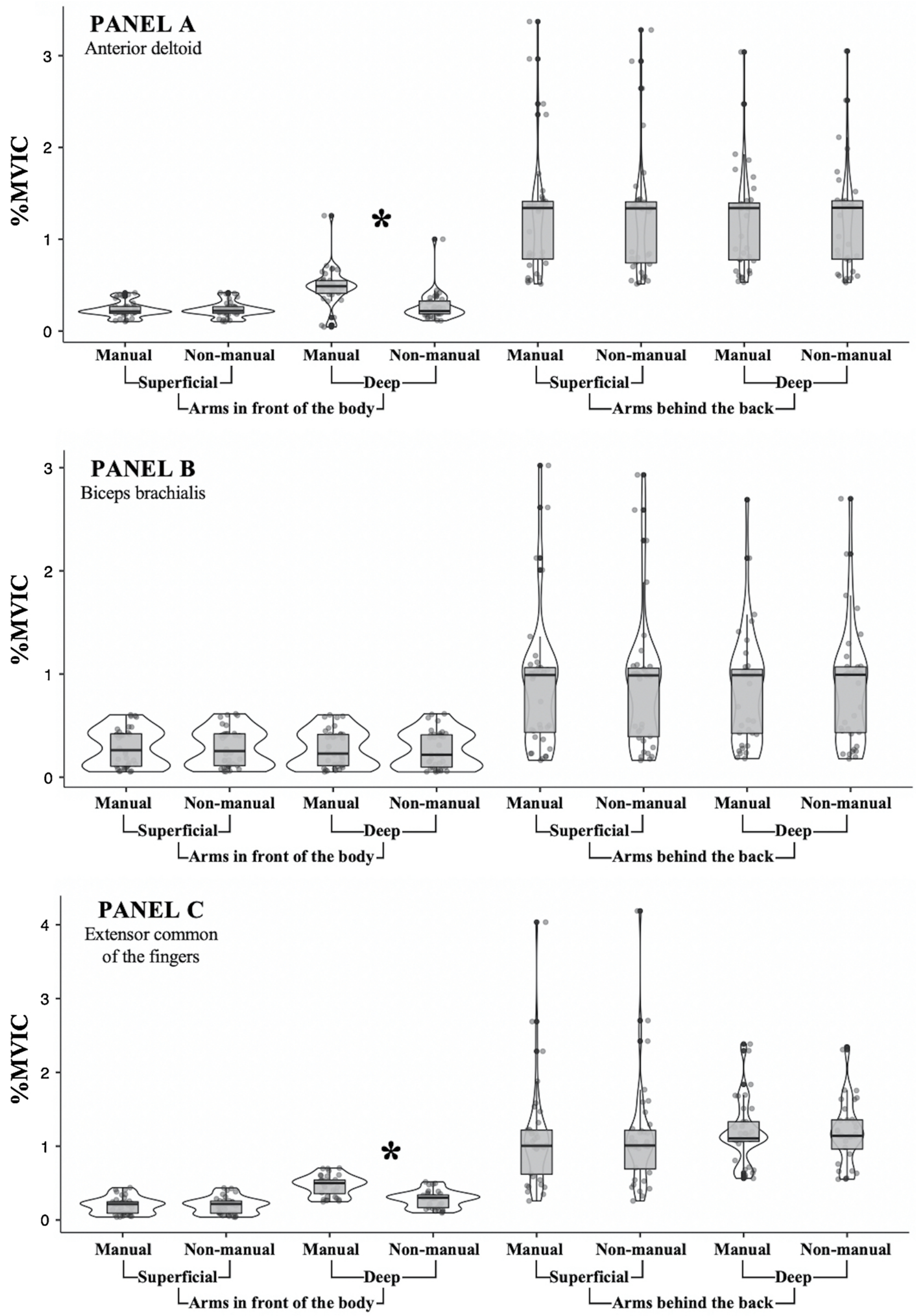

Fig. 3. Interactions of arms posture x semantic processing x type of verb with respect to %MVIC for anterior deltoid (Panel A), biceps brachialis (Panel B) and extensor common muscle of the fingers (Panel C).

3.4. Mean reaction time

For the mean reaction time for voice response (ANOVA arms posture × semantic processing × type of verb, see Panel A of Fig. 4), the robust test was significant: $F(3.13, 65.76) = 55.73$, $p < 0.001$. A significant main effect of arms posture was obtained, $F(1, 35) = 58.42$, $p < 0.001$, $\eta_p^2 = 0.63$, with slower responses in the arms behind the back condition than in the arms in front of the body condition (1090 ms vs. 965 ms, respectively). Significant main effects of semantic processing and type of verb were observed ($F(1, 35) = 181.11$ $p < 0.001$, $\eta_p^2 = 0.84$ and $F(1, 35) = 24.47$, $p < 0.001$, $\eta_p^2 = 0.41$ respectively). The only significant interaction was semantic processing x type of verb, $F(1, 35) = 30.56$, $p < 0.001$, $\eta_p^2 = 0.47$. Planned comparisons showed that in the superficial semantic processing condition, there were no differences between the reaction times in responses for manual and non-manual verbs ($p = 0.887$). By contrast, in the deep semantic processing condition, reaction times for manual verbs were faster than for non-manual verbs (1086 ms and 1193 ms, respectively, $\eta_p^2 = 0.44$, $p < 0.001$).

3.5. Mean error rate

According to the mean error rate analysis for the next ANOVA (ANOVA arms posture × semantic processing × type of verb, see Panel B of Fig. 4), the robust test was significant, $F(3.39, 71.11) = 10.00$, $p < 0.001$. The main effect of arms posture was not significant, $F(1, 35)$

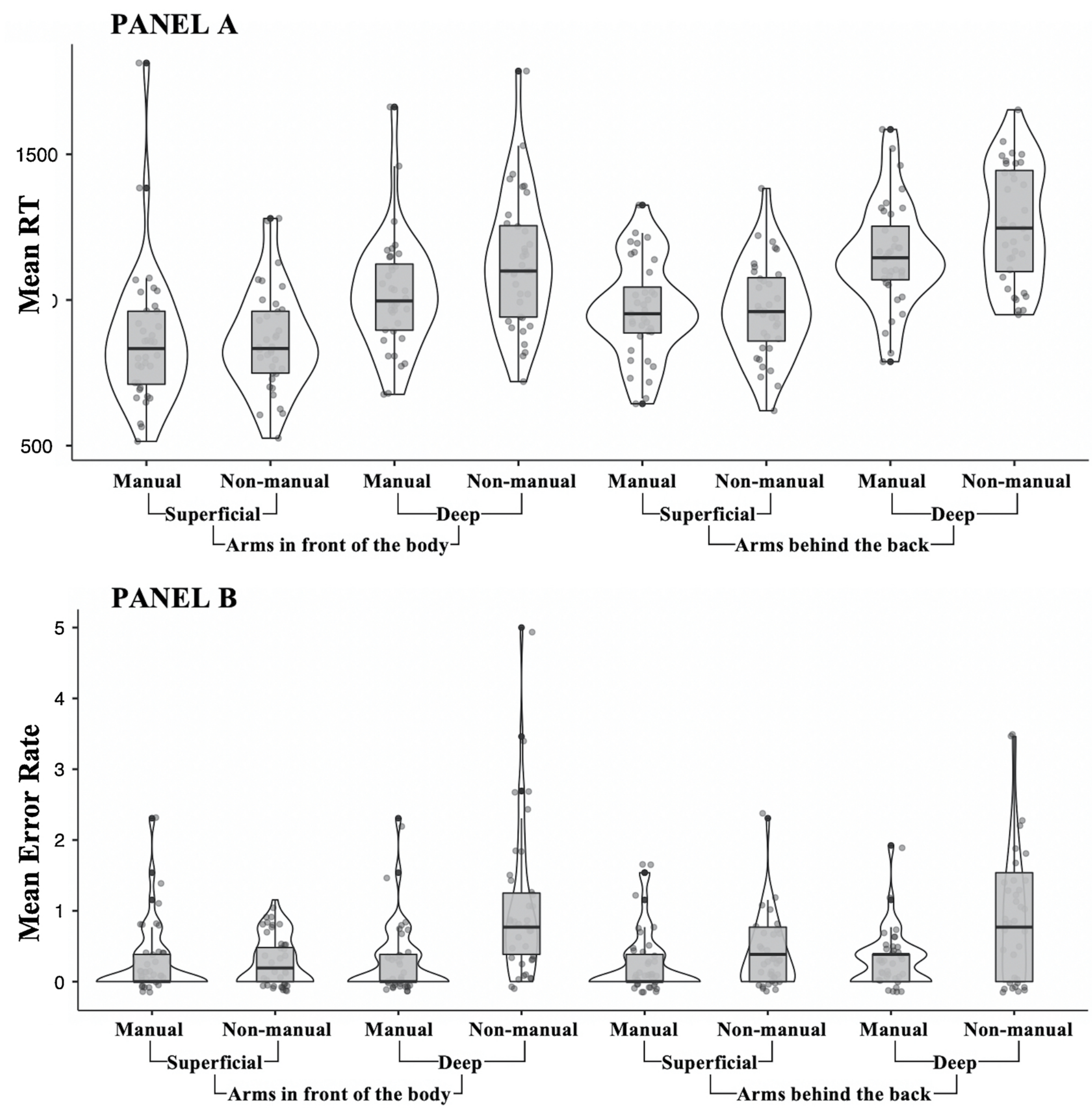

Fig. 4. Interactions of arms posture x semantic processing x type of verb with respect to mean reaction time (Panel A) and mean error rate (Panel B).

= 0.01, $p =$ 0.961, $\eta_p^2 = 0.00$. Significant main effects of semantic processing and type of verb were observed ($F(1, 35) = 12.02$, $p =$ 0.001, $\eta_p^2 = 0.26$ and $F(1, 35) = 19.98$, $p = 0.001$, $\eta_p^2 = 0.36$ respectively). The interaction of semantic processing and type of verb was significant, $F(1, 35) = 14.20$, $p < 0.001$, $\eta_p^2 = 0.29$. Within the superficial semantic processing condition there is no difference between the mean error rate of the verbs ($p = 1.000$), whereas in the deep semantic processing condition there is a larger mean error rate for the non-manual verbs than the manual verbs (0.99 % vs. 0.31 %, respectively; $p = 0.001$, $\eta_p^2 = 0.36$). The ANOVA did not show any other interaction.

4. Discussion

The aim of this study was to determine the spontaneous activity of arm muscles during semantic processing in two hypothesized conditions that could impact on this electromyography activity: a) the posture of the arms (i.e., in front of the body vs. behind the body), and b) deep vs. superficial semantic processing of the verbs. According to an embodied perspective of language processing, we hypothesized greater muscle activation when there was postural priming for the action (i.e., arms in front of the body), and when semantic content of the verbs was actively attended (i.e., deep semantic processing), which is consistent with the previous literature on emotional processing (e.g., Niedenthal et al., 2009).

The results revealed a spontaneous activation for the anterior deltoid and the extensor common muscle of the fingers when arms were placed in front of the body and the participants processed the semantic content of the verbs deeply. Our results are in line with previous ones, supporting the embodied language where motor resonances have been observed during semantic processing and the existence of binding with cognition and action in general (Glenberg, 2017; Pulvermüller, 2018). Other studies are in line with our results; for example, motor imagery studies have shown that subliminal mental activity is directly related to subliminal EMG (i.e., the activity was higher when participants imagine lifting a heavy weight compared to a light weight). In addition, our results are in agreement with previous studies which suggest that the neural substrates for action planning and execution are related to the processing of action words but not non-action words (e.g., Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Hauk et al., 2004; Raposo, Moss, Stamatakis, & Tyler, 2009).

In our study, we did not observe any effect of attention to superficial or deep aspects of language or type of verb on the activation of the biceps brachialis (i.e., there are no effects of semantic processing or type of verb). Our hypothesis is that this result could be due to the biomechanics inherent in the movements related to the manual verb. If participants had performed the actions described in the manual verbs, arms would be released from the table. Previous studies have found that the anterior deltoid and extensor common muscle of the fingers are involved in this lifting action (Gálvez-García, Gabaude, de la Rosa, & Gomez, 2014). However, the biceps brachialis is not necessary for the lifting action. Future studies are needed to address the explanation of these results by manipulating the compatibility between manual verbs and muscles related to the implicit action of the verbs.

Our null result for spontaneous activity when the position of the arms is constrained (i.e., arms behind the back condition) is consistent with previous evidence in the field of mental imagery, where a negative effect to perform a task has been observed when the limbs are immobilized for 24 h (Meugnot, Almecija, & Toussaint, 2014), or there is a load attached to the arm (Cerritelli, 2000). In this regard, our results in vocal reaction time confirm and expand the findings of Yasuda et al. (2017). Specifically, they found that the semantic processing of non-manual verbs was related to slower reaction times and lower accuracy rates compared to the semantic processing of manual verbs. In addition, they observed that manual and non-manual verbs were temporally delayed when the posture of the arms was constrained (arms behind the back condition in our study). In this study, we found similar results, even with no emphasis in the speed of the response, but with the requirement that there be deep processing of semantic information. As Yasuda et al. (2017) explained, this pattern of results could be evidence that the processing of all verbs takes place in the motor systems in keeping with neuroimaging studies (e.g., Siri et al., 2008; Yokoyama et al., 2006). Interestingly, the results in voice reaction time show that semantic processing does not impact the motor response and premotor response (i.e., spontaneous activation of the muscles) in the same way, considering that in the latter the semantic processing interacts directly with the position of the arms. Future studies with similar manipulations should take these differences into consideration.

Some consideration must be given to the difference between the present study and the results reported by Stins and Beek (2013), where participants were lying down. As has been pointed out, they observed that attention modulates the effect of language processing on spontaneous muscle activity. Specifically, lower electromyographic activity was found for the congruent conditions, such as arm words with arm muscles, only when there was deep processing of the word with a high level of activation from attentional processes. Furthermore, they found this decrease in muscle activation for manual and non-manual verbs, suggesting that a supine and relaxed position could have suppressed the motor activity related to semantic processing. In the present study, we have expanded these results. First, it has been confirmed that attention, but also the posture, modulates the effect of language processing on spontaneous muscle activity in the anterior deltoid and extensor common muscle of the finger. However, this modulation is linked to increased muscle activity only in manual verbs and circumscribed in conditions of semantic processing, with postural priming for the action. In short, it has been proven that an active position of the arms is related to the activation of spontaneous muscle activity for manual verbs, which is not the case for passive positions such as constrained arms and lying down, which could even lead to the inhibition of spontaneous activity. Here, it is worth noting that in the current experiment, higher muscle activity for the behind arms position was expected due to the biomechanics inherent in the arms behind the back condition, which produces a higher tension of the measured muscles. This is due to the slight internal rotation of the arms to place the hands behind the back. However, the different tension for the muscles in the arms behind the back condition has been ruled out as a possible explanatory factor (or co-factor) for the muscle differences in the data pattern: the biceps brachialis has different tension between the two positions (i.e., higher activation for behind arms conditions). Nevertheless, there are no differences in spontaneous activity between the posture conditions for this muscle. In this sense, the strain for the measured muscles (i.e., stretching of muscle fibers or distance between origin and insertion of the muscle) differs slightly only for the anterior deltoid muscle (greater stretching for backward posture). However, the differences in muscular strain have been ruled out as a possible explanatory factor (or co-factor) for the muscle differences in the data pattern. The extensor common muscle of the fingers has equal strain for both postures with differences in the spontaneous activity between these conditions.

Future research is needed to understand the relation between the motor system and language processing. First, the present study has focused on manual verbs; therefore, future studies are must deepen the characterization of semantic processing in spontaneous muscle activity in other body segments such as legs, in line with previous research (Stins & Beek, 2013). Second, the muscle activity of the non-dominant arm should be measured in order to study the role of intracortical inhibition and facilitation (see McCombe Waller, Forrester, Villagra, & Whitall, 2008 for more information) in semantic processing and spontaneous muscle activity.

Finally, and in order to define the direct replication of the described data pattern, some considerations must be taken into account. We expect the results to generalize to situations where similar verbs and manipulations were used and with participants of different ages. However, we do not have any expectations that the findings can be replicated beyond the laboratory. Spontaneous muscle activity from manual verbs was triggered by a specific laboratory induction, and there is insufficient evidence to demonstrate that the results can be extrapolated out to a natural situation. There is no reason to assume that the results are dependent upon other characteristics involving the participants, materials or context.

5. Conclusion

In summary, spontaneous arm muscle activation was observed, but only with an active position of the arm and when manual verbs were actively processed. These findings expand on the literature with respect to how processing semantic information involves motor activity. Specifically, our findings support the notion that language comprehension involves dynamically spontaneous and embodied actions, where verbs are acted while being semantically processed.

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Declaration of Competing Interest

The authors declare that they have no known competing financialinterestsor personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.biopsycho.2020.107881.

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