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An ERP study of motor compatibility effects in action language

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ABSTRACT

This ERP study explores the brain's response to the manipulation of motor compatibility in action-related language. In Experiment 1 participants read sentences in which a protagonist performed two different manual actions either simultaneously or consecutively (e.g. *While/after cleaning the wound he unrolled the bandage…*). The ERPs were measured in the second-clause verb (e.g. *unrolled*) and noun (e.g. *bandage*). Notably, only the noun showed compatibility effects, namely a larger N400 in the simultaneous (incompatible) version than in the consecutive (compatible) version, suggesting that readers need to integrate the meaning of the whole sentence to evaluate the feasibility of the actions. In Experiment 2, motor compatibility was manipulated in a different way: all the sentences described the protagonist as performing two simultaneous actions that were both manual (*While cleaning the wound he unrolled the bandage*), or one action that was perceptual and the other manual (*While looking at the wound he unrolled the bandage*). The N400 effects for the former incompatible condition were replicated, again in the second-clause noun. The results demonstrated that readers of action language employ their pragmatic world knowledge to test the feasibility of motor actions, taking into account the embodied constraints of such actions.

1. Introduction

Performing motor actions is strongly constrained by the properties of our body as well as by temporal parameters. For instance, we can perform an almost infinite variety of manual actions at different moments, but we get into difficulty if we want to do two manual actions at once (e.g., cutting bread and opening a bottle), since many manual actions involve the use of both hands. By contrast, it could be feasible to perform two simultaneous actions if one action is perceptual and the other is motor (smelling bread and opening a bottle), or the two actions are motor but rely on different effectors (chewing bread and opening a bottle). The embodied and temporal constraints of action are incorporated in our implicit sensory–motor knowledge; we implicitly assume that it is not possible to cut the bread and fill the glass of water at once, without needing to run failing trials. What's more, this sensory–motor knowledge could penetrate the comprehension of action language. For instance, de Vega et al. (2004) created incongruent sentences violating embodied constraints, namely describing a character performing two actions with the same body effectors at once. In this

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condition they reported longer reading times than for sentences in which the same motor actions were described as consecutive, or were simultaneous but involved different body effectors. More recently, Santana and de Vega (2013) gave participants carefully controlled sentences describing two manual actions as either simultaneous or consecutive using the adverbs *while* or *after* respectively, and they found that sentences describing the two manual actions as performed simultaneously were more difficult to understand (longer reading times and lower sensibility rates) than the same actions described as consecutive.

The current study goes one step further than the aforementioned behavioral experiments, exploring for the first time the brain response to motor compatibility in the context of language comprehension. Participants read sentences describing a single agent performing two manual actions that were either compatible or incompatible, while their EEG was recorded. For instance, they read that a protagonist performed two actions either simultaneously or consecutively (e.g. *While* [*After*] *cleaning the wound he unrolled the bandage*). Notice that the two actions in a given sentence were clearly distinct, namely they involved specific goals or subgoals and independent motor programs, rather than being part of a single coordinated bimanual action (e.g., playing piano or typewriting). This feature of the materials makes the performance of both actions at once pragmatically difficult. Certainly, one could perform two manual actions at once, like cleaning the wound and unrolling the bandage, by means of careful bimanual coordination, but this is pragmatically odd given the fact that in most situations the actions could be more efficiently performed consecutively. We expected to find specific brain responses for sentences with incompatible manual actions performed at once, namely an increase in the amplitude in the N400 component, a general brain signature for semantic incongruence, in comparison with sentences either describing the same manual actions performed as consecutive, or a perceptual and a motor action performed simultaneously.

The N400, first described by Kutas and Hillyard (1980), was initially considered as a purely linguistic marker. However, recent research has shown that N400 is also sensitive to inconsistency in non-linguistic materials, such as images (Willems et al., 2008), mathematical problems (Galfano et al., 2004) or gestures (Kelly et al., 2004). Consequently, in recent years, some authors have started to consider N400 as a general marker of meaning inconsistencies (Kutas and Federmeier, 2011). Especially relevant for this paper is the literature on the observation of action pictures and action movies, which obtain N400-like effects sensitive to the presence of incongruent or unexpected events (see review by Grafton and Tipper, 2012). For example, Proverbio and Riva (2009) presented to their participants pictures of sensible actions (e.g., a woman taking clothes out of a washing machine) or non-sensible actions, which either had no purpose, or were inappropriate (e.g., a woman slicing bread with a saw), and they found that sensible actions elicited larger N250 (recognition potential) than non-sensible actions, whereas non-sensible actions were associated with a greater N400-like wave, with a fronto-central distribution. In the same vein, watching images of hands ready to perform an action towards an object elicits larger N400 at parietal sites when the hand shape or its orientation is inappropriate to manipulate the object than when it is appropriate (Shibata et al., 2009; Bach et al., 2009). Some studies create congruent/incongruent conditions by combining in each trial different modalities of action-related information, including language. Thus, in an experiment by Willems et al. (2008) participants listened to sentences in which a critical word, a simultaneously depicted object, or both could be contextually congruent or incongruent. They found N400 effects for all the incongruent conditions, providing direct evidence of integration processes between action sentences and pictures. In another study, van Elk et al. (2008) asked their participants to prepare to execute meaningful actions (e.g., grasping a cup to take it to the mouth) or meaningless actions (e.g., grasping a cup to take it to the eye), but before carrying out the action they performed a semantic categorization task. The authors found that while participants were preparing for meaningful actions, words that were incongruent with their goal elicited larger N400 than words that were congruent with their goal. No congruence effect was found while preparing meaningless actions. Finally, Aravena et al. (2010), using an action-sentence compatibility paradigm, reported an enhanced N400 when participants were asked to perform a response with a hand shape mismatching the action sentence they had just listened to; for instance, pressing a button with the closed hand after hearing “The show was praiseworthy, so Rocío applauded”.

The aforementioned studies showed that the N400 is sensitive to different kinds of incongruence in observed or performed motor actions, suggesting a semantic processing of action meaning with non-linguistic materials and tasks. The aim of this paper is to study the brain response to the degree of motor compatibility between pairs of actions using carefully matched linguistic materials. To do that, we employed two-clause sentences describing two actions that could result in compatible or incompatible motor events. In Experiment 1 the manipulation of motor compatibility was associated with the use of the temporal adverbs *while* or *after*, following the procedure reported elsewhere (de Vega et al., 2004; Santana and de Vega, 2013). Participants were required to read sentences in which a character was described as performing two manual actions either simultaneously or consecutively, marked by the adverbs *while* or *after*, respectively. We expected that the ERP component N400, time-locked to words in the second clause, would be sensitive to the motor compatibility, increasing its amplitude when the two manual actions were described as simultaneous. In Experiment 2 the manipulation of the motor compatibility was different. The experimental sentences always described a character as performing two simultaneous actions. In half of the items both actions were manual (e.g., *While cleaning the wound he unrolled the bandage*), and in the other half of the items the first action was perceptual and the second one was manual (e.g., *While looking at the wound he unrolled the bandage*). Like in Experiment 1, we predicted larger N400 in incompatible sentences (motor+motor) than in compatible sentences (perceptual+motor). In both experiments, the incompatible and compatible conditions were matched in most linguistic features, but they differed in the degree of difficulty to perform the referred actions simultaneously, because of embodied constraints.

Our main hypothesis is that the participants' implicit knowledge of these embodied constraints may enhance the N400 component in the motor incompatibility case. If so, this would be the first demonstration that linguistic materials describing complex motor actions performed by an agent show semantic congruence effects in the ERPs, comparable to those reported in the aforementioned studies with action pictures and movies (Bach et al., 2009; Proverbio and Riva, 2009; Shibata et al., 2009), or with action-sentence compatibility procedures (Aravena et al., 2010). Another relevant issue explored here is the temporal course of the motor compatibility effects across the sentence. With this aim we recorded the ERPs time-locked to different loci in the second clause, where the motor compatibility or incompatibility emerges. Some studies have reported that action verbs alone elicit automatic activation of somatotopic brain areas (Hauk et al., 2004). However, other studies suggest that when complex language units are processed, contextual information in addition to the action verbs is needed to elicit the activation of the motor system (v.g., Taylor and Zwaan, 2009; Schuil et al., 2013). To distinguish between the lexical and the contextual hypotheses, we analyzed ERPs at two different sites in the second clause: the action verb and the object noun completing the description of the action. If the motor compatibility effects (N400) occur at the verb, this would support the idea that motor activations could be associated with the lexical processing of the verb. By contrast, if the compatibility effects are delayed till the noun, this could suggest that readers need to get sufficient contextual information to represent the motor action and check its congruence.

2. Results

2.1. *Experiment 1: motor compatibility determined by temporal adverbs*

2.1.1. *Behavioral results*

Reaction time data two standard deviations above or below the participant's mean were discarded as outliers (approximately 15% of data). Filler sentence data were also analyzed separately to verify whether participants were sensitive to their reversed sensibility values. Only sentences with a congruent third clause were analyzed (15 experimental and 8 filler sentences). As Table 1 shows, in experimental sentences, *while* versions were associated with longer reaction times ($t_2(14)=2.64$; $p<0.008$) and were judged as less sensible ($t_2(14)=8.152$; $p<0.0001$) than *after*-sentences. The *while* and *after* filler sentences did not differ in reaction times, whereas *after* filler sentences were judged as less sensible than *while* filler sentences ($t_2(7)=1.99$; $p<0.048$).

2.1.2. *ERP results*

Although the ERPs were time-locked both to the verb and the noun in the second-clause, we will report only the results corresponding to the noun, given that the verb did not show any significant effects in the ERPs. Fig. 1 shows the grand average of all participants plotted in a representative sample of electrodes, and Fig. 2 represents a topographical distribution of the ERP differences between *while* and *after* sentences. Waves start with a P1, followed by negativity around 200 ms (N200) and then a negative-going wave in the temporal range of the N400. Finally, there was a late negativity peaking around 600 ms after the word onset. Significant differences between *while* and *after*-sentences can be found in the three windows analyzed.

Table 1 – Reaction times in the coherence judgment (in milliseconds) and the percentage of participants responding affirmatively to the sensibility rates. *SDs* in parentheses.

	Experimental		Filler	
	Mean	%	Mean	%
While (W)	1160 (532)	35 (21)	1006 (472)	70 (17)
After (A)	1011 (497)	80 (23)	1068 (511)	35 (19)
W–A	149*	−45**	−62	35*

* $p<0.05$.
** $p<0.01$.

2.1.2.1. *Time window 150–250 ms.* In this early time window, the amplitude of the occipital N200 was significantly more negative for the *while* (incompatible) than for the *after* (compatible) condition ($F(1, 23)=11.49$; $p<0.002$). Differences were observed in right (*while*: $M=-1.55\ \mu V$; $SD=2.47$; *after*: $M=-0.86\ \mu V$; $SD=2.36$; $t(23)=3.5$; $p<0.002$) and left electrodes (*while*: $M=-2.89\ \mu V$; $SD=2.36$; *after*: $M=-2.28\ \mu V$; $SD=2.13$; $t(23)=2.43$; $p<0.022$).

2.1.2.2. *Time window 350–550 ms.* The Adverb × Frontality interaction was statistically significant ($F(2, 46)=6.09$; $p<0.013$; $\varepsilon=0.653$), given that *while*-sentences elicited larger negativities than *after*-sentences only in the posterior electrodes (*while*: $M=-0.44\ \mu V$; $SD=1.22$; *after*: $M=0.25\ \mu V$; $SD=1.37$; $t(23)=3.25$; $p<0.003$). There was also an Adverb × Region interaction ($F(6, 138)=4.19$; $p<0.008$; $\varepsilon=0.516$). In the pairwise comparisons, *while*-sentences elicited larger negativities than *after*-sentences in the central (*while*: $M=-0.81\ \mu V$; $SD=1.31$; *after*: $M=-0.11\ \mu V$; $SD=1.24$; $t(23)=2.71$; $p<0.012$), right central (*while*: $M=-0.53\ \mu V$; $SD=1.13$; *after*: $M=0.14\ \mu V$; $SD=1.14$; $t(23)=2.34$; $p<0.02$), left parietal (*while*: $M=-0.55\ \mu V$; $SD=1.36$; *after*: $M=0.09\ \mu V$; $SD=1.52$; $t(23)=3.18$; $p<0.004$), and right parietal (*while*: $M=-0.41\ \mu V$; $SD=1.23$; *after*: $M=0.51\ \mu V$; $SD=1.41$; $t(23)=3.48$; $p<0.002$) electrodes

2.1.2.3. *Time window 600–800 ms.* There was a main effect of Adverb ($F(1, 23)=5.88$; $p<0.02$). *While*-sentences elicited larger negativities than *after*-sentences on left central (*while*: $M=-0.02\ \mu V$; $SD=0.94$; *after*: $M=0.42\ \mu V$; $SD=1.28$; $t(23)=2.47$; $p<0.021$) and left parietal electrodes (*while*: $M=-1.85\ \mu V$; $SD=1.55$; *after*: $M=-1.16\ \mu V$; $SD=1.81$; $t(23)=3.24$; $p<0.004$).

2.1.3. *Discussion*

The behavioral data confirm the predictions. *While*-sentences were associated with slower reaction times and were judged

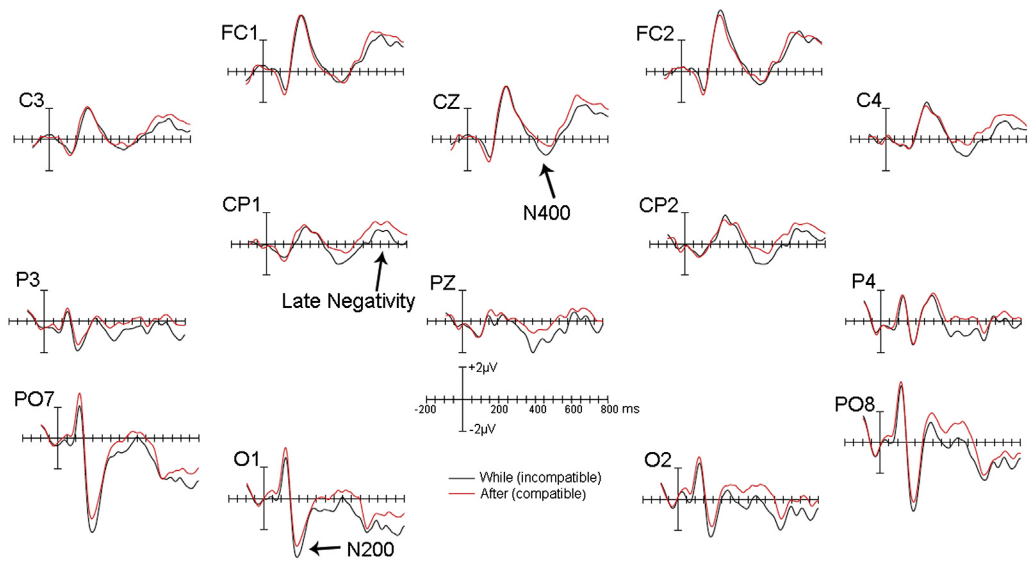

Fig. 1 – Experiment 1. *While*-(incompatible) and *after*-sentences (compatible) average waves, measured at the noun (e.g., bandage) in the second clause (e.g., he unrolled the bandage…).

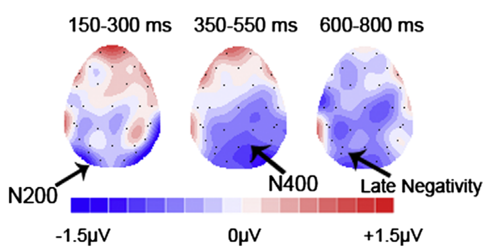

Fig. 2 – Experiment 1: Topographical distribution of the ERP differences between *while*-(incompatible) and *after*-sentences (compatible) in the three temporal windows analyzed.

as less coherent than *after*-sentences in the experimental materials, whereas no differences (in time) or the opposite pattern (in sensibility rates) was found for the filler sentences. With regard to the ERP data, the most important result was a robust negativity, corresponding in latency, amplitude, topographical distribution and shape to the N400 component, which was larger in *while*-sentences than in *after*-sentences, and these differences extended to the late temporal window (600–800 ms). In accordance with our expectations, this N400 effect reveals that readers have difficulties to understand descriptions of two manual actions performed simultaneously by a single agent. Though ERPs were analyzed at two different sites in the second clause, the N400 effect does not appear in the second clause action verb but only in the object noun, when the description of the action event is completed and the whole situation model can be updated. This interesting delay of the compatibility effects will be examined in the General Discussion.

The motor congruence effect obtained here could not be attributed to lexical factors, because the second clause, which was analyzed in the ERPs, was exactly the same across counterbalanced conditions in the compatible as in the incompatible sentences. Even the first clause described the same motor event in both versions of the materials. We can also rule out that participants "discovered" that *while*-sentences were always incompatible and *after*-sentences compatible, and hence applied a rule of thumb to judge the sentences' sensibility. The filler sentences, reversing congruence values of *while* and *after*, and the presence of a third clause that could be also incongruent, made such a superficial strategy irrelevant. So, why does the brain react differentially to motor compatibility? One possibility is that readers attempt to simulate the events in the sentence, and they fail to do so in the case of simultaneous manual actions, eliciting N400. Still, there is a possibility that the adverbs themselves produced the differences. Maybe *while*-sentences require more cognitive resources, independently of their content, than *after*-sentences simply because the semantics of simultaneity is cognitively more demanding, as it violates the temporal iconicity principle (Dowty, 1986; Zwaan, 1996). For example, Münte et al. (1998) reported an ERP study with two-clause sentences starting with either the adverb *after* or *before* (e.g., *Before/after the psychologist submitted the paper, the journal changed its policy*). The *after*-sentences followed the iconicity principle (the order of the clauses matched the order of the referred events) whereas the *before*-sentences did not. They found a negative-going wave in the non-iconic *before* sentences. In the present experiment, *after*-sentences also follow the iconicity principle, whereas *while*-sentences do not, because the two consecutive clauses describe simultaneous events. The next experiment tries to rule out this possibility by using only *while*-sentences and manipulating the motor congruence in another way.

2.2. *Experiment 2: motor compatibility determined by motor effectors*

To rule out the possibility that it was just the temporal condition of simultaneity and not the motor constraints that produced the N400 effects in Experiment 1, another experiment was designed. We employed materials similar to those of Experiment 1, but including always the adverb *while* to establish the temporal relation between two actions. The critical manipulation was that the first clause event could be motor or perceptual, whereas the second event was motor in all cases. So, we discarded the *while/after* manipulation, and made congruence dependent on the fact that the events were or were not simultaneously feasible, depending on their motor features. In the compatible condition, the first action was perceptual and the other one motor (e.g. *While looking at the wound he unrolled the bandage*), whereas in the incompatible condition both events were manual actions (e.g., *While cleaning the wound he unrolled the bandage*). We also included a condition in which the second-clause noun was of low cloze probability or anomalous. In this way we could contrast the N400 elicited by motor incongruence with the standard N400.

2.2.1. Behavioral results

Data two standard deviations above or below the condition mean were discarded (approximately 16%). As Table 2 shows, in the experimental sentences, *motor–motor* versions were associated with longer reaction times ($t_2(13)=2.53$; $p<0.025$) and were judged as less sensible ($t_1(20)=4.05$; $p<0.001$; $t_2(13)=4.87$; $p<0.0001$) than *perceptual–motor* sentences. Also, *motor–motor* sentences produced longer latencies ($t_1(20)=2.1$; $p<0.048$) and were judged as relatively more sensible ($t_1(20)=5.82$; $p<0.0001$) than *anomalous* sentences. Interestingly, no significant differences were found between the *perceptual–motor* and the *motor–perceptual* conditions either in reaction times or sensibility rates.

2.2.2. ERP results

Again, as in the previous experiment, no significant differences between conditions were found in the verb of the second clause at any of the analyzed time windows, so we will focus on the results of the noun in the second clause. Fig. 3 shows the grand average of all participants plotted at some representative electrodes, and Fig. 4 represents the distribution of the ERP differences between *motor–motor* and *perceptual–motor* sentences. Fig. 5 shows a comparison between the four sentence types at electrode site CZ. Waves start with a P1, followed by a slight negativity around 200 ms, noticeable at occipital sites. Then, much as in Experiment 1, two negative-going waves can be observed, the first one reaching its maximum amplitude around 400 ms, and the second one about 700 ms. The statistical tests were performed on the same three temporal windows as in Experiment 1. However, the effects were not significant for the earlier temporal window (150–250 ms), and we will report only the differences between *motor–motor* and *perceptual–*

Table 2 – Mean reaction times (in milliseconds) and mean percent of affirmative responses in the coherence judgment task. Standard deviations are in brackets.

Experimental			Filler		
	Mean	%		Mean	%
Motor–motor (MM)	1328 (390)	32 (18)	Anomalous	1232 (390)	17 (15)
Perceptual–motor (PM)	1191 (507)	87 (18)	Motor–perceptual	1138 (399)	86 (20)
MM–PM	137*	−55**			

* $p<0.05$.
** $p<0.01$.

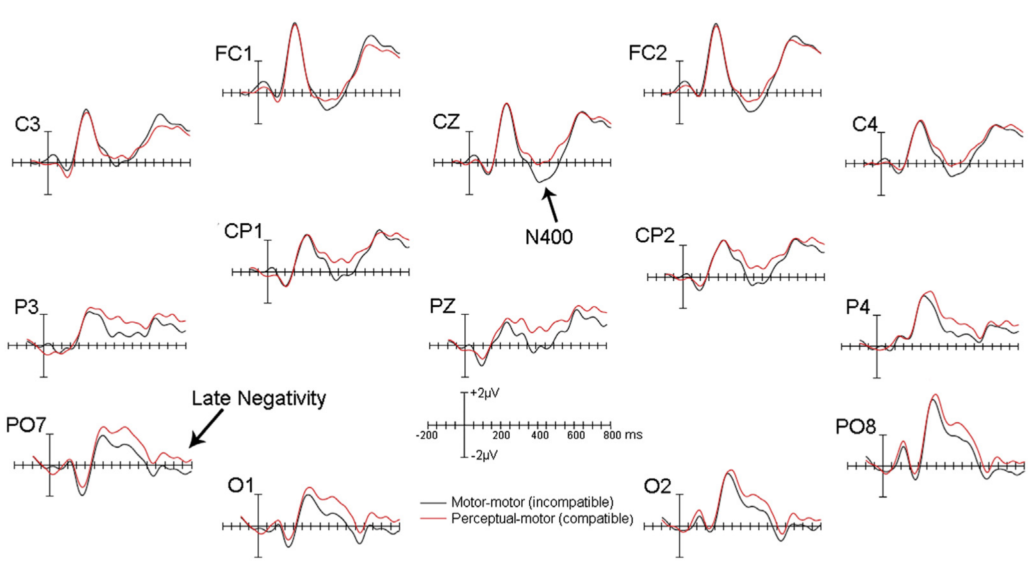

Fig. 3 – Experiment 2: Average waveforms for *motor–motor* (incompatible) and *perceptual–motor* (compatible) sentences, measured at the noun in the second clause.

motor sentences for the second (300–500 ms) and the third (600-800 ms) temporal windows.

2.2.2.1. *Time window 300–500 ms*. In the first set of ANOVAs, restricted to *motor–motor* vs. *perceptual–motor* sentences, the most relevant effects were the Sentence type x Region interaction ($F(6, 120)=2.79$; $p<0.05$; $\varepsilon=0.47$), as well as the main effects of Sentence type $F(1, 20)=5.67$; $p<0.02$) and Region ($F(6, 120)=9.96$; $p<0.0003$; $\varepsilon=0.32$). *Motor–motor* sentences elicited larger negativities than *perceptual–motor* sentences at left central (*motor–motor*: $M=0.09$ μV; $SD=1.88$; *perceptual–motor*: $M=0.75$ μV; $SD=1.18$; $t(20)=2.57$; $p<0.018$), central (*motor–motor*: $M=-0.34$ μV; $SD=3.61$; *perceptual–motor*: $M=0.89$ μV; $SD=2.59$; $t(20)=2.71$; $p<0.01$), left parietal (*motor–motor*: $M=0.81$ μV; $SD=2.37$; *perceptual–motor*: $M=2.04$ μV; $SD=2.19$; $t(20)=3.92$; $p<0.0008$) and right parietal electrodes (*motor–motor*: $M=1.44$ μV; $SD=2.51$; *perceptual–motor*: $M=2.39$ μV; $SD=1.94$; $t(20)=2.64$; $p<0.016$).

In the extended set of ANOVAs again a significant Sentence type × Region interaction was obtained ($F(18,360)=2.45$; $p<0.027$; $\varepsilon=0.34$), as well as the main effects of Sentence type ($F(3,60)=6.01$; $p<0.007$; $\varepsilon=0.59$) and Region ($F(6,120)=10.04$; $p<0.0003$; $\varepsilon=0.32$). *Anomalous* sentences elicited larger negativities than *motor–motor* sentences at left frontal (*anomalous*: $M=-1.67$ μV; $SD=2.67$; *motor–motor*: $M=-0.57$ μV; $SD=2.77$; $t(20)=3.67$; $p<0.0015$) and left central electrodes (*anomalous*: $M=-0.81$ μV; $SD=1.96$; $t(20)=3.81$; $p<0.001$). *Anomalous* sentences were also associated with larger negativities than *perceptual–motor* sentences at left frontal (*perceptual–motor*: $M=-0.39$ μV; $SD=2.12$; $t(20)=2.69$; $p<0.01$), left central ($t(20)=4.47$; $p<0.0002$), central (*anomalous*: $M=-1.25$ μV; $SD=3.32$; $t(20)=4.76$; $p<0.0001$), right central (*anomalous*: $M=-0.37$ μV; $SD=2.29$; *perceptual-motor*: $M=0.92$ μV; $SD=1.47$; $t(20)=3.59$; $p<0.002$), left parietal (*anomalous*: $M=0.49$ μV; $SD=3.13$; *perceptual–motor*: $M=2.04$ μV; $SD=2.19$; $t(20)=3.76$; $p<0.001$) and right parietal electrodes (*anomalous*: $M=1.13$ μV; $SD=2.72$; $t(20)=3.22$; $p<0.004$). Finally, *anomalous* sentences were associated with larger negativities than *motor–perceptual* sentences at left frontal (*motor–perceptual*: $M=-0.31$ μV; $SD=1.84$; $t(20)=2.67$; $p<0.019$), left central (*motor–perceptual*: $M=0.61$ μV; $SD=1.39$; $t(20)=3.12$; $p<0.005$), central (*motor–perceptual*: $M=0.76$ μV; $SD=2.53$; $t(20)=3.57$; $p<0.0019$), right central (*motor–perceptual*: $M=0.68$ μV; $SD=1.61$; $t(20)=2.61$; $p<0.017$) and right parietal electrodes (*motor–perceptual*: $M=1.98$ μV; $SD=1.83$; $t(20)=2.22$; $p<0.037$). As expected, no significant differences were obtained between *perceptual-motor* and *motor-perceptual* conditions.

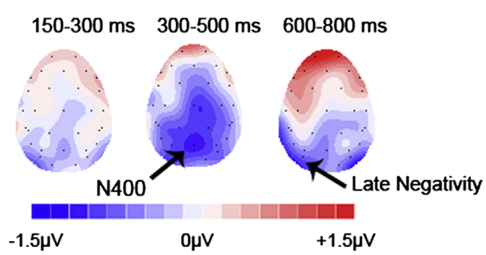

Fig. 4 – Experiment 2: Topographical distribution of the ERP differences between the *motor–motor* (incompatible) and the *perceptual–motor* (compatible) conditions at the second-clause noun.

2.2.2.2. *Time window 600–800 ms*. In the restricted set of ANOVAs, a significant Sentence type × Frontality interaction was found ($F(2,40)=4.73$; $p<0.035$; $\varepsilon=0.58$), as well as a main effect of Frontality ($F(2,40)=13.46$; $p<0.0008$; $\varepsilon=0.58$). *Motor–motor* sentences elicited larger negativity or more reduced positivity than *perceptual–motor* sentences at the left parietal electrodes (*motor–motor*: $M=0.21$ μV; $SD=1.99$; *perceptual–motor*: $M=0.91$ μV; $SD=1.32$; $t(20)=1.69$, $p<0.01$).

In the extended set of ANOVAs the most important effects were the Sentence type × Region interaction ($F(18,360)=2.83$; $p<0.012$; $\varepsilon=0.34$) and the main effect of Region ($F(6120)=12.58$; $p<0.0001$; $\varepsilon=0.41$). *Motor–motor* sentences were associated with more negativity or reduced positivity than *anomalous* sentences at left parietal (*anomalous*: $M=1.38$ μV; $SD=1.82$; $t(20)=2.66$; $p<0.015$) and right parietal sites (*motor–motor*: $M=0.15$ μV; $SD=2.35$; *anomalous*: $M=1.19$ μV; $SD=2.07$;

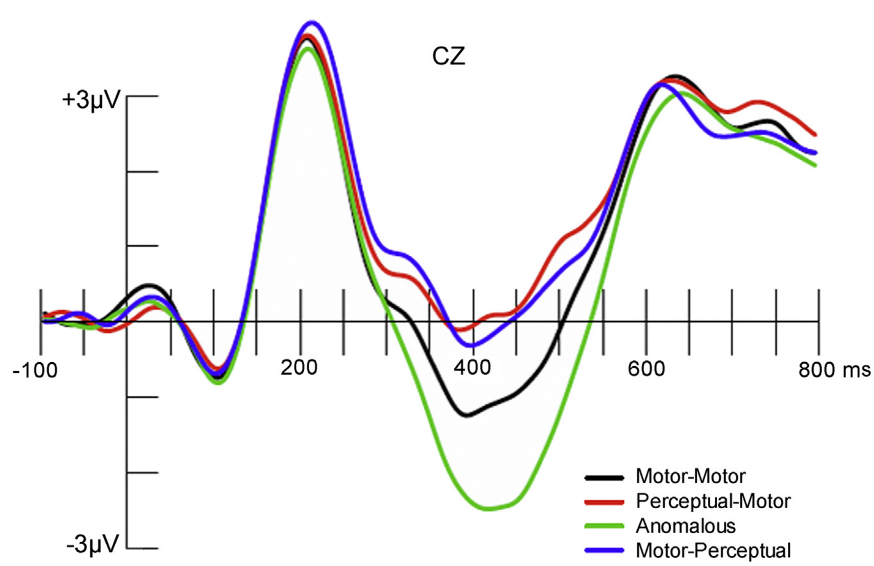

Fig. 5 – Experiment 2: N400 effect for each sentence type at electrode CZ.

$t(20)=2.18$; $p<0.04$). Also, *motor–perceptual* sentences elicited more negativity than *anomalous* sentences at left parietal (*motor–perceptual*: $M=0.27\ \mu V$; $SD=1.71$; $t(20)=2.93$; $p<0.008$) and right parietal electrodes (*motor–perceptual*: $M=0.34\ \mu V$; $SD=1.45$; $t(20)=2.43$; $p<0.025$).

2.2.3. Discussion

Despite the fact that the adverb was not manipulated in this experiment (*while* was kept fixed across the materials), the congruence effects of Experiment 1 were basically replicated, in both the behavioral and the ERP data. As expected, sentences describing two simultaneous motor actions were judged as less sensible than sentences describing a perceptual and a motor action happening simultaneously. The ERPs recorded on the noun of the second clause confirm and qualify this impression. Like in Experiment 1 the ERP effects do not appear in the action verb but were delayed till the object noun, and here again, a negative deflection with the shape, scalp distribution and latency of the N400 component (although starting about 50 ms earlier) was larger in the *motor–motor* (incompatible) than in the *perceptual–motor* (compatible) sentences. As in the Experiment 1, this congruence effect had a predominantly posterior scalp localization. When comparing *motor–motor* sentences to *anomalous* sentences associated with an ordinary N400 effect, two findings are remarkable. First, as expected, *motor–motor* and *anomalous* sentences produced a similar N400 waveform, although they were larger in the former condition. Second, *motor–motor* sentences extended their negativity, or reduced the positivity going waves, in the 600–800 ms time window at parietal sites, in comparison with both *perceptual–motor* and *anomalous* sentences. In other words, the late negativity would seem to be a specific long-term brain reaction to motor incongruence.

In sum, two main conclusions are remarkable here. First, Experiment 2 shows that the motor compatibility effect found in Experiment 1 cannot be attributed to the general fact that the adverb *while* is semantically more complex (e.g., it violates temporal iconicity) than the adverb *after*. In Experiment 2 the adverb was not manipulated, and only reader's pragmatic knowledge about the difficulty to performing two incompatible motor actions at once seems to account for the increase of the N400 component. Second, the N400 effect associated with motor compatibility is similar to that obtained with the standard low cloze probability sentences, although smaller. Finally, motor compatibility effects involve a specific later component, absent in the low cloze probability sentences.

3. General discussion

This study aimed to explore for the first time the brain electrophysiological response to motor compatibility of actions described by sentences. Experiment 1 showed that the comprehension of *while*-sentences that describe an agent performing two manual actions simultaneously elicits an N400-like wave. When the same manual actions were described as being performed consecutively, by means of the adverb *after*, the N400 diminished. In Experiment 2 all the sentences included the adverb *while*, and the N400 effect was observed when the two simultaneous actions were manual but not when one action was perceptual and the other manual. This ruled out that the N400 obtained here could be caused by the cognitive cost of understanding linguistic constructions with the adverb *while*. Notice also that in both experiments, the incongruent conditions did not include bizarre actions such as "approaching a cup of coffee to the ear" or "cutting bread with a saw" (e.g., Proverbio and Riva, 2009), as the two actions in a sentence, considered separately, were functional and contextually appropriate. The congruence was determined by the embodied and temporal constraints of the two described actions.

There are some limitations to this study. First, the electrode density was not sufficient to perform a source estimation analysis, which could have shown the possible activation of the brain motor areas, associated with compatibility effects. Second, ERPs averages comprised a slight reduction in the number of trials in Experiment 2 (35 per condition) in comparison with Experiment 1 (40 per condition), and this could explain the absence of the N200 effect, which was obtained in Experiment 1. In spite of this, the expected N400 effects as well as significant effects at the later temporal window were obtained in both experiments, and we will comment them.

The N400 effect associated with motor incompatibility cannot be confused with the classical N400 obtained for low cloze probability words. Experiment 2 directly contrasted the motor incompatibility effects with the classical N400 obtained for *anomalous* sentences and, as expected, the locus, morphology and latency were similar in both cases, although the *anomalous* sentences had larger amplitude. More importantly, unlike in the classical N400, in this article motor incompatible words were consistent in the local context of the second clause, as their incongruence only emerged with respect to the previous context. Furthermore, the N400 was obtained in the noun that followed the second-clause verb, rather than in the verb itself. This means that the brain detects the incompatibility only when the action information is completed, after integrating the action and the object that the action refers to, and after integrating such information with the previous context. In other words, the compatibility effect is not produced by a simple violation of verb lexical expectations. By contrast, it seems that action verbs alone are too indeterminate in some cases to represent the motor properties of actions; for instance, *to open* can lead to quite different motor programs depending on the specific object on which the action is performed (compare *he opened the umbrella* and *he opened the folder*). Consequently, the delayed N400 we found in the noun could reflect a global discourse integration process that allows readers to "discover" the unfeasibility of the actions. Moreover, these results suggest that action verbs embedded in sentences, do not automatically trigger motor representations, but rather these representations are context-dependent. This proposal is consistent with a recent fMRI study reported by Schuil et al. (2013). They presented their participants Dutch sentences, containing action verbs in the last position of the subordinate clause, so that, depending on the previous context, these action verbs could be interpreted in a literal or a non-literal sense. They found that action verbs presented in literal contexts were associated with more activation of the motor areas than these verbs presented in the non-literal contexts. In our study, the N400 effects found on the noun, and not at the verb, could reflect that the brain motor areas are engaged only when sufficient information is given to appropriately represent the referred action.

But why do people find it difficult to understand the simultaneous performance of two manual actions? The N400 is an ERP marker of semantic incongruence, and a simple explanation is that this study reveals just another case of N400 sensitivity to discourse-level incongruence similar to those described in the literature (e.g., van Berkum, 2009; van Berkum et al., 1999, 2003). This would be interesting enough because, to our knowledge, this is the first ERP study reporting motor incongruence effects with linguistic contexts. The ERP literature reported that discourse–anomalous words, even if appropriate in the local sentence context, elicit a larger N400 than discourse–consistent words. In some of these studies the incongruence consisted of a semantic conflict between the target information and the previous linguistic context. For instance, the word “slow” in the sentence “Jane told her brother that he was exceptionally slow” could be made inconsistent when the sentence was preceded by a previous narrative in which the brother's behavior could better be described as quick (e.g., van Berkum, 2009; van Berkum et al., 1999, 2003). In the same vein, the valenced word “failure” in the sentence “Today Hector felt like a complete failure” was inconsistent after reading a narrative in which Hector published a novel selling hundreds of thousands of copies and receiving positive reviews (León et al., 2010). On other occasions the N400 effect was associated with world knowledge inconsistencies (Hagoort et al., 2004; Otten and van Berkum, 2007; van Berkum, 2009). For instance, the word “white” in the context of a sentence such as “Dutch trains are white and very crowded,” enhanced N400, not because of any semantic violation, but because it conflicts with the fact that Dutch trains are yellow (Hagoort et al., 2004). The source of the current N400 effect is not obvious. Apparently in our study there is no semantic violation or world knowledge inconsistency; the two actions were perfectly compatible and appropriate for the scenario according to previous normative studies (Santana and de Vega, 2013). Thus, “cleaning the wound” and “unrolling the bandage” are two complementary actions, ordinarily performed in the same wound-curing scenario. In fact, when the two actions are described as consecutive, they become compatible and the N400 fades.

In addition to the N400, there was also an enhancement of N200 waveform at parieto-occipital electrodes (significant in Experiment 1) and a significant negativity or a reduced positivity in the later time window of 600–800 ms, both associated with the motor incongruence condition. The N200 is similar to the recognition potential (RP) reported elsewhere as an early marker of visual word recognition or semantic processing (see review by Martín-Loeches, 2007). However, the standard interpretations of the RP do not fit exactly with the current N200 effects. First, word recognition processes should not differ between compatible and incompatible conditions, because in both cases the target words (and the carrying clause) were exactly the same. Second, the semantic interpretation is also troublesome, because the RP is usually reported as more negative for compatible sentences (Martín-Loeches et al., 2004) and for compatible action pictures (Proverbio and Riva, 2009) than for their incongruent versions, because they are more recognizable. Notice, however, that the actions in the second clause were always recognizable here. In addition, the N200 was larger for the motor incompatible version, reversing the usual RP pattern. It is possible that the discourse-level motor incongruence determines an extra attentional effort to the second clause, to try to integrate it into the previous context, and this enhances the N200. Concerning the late negativity in incompatible conditions, Shibata et al. (2009), and Nittono et al. (2002) reported similar effects during the observation of incompatible actions, and they suggest that it is a sort of second N400, aimed at dealing with incongruence at a late stage.

A possible explanation for the motor congruence effects comes from embodied theories of meaning: comprehension may involve a simulation of the sensory–motor events described by the sentences (e.g., Boulenger et al., 2006; Buccino et al., 2005; Glenberg et al., 2008; Taylor and Zwaan, 2008). For instance, the indexical hypothesis claims that a sentence can be understood as long as the *affordances* derived from the words can be coherently meshed into a feasible simulation, according to the grammar specifications (de Vega et al., 2004; Glenberg et al., 2007; Glenberg and Robertson, 1999, 2000). Turning back to the “cleaning the wound and unrolling the bandage” scenario of Table 3, both adverbial versions are grammatically correct and lead to coherent propositions. However, the *while*-version “instructs” readers to simulate the two actions performed at once and they fail because of their motor incompatibility.

Given the poor spatial resolution of the ERP technique, this study does not provide direct evidence of motor or premotor cortex activation during the simulation of manual actions. As mentioned before in this paper, and elsewhere in the literature, the N400 component is a general marker of semantic evaluation processes, rather than embodied processes in the brain. However, semantic evaluation could be the final stage of quite diverse processes, at the lexical, sentence, or discourse level. In the case of action-related materials, it is possible that the semantic evaluation processes associated with N400 are the outcome of embodied simulations carried over by specific motor networks. In other words, the motor brain could try to simulate the two actions according to the embodied constraints, and in case of failure (simultaneous motor–motor actions), the semantic analyzer in the brain would increase the N400 response. The aforementioned study by Aravena et al. (2010) demonstrated that this was the case when participants concurrently processed action sentences and mismatching motor actions. The resulting N400 clearly showed that this component is sensitive to mismatching linguistic and motor brain processes. The two studies differ, however, in that here the motor incongruence was exclusively created by means of the verbal modality, whereas in Aravena et al.'s study, the incongruence included a real mismatching motor response.

Beyond ERP, other techniques have supported the idea that sensory–motor processes are activated in the brain during the comprehension of action language. Thus, fMRI studies have shown activations in motor and premotor brain

Table 3 – Examples of the original Spanish materials and their approximate english translation. Automatically paced segments are separated by slashes. The ERP recording was time-locked to the words in bold.

EXPERIMENT 1
EXPERIMENTAL SENTENCES
WHILE-VERSION (INCONGRUENT)
ARAÑAZO/Mientras limpiaba la herida/**desenrolló**/el/**esparadrapo**/para ponérselo/en la/rodilla
SCRATCH/While cleaning the wound/he unrolled/the/bandage/to put it/over the/knee
PASTELERÍA/Mientras amasaba la harina/**batió**/los/**huevos**/para hacer/la/tarta
BAKERY/While kneading the dough/she stirred/the/eggs/to make/the/cake
AFTER-VERSION (CONGRUENT)
ARAÑAZO/Después de limpiar la herida/**desenrolló**/el/**esparadrapo**/para ponérselo/en la/rodilla
SCRATCH/After cleaning the wound/he unrolled/the/bandage/to put it/over the/knee
PASTELERÍA/Después de amasar la harina/**batió**/los/**huevos**/para hacer/la/tarta
BAKERY/After kneading the dough/she stirred/the/eggs/to make/the/cake
WHILE FILLER (CONGRUENT)
BARRENDERO/Mientras barría el suelo/**recogió**/una/**lata**/para meterla/en la/papelera
SWEEPER/While sweeping the floor/he picked up/a/can/to put it/into the/litterbin
AFTER FILLER (INCONGRUENT)
CORREDOR/Después de cruzar la meta/adelantó/al/rival/para ganar/la/carrera
RUNNER/After crossing the finish line/she overtook/the/rival/to win/the/race

EXPERIMENT 2
EXPERIMENTAL SENTENCES
MOTOR-MOTOR (INCONGRUENT)
ARAÑAZO/Mientras limpiaba la herida/**desenrolló**/la/**venda**/del/botiquín
SCRATCH/While cleaning the wound/he unrolled/the/bandage/from the/cabinet
PASTELERÍA/Mientras amasaba la harina/**batió**/las/**claras**/de/huevo
BAKERY/While kneading the dough/she stirred/the/eggs/whites
PERCEPTUAL-MOTOR (CONGRUENT)
ARAÑAZO/Mientras miraba la herida/**desenrolló**/la/**venda**/del/botiquín
SCRATCH/While looking at the wound/he unrolled/the/bandage/from the/cabinet
PASTELERÍA/Mientras vigilaba el horno/**batió**/las/**claras**/de/huevo
BAKERY/While keeping an eye on the oven/she stirred/the/eggs/whites
MOTOR-PERCEPTUAL FILLERS (CONGRUENT)
TALLER/Mientras lijaba la tabla/**olió**/el/**barniz**/de la/madera
WORKSHOP/While sanding the plank/he smelled/the/varnish/of the/wood
ANOMALOUS FILLERS (INCONGRUENT)
NOTICIA/Mientras miraba el periódico/se **encendió**/un/**pimiento**/en/tiras
NEWS/While looking at the newspaper/he lighted/a/pepper/into/strips

areas while participants understood simple action-related sentences (e.g., Aziz-Zadeh et al., 2006; Moody and Gennari, 2010; Rizzolatti and Craighero, 2004; Tettamanti et al., 2005, 2008; Urrutia et al., 2012); TMS studies have revealed that understanding action words or sentences modulates cortico-spinal responses (Buccino et al., 2005; Pulvermüller et al., 2005; Tomasino et al., 2008), and oscillatory mu rhythms in the EEG, which are considered markers of motor processes in the brain, are desynchronized by action language in the same way as by performing or observing actions (Moreno et al., 2013; van Elk et al., 2010). Given that the above studies utilized action language, including action sentences not very different from the ones used here, we can assume that in the current experiments there was also motor activation undetected by the ERP. However, the analogy is limited, because this study employed for the first time complex action-related sentences, involving an agent performing two actions in time. The combinatorial processes occurring here, marked by the temporal adverb, and the derived motor congruence or incongruence, have not been yet studied by means of neuroimaging or other techniques. This is the first study to explore this issue by means of ERP, and further studies will be necessary to check how the motor congruence and incongruence, conveyed by language, are realized in the brain.

4. Conclusion

In sum, this research showed how brain activity, as measured by means of ERP, is sensitive to the motor congruence of sentences describing two actions as simultaneous or consecutive. The obtained N400 and late negativity effects could not be attributed to lexical, grammatical or sentence-level processes, given the fact that the local context was the same in compatible and incompatible sentences, nor can they be attributed to semantic violations of conflicts with general world knowledge, because the actions, typical of the human repertoire, belonged to the same script or scenario and were complementary. The results are consistent with an embodiment approach to meaning, as the factor determining compatibility was the violation of motor constraints of actions: participants can easily simulate two motor actions performed consecutively, and also a perceptual and a motor action performed simultaneously, but they have difficulties simulating two motor actions performed at once and this led to the observed increase of N400.

5. Experimental procedures

5.1. Participants

Twenty-five native Spanish-speaking students of the University of La Laguna (15 women, ages ranging between 18 and 30 years; $M=20.4$; $SD=2.1$), took part voluntarily in Experiment 1 in exchange for academic credits. Another group of twenty-five students of the University of La Laguna (13 women, ages ranging between 18 and 31 years; $M=21.9$; $SD=4.19$) took part voluntarily in Experiment 2 in exchange for academic credits. All participants were native Spanish speakers. They all had normal or corrected to normal vision, were neurologically healthy and were right-handed as measured by the Spanish version of the Edinburgh inventory (Oldfield, 1971). Data from four subjects in Experiment 2 were discarded due to technical problems with electrode impedances or excessive ocular artifacts.

5.2. Design and materials

In Experiment 1, a simple within-participants design was employed, consisting of manipulating the Adverb (*while* vs. *after*). Two counterbalance conditions, depending on the assignment of the adverbs to the items, were created and each was administered to half of the participants. The experimental materials consisted of 80 sentences (40 *while* vs. 40 *after*), describing two actions. All had the same structure: The title, the first clause containing the adverb *while* or *after* and the first motor action, the second clause containing a second motor action, and a third clause describing the purpose of the actions. Given that *while* experimental sentences were always inconsistent and *after* experimental sentences were always consistent, it was crucial to avoid having participants rely on a superficial or strategic processing of the materials (e.g., if the sentence begins with *while*, then it is non-sensible). To this end, 60 filler sentences–not analyzed in this experiment–were created (30 *while* and 30 *after*) with the same structure as the experimental sentences, but reversing the congruence values: *while*-sentences were made compatible and *after*-sentences were incompatible. Compatible *while* fillers included a motor action in the second clause, whereas the first clause either was a perceptual action or it was a long-duration motor action, which could be interpreted as a *ground* event that is momentarily interrupted to perform the critical action of the second clause (de Vega et al., 2007). Incompatible *after* fillers presented an alteration of the regular sequence of two actions. An additional measure to avoid superficial processing was to include a third clause in the experimental sentences that sometimes was inconsistent with the previous context, even in the *after* consistent condition, inducing participants to focus on the whole text rather than just on the critical motor clauses. Examples of each type of items are available in Table 3.

Forty additional fillers with varied structure, not bearing the *while/after* adverbs, were also employed to further hinder the development of response strategies. In addition, five practice items were presented before the experiment to familiarize participants with the task.

Lexical variables were automatically controlled in the experiment, given the fact that the second clause, in which the ERP data were recorded, was shared by the *while* and *after* experimental conditions. Other semantic variables were also controlled, as detailed in Santana and de Vega (2013), by means of three norming studies performed with different samples of participants. They were given the experimental sentences with pairs of actions, and were asked to estimate their duration and preferred representation (visual or motor), and whether they belonged to the same or different scenarios. All of the selected pairs of actions were judged to be of equivalent duration, as being preferably represented in a motor rather than a visual manner, and as belonging to the same scenario.

In Experiment 2, two types of critical sentence (*motor–motor* vs. *perceptual–motor*) were manipulated within-participant. Experimental materials consisted of 70 motor sentences in two versions each. Each participant received one of the two counterbalanced versions of the materials, namely 35 *motor–motor* and 35 *perceptual–motor* sentences. Furthermore, 35 *anomalous* sentences were included with a similar structure and a low cloze probability noun in the second clause. To avoid having participants employ superficial strategies (e.g. the rule of thumb "first clause is motor=incompatible"), 35 *motor–perceptual* sensible filler sentences were also included, as well as thirty fillers of varied structure. All sentences had the same structure (except the varied-structure fillers): title, first clause (containing the adverb and the first event), second clause (containing a second event), and a noun complement. Examples of the materials are shown in Table 3.

To make them comparable, *anomalous* sentences and *motor–perceptual* sentences were matched with experimental sentences in lexical frequency and length at the critical noun in the second clause, as illustrated in Table 4. Word frequency was obtained from the Alameda and Cuetos (1995) frequency dictionary of the Spanish language.

5.3. Procedure

During the EEG session, participants sat in a soundproof and electrically shielded room. Stimuli were presented on a computer screen situated at a distance of 80 cm from

Table 4 – Word frequency (occurrences per million) and length (in syllables) of the critical noun in the second clause. SDs in parentheses.

	Experimental	Anomalous	Motor–perceptual
Frequency	83 (139)	73 (112)	139 (252)
Length	2.71 (0.76)	2.60 (0.65)	2.87 (0.77)

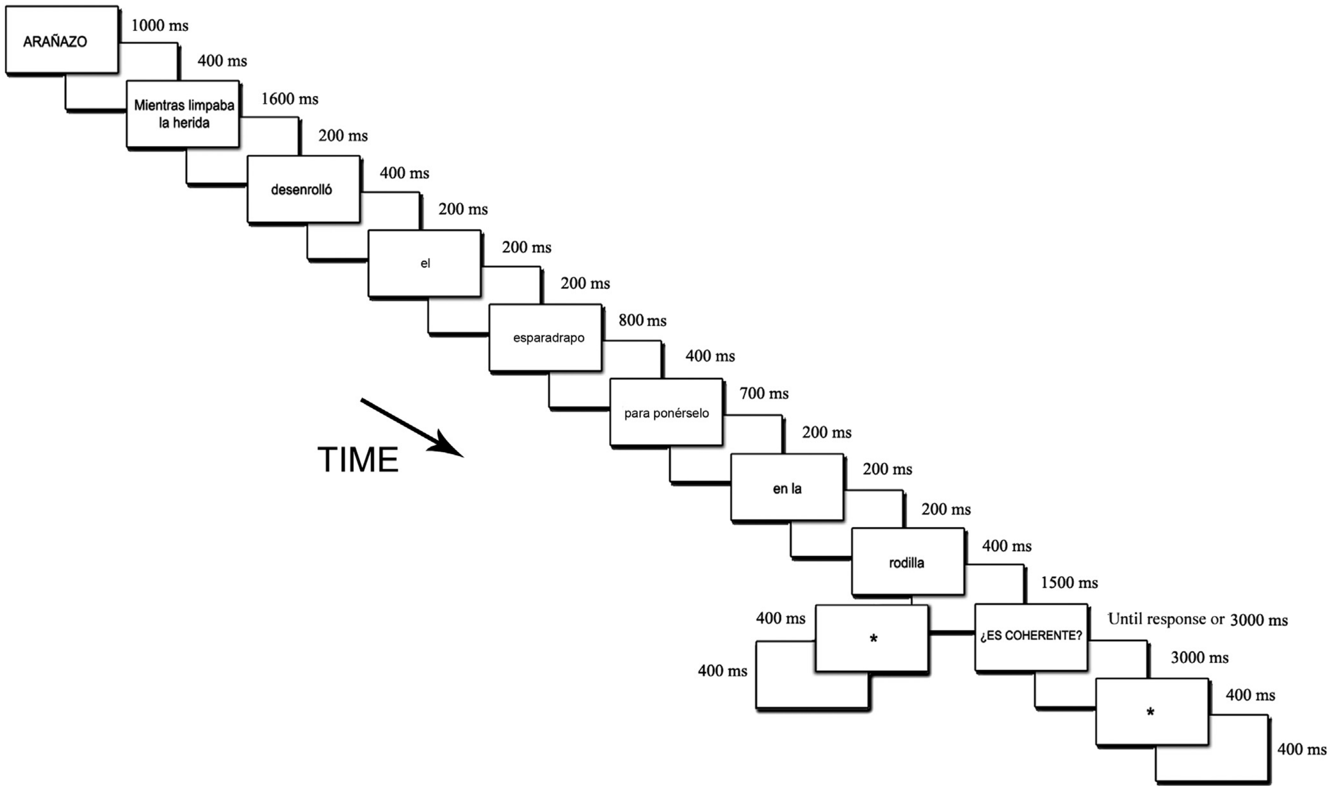

Fig. 6 – Sequence of events in a sentence trial. The approximate English translation of the example is: "SCRATCH/ While cleaning the wound/ (he) unrolled/ the/ bandage/ to put it/ over the/ knee".

participants' eyes. Sentences appeared automatically on the screen, divided into segments. A scheme of materials segmentation and exposition duration can be found in Fig. 6. Coherence judgments were required only in 20% of the items, prompted by the message *Is this coherent?* Participants were required to respond Yes/No with the middle and the index finger of the left hand using the assigned keys of the keyboard. We used this low proportion of coherence judgments to minimize the potential interference between responses and the motor processes presumably associated with the comprehension task. Nevertheless, there were enough judgments to grant participants' attention to the task, and to perform statistical analysis of the behavioral data.

5.4. *EEG recording and ERP analysis*

Electroencephalogram (EEG) was recorded with 31 AgCl electrodes embedded in an elastic cap that fit the head at locations FP1, FP2, F7, F3, FZ, F4, F8, FC5, FC1, FC2, FC6, T7, C3, CZ, C4, T8, TP7, CP5, CP1, CP2, CP6, TP8, P7, P3, PZ, P4, P8, PO7, PO8, O1, and O2. Two electrodes placed above and below the left eye were also used to register blinks and eye movements. Finally, two electrodes placed over the right and left mastoid processes served as references for the rest of the electrodes. Skin-to-electrode impedances were equal to or less than 5 kΩ. Electric activity was amplified with a 0.01–100 Hz bandwidth and a sampling rate of 250 Hz using NeuroScan SymAmp RT amplifiers (http://www.neuro.com/synamps.cfm) and NeuroScan Scan 4.5 software. Stimuli were presented through E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm). EEG was stored and ERP were analyzed offline using NeuroScan Edit 4.2 software. An offline low cutoff filter of 0.1 Hz (12 dB/oct) and a high cutoff filter of 30 Hz (12 dB/oct) were employed. Results were re-referenced to the arithmetic mean of the two mastoids. For the blink and ocular movement artifact correction, we used the automatic NeuroScan Edit 4.2 procedure, which resulted in the elimina tion of approximately 5.4% of the data. Data were segmented for ERP analysis in epochs between 100 ms before and 900 ms after the onset of the critical words in the second clause (the verb, and the noun). A baseline correction was applied using the average electrical activity of the 100 ms prior to the onset of each critical word.

The ERP recording was time-locked to the verb and the noun placed in the second clause, which was shared by the two experimental conditions. We could check in this way whether incongruence is immediately detected when the reader finds the second action verb, or if it is delayed until the processing of the object noun completing the information on the motor event. The selection of the time windows for the statistical analyses was made after performing a point-to-point comparison of grand averages between conditions. When choosing a window, the criterion was to obtain significant differences for ERP segments longer than 50 ms; also, the segment had to correspond to time windows described in the literature. In this way, the complete 1000 ms time window was divided into the following three time windows: 150–250, 350–550 and 600–800 ms.

Mean voltage amplitude was included as a dependent variable in three groups of repeated measures ANOVAs, where the topographic region was included as a within-subjects factor. A first global ANOVA included the factor Adverb (*while* vs. *after*) and two topographic factors: Hemisphere and Frontality. The Hemisphere factor included nine left electrodes (F7, F3, FC5, T7, TP7, CP5, P7, P3, and PO7) and nine right electrodes (F8, F4, FC6, T8, TP8, CP6, P8, P4, and PO8). The Frontality factor included nine anterior electrodes (FP1, FP2, F7, F3, FZ, F4, F8, FC1, and FC2), nine central electrodes (T7, C3, CZ, C4, T8, CP5, CP1, CP2, and CP6) and nine posterior electrodes (O1, O2, PO7, PO8, P7, P3, PZ, P4, and P8). A second group of ANOVAs analyzed seven regions of four electrodes each, namely Left Frontal (F7, F3, FC5, and FC1), Right Frontal (F8, F4, FC6, and FC1), Left Central (C3, T7, CP5, and TP7), Central (CP1, CZ, CP2, and PZ), Right Central (C4, T8, CP6, and TP8), Left Parietal (P7, P3, PO7, and O1) and Right Parietal (P8, P4, PO8, and O2). Additionally, the visual recognition potential (RP) was explored at the 150–250 ms time window (N200), for posterior right (O2 and PO2) and left (O1 and PO1) electrodes. All statistical analyses were performed using R software (http://www.r-project.org) with the package elaborated by Hernández (2011). When violations of the sphericity assumption occurred, Greenhouse–Geisser cor rection was applied and epsilon (ε) is reported. Only signifi cant differences in the ERPs were reported.

In Experiment 2, the EEG recording procedure and the temporal windows analyzed in the ERPs were exactly the same as in Experiment 1, although, unlike in Experiment 1, no significant differences were found in the early temporal window (150–250 ms). Also the middle temporal window differs slightly from the equivalent window of Experiment 1 (300–500 ms vs. 350–550 ms), but was still clearly identifiable as an N400 window. The statistical analyses included the same electrode grouping as in Experiment 1, but they were organized into a set of restricted ANOVAs and a set of extended ANOVAs. The restricted set of ANOVAs contrasted the *motor–motor* (incompatible) and *perceptual–motor* (compatible) conditions which, as in the homologous conditions in Experiment 1, shared the second clause. The extended set of ANOVAs included the latter conditions, and also the *anomalous* and the *motor–perceptual* conditions, which did not share the second clause with the *motor–motor* and the *perceptual–motor* materials, but were matched in word length and frequency, as explained above. The former contrasts allow comparing the N400 presumably obtained for the incompatible *motor-motor* condition with the standard N400 in the *anomalous* condition. Also, we expected to find no modulation of N400 in the compatible *motor–perceptual* condition, equivalent to the experimental *perceptual–motor* version.

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