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Research paper

On the interplay between motor sequencing and linguistic syntax: Electrophysiological evidence

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ABSTRACT

In this study, we used a paradigm combining two different sequential motor tasks, namely linear vs. non-linear self-administration of sentences, with correctness judgment of the sentences (half of them could include a morphosyntactic violation) while recording event-related potentials, ERPs. The sentences could be of either three types: subject-relative sentences, embedded PP sentences -with a displaced prepositional phrase between the subject and the verb-, or coordinate subject sentences - with two conjoined noun phrases as subject. Overall, results revealed significant modulations in the ERP components, connected to the number of different actions involved in both the motor task and the sentence (number of verbs). The motor task seemed always to hamper the occurrence of proper early syntactic processes, as no frontal negativities (LAN) could be observed. The latter were replaced by an N400 effect when motor and sentential structures matched, a component that reflects lexico-semantic processing. In turn, a mismatch in this regard seemed to completely impede the appearance of any type of early processing. The present findings extend support that syntax and motor task computations draw upon interdependent resources, in line with embodied perspectives of language processing.

1. Introduction

Within the frame of embodied cognition theories, and particularly in relation to language processing, a central challenge is to determine whether and how syntax-based representations could be partially common to the motor sequencing systems. In this regard, a promising approach is investigating how the establishment of the structural relation between words within a sentence is modulated by concurring motor structuring.

There are different issues involved in signaling structural relations in the syntactic domain, but one of the most used across different languages is subject-verb agreement, especially in languages with a relatively free word order, like Spanish. Numerous ERP studies have often reported two ERP components —a left anterior negativity or LAN and a P600— when subject-verb agreement anomalies are compared to correct sentences (for a review see Molinaro, Barber, & Carreiras, 2011) across different languages (e.g., English: Coulson, King, & Kutas, 1998; German: Roehm, Bornkessel, Haider, & Schlesewsky, 2005; Spanish: Silva-Pereyra & Carreiras,

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2007). A review of the literature shows that this pattern is affected by a variety of linguistic factors, including the category of the violation (i.e. morphosyntactic or word-category violation, Hinojosa, Martín-Loeches, Muñoz, Casado, & Rubia, 2003), morphological features (i.e. person and number, Mancini et al., 2011a, 2011b), and syntactic complexity (Martín-Loeches, MuñozCasado, Melcón, & Fernández-Frías, 2005). However, how concurring motor sequencing could impact sentences structuring (reflected in subject-verb agreement processing) has been very scarcely explored, while being of the highest interest for embodied language perspectives (e.g.,Pulvermuller, 2005).

In a recent study (Casado et al., 2018), we have demonstrated that establishing subject-verb agreement in sentences with center-embedded relative clauses is modulated by a concomitant motor task that somehow parallels the non-linear structure of relative sentences. The experimental paradigm was inspired in studies revealing that sentences' meaning comprehension is modulated by performing simultaneously movements that could either match or mismatch the action described in the sentence, the so-called action-sentence compatibility effect, ACE (Glenberg and Kaschak, 2002).

The ACE paradigm has been also combined with the study of ERPs in order to explore the electrophysiological response to motor compatibility (or incompatibility) of actions described by sentences. The N400 effect of the ERP is a negative going component reflecting semantic processing (Kutas & Hillyard, 1980). Typically, the amplitude of this component increases when semantic incongruences occur (Kutas & Federmeier, 2011). As the ACE paradigm is semantic in nature, incongruences between the movements and the actions described in sentences significantly increase the N400 component (Aravena et al., 2010; Bach, Gunter, Knoblich, Prinz, & Friederici, 2009; Santana & de Vega, 2013; Shibata, Gyoba, & Suzuki, 2009; van Elk, van Schie, & Bekkering, 2008; Willems, Özyürek, & Hagoort, 2008). By contrast, the ACE-like design in Casado et al., 2018 was focused on syntactic structuring rather than the meaning of the sentences, with the aim of investigating whether the processing of the syntax of a sentence is affected by the structural features of a concomitant motor task. The results of that experiment revealed that non-linear self-administration yielded a reduction of the LAN and an increment of the P600 amplitudes, relative to linear self-administration. The findings frame into embodied language approaches, according to which the allocation of cognitive resources to plan and perform motor sequences may be shared in generating and comprehending some linguistic structures (Barsalou, 2008; de Vega, Glenberg, & Graesser, 2008; Fischer & Zwaan, 2008; Glenberg & Gallese, 2012; Pulvermuller, 2005). We concluded that in the interplay between motor actions and syntactic processing, a competing situation between at least partly shared neural circuits could occur, yielding in that case a detrimental syntactic processing. Nonetheless, only one way to structure sentences, i.e. relative sentences, was tested in that study.

Accordingly, we here performed a new experiment to explore whether the interplay between the structure of motor sequencing and the structures of linguistic syntax could also been found for other types of sentences differing in complexity. To that end, we constructed two more sets of sentences by transforming the relative sentences previously used. The procedure consisted, accordingly, in substituting the **center-embedded clause** (e.g., *Mis amigas, que vinieron de visita, ayudaron en la mudanza./My friends, who came to visit, helped with the move.*) by a prepositional phrase that modifies the verb in one of the cases -**embedded PP sentences**- (*Mis amigas, con sus coches viejos, ayudaron en la mudanza./My friends, with their old cars, helped with the move.*), and by creating sentences with two conjoined noun phrases as subject -**coordinate subject sentences**- (*Mis amigas y sus respectivas parejas ayudaron en la mudanza./My friends and their respective partners helped with the move.*).

Sentences with center-embedded relative clauses are the result of a *Movement*, a syntactic operation where an element at some position in the sentence is displaced; therefore, they are considered structures with non-local combinations (Chomsky & Miller, 1958). In order to explore whether the processing of subject-verb agreement of another type of gap structure could be affected by the motor task, in the current study we included the embedded-PP sentences. In these sentences, a prepositional phrase that modifies the verb, and consequently should (canonically) appear afterwards, was displaced between the subject and the verb. In addition, we wanted to test whether the type of self-administration could affect the processing of sentences in which the relation between the subject and the verb is linear. For that, we created the coordinate subject sentences.

As in our previous study, *Linear* self-administration consisted in successively pressing three buttons with three consecutive fingers of the right hand, while in the *Non-linear* self-administration the finger in the middle position was substituted by pressing another button with the right foot. This design mirrored the ACE paradigm, intending to parallel to some extent the syntactic organization of our sentences. In this regard, the linear self-administration, where the relation between the different constituents is linear as the fingers in the right hand are represented in the same body loci, somehow parallels the locally syntactic organization of the coordinate subject sentences. On the other hand, the non-linear self-administration constitutes a structure with non-local dependencies as the hand and the foot represent different body loci. This non-adjacent configuration can be assumed to partially parallel the combinatorial operations involved in our non-linear, recursive and embedded-PP sentences.

The interest of the comparison between sentences and manner of self-administration lies in the supposedly different processing demands of the three types of sentences that can be tapped by the motor task. We hypothesize that if linear and non-linear action structuring impacts the processing of subject-verb agreement, we should observe a differential electrophysiological pattern for morphosyntactic violations of this type of agreement in the three types of sentences depending on the manner of self-administration. In this regard, if the parser requires extra resources to establish agreement when the motor task and the sentence structure are to some extent parallel, a decrease in LAN amplitude and an increase in P600 amplitude are expected for matching conditions (relative and embedded-PP sentences self-administered in non-linear manner, and coordinate subject sentences self-administered in linear manner). This pattern usually appears when syntactic processing has been difficult or detrimental (King & Kutas, 1995; Martín-Loeches et al., 2012). Alternatively, or complementarily, if the compatibility between the motor task and the syntactic structure enhances (by priming or facilitating) brain sensitivity to the establishment of the agreement, an increase in LAN amplitude and a decrease in P600 amplitude are expected for matching conditions (relative and embedded-PP sentences self-administered in non-linear manner, and coordinate subject sentences self-administered in linear manner).

2. Method and materials

2.1. Participants

Twenty-four (15 females) healthy, native Spanish speakers (mean age 20 years, range 18–29) participated in the study. All were right-handed with average handedness scores of +80 (range 60–100), according to the Edinburgh Handedness Inventory (Oldfield, 1971) and declared normal or corrected-to-normal vision. Participants gave written informed consent and received monetary reimbursement. The study was approved by the ethics committee of the Hospital Clínico Universitario, UCM, and conducted in accordance with the Declaration of Helsinki.

2.2. Design and material

A 3 x 2 x 2 repeated-measures experimental design was used in which Type of Sentence (relative/embedded-PP/coordinate subjects), Correctness (correct/incorrect) and Manner of self-administration (linear/non-linear) were manipulated independently.

The linguistic material used in this experiment was partially taken from Casado et al., 2018. In that case, the experimental language material consisted of 210 Spanish relative sentences with a center-embedded subject-relative clause introduced by different subordinate conjunctions and separated by commas from the main clause (*relative sentences*). In the current study, we constructed 150 additional sentences of the same type in order to have enough sentences in the new design. From this initial pool of 360 relative sentences, another two sets were constructed by transforming them. In the first version, the relative clause was substituted by a displaced verb complement (a prepositional phrase), also separated by commas from the main clause (*embedded PP sentences*). In the second, the subject of the sentences was formed by two conjoined noun phrases joined by the "and" conjunction (*coordinate subject sentences*). The structure of the three types of sentences allows dividing them into three segments, to fit the self-administration motor task. It is important to state that the number of words between the first noun in the sentence and the verb was identical on average for the three types of sentences (4.8 words on average, range 4–6). Therefore, the distance between the subject and the verb was kept constant, and the only difference between the three types of sentences was the syntactic complexity.

Furthermore, for each of the 360 experimental sentences, two different versions were composed by incorporating morphosyntactic violations. In the incorrect versions, the verb of the main clause in the relative sentences, and the only verb in the embedded PP and coordinate subject sentences could present person, number, or both subject-verb agreement violations. The length (number of syllables) of the target words was matched across conditions (i.e., correct and incorrect). Other linguistic variables, such as word frequency, familiarity, concreteness and imageability, were counterbalanced since the verbs were the same in the three types of sentences. The sentences were organized into six experimental sets containing each of them 60 correct relative sentences, 60 incorrect relative sentences, 60 correct embedded PP sentences, 60 incorrect embedded PP sentences, 60 correct coordinate subject sentences and 60 incorrect coordinate subject sentences.

Examples of each type of sentence and of the violations are given below.

a. Relative sentences:
   - Correct: Los árboles [N, Pl.], donde anidaron los polluelos, florecieron [V, Pl., 3rd person] en primavera. (The trees [N, Pl.], where the chicks nested, blossomed [V, Pl., 3rd person] in spring.)
   - Morphosyntactic violation: Los árboles [N, Pl.], donde anidaron los polluelos, *florecimos* [V, Pl., 1st person] en primavera. (The trees [N, Pl.], where the chicks nested, blossomed [V, Pl., 1st person] in spring.)

b. Embedded PP sentences:
   - Correct: Los árboles [N, Pl.], lejos de la ciudad, florecieron [V, Pl., 3rd person] en primavera. (The trees [N, Pl.], far from the city, blossomed [V, Pl., 3rd person] in spring.)
   - Morphosyntactic violation: Los árboles [N, Pl.], lejos de la ciudad, *florecimos* [V, Pl., 1st person] en primavera. (The trees [N, Pl.], far from the city, blossomed [V, Pl., 1st person] in spring.)

c. Coordinate subject sentences:
   - Correct: Los árboles [N, Pl.] y las fragantes flores florecieron [V, Pl., 3rd person] en primavera. (The trees [N, Pl.] and the fragrant flowers blossomed [V, Pl., 3rd person] in spring.)
   - Morphosyntactic violation: Los árboles [N, Pl.]y las fragantes flores *florecimos* [V, Pl., 1st person] en primavera. (The trees [N, Pl.] and the fragrant flowers blossomed [V, Pl., 1st person] in spring.)

Each set contained a different version of each sentence. Since every participant performed one of the six sets, sentences were presented to a given participant only once. The presentation of the sentences within a set was randomized.

2.3. Procedure

Participants were comfortably seated in a quiet shielded chamber, in front of an LCD screen (placed 65 cm from their eyes, visual angles around 0.8°–4° width) where the stimuli were presented in white against a black background in the center of the monitor and controlled by Presentation® Software.

The procedure was modeled after that of Casado et al.'s (2018) study. Each trial started with a fixation cross presented on the center of the screen for 500 ms followed (200 ms of inter-stimulus interval, ISI) by an asterisk indicating the participants to press the

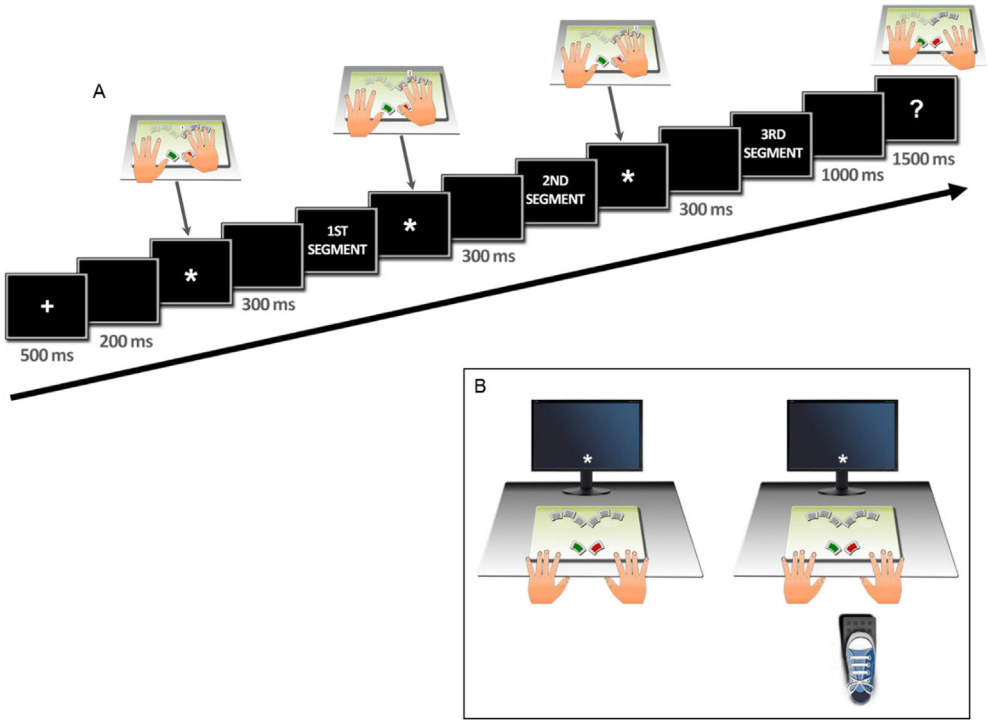

Fig. 1. Schematic representation of the stimulation procedures (A). Participants were presented the three segments of each sentence word by word. Participants' task consisted of pressing a button to get the segments displayed every time they saw an asterisk in the center of the monitor in order to continue the task. At the end of each sentence, a judgment of grammaticality was requested. Buttons for self-administration (B). Left: Linearly sequenced manner of self-administration required the participants to press three buttons with three consecutive fingers in their right hand. Right: Non-linearly sequenced manner of self-administration required the participants to replace the finger pressing in the middle position by pressing a pedal with the right foot.

first button to get the first segment displayed. As soon as the participants pressed the button, a 300-ms blank appeared followed by the first segment, which was presented word-by-word (300 ms of duration each, 300 ms ISI). An asterisk appeared at the end of the segment, indicating to the participants to press a button to continue the task. This schema was repeated for the next two segments of every sentence. The first word in the sentences always began with a capital letter and the last word was presented together with a period at the end. One second after the offset of the last word, a question mark was presented for 1,5 s inducing the participants to judge whether the sentence was correct or not, by pressing one of two keys with either the right or the left thumb. Hand assignment to correctness response was counterbalanced across participants. Participants were assigned randomly to one of the six sets of trials. The outline of a trial is illustrated in Fig. 1A.

Participants were asked to self-administer the sentences' segments in either two manners. Half of the sentences were self-administered following a linear manner. In this case, participants were asked to press consecutively three buttons using the index, middle and ring fingers of their right hand, respectively. In the other half of the sentences, the self-administration was non-linear, which differed from the former in that the second segment of the sentence required pressing a pedal with the right foot rather than pressing a button with the middle finger (see Fig. 1B). Across participants, the order of the two manners of self-administering the sentences was counterbalanced. As this changed at the middle of the experimental session, a training session was performed at the beginning of every stage, allowing participants to practice both manners of self-administration. Participants were thoroughly informed about the experimental tasks. The experimental session lasted about 50 min, plus electrode preparation.

2.4. Electrophysiological recording and analysis

EEG was recorded from 59 Ag/AgCl electrodes mounted in an electrode cap (EasyCap), following the 10/20 International System. Bipolar vertical and horizontal EOGs were recorded to monitor blinks and horizontal eye movements. The impedance of all electrodes was kept below 5 kΩ. Raw data were sampled at 250 Hz and recorded with a band-pass from .01 to 100 Hz. The EEG recording was initially referenced to the right mastoid (M2); offline, all electrodes, were re-referenced to the average of the right and left mastoids and a band-pass filter from 0.1 to 40 Hz was applied.

Data were analyzed with Brain Vision Analyzer® software. EEG epochs of 1200 ms were extracted, starting 200 ms before critical word onset. The first 200 ms (−200 to 0) were used as baseline. A semi-automatic mode for artifact rejection was implemented to eliminate epochs with artifacts from the data and ocular correction was applied following the algorithm of Gratton, Coles, and

Table 1
Mean (and SD) Reaction Times (in ms.).

	Linear		Non-linear	
	Correct	**Incorrect**	**Correct**	**Incorrect**
Relative	539.9 (202.6)	534.7 (194.6)	529.9 (190.3)	481.6 (179.7)
Embedded PP	536.6 (209.1)	493.2 (200.7)	528.7 (185.9)	472.9 (133.0)
Coordinate subject	544.4 (220.8)	491.2 (173.3)	497.4 (166.9)	460.4 (161.2)

Donchin (1983). Additionally, incorrectly classified stimuli (correct sentences judged as incorrect and vice versa) were also excluded from the ERP averages. The final mean rejection rate was 19% of epochs, and there were no significant differences between conditions nor interactions in this regard (repeated-measures ANOVA with the factors Type of sentence, sentence Correctness, and Manner of sentence self-administration: all Fs (1,23) $<$ 4.00; all ps $>$ .1).

Artifact-free subject weighted average waveforms were calculated separately for epochs containing verbs in the sentences as a function of their type, correctness, and whether they were linearly or non-linearly self-administered. To avoid a loss of statistical power when repeated-measures ANOVAs are used to quantify a large number of electrodes, regions of interest (ROIs) were specified out of the 59 cephalic electrodes as a function of the main results (see Results section). Overall repeated-measures analyses of variance (ANOVA) were then performed for amplitude in each ROI, including Type of Sentence (three levels: relative, embedded PP, coordinate subject), Correctness (correct vs. incorrect), Manner of sentence self-administration (linear vs. non-linear), and Electrode (the electrodes included varied as a function of the region of interest for a given component) as within-subjects factors. Post-hoc ANOVAs were also performed when applicable. The Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) was always applied when appropriate.

3. Results

3.1. Performance

3.1.1. Reaction times

The mean reaction times (RTs) as a function of the manipulated variables are displayed in Table 1. An ANOVA indicated a significant effect of Type of sentence (F (1,23) = 4.08, p $<$ 0.05) and Correctness (F (1,23) = 6.52, p $<$ 0.01). Overall, RTs were larger for relative sentences when compared to the other two types, though significant differences only appeared between relative and coordinate subject sentences (t = 3.5; p $<$ .005). RTs were also longer for correct sentences than for incorrect sentences.

3.1.2. Accuracy

Regarding accuracy, the results are displayed in Table 2. No significant main effects of Type of sentence, Manner of self-administration, or Correctness were obtained, as is the case for their interactions, and indeed the results were very similar across conditions. However, a planned post-hoc ANOVA indicated a significant effect of Manner of self-administration in relative sentences administered non linearly (F (1,23) = 4.38, p $<$ 0.05) suggesting that this factor seemed to impact the final correctness judgments of these sentences. No effects were observed for the other post-hoc comparisons (p $>$ .1).

3.2. Event-related potentials

As can be seen in Figs. 3–6, the main findings consisted in apparent overall modulations of Manner of self-administration in frontal regions, while morphosyntactic violations (Correctness) mainly elicited a central negativity followed by a parietal positivity. The latter could be recognized as an N400 and subsequent P600 pattern, instead of the LAN/P600 customarily obtained for these anomalies. Noticeably, the fluctuations evoked by morphosyntactic anomalies seemingly differed as a function of the motor task, that is, between linear and non-linear self-administrations. Moreover, and strikingly, the latter dissimilarities did not follow a unitary pattern, but varied as a function of the Type of sentence. In this regard, embedded PP and coordinate subject sentences exhibited N400/P600 pattern only during linear self-administrations, while the N400 vanished and the P600 decreased somehow in non-linear manner. The opposite seems the case for relative sentences. After the apparent results, three ROIs were defined in order to further

Table 2
Mean (and SD) accuracy rates (in %.).

	Linear		Non-linear	
	Correct	**Incorrect**	**Correct**	**Incorrect**
Relative	98.4 (98.6)	98.7 (98.2)	98.2 (98.3)	97.7 (97.3)
Embedded PP	98.3 (98.2)	98.2 (97.3)	98.4 (98.7)	98.2 (97.1)
Coordinate subject	98.8 (98.4)	98.4 (98.1)	98.4 (98.7)	98.2 (97.8)

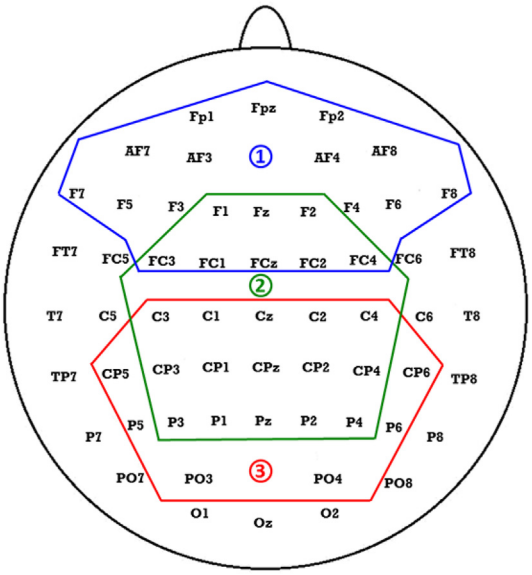

Fig. 2. Layout of the 3 Regions of Interest defined after inspection of main results.

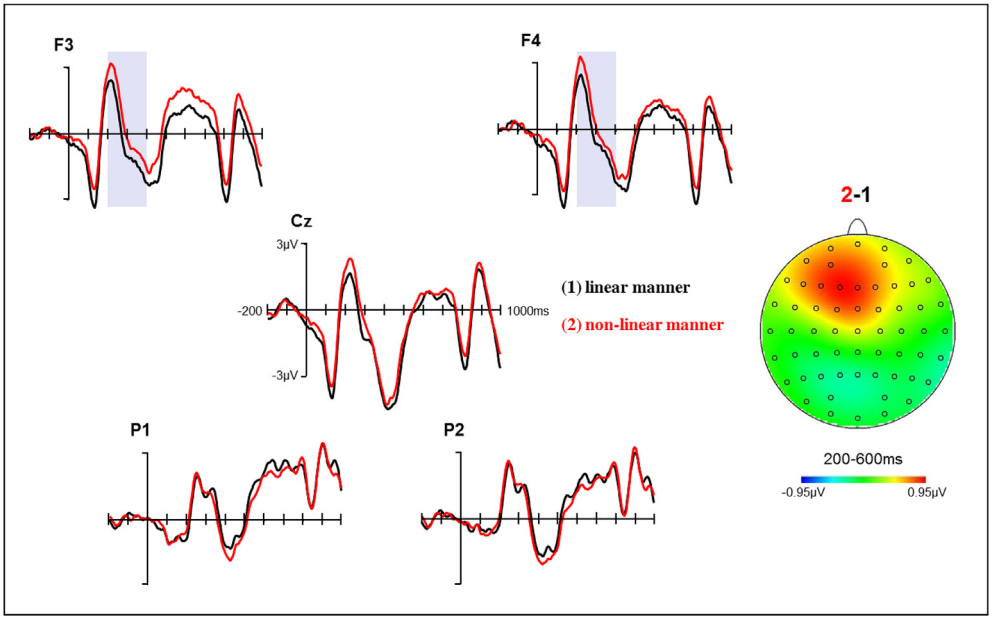

Fig. 3. ERP waveforms displaying the main effects as a function of the Manner of Self Administration of the sentences (left) and difference maps to non-linear vs linear manners (right). Violet boxes indicate statistical differences between linear and non-linear of Manner of Self Administration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

examine these findings while avoiding a reduction of statistical power due to large number of compared variables in a limited sample. Accordingly, ANOVAs were performed in the 3 ROIs depicted in Fig. 2 separately, for the time windows at which each effect was observable. Please note that although the ROIs partially overlap in topography, they applied to temporally distinct –and therefore independent- ERP modulations. In the following, statistical results and analyses are depicted for each of the main described results.

3.2.1. Main effects of manner of self-administration

To explore the frontal positivity that appeared when the sentences were non-linearly self-administered in comparison to linear self-administration, independent of the type of sentence or correctness (Fig. 3), an overall ANOVA was performed in the frontal ROI (ROI 1 in Fig. 2) along five 200-ms-wide consecutive windows covering the whole epoch, as this effect appeared to be long lasting. A main effect of Manner of self-administration was significant only in the 200–400 ms window ($F(1,23) = 6.1$; $p < .05$; $\eta_p^2 = 0.21$), at

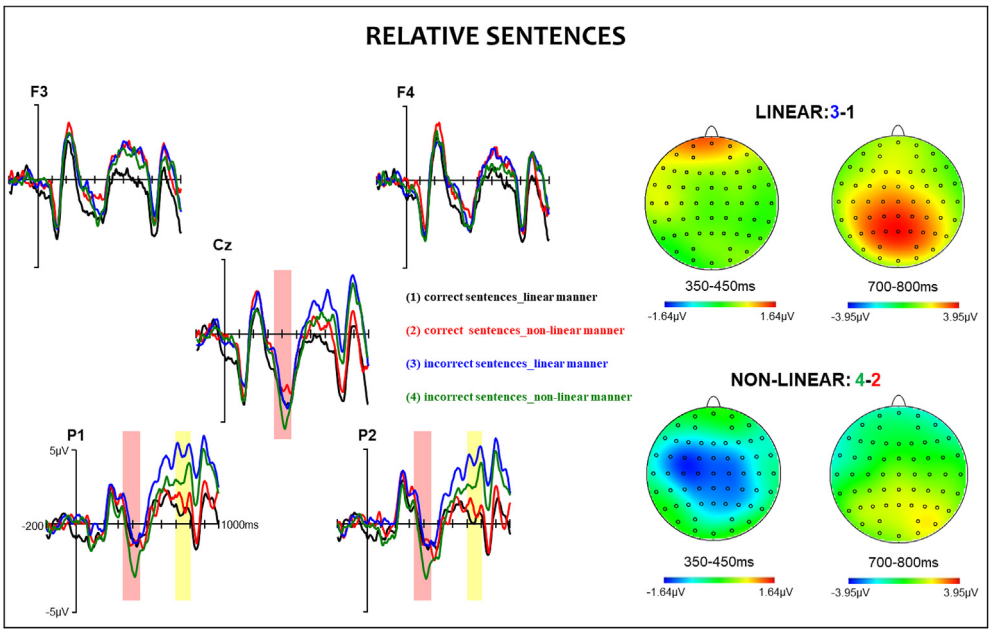

Fig. 4. ERP waveforms for relative sentences at selected electrodes (left) and difference maps to syntactically correct vs. incorrect verbs (right) in relative sentences in the two manners of self-administering. Red boxes indicate statistical differences in the 350–450 ms window. Yellow boxes indicate statistical differences in the 700–800 ms window. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

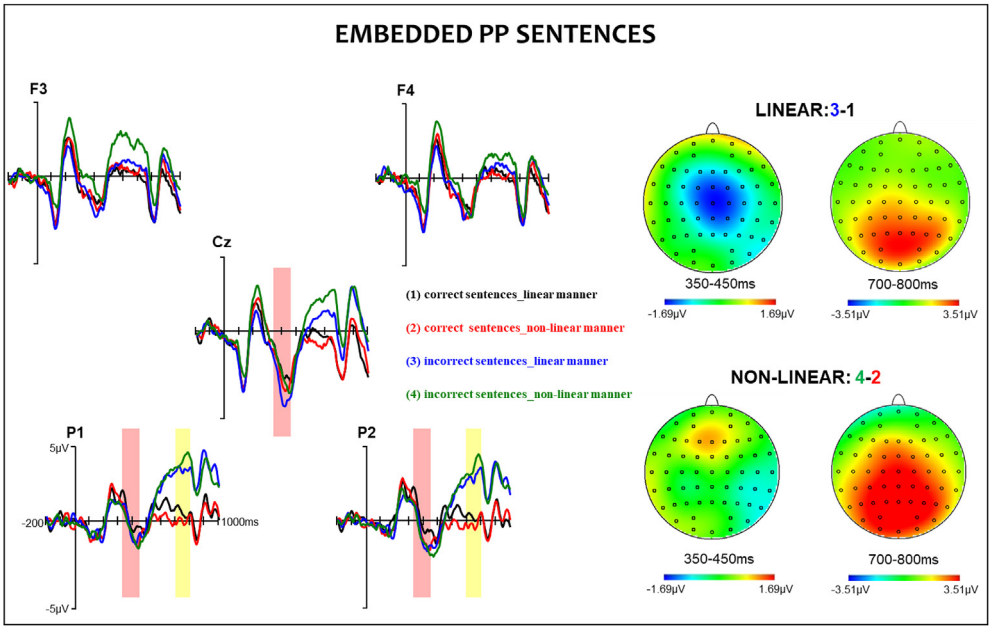

Fig. 5. ERP waveforms for embedded PP sentences at selected electrodes (left) and difference maps to syntactically correct vs. incorrect verbs (right) in embedded PP sentences in the two manners of self-administering. Red boxes indicate statistical differences in the 350–450 ms window. Yellow boxes indicate statistical differences in the 700–800 ms window. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

least partially substantiating the main observation. No other significant effects emerged for the explored windows in this ROI, neither as main effects nor in interaction (all Fs below 2.9, ps $>$ .1; η_p^2 always $<$ 0.07).

3.2.2. Effects of morphosyntactic correctness as a function of type of sentence and manner of self-administration

This was actually the main goal of the present study. i.e., to explore how morphosyntactic processing might be affected by a

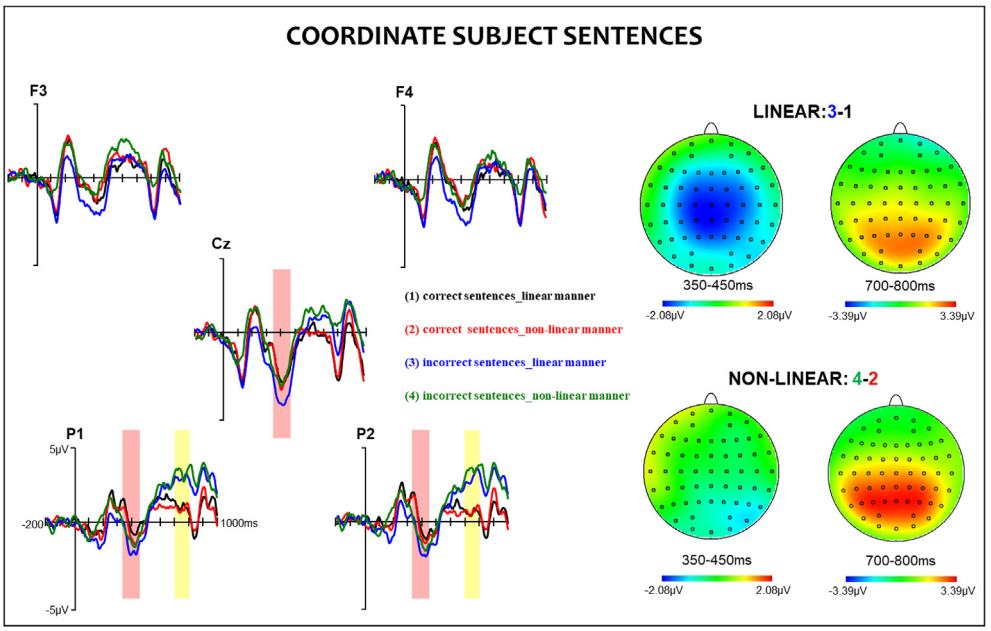

Fig. 6. ERP waveforms for coordinate subject sentences at selected electrodes (left) and difference maps to syntactically correct vs. incorrect verbs (right) in coordinate subject sentences in the two manners of self-administering. Red boxes indicate statistical differences in the 350–450 ms window. Yellow boxes indicate statistical differences in the 700–800 ms window. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

concurrent motor sequencing task and whether these effects might differ between types of sentences, as the latter may parallel, differentially, at least part of the motor sequencing structures. As the effects of Correctness mainly consisted in N400 and P600 components, ANOVAs were performed for each of these fluctuations separately in the central and parietal ROIs, respectively.

An overall ANOVA in the N400 ROI (ROI 2 in Fig. 2) and time window (350–450 ms) revealed Correctness significant effects only in interaction with Manner of self-administration and Type of sentence ($F(2,46) = 3.9$; $p < .01$; $\eta_p^2 = 0.15$), as well as with Manner of self-administration, Type of sentence and Electrode ($F(44,1012) = 2.5$; $p < .01$; $\eta_p^2 = 0.11$), supporting that the fluctuation triggered by morphosyntactic violations emerged contingent on how the sentence was self-administered, and that this differed by type of sentence. The overall ANOVA in the P600 ROI (ROI 3 in Fig. 2) and time window (700–800 ms), however, did not support the observation that this component appeared reduced in the conditions in which the N400 was apparent, as only a significant Correctness by Electrode interaction could be accounted ($F(20,460) = 5.3$; $p < .005$; $\eta_p^2 = 0.19$). No other significant effects emerged in this ROI, neither as main effects nor in interaction (all Fs below 1.8, ps $> .1$; η_p^2 always < 0.06). Considering the interactions found in the N400, the impact of the manner of self-administration on the correctness effects was analyzed for each type of sentence separately.

3.2.2.1. Relative sentences. The results obtained in relative sentences are depicted in Fig. 4, and reveal that an N400 was obtained to morphosyntactic violations only in the sentences non-linearly self-administered. A post-hoc ANOVA supported this finding, where Correctness and Manner of self-administration interacted significantly ($F(1,23) = 4.1$; $p < .05$; $\eta_p^2 = 1.15$), while Correctness did not show main effects ($F(1,23) = 1$; $p > .1$; $\eta_p^2 = 0.04$) nor in interaction with Electrode ($F(22,506) = 0.3$; $p > .1$; $\eta_p^2 = 0.01$). A possible frontal positivity in the linear self-administration was disregarded, as an ANOVA comprising the electrodes Fp1, Fpz, Fp2, AF1, AF3, AF4 and AF8 engendered null significant effects. Interestingly, the difference in the P600 between linear and non-linear manners of self-administration appeared very remarkable, in spite of the absence of significant interactions in the overall ANOVAs, as described above. Accordingly, a planned post-hoc ANOVA was determined, yielding significant Correctness effects in interaction with Electrode ($F(20,460) = 3.9$; $p < .01$; $\eta_p^2 = 0.15$) as well as of Correctness by Manner of self-administration ($F(1,23) = 4$; $p < .05$; $\eta_p^2 = 0.15$). This suggests that the P600 is present in either manner of self-administration, but also that both manners exhibited different amplitudes.

3.2.2.2. Embedded PP sentences. These results are displayed in Fig. 5. In this occasion, and contrasting with the relative sentences, the N400 was observed only in the linear self-administrations of the sentences. The post-hoc ANOVA supported this depiction, as Correctness, Manner of self-administration and Electrode interacted significantly ($F(22,506) = 3.7$; $p < .05$; $\eta_p^2 = 0.14$), while Correctness did not show main effects ($F(1,23) = 2.4$; $p > .1$; $\eta_p^2 = 0.09$) nor in interaction with Electrode ($F(22,506) = 1.9$; $p > .1$; $\eta_p^2 = 0.08$). Again, a possible frontal positivity around the Fz electrode, in this occasion in the non-linear self-administration, was disregarded, as an ANOVA comprising the electrodes F1, Fz, and F2 yielded null significant results. For consistency with the analyses in the relative sentences, a planned post-hoc ANOVA was computed for the P600, although the differences between linear

and non-linear manners were not outstanding. Only Correctness by Electrode effects yielded significant results ($F(20,460) = 4.1$; $p < .01$; $\eta_p^2 = 0.15$), while neither Correctness by Manner of self-administration ($F(1,23) = 0.6$; $p > .1$; $\eta_p^2 = 0.03$) nor Correctness by Manner of self-administration by Electrode were significant ($F(20,460) = 0.6$; $p > .1$; $\eta_p^2 = 0.03$). Accordingly, the P600 does not seem to be affected by the manner of self-administration of the embedded PP sentences.

3.2.2.3. Coordinate subject sentences. The results obtained for coordinate subject sentences can be seen in Fig. 6. They largely resemble those observed for embedded PP sentences, that is, the N400 was observed only in the linear self-administrations of the sentences. The post-hoc ANOVA also supported this depiction, as Correctness and Manner of self-administration interacted significantly ($F(1,23) = 4.1$; $p < .05$; $\eta_p^2 = 0.15$), as was the case for the interaction of Correctness, Manner of self-administration and Electrode ($F(22,506) = 3.5$; $p < .05$; $\eta_p^2 = 0.13$). In turn, Correctness did not show main effects ($F(1,23) = 1.6$; $p > .1$; $\eta_p^2 = 0.05$) nor in interaction with Electrode ($F(22,506) = 0.7$; $p > .1$; $\eta_p^2 = 0.03$). Again, for consistency with the analyses in the relative sentences, a planned post-hoc ANOVA for the P600 was computed although the differences between linear and non-linear manners were not outstanding. Only Correctness by Electrode effects yielded significant results ($F(20,460) = 2.7$; $p < .05$; $\eta_p^2 = 0.11$), while neither Correctness by Manner of self-administration ($F(1,23) = 0.1$; $p > .1$; $\eta_p^2 = 0.005$) nor Correctness by Manner of self-administration by Electrode were significant ($F(20,460) = 0.5$; $p > .1$; $\eta_p^2 = 0.02$). Consequently, the P600 of the coordinate subject sentences does not seem to be affected by the manner of self-administration.

4. Discussion

The main aim of this study was to explore the effects of different types of motor sequencing on the processing of sentences, the latter diverging in the complexity of their syntactic structuring. In a previous study we demonstrated that a concurrent motor task is able to affect subject-verb agreement processing (reflected in the electrophysiological pattern) in relative -non-linearly structured- sentences. Consequently, we expected the syntactic processing of other sentences differing in their syntactic structuring to be affected differentially by the same tasks (linear or non-linear). Overall, results revealed apparent and significant modulations at the ERP and -at least to some extent- at the behavioral levels.

Behavioral data showed that RTs appeared longer to correct than to incorrect sentences, an expected finding in line with previous studies (e.g., Martín-Loeches, Nigbur, Casado, Hohlfeld, & Sommer, 2006; Martín-Loeches et al., 2012). Further, the motor task seemed to affect the correctness judgment of incorrect relative sentences only, being more accurate for sentences linearly self-administered than in the non-linear self-administration. This might be considered a first clue indicating some type of conflict between non-linear (relative) sentences and the non-linear motor task in our data. The ERP data, in turn, revealed a peculiar and more striking pattern. First, when correctness effects were observed, these did not consist in the typical LAN/P600 pattern for the morphosyntactic violations used here but instead an N400 followed by a P600. Second, this N400/P600 pattern only appeared for concrete conditions, resulting from the interactions between correctness, manner of self-administering the sentences and type of sentence. Namely, in the relative sentences non-linearly self-administered and in the embedded PP and coordinate subject sentences linearly self-administered. In the other three conditions (relative sentences linearly administered and embedded PP and coordinate subject sentences non-linearly administered) the N400 vanished and the P600 seemed to increase. This P600 augment in the conditions in which the N400 fades away was supported statistically for the relative sentences only, however, though it seemed observable in both the waveforms and the maps of the other types of sentences.

One immediate conclusion is that our paradigm has been successful in substantiating the impact of sequencing a motor task on the syntactic processing of sentences with different structures. As such, the finding adds to our previous report (Casado et al., 2018) supporting that a concurring motor task can outstandingly conflate with syntactic sentence processing and, hence, that motor sequencing and syntax seem to share brain mechanisms. The finding contributes therefore to endorse embodied perspectives claiming that action and perception circuits might mediate syntactic processing of language (Pulvermuller, 2005; Pulvermüller & Fadiga, 2010; van Schie, Toni, & Bekkering, 2006).

Although a gap between subject NP and the main verb can be assumed both in relative and in embedded PP sentences, this not being the case for the coordinate subject sentences, our data indicate that the sentential structures would be grouped otherwise when considering the differential impact of motor sequencing, contrasting with our initial expectations. On one side, they are the relative sentences and, on the other, the embedded PP and the coordinate subject sentences. The main difference according to this clustering is indeed not the NP-verb gap but rather the presence of an additional verb between the NP and the main verb. This extra verb in relative sentences implies an extra action within another (main) action, which, from a structural view, seems to fit very well with the structure of our non-linear (vs. linear) motor sequences. Certainly, our non-linear sequences imply a different action (pressing a pedal with the foot) from the preceding and subsequent actions (pressing a button with a finger), while linear motor sequences involve always the same and one action along the sequence. It seems plausible, therefore, that our non-linear sequences could be bearing at least part of the properties of recursion. In recursion, one item is embedded as hierarchically dependent of another item of the same category (Martins, Muršič, Oh, & Fitch, 2015). Although a hierarchical dependency between the different movements involved in our non-linear sequences is not necessarily presumed, the fact that our recursive (relative) sentences constituted a case apart could support this observation. In any event, the number of different actions involved would be, in our view a main factor in the motor tasks affecting sentence processing as a function of its syntactic structure. In this regard, when the motor pattern parallels the sentential structure in the number of actions concerned, the ERP to syntactic violations exhibited a large N400 (and a possible reduction of the P600). In the opposite cases, none of the earlier customary components -N400 or LAN- emerges, while the P600 seems to display its

maximal magnitude.

The result is also outstanding considering that no LAN could be observed for our morphosyntactic anomalies, but a (semantic) N400 component instead. Several studies have reported N400 instead of an anterior negativity or LAN in response to agreement violations (e.g., Barber & Carreiras, 2005; Molinaro, Vespignani, & Job, 2008; Wicha, Moreno, & Kutas, 2004). Specifically, a central posterior negativity elicited by subject-verb person disagreement has been reported (Mancini, Molinaro, Rizzi, & Carreiras, 2011a), as is the case in our material. This could be interpreted as a change in the cognitive strategy to identify grammatical errors (e.g., Martín-Loeches et al., 2012), most probably the use of a strategy based on the more heuristic processes of semantic plausibility. This could in turn be more prone to error commitment than a morphosyntactic analyses, unless a second stage, as reflected in the P600, balances the situation. The outstanding reduction of the P600 in the relative sentences administered non-linearly might then explain the reduced accuracy in this condition.

The question, then, is why this shift in strategy arose. A plausible explanation is the depletion of available resources for syntactic processing by their use in planning the motor sequences. When processing conflicts tap on shared resources, the biphasic LAN-P600 pattern is affected, normally by significantly reducing or even vanishing the amplitude of the LAN and increasing of the P600 (King & Kutas, 1995; Vos, Gunter, Kolk, & Mulder, 2001, Tanner & van Hell, 2014). Indeed this was our prediction for the present study if the motor tasks shared processing resources with morphosyntactic analyses. A domain-general sequential processor in the inferior frontal lobe has been proposed (Fadiga, Craighero, & D'Ausilio, 2009; Fiebach & Schubotz, 2006; Tettamanti & Weniger, 2006), while the LAN component of the ERPs appears to be generated in left inferior frontal regions (e.g., Molinaro et al., 2011). At earlier stages, then, the resources to grammatically process the critical word might be depleted by the motor sequencing task and, then, an alternative strategy might be the use of lexico-semantic information. Importantly, this would occur only when the motor pattern is structurally paralleling the sentence structure, as outlined above. In case of structural incompatibility between the motor sequence and the sentence structure, the earlier processes would not emerge at all, and morphosyntactic operations appear restrained to the P600 stage –which in turn might be the reason why this component appeared to increase in these conditions, although this was not substantiated statistically.

In sum, the present results support that syntax and motor task computations draw upon interdependent resources. A syntactic processing impairment at earlier stages would occur, both when the motor sequence is compatible and incompatible with the structure of the sentence -according to whether there is a different action between the NP and the main VP. The effect on earlier stages is however more detrimental in cases of structural incompatibility. It must be noted that our observed effects appear directly the consequence and specific of our motor tasks and not the result of an overloading of general processing resources due to the cognitive shift involved by alternating a motor and a grammaticality task. This assertion would be supported by the differential effects as a function of the structure of the motor sequencing and of the structure of the sentence.

The present results are somehow different to our previous (Casado et al., 2018) results. In that occasion, both manners of self-administration resulted in an N400/P600 pattern in the relative sentences, while a LAN could be observed only as a difference between linearly and non-linearly self-administered incorrect relative sentences. Both studies are nevertheless not directly comparable. In Casado et al. (2018), no other but relative sentences were explored while all the sentences presented to the participants had always two verbs. In this regard, the fillers in our previous study were constructed by transforming each relative sentence into its copulative version, joining two transitive clauses by the “and” conjunction. In the present study there were no fillers, as the three types of sentences included guaranteed structural variability. As an outcome, while all of the sentences in the previous study contained two verbs or actions, this was the case of only one third of the sentences in the present study. To the extent that it seems that the effects of the manner of self-administration depend on this circumstance, the differences in the effects that a motor task may cause in a block design as the used in both studies would diverge. It seems therefore that the effects observed may vary as a function of task demands and situational variables. But both studies sum up and sustain that the effects of concurrent sequential motor tasks on grammatical judgements seem incontrovertible, in line with embodied proposals of language processing.

The same situational and contextual differences plausibly underlay the dissimilarities between studies relative to the main effects of the manner of self-administration. While in Casado et al. (2018) we observed a central negativity and a frontal positivity in non-linearly administered correct sentences, in the present study we have found a frontal positivity for non-linearly administered sentences regardless of the correctness of the critical word. In the frame of psycholinguistic studies, frontal positivities have been reported for implausible and unexpected material, therefore reflecting the engagement of extra processing resources (e.g., Moreno, Casado, & Martín-Loeches, 2016; Thornhill & Van Petten, 2012). This interpretation might also apply to our results, as the number of sentences structurally incompatible with non-linear motor sequences largely exceeded the more compatible ones.

In conclusion, we have been able to find effects of a concurrent motor sequencing task on morphosyntactic processing of an ongoing sentence. These effects seem to be connected to the number of different actions involved in both the motor task and the sentence (verbs). The effects of the motor task seemed always to hamper the occurrence of proper early syntactic processes. However, while the latter were replaced by processes based on lexico-semantic processing when motor and sentential structures matched, a mismatch in this regard seemed to completely impede the appearance of any type early processing. The present findings add to recent evidence supporting that action and perception circuits might mediate syntactic processing of language.

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