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Left fronto-temporal dynamics during agreement processing: Evidence for feature-specific computations

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ABSTRACT

Grammatical agreement is a widespread language phenomenon that indicates formal syntactic relations between words; however, it also conveys basic lexical (e.g. grammatical gender) or semantic (e.g. numerosity) information about a discourse referent. In this study, we focus on the reading of Spanish noun phrases, violating either number or gender determiner–noun agreement compared to grammatical controls. Magnetoencephalographic activity time-locked to the onset of the noun in both types of violation revealed a left-lateralized brain network involving anterior temporal regions (~220 ms) and, later in time, ventro-lateral prefrontal regions (>300 ms). These activations coexist with dependency-specific effects: in an initial step (~170 ms), occipito-temporal regions are employed for fine-grained analysis of the number marking (in Spanish, presence or absence of the suffix '*-s*'), while anterior temporal regions show increased activation for gender mismatches compared to grammatical controls. The semantic relevance of number agreement dependencies was mainly reflected by left superior temporal increased activity around 340 ms. These findings offer a detailed perspective on the multi-level analyses involved in the initial computation of agreement dependencies, and theoretically support a derivational approach to agreement computation.

Introduction

Agreement is a linguistic device that many languages have developed to signal grammatical relations among words while conveying basic information about discourse referents. In everyday conversations, agreement is expressed almost once a second (in English twice every five seconds), which represents a real linguistic challenge for the language processor. For example, sentences like *En Español* "*concordancia*" *es una palabra feminina* — [In Spanish $_{\text{masculine–singular}}$ "agreement" $_{\text{feminine–singular}}$ is $_{\text{singular}}$ a $_{\text{feminine–singular}}$ feminine $_{\text{feminine–singular}}$ word $_{\text{feminine–singular}}$], express numerosity (singular) in six words and grammatical gender (masculine or feminine) in five of these. Words that relate to number and gender features of the same referent *agree* with each other: above, we can reconstruct that the term "agreement" but not the term "Spanish" is a feminine word. This example shows how different *features* (here number and grammatical gender) determine the relation between sentence constituents. European languages (such as Spanish, Italian, Dutch and German) present multiple agreement configurations depending on the type of feature (either number or gender or person agreement patterns; Wechsler, 2009). Across all of them, grammatical agreement is the covariation of agreement features between syntactically related words.

The available neuroscientific literature proposes alternative views about agreement processing and the role played by agreement features. According to what we will call a *lexicalist* approach (Hagoort, 2005; based on Pollard and Sag, 1994; Vosse and Kempen, 2000; Wechsler, 2009) agreement computation consists in the structural binding – *Unification* – between lexical frames. In this view, each different word form is available in the lexicon (hence, for example, in Spanish both plural and singular forms of a noun independently, i.e. both *mesa* and *mesas*, table and tables) ready to be linked to the agreeing elements (for example with a marked definite determiner: *la mesa* or *las mesas*, the table or the tables). Lexical frames would be retrieved from the posterior regions of the left temporal lobe (*Memory* component of this model) and syntactic unification would be under the control of the left inferior frontal regions (and specifically, portions of Brodmann areas 44 and 45). Importantly for the present study, this theoretical perspective does not distinguish between different neurocognitive operations for the processing of different agreement features.

A different approach (which we will call the *derivational* view) emphasizes a more composite processing of agreement dependencies

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(Mancini et al., 2013; Molinaro et al., 2011a; see also Bornkessel and Schlesewsky, 2006). This proposal states that agreement patterns are uniformly dealt with by *Agree* (Mancini et al., 2013; see Chomsky, 1995), the operation that is responsible for checking and matching feature values between related sentence constituents (such as a determiner with a noun). This operation is part of the syntactic processing algorithms that build up the syntactic structure of sentences; *Agree* critically depends on how each feature is encoded in the linguistic input. Number features in Spanish nouns are expressed by the presence or absence of the final *-s* suffix (*la-s mesa-s*, the table-s); covariation of the presence or absence of the suffix *-s* between determiner and noun determines agreement match. Derivational theories imply that an initial morphological decomposition is required to decode number features, since there are no distinct forms for one lexical item (only *mesa*, table, but not *mesas*, tables, would be stored in the lexicon). On the other hand, in Spanish (and many other agreement-rich languages) grammatical gender features are encoded in the lexical representation of nouns (Harris, 1991), since each noun has its own grammatical gender (*mesa*, table, is only feminine; see also Levelt et al., 1999). In the majority of cases *-o* and *-a* Spanish endings are associated to respectively masculine and feminine singular nouns; however, the number of exceptions is large (around 32%, similar to other Romance languages; Teschner, 1987[1]), with highly familiar nouns that can be irregular (*la mano*, the hand, is feminine but presents the *-o* ending) or opaque (*la leche*, the milk, is feminine and its *-e* ending can be equally present in both masculine and feminine nouns). According to Heim (2008) (see also Gollan and Frost, 2001) two strategies can be employed to decode the grammatical gender of nouns: a lexically-based or a morphologically-based strategy. In Spanish, morphological cues (noun endings) are not very diagnostic, so that unambiguous grammatical gender decoding depends on the lexical identification of the noun (without the need to decompose unreliable gender-relevant endings); on the other hand, as previously discussed, morphological decomposition is the mandatory step for decoding number features.

Grammatical relational processing would then be pursued through *Agree* to syntactically link different sentence constituents. Syntactic relational analysis in agreement-rich languages (such as many European languages) strongly depends on covariation of agreement features. *Agree* operations would support syntactic processing and would not differ depending on the type of feature. However, *Agree* is contingent on different feature decoding operations to establish syntactic relation (as indicated in the previous paragraph). In an influential model of sentence processing, Bornkessel and Schlesewsky (2006) also distinguish between two phases for agreement processing: 'feature decoding' and '*Agree* operations' can potentially be mapped onto Phase 2a and 2b in the model they propose. According to these authors, the *pars opercularis* of the inferior frontal gyrus would be involved in this type of analyses (see also Friederici, 2011).

Recent developments of the derivational view (Mancini et al., 2013; Molinaro et al., 2011a; Sigurdsson, 2004) assume that different features are '*anchored*' differently at a more interpretative level, since they convey different types of information. Number agreement would be semantically more salient than gender agreement (Carminati, 2005; De Vincenzi, 1999; Faussart et al., 1999; Sigurdsson, 2004). This is due to the fact that number agreement conveys meaning (i.e. numerosity information, Ritter, 1988), while grammatical gender is an arbitrary property of Spanish nouns that lacks meaning (Harris, 1991). This implies an additional dissociation between derivational and lexicalist approaches, since the latter view considers agreement features only as formal syntactic operators (Hagoort, 2003). On the other hand, the derivational approach assumes that features can be differently 'interpreted' semantically: according to the feature hierarchy hypothesis (Carminati, 2005; based on Greenberg, 1963), grammatical gender would be 'lower' in hierarchy compared to number since it is a – semantically empty – lexical property of each inanimate noun. On the other hand, number would be 'higher' in the hierarchy since it conveys information about the numerosity of referents; this would be in turn directly mapped (*anchored*, Mancini et al., 2013) onto the discourse level representation of referents. Interestingly, discourse mapping is included in Phase 3 of Bornkessel and Schlesewsky's model (2006, see also Friederici, 2011, for similar proposals) and it would be subserved by left superior temporal regions.

In sum, lexicalist approaches propose an economic view according to which agreement dependencies would be processed similarly across different features: Hagoort (2005, 2009) proposes that word frames (stored in left posterior temporal regions) would be selected and syntactic unification would be under the control of inferior frontal regions. Derivational views propose (i) differential processing between features for what concerns feature decoding in the initial computational stages; (ii) relational processing operations (*Agree* in Mancini et al., 2013), required to establish syntactic relations (subserved by left inferior frontal regions), would operate similarly for different agreement features. Finally, (iii) feature anchoring during later interpretative stages (recruiting left superior temporal regions) would differ depending on the semantic status of the agreement feature. Processing dissociations between different agreement features emerge from the neurophysiological literature on agreement mismatches (Molinaro et al., 2011a, for a review). When comparing, for example, both number and grammatical gender agreement mismatches to grammatical controls ('*feature-specific processing* designs', see examples in [1] below), lexicalist and derivational perspectives on agreement differ in their predictions concerning the effects that these two types of violations should elicit. The lexicalist approach predicts that number and gender agreement violations (compared to the grammatical control) should elicit qualitatively similar processing difficulties in syntactic unification. On the other hand, the derivational approach predicts differential effects elicited by different types of mismatch, at least for what concerns both feature decoding and feature interpretation (*anchoring*), while *Agree* operation should be similarly impaired for different agreement mismatches.

Few fMRI studies have focused on agreement processing (Carreiras et al., 2010; Kuperberg et al., 2008; Newman et al., 2003; Nieuwland et al., 2012). Critically, very few directly compared feature specific effects. Carreiras et al. (2010) compared the processing of Spanish word-pairs that could present either number or grammatical gender mismatches: compared to grammatical controls, both feature mismatches elicited increased activity in the left inferior frontal regions and number mismatches elicited additional increased activity in the right inferior parietal regions, an effect interpreted by the authors as reflecting the additional semantic relevance of number features compared to gender features. However, this study mainly focused on the morphosyntactic matching of word pairs that were isolated from a sentence context, i.e. in a non-linguistic scenario.[2] In addition, fMRI does not offer sufficiently fine-grained temporal detail to determine the temporal sequence of those effects.

To better disentangle among multi-level linguistic computations, fine-grained neurophysiological temporal resolution measures are more useful. Event-related Potential (ERP) studies have distinguished between *early* and *late* increased effects associated to the detection of agreement violations (compared to grammatical controls; Hagoort, 2003; Molinaro et al., 2011a; Osterhout and Mobley, 1995[3]). The *early*

[1] Spanish presents nouns that are morphologically ambiguous for number, since the *-s* ending can be both singular and plural (such as *tesis*, thesis). The percentage of these exception is, however, very low (~4%) compared to gender ending exceptions.

[2] Barber and Carreiras (2005) reported clear dissociable Event Related Potential patterns for the processing of grammatical gender and number agreement violations in isolation compared to when the same stimuli were embedded in a sentence context.

[3] Osterhout and Mobley (1995) compared the processing of number and gender mismatches during pronoun resolution reporting similar (late) P600 effects. However, the resolution of a pronoun–antecedent relation has been shown to engage specific antecedent-retrieval and integration mechanisms that a local agreement dependency does not require.