



Review

Stable brain loci for the processing of complex syntax: A review of the current neuroimaging evidence[☆]

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ABSTRACT

We conducted a retrospective review of fMRI studies of complex syntax, in order to study the stability of the neural bases of mechanisms engaged in syntactic processing. Our review set out rigorous selection criteria of studies which we discuss, including transparency and minimality of the contrasts between stimuli, and the presence of whole brain analyses corrected for multiple comparisons. Seventeen studies with 316 participants survived our sieve. We mapped the 65 resulting maxima onto *JuBrain*, a state-of-the-art cytoarchitectonic brain atlas (Amunts et al., 2020), and a sharp picture emerged: syntactic displacement operations (*a k a* MOVE) produce highly consistent results, activating left Broca's region across-the-board and unambiguously; to a somewhat lesser extent, maxima clustered in left posterior brain regions, including the STS/STG. The few studies of syntactic tree-building operations (*a k a* MERGE) produce a murkier picture regarding the involvement of the left IFG. We conclude that the extant data decisively point to the *JuBrain*-defined Broca's region as the main locus of complex receptive syntax in healthy people; the STS/STG also are involved, but to a lesser extent.

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1. Introduction

This paper reviews the evidence regarding the cerebral localization of components of the human sentence processing device, focusing on fMRI results from studies in healthy

individuals. Since the first clues on brain-language relations were discovered (Broca, 1861), the nature and location of brain mechanisms underlying language processing in humans have been debated. Investigations of aphasia have projected light on processes that are disrupted subsequent to focal brain damage (Hughlings-Jackson, 1874; Lichtheim, 1885; Pick, 1913;

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Geschwind, 1970); and the rise of linguistically-inspired research has underscored the centrality of the sentence processing deficits in aphasia (Caramazza & Zurif, 1976; Goodglass, 1968; Goodglass & Hunt, 1958; Grodzinsky, 1984, 1986; Schwartz, Saffran, & Marin, 1980; Zurif, 1980), which led to debates regarding their nature.

While aphasia studies have been useful in the effort to identify patterns of functional selectivity in language processing, their anatomical localizing value is limited, due to the arbitrariness of lesion location, size and position. Some have even called for the abandonment of such evidence, alleging instability (Caramazza, 1986, though the opposite conclusions are drawn by the retrospective data analyses in Draai and Grodzinsky (2006a,b), and the large-scale experimental investigation in Choe-Reyes & Thompson, 2012). The advent of high-resolution neuroimaging technologies has enabled studies of active brain regions in the healthy brain. This positive development should have brought the debate closer to being resolved; instead, the opposite has happened: the recent imaging literature on language is rife with debate about localization, and the extent of disagreement only seems to have grown.

We find this situation curious: despite improved technologies, interpretations of extant evidence have grown further apart. As all parties concerned cite experimental data in support of their positions, different conclusions must arise from differences in the interpretation of the studies on which one relies. At an age where replicability is (justifiably) an important criterion for good science, this is worrisome. Is the apparent variability in our field due to differences in design, analysis, or interpretation? Such questions are currently addressed in the cognitive literature (e.g., Botvinik-Nezer et al., 2020), and in our view, deserve to be considered most seriously in neurolinguistics as well.

1.1. Our focus

In an attempt to understand the source of disagreement, and more importantly, to paint a picture that is at least a bit clearer, we set ourselves to review the neuroimaging literature on brain loci of components of sentence processing. In doing so, we adopt a strategy that is slightly different from that of other recent reviews (e.g., Meyer & Friederici, 2016; Vigneau et al., 2006; Zaccarella, Meyer, Makuuchi, & Friederici, 2017). Namely, we not only report the results of studies and the extent to which they converge or not; we examine the details of their design, particularly with regard to the specific linguistic contrasts that they use. Components of the sentence processing device are isolable neuro-cognitively only via suitable experimental contrasts. We evaluate these with linguistic tools, critical for a fine typology of the empirical results that we consider.

Our focus on components of the anatomical bases of the sentence processing device requires a further delineation of our territory within the vast domain of investigations of brain/language relations. This means, unfortunately, that we will exclude some lines of potentially important work, that are simply not relevant to the present discussion. First of all, we refrain from discussing studies that try to identify overall activation patterns of linguistic objects, but with no concern about anatomy (especially “mind-reading” studies of

“semantic categories”, e.g., Huth, De Heer, Griffiths, Theunissen, & Gallant, 2016; Wang, Cherkassky, & Just, 2017). Moreover, not every study that uses sentence stimuli is within our domain: e.g., we do not discuss studies that seek to distinguish general language mechanisms from those dedicated to other cognitive capacities (e.g., language vs math or music, e.g., Fedorenko et al., 2012a, b; Blank, Balewski, Mahowald, & Fedorenko, 2016; Friederici, Fiebach, Schlesewsky, Bornkessel, & Von Cramon, 2006).

As well, we refrain from discussing studies that use sentence stimuli in an attempt to distinguish linguistic “levels of representation” from one another (e.g., syntax vs semantics, Fedorenko et al., 2012b), or morphology (Friederici, Meyer, & Von Cramon, 2000). We are unable to distinguish “syntax” from “lexicon” or “semantics” in the absence of an explicit theoretical framework that draws clear lines between these components – lines that can be clearly operationalized by translation into minimal experimental contrasts. To illustrate, consider an fMRI study by Fedorenko et al. (2012a, b), fashioned after several earlier ones (e.g., Friederici et al., 2000). These authors sought to ‘distinguish between “pure” lexical information (lists of words) and “pure” abstract syntactic information (jabberwocky sentences) in the pattern of activity’. Table 1 (adapted from their study) presents a bi-factorial design. Yet, is there a pair (let alone a factor) that is minimal? We must answer in the negative: no pair of boxes (or columns, or rows) is minimal: sentences and word lists differ not only along a host of syntactic dimension, but also, along phonological and morphological ones; the same holds of the pair “Sentences” and Jabberwocky sentences”, and so on. Indeed, arbitrarily selected and ordered real or nonce words are not minimally distinct from arbitrarily selected well-formed sentences (containing real or nonce words).¹

We therefore exclude these studies from our review. Still, left for us is a rather large and focused literature. Many researchers have realized that the human sentence processing device is a complex machine at the core of our linguistic ability (e.g., Friederici et al., 2006, Santi & Yosef, 2007; Rogalsky, Matchin, & Hickok, 2008, Mack, Meltzer-Asscher, Barbieri, & Thompson, 2013; and many, many others). Understanding their functional structure and neural representation requires neurological investigations that localize the components. Our review thus touches on a variety of relevant studies, which we examine, in an attempt to obtain the sharpest possible picture of the neurology of syntax. To forecast, we demonstrate that contrary to some recent claims (e.g., Tremblay & Dick, 2016; Matchin & Hickok, 2020) the results of tightly controlled fMRI studies of major syntactic components are highly stable, indicating that underlying processes are well

¹ In a similar manner, Fedorenko et al. (2016a, b) report that “to search for language-responsive regions within Broca’s area, we asked whether any voxels within left-hemisphere Brodmann areas (BAs) 44 and 45 responded significantly more strongly to sentences than to nonword lists. To search for regions sensitive to broad cognitive demands, we used the opposite contrast (nonwords > sentences) because the nonword task is substantially and significantly more difficult than the sentence task.” (p. 2059). We do know how to incorporate contrasts such as “sentences versus non-words”, as it does not yield to any known linguistic generalization.

Table 1 – The design matrix of Fedorenko et al. (2012b).

Lexical info	Syntactic info	
	<i>Sentences</i> The speech that the politician prepared was too long for the meeting	<i>Word lists</i> In because new robbery soon every angry direction tracy morning and battle
	<i>Jabberwocky sentences</i> After the bonter mellvered the perlen He mested to week on colmition	<i>Nonword lists</i> Was during cusarists fick prell pront The pome villpa and wornetist she

localized in the traditional language regions, namely the left Inferior Frontal Gyrus (IFG) and to some extent, the left Superior Temporal Gyrus and Sulcus (STG/STS). These results are important, as they may help us focus future studies. We therefore hope that our survey can serve as a reference point for students and researchers of the neurology of syntax.

1.2. Organization

Our paper is organized as follows:

1. We lay down assumptions required for neuro-syntactic studies, that seem to be common ground to researchers working in the field.
2. We specify three inclusion criteria which we use as a guideline for the selection of studies in our review.
3. We review commonly tested syntactic processing components, with emphasis on well-defined operations for tree structure building (*a k a* MERGE) and for displacement (*a k a* MOVE).
4. We produce tables with results from these studies, and use a state-of-the-art anatomical atlas (JuBrain, Amunts et al., 2020) to draw a clearer picture of the neural bases of complex receptive syntactic processing operations.

To anticipate, here are our conclusions:

- a. The neural mechanism central to syntactic operations is consistently found to be located in the left Broca's region. Additionally, there is evidence for contributions of left temporal regions (STG, STS and MTG) in syntactic analysis.
- b. The syntactic operations under discussion (MERGE and MOVE) can be teased apart functionally; however, their separability on the basis of anatomical criteria is only partial at present.
- c. With few exceptions, other regions that have been implicated seem to host noise, and co-activate in syntactic contrasts only as a consequence of experimental artifacts and/or confounds.
- d. An important example of a potential artifact comes from studies of German and Japanese Scrambling – an instance of MOVE: Scrambling (somewhat similar to left dislocation in English) is a syntactic operation that serves Focus purposes. It is thus mostly coupled with emphatic prosody, whose consequences are consistently observed in the fMRI results. Scrambling activates the same areas as English MOVE, but also, right hemispheric areas known to govern prosody.

Making a case for these claims is a tall order. We begin.

2. Common ground

Every neuroimaging experiment of syntax consist of a set of stimuli, a task, and a collection of analytic methods. There seems to be broad agreement on the basic tenets of experimentation in this field. We therefore lay down assumptions that seem to be common to all, and use them as a sieve to select studies for our review.

2.1. Methodological assumptions

2.1.1. Dependent variables

Psycholinguistic investigations of the components of the sentence processing device use behavioral measures, analyzed as either bi-valued, behavioral *categorical variables* (e.g., YES/NO, MATCH/MISMATCH), or *continuous variables* such as Reaction Time (RT). In neuroimaging, the main dependent variable of interest is *continuous*: the intensity of the BOLD signal acquired in a Magnetic Resonance Imaging device. Its locus is then entered into consideration. Psycho- and neuro-syntacticians (such as ourselves), who are interested in the processes that implement syntactic knowledge and their neural underpinnings, test localizing hypotheses through indices of behavior and brain activity.

2.1.2. Minimal contrasts and minimal pairs

We seek to identify the neural bases of mental operations involved in the analysis of incoming sentences. A fundamental requirement of any such study is that experimental conditions consist of pairs of stimuli that differ along a single dimension – the dimension of interest – with everything else being kept constant across conditions, lest the comparison be confounded by an additional dimension or dimensions (cf. Grodzinsky, 2010, for discussion). We discuss many such contrasts and confounds below. To forecast, *the best, most tightly controlled, studies of syntactic processing are those in which all conditions contain different sequences of the same “bag of words”, that differ along a single linguistic dimension.* We focus on these.

2.1.3. Cumulativity and functional resolution

We can only measure syntactic processes whose behavioral or neural reflexes are *cumulative*. That is, the addition of syntactic processing components, in turn, must add to processing cost: if the representation of sentence S2 requires one additional analytic process compared to S1 (i.e., S1 and S2 differ along the dimension of interest), then there must be a measurable variable V , $V_{S1} < V_{S2}$ that reflects that difference.

The detection of this variable is critical for *functional resolution*. That is, only a paradigm that measures a cumulative dependent variable and elucidates the differences between V_{S1} and V_{S2} can address syntactic processing. As we will see below, in some experiments, the dependent variable does not measure what it purports to measure, as it lacks functional resolution. In functional imaging, the BOLD response is taken to reflect processing cost in a given location, and thus we seek specific loci of increased BOLD response – the neurological signature of the process under exploration.

3. Our study selection criteria

In selecting studies for our review, we used the following inclusion criteria:

- A. *Transparency*: clearly described behavioral and neuro-imaging tasks that may lead to a *transparent interpretation* via the available theoretical apparatus.
- B. *Minimality*: clear distinctions between components of syntax that lead to clear choices of experimental materials, which would enhance *functional resolution*, sufficient to identify neurologically isolable processing components.
- C. *Whole brain*: Sound analytic procedures and interpretable results: as the debate pertains to multiple brain loci, we restrict ourselves to *whole brain* (as opposed to ROI) analyses. We therefore steer clear from a host of fine studies that may bear on more specific issues but not on overall localization of specific syntactic functions (e.g., Makuuchi, Bahlmann, Anwender, & Friederici, 2009, and many others). Likewise, we do not review results that are uncorrected for multiple comparison.²

² Our review consists of mostly auditory studies, but features some visual ones as well. A reviewer points out that “auditory materials are more naturalistic than their written counterparts, and relevant prosodic information is missing in visual materials, which may introduce more individual variability in the fMRI data.” We agree that there are modality differences. Yet we also note that there is a remarkable convergence of findings from sentence processing studies in the two modalities. Event-related potential studies consistently find that ERP components are largely similar across modalities. P600 and left anterior negativity (LAN) effects, which are evoked in response to morpho-syntactic violations, are found in both modalities, with only minor differences in timing and scalp distribution (Balconi & Pozzoli, 2005; Hagoort & Brown, 2000; Lück, Hahne, & Clahsen, 2006; Regel, Gunter, & Friederici, 2011). fMRI studies directly comparing the same stimuli across modalities also have found brain regions that respond to both (i.e., portions of left IFG and posterior superior/middle temporal gyri (STG/MTG)) (Buchweitz, Mason, Tomich, & Just, 2009). In a recent meta-analysis, Walenski, Europa, Caplan, and Thompson (2019) found five clusters of significant overlap between auditory and visual modalities from a total of 45 contrasts (31 auditory, 14 visual) from healthy adult participants (all left hemisphere): four in frontal cortex and one in temporal and parietal cortices. In the frontal lobe, clusters of significant overlap were in IFG (pars orbitalis, pars triangularis, and pars opercularis), a distinct cluster in pars opercularis of IFG, another in precentral gyrus, and one in SMA. In the temporal lobe, one cluster was found in MTG (posterior and temporooccipital parts), extending superiorly to AG.

4. Commonly tested syntactic processing components

To evaluate the neural underpinnings of syntactic processing using fMRI, most studies use some “syntactic complexity” metric to isolate its component processes. The idea is that if a localizable syntactic operation is deployed more intensely than others, it would distinguish itself via stronger BOLD response in the brain region that supports it. Our reading of the rich literature has identified 4 topics in syntax that have been studied in fMRI:

- a) Complexity of structure building processes (*a k a* MERGE, e.g., Friederici et al., 2000; Pallier, Devauchelle, & Dehaene, 2011, Matchin, Hammerly, & Lau, 2017).
- b) Complexity of processes that build intra-sentential dependency relations involved in the displacement of elements (*a k a* MOVE, e.g., Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; Friederici et al., 2006; Mack et al., 2013; Thompson et al., 2010).
- c) Complexity of processes that establish non-MOVE intra-sentential dependency relations (e.g., BINDING, Santi & Yosef, 2007).
- d) Complexity of lexical properties associated with syntactic structure building (ARGUMENT STRUCTURE, e.g., Shetreet, Friedmann, & Hadar, 2009; Meltzer-Asscher, Mack, Barbieri, & Thompson, 2015).

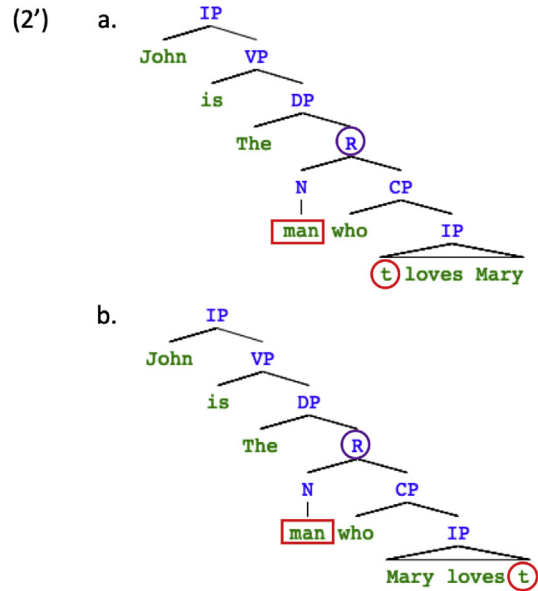
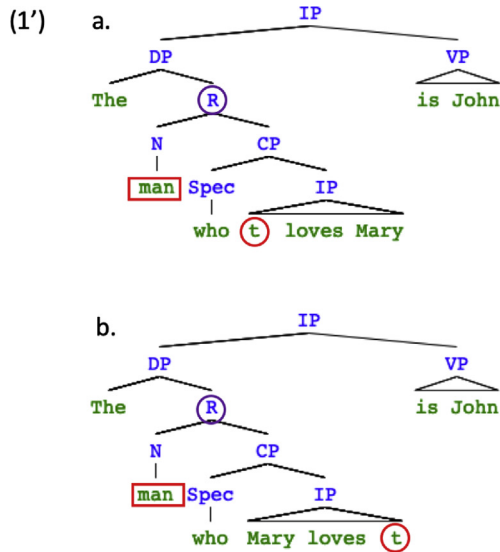
Of these, the first two have received the most attention, creating a substantial body of literature that is at the center of the debate. We, thus, focus on MERGE and MOVE. We use these labels with no endorsement of their theoretical significance – all syntactic frameworks of which we are aware accommodate these processes.

4.1. MERGE and MOVE

We begin by discussing the oft-used relative clauses, illustrated in (1)–(2). A critical point about these is their nearly identical meaning (modulo thematic-role reversal), manifest in four different syntactic configurations. Both MERGE and MOVE are instantiated within these examples (where structural annotation is intentionally simplified), that vary along two dimensions: location of embedding and location of the gap. All contain a Determiner Phrase (DP), which embeds a relative clause (marked [^R ...]) that has a gap inside it (marked t for the familiar empty category trace; again, no theoretical commitment is attached to these constructs, as any account must assume an equivalent). Importantly, these sentences feature the same words, but differ in structural properties, in ways that have long been deemed relevant to processing (Miller & Chomsky, 1963; Fodor, Bever, & Garrett, 1974; Grodzinsky, 1989; Gibson, 1998, Lewis & Vasishth, 2006, Levy, 2008 and many, many others). Sentences (1a-b) differ from (2a-b) in the way MERGE is applied, because they contrast the location of the embedded clause. The subject-relative sentences (1a), (2a) differ in trace location, hence in MOVE, from their object-relative counterparts (1b), (2b). It is also well-known that this difference has processing costs:

- (1) a. [IP[DPThe [R [Nman] [CP who [IP t loves Mary]]] [VPis John]]] (subject-relative; center embedded)
- b. [IP[DPThe [R [Nman] [CP who [IP Mary loves t]]] [VPis John]]] (object-relative; center embedded)
- (2) a. [IPJohn [VPis [DPthe [R [Nman] [CP who [IP t loves Mary]]]]]] (subject-relative; right branching)
- b. [IPJohn [VPis [DPthe [R [Nman] [CP who [IP Mary loves t]]]]]] (object-relative; right branching)

In (1'-2'), we depict the structure of (1-2) by tree graphs, suppressing much irrelevant notation (triangles denote underspecified subtrees):



The design in Table 2 makes MERGE and MOVE distinct factors, thereby helping to distinguish between them (rows and columns of Table 2, corresponding to the graphs in (1'-2')). This design meets the Minimality requirement, as it includes two minimal pairs made out of the same words, one differing in position of R, where the embedded clause is merged into a higher structure (encircled purple, on the subject or the object of the main clause) (1a, 2a; 1b, 2b); the other in the position of a trace (red circle, subject or object of R) and the antecedent of the trace (red box) (1a, 1b; 2a, 2b). It also meets the Transparency requirement.

But wait: we must first introduce complexity metrics or cost functions to each factor, in order to guarantee interpretable

Table 2 displays a typical factorial 2X2 design used in fMRI studies to evaluate neural activation associated with the four relative clause types:

As processing costs for both types of contrast (embedding and trace location) is documented, one can ask whether the complexity leading to these costs is taxed along a single dimension and recorded in a single set of brain loci, or rather, each source of processing cost is taxed separately, and by a different brain region. Early neuroimaging work on syntactic complexity (Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Stromswold, Caplan, Alpert, & Rauch, 1996) conflated both dimensions, as it contrasted (1b) against (2a) – two sentence types that differ along both MERGE and MOVE dimensions.

The instantiation of levels of the MERGE factor: Center Embedding versus Right Branching (columns in Table 2) – has long been claimed to impact perceptual complexity. Simply put, it has been known since Yngve (1960) that Center Embedding (1'a-b) is more taxing than Right Branching (2'a-b). Regarding the MOVE factor (rows), the relation between the antecedent (red box) and trace (red circle) has also been said to impact perceptual complexity, as the trace-antecedent relation in (1'- 2'a) appears to be less taxing, due to both linear and structural distance as well as the amount of relevant intervening material. Rows and columns in (1)-(1') thus constitute minimal pairs vis-à-vis clear aspects of syntactic complexity.

Table 2 – A typical experimental design with four relative clause types.

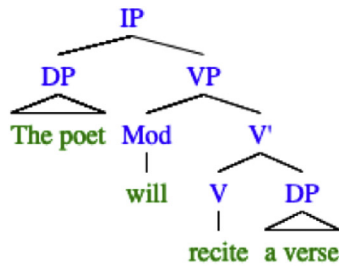
		<i>MERGE complexity</i>	
		Position of R in the main clause	
		<i>Subject</i>	<i>Object</i>
<i>MOVE complexity</i> Position of the gap in R	<i>Subject</i>	(1a)	(2a)
	<i>Object</i>	(1b)	(2b)

4.2. fMRI studies of MERGE

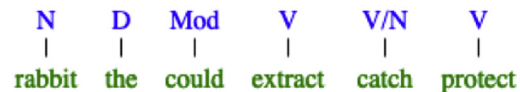
Studies examining phrase structure building operations (i.e., MERGE) require conditions with minimal pairs (i.e., structures) and cumulatively such that differences between conditions are detectable and the results are interpretable in terms of processing complexity. Early investigations of phrase structure complexity (Fodor et al., 1974; Miller & Chomsky, 1963; Yngve, 1960) used word strings of equal length that differ in the total number of nodes, number of branching nodes, number of nodes with particular labels, number of center-embeddings, etc. Neuroimaging studies of MERGE have evaluated tree-building complexity in three ways: by (1) contrasting sentences versus scrambled word lists, (2) manipulating the depth of the syntactic tree, and (3) contrasting sentences with different embedding types. We discuss representative studies of each below. Each design type is sufficient to reveal information about phrase structure building, however, they differ in important ways such that summarizing the results derived across design types would likely not lead to uniformity in results.

1. *Sentences versus word lists*. This design, aimed to test overall structure, is set out to compare sentences of any structural type, with scrambled word lists, while keeping the total number of words (though not their actual identity or even lexical category) constant (3):

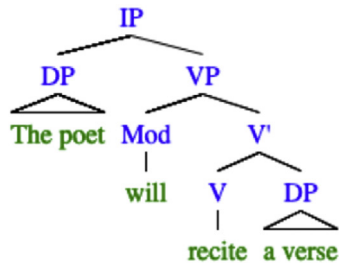
(3) a.



b.



(4) a.



b.



Mazoyer et al. (1993) used this design strategy, contrasting well-formed sentences of a particular type with strings of scrambled words. The thought behind this design is that sentences are structured lists of words, hence structured sentences versus scrambled word strings constitute a minimal pair with respect to structure (*ceteris paribus*). But there are

other differences between the stimulus types: (i) processing of word lists, but not sentences, may involve list memorization, (ii) not all sentences are alike, and the neurocognitive load of a sentence stimulus depends on its exact structure; (iii) sentence processing (auditory or visual) involves not only structural analysis but also, meaning composition. While Mazoyer et al. were not interested in MERGE *per se*, Friederici et al. (2000) explicitly aimed to localize tree-building operations using a similar design. They described their design difficulties in impressive detail (p. 221), and proposed control measures that led to a choice of materials and 2X 2 (\pm syntax X \pm semantics) design, implemented with a judgment task. We agree that such measures would improve the ability to hone in on brain loci for MERGE, revealed by syntactic, but not semantic effects. Unfortunately, this study did not include whole brain analyses (possibly due to the paucity of subtle procedures for the correction of multiple comparisons at the time). Yet we bring it up to underscore the design difficulties that studies of MERGE impose, which should help us when we review later studies.

2. *Tree depth*. Studies of deep versus shallow tree structures also are used to evaluate phrase structure building. Because the deeper the tree, the more words are required, the shallow tree conditions control for the number of words using repeated strings of the shallow tree as in (4) (e.g., Matchin et al., 2017; Pallier et al., 2011).

To control for content, many studies have also included a condition to control for semantic context. Conditions with all word sequences are reproduced with phonologically legal strings of non-words (i.e., jabberwocky). Table 3 illustrates such a design, where strings of stimuli within jabberwocky cells (that contain content non-words) are inserted in

Table 3 – Various designs to test MERGE complexity that include a non-word “jabberwocky” condition.

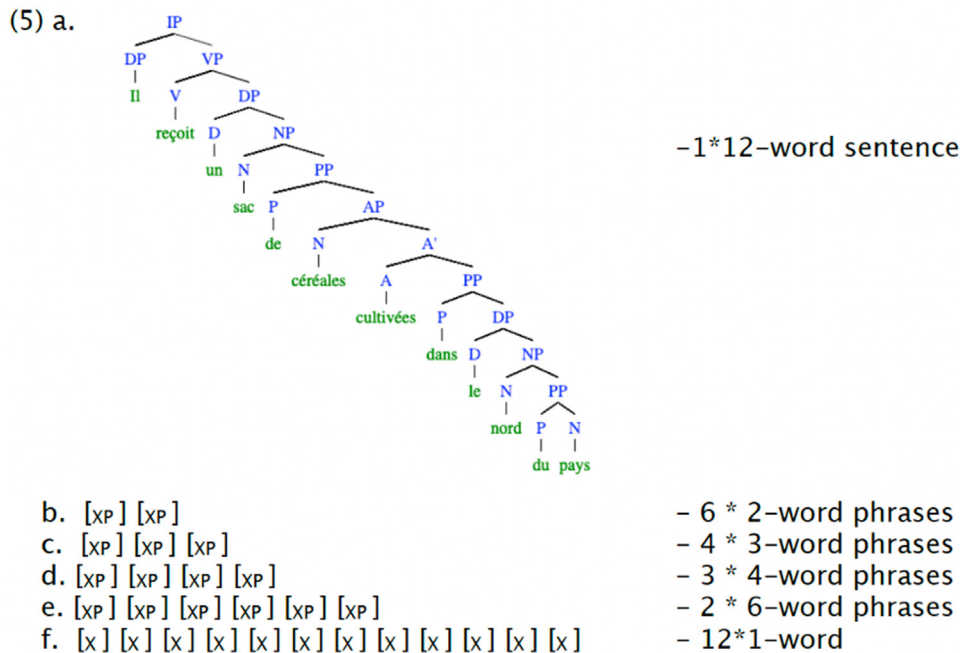
		MERGE complexity					
		A. Overall structure Tree/words		B. Embedding type		C. Tree depth	
Semantic complexity	Words	(4a)	(4b)	(1'a,b)	(2'a,b)	(5a)	(5b)
	Non-words “Jabberwocky”						

sentences with the same structure as those above them in the same column.

Pallier et al. (2011) impressive parametric fMRI study of constituent size (MERGE), carried out in French, followed Friederici et al. (2000) design, and included a syntactic and a semantic factor. Pallier's syntactic factor consisted of 6 levels of 12-word stimuli, where a tree–depth parameter was varied and included the following conditions: a 12-word sentence (1*12), 6*2-word phrases, 4*3-word phrases, 3*4-word, 2*6-word, and a 12-single word sequence (see 5). The schema below is a rough reconstruction of the levels of the syntactic factor (X, XP = categories whose identity varied according to each condition's specifications):

(n = 1,2,3,4,6,12) – served as predictors of signal intensity across both real and Jabberwocky sequences. A sparsely used detection task produced high accuracy rates.

Pallier et al. assumed signal additivity in tree complexity. They therefore expected that a tree with a larger number of words would lead to greater activation levels in the neural cluster that supports it than a tree that packages a smaller number. But they also needed to control for length and duration. Therefore, they lowered package sizes and increased the number of these packages to maintain a 12-word constant. However, a theory that counts nodes in a stimulus may not predict change in signal intensity under this manipulation. Moreover, this notion of complexity is at



For the second, ±semantic, factor, “Jabberwocky” sequences were used in parallel. Parametric values – the number of units in a sequence presented to participants

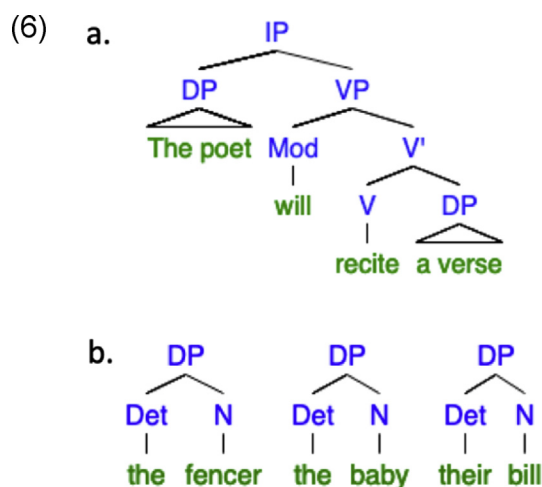
odds with standard psycholinguistic ones: examples (1)/(1')-(2)/(2') feature minimal pairs that differ in standard psycholinguistic complexity measures, despite having root

nodes that contain the same number of words.³ Still, the results of the study speak for themselves: Pallier et al. found MERGE-relevant regions, namely ones in which the syntactic, but not semantic, manipulation affected BOLD signal activation in three left hemispheric clusters: the orbital part of the IFG; (–45 33 –6), the triangular part of the IFG; (–51 21 21), and the pSTS; (–51 –39 3).

However, a close inspection of the test materials revealed potential sources of noise, which we note here in brief: (a) The sequences were not made of the same bag of words. (b) Moreover, they differed not only in constituent size, but also in the number of branching nodes, number of separate structural units, category labels, and most notably, compositional meaning (which is not absent in “jabberwocky” conditions, because the presence of real syntactic categories naturally lends itself to attempts at semantic composition). (c) Another confound may have arisen from the lack of syntactic uniformity of stimuli within the syntax conditions: Although the actual stimuli were not reported, precluding clear syntactic depictions, as far as one can tell, some items contained a MOVE relation whereas others did not: e.g., a third of the items in the sentence condition featured MOVE (e.g., #4: *Il cherche le nom de la fille qui t a appelé ses parents*; #183: *Le fils crache en regardant sa mère qui t garde un silence agacé*) (see Supp. Info., pp. 24–27). Thus, while some of the results of the study seem clear and robust, these potential confounds may have affected study outcomes.

In sum, Pallier et al. conducted a very careful and sophisticated study, and chose a peculiar notion of complexity. This choice led to design problems, and possibly important differences between their study and others.

Inspired by this study, Matchin et al. (2017) implemented a similar design, also intended to track down brain loci that are modulated by MERGE in very much the same way as Pallier et al. They, too, assumed additivity, and posited a syntactic factor with 3 levels and a semantic factor with words and “Jabberwocky” levels. All conditions featured 6-word long stimuli with different degrees of structure – sentences (6a), 3-phrase long sequences (6b), and 6-word lists (6c). All conditions had a “Jabberwocky” analog:



Sixteen participants were tested using a Rapid Serial Visual Presentation paradigm in which they were asked to read words and, in addition, they carried out a secondary word monitoring task. This complex setup was expected to identify brain areas that are modulated by tree-depth, i.e., different degrees of MERGE (illustrated by the number of stacked branching nodes in (4) – five in the sentence condition, three in the phrase condition, none in the word list condition).

Before examining the results, we need to ask: (a) did the test conditions constitute *minimal pairs*, i.e., were they identical up to MERGE? (b) did the task guarantee that participants analyzed the word sequences they saw? That is, can we safely assume signal *additivity* in MERGE complexity? The answer to both questions is negative: (i) the sentences in (6a) differed from the phrases in (6b) and the lists in (6c) differed not only in MERGE, but also, in number of branching nodes, number of separate structural units (1 for sentences, 3 for phrases, 6 for words), category labels, and finally, compositional meaning; (ii) the word monitoring task did not require structural analysis, and could be performed even in its absence.

Still, careful analyses might obtain effects that are robust enough so as to defy noise. Treading in the footsteps of Pallier et al. would require the discovery of clusters (in a whole brain analysis) in which the syntax factor modulates BOLD signal intensity parametrically across both real and Jabberwocky sentences. No such clusters were found. ROI analyses produced weak results (non-corrected for multiple comparisons). Of the many contrasts tested, only a subtraction of (6b) from (6a) yielded significant results in some brain areas, whose peaks are in the LIFG, LMTG, Right Cerebellum and Amygdala. However, the presence of multiple confounds violates *Minimality*, and the absence of a detailed task analysis violates *Transparency*, which preclude the attribution of any specific cluster to any function. Finally, none of the results were corrected for multiple comparisons. This study, then, cannot be included in our review.

A somewhat related study was conducted by Zaccarella, Meyer, Makuuchi, and Friederici (2017), who contrasted 3-word German sentences and phrases against word lists,

³ We have identified several sources of noise in Pallier et al.’s paper: Two thirds of the of the 12-word stimuli, and possibly 6-word stimuli, from which “constituents were extracted”, contained no embedded sentence. The remaining third was right branching, containing an embedded relative clause on the matrix object, hence syntactic movement. That is, they featured a subject-gap, such as the following. (i) *Il cherche le nom de la fille qui a appelé ses parents.* (#4). (ii) *Le fils crache en regardant sa mère qui garde un silence agacé.* (#183). More than half of the 12-word stimuli from which “non-constituents were extracted”, and possibly 6-word stimuli, contained syntactic movement, as they were center-embedded sentences, with subject-gap relative clauses, such as the following. (iii) *Le jardinier qui a planté ces géraniums rouge vif regrette son choix.* (#60). (iv) *Ce conducteur qui refuse de prendre plus de repos causera des accidents.* (#70). Finally, there was no task on the experimental stimuli, hence no behavioral data are reported that can provide a sanity check for the efficacy of the task.

Table 4 – Zaccarella et al.’s design.

		MERGE	
		+ (sentence/phrase)	- (word list)
Sentence vs. phrase	3-word sentence	Das Schiff sinkt (the ship sinks)	Halm Schiff Saft (stem ship juice)
	3-word phrase	Auf das Schiff (on the ship)	Lauch Mund Schiff (leek mouth ship)

hoping to find the neural bases for MERGE as shown in Table 4.

They asked 18 participants to make a meta-linguistic judgment on sequentially presented visual one-word stimuli (i.e., to indicate whether they constituted a sentence, a phrase, or just a word list). Zaccarella et al.’s design is similar to those above, hence susceptible to a similar critique. Yet, one result cannot be ignored: a whole brain analysis, corrected for multiple comparisons, revealed a main effect of MERGE (syntactically structured stimuli vs word lists) in BA 44 and in a small pSTS cluster.

3. *Embedding type.* As discussed above, MERGE can be studied by contrasting the type of embedding, where the minimal pair is a relative clause I which is center embedded (1) or right branching (2) and other aspects of the syntax, content as well as the number of words are kept constant. Santi and Grodzinsky (2010) is the only study we know to have tested exactly this contrast.⁴ Their fMRI adaptation (repetition suppression) study deployed the complete paradigm in (1)–(2), which enabled them to test MERGE while meeting both *Minimality* and *Transparency*. A whole brain analysis revealed no cluster that was exclusively activated by the embedding contrast (1) versus (2). A partial adaptation effect for MERGE was detected by enhancement, via a conjunction analysis with the MOVE contrasts – a conjunction that sought voxels which adapted to both (1) versus (2) and (1-2a) versus (1–2b). This analysis uncovered three distinct regions: left posterior IFG (part of which localized to BA44 on Amunts et al.’s 1999 probabilistic map, and extended to BA 6/8), the left STG, and the right inferior precentral sulcus (RiPS). We cannot be sure, though, about the extent of this effect that is due to MERGE.

Let us summarize: of the four studies reviewed, three (Table 5) used somewhat different methods to isolate the

processing costs of MERGE; the fourth (Matchin et al.) reports uncorrected results and is therefore excluded. Of these, two recorded MERGE-related, cost-reflecting activations in several loci of the left IFG and in various temporal loci. Santi & Grodzinsky only found hints for MERGE-related effects via a conjunction analysis.

4.3. fMRI studies of MOVE

In this section we discuss studies examining activation associated with certain instantiations of MOVE, a syntactic operation entrusted with the overt or covert displacement of elements in a syntactic representation of an input string. While the empirical coverage of MOVE spans a broad variety of instances, we focus on cases for which imaging evidence is currently available. In neuropsychology, there is a long tradition of testing individuals with aphasia on overt instances of MOVE, long known to be selectively affected by focal brain disease (Grodzinsky, 1984, 1986, 2000). As well, considerable neuroimaging evidence has accumulated regarding its associated neural mechanisms. We discuss the main results below.

4.3.1. MOVE in English relative clauses

Most of the studies on MOVE in English are on relative clauses. In this section, we focus on these studies, which are typically tested when object-relative clauses are compared to subject-relative clause constructions. These have received much attention in aphasiology, starting with Caramazza & Zurif, 1976, and continuing with Grodzinsky, 1984; 1989, as well as many others; see Drai & Grodzinsky, 2006 for a survey). With regard to neuroimaging studies, we begin by reviewing three highly-cited studies (which together have been cited over 2000 times in Google Scholar), as each of them exemplifies a problem of a type discussed in our introductory remarks.

4.3.2. Early imaging studies

Just et al., 1996 and Stromswold et al., 1996 pioneered these investigations. Both studies sought to obtain a “syntactic effect” in relative clauses, and therefore tested healthy participants (in fMRI and PET, respectively) on two of the four types of relative clauses presented in (1). Namely on a sentence that has an object-extracted relative on its subject (7a), and one with a subject extracted relative on its object (7b). As can be easily seen, this simple design confounds MERGE and MOVE:

⁴ The design by Rogalsky et al. (2015) in principle allows for a test of MERGE. They used sentences that differed in degree of embedding (“deep” and “shallow”). However, the results of such a comparison are not reported. Moreover, these authors only report results that were not corrected for multiple comparisons. We return to this issue below, when we discuss their work in the context of MOVE.

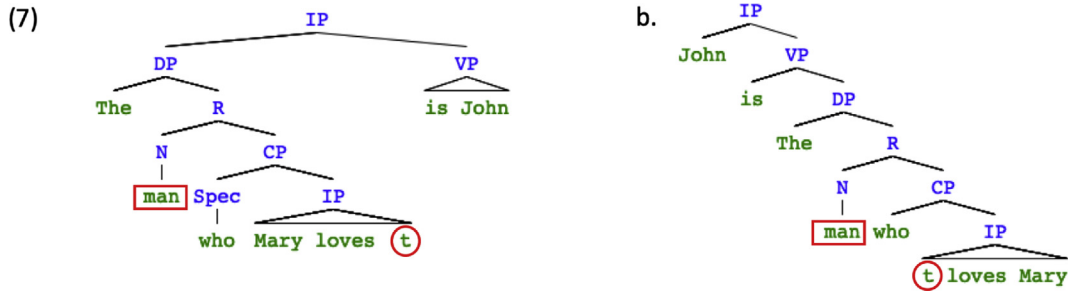


Table 5 – Three studies of MERGE.

Study	Design	Participants/Task	analyses	Peak locations as reported (Tal/MNI)	Unified Peak locations		
					MNI Coords	Anatomical	JuBrain
Pallier (2011)	<p>"level" of structure, each with actual OR nonce (Jabberwocky) nouns and verbs:</p> <p>A. [IP_{DP}] [VP [MOO [v]] [DP]]] – 2 word sentence</p> <p>B. [XP] [XP] – 2 * 6 word phrases</p> <p>C. [XP] [XP] [XP] – 3 * 4 word phrases</p> <p>D. [XP] [XP] [XP] [XP] – 4 * 3 word phrases</p> <p>E. [XP] [XP] [XP] [XP] [XP] – 6 * 2 word phrases</p> <p>F. – 12 words</p>	40 participants. Passive reading. No task.	# of word/phrase parameter (n=1,2,3,4,6,12) as predictor across both types	<p>MNI (-51 21 21); LIFGtri/TE22</p> <p>LpSTS; (-51 -39 3),</p> <p>Left Putamen (-18 16 12)</p> <p>LIFGorb; (-45 33 -6),</p>	-51 21 21	LIFGtri	Broca-45-L, IFS4-L
Zaccarella (2017)	<p>Sentences and phrases:</p> <p>A. [IP_{DP}] [N] [VP [v]]] – 3-word sentence</p> <p>B. [FP [p]] [NP [N]]] – 3-word phrase</p> <p>Word lists:</p> <p>C. [N] [N] [N] – 3-word list</p> <p>D. [N] [N] [N] – 3-word list</p>	18 participants; a meta-linguistic judgment	(A+C) – (B+D)	<p>MNI LIFG BA 44 (-51 11 16); LpSTS (-57 -43 1)</p>	-51 11 16	LIFG	Broca-44-L
Santi & Grodzinsky (2010)	<p>Center embedded</p> <p>A. (1a) – Subject-relative [IP_{DP}] [N] [R] [t] [VP [v]]] [CP [IP [t] [VP [v]]]]] [VP]]</p> <p>B. (1b) – Object-relative [IP_{DP}] [N] [R] [DP] [VP [v]]] [CP [IP [t] [VP [v]]]]] [VP]]</p> <p>Right branching</p> <p>C. (2a) – Subject-relative [IP_{DP}] [VP [v]] [DP] [R] [t] [VP [v]]] [CP [IP [t] [VP [v]]]]] [VP]]</p> <p>D. (2b) – Object-relative [IP_{DP}] [VP [v]] [DP] [R] [DP] [VP [v]]] [CP [IP [t] [VP [v]]]]] [VP]]</p>	17 participants; a meta-linguistic judgment	(A+B) – (C+D)	ns			Gapmap-Frontal-to-Parietal-L

In all results tables, Unified peak location column shows the MNI coordinates of each peak (either given or transformed from Taillarach), its topographic locus, and JuBrain cytoarchitectonic area.

Of the four types of relatives we have reviewed, (7a) has long been known to be the most difficult, whereas (7b) is the easiest (cf. Fodor et al., 1974; Yngve, 1960). Testing this contrast produced effects in Broca’s region in both studies, but the inherent confound precluded the possibility of teasing the MERGE and MOVE factors apart. This seemingly intended confound (as well as a host of issues with early data analysis) leads us to exclude the findings derived from these studies from our summary of the neural mechanisms of syntactic processing.

Another illustration of how principles that are common ground are violated comes from a second widely cited early fMRI study by Cooke et al. (2001). As in (1), their study featured a factorial 2X2 design, but differed from the schema in Table 1: as the examples in (8)–(9) indicate, instead of manipulating the Position of R in the main clause, Cooke et al. manipulated the length (i.e., the number of words) of the distance between the putative antecedent (bolded) and the gap (marked t):

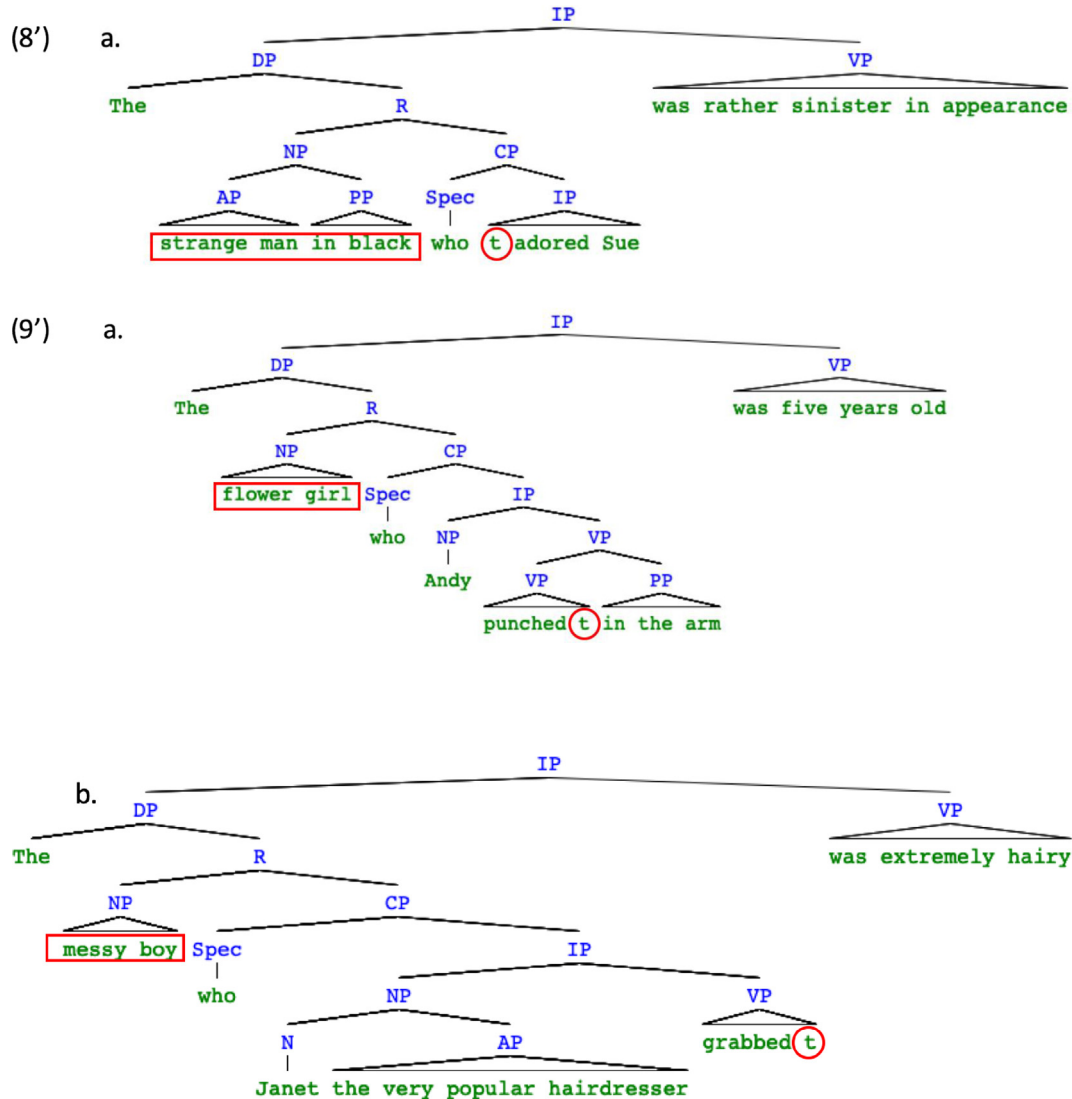
- (8) a. Subject Relative, short: [IP_{DP}The [R [N **strange man** in black] [CP who [IP t adored Sue]]] [VP was rather sinister in appearance]]]
- b. Subject Relative, long: [IP_{DP}The [R [N **cowboy** with the bright gold front tooth] [CP who [IP t rescued Julia]]] [VP was adventurous]]]
- (9) a. Object Relative, short: [IP_{DP}The [R [N **flower girl**] [CP who [IP Andy punched t in the arm]]] [VP was five years old]]]
- b. Object Relative, long: [IP_{DP}The [R [N **messy boy**] [CP who [IP Janet the very popular hairdresser grabbed t]]] [VP was extremely hairy]]]

This paradigm leads to a 2X2 design, illustrated in Table 6.

A close inspection of the experimental conditions shows that members of each pair (both rows and columns) differ from one another along multiple dimensions, apparent in the two syntactic graphs (8'–9'): sentences that are said to differ along the “displacement/movement” or “canonicity” dimension differ in several ways. Specifically, their tree structures are different with regard to the number of branching nodes, depth, node identity, and other factors that may contribute to complexity. Further, the lexical ingredients of sentences across conditions are different (which results in very different meanings). Viewed thus, no prediction can be derived regarding brain loci for syntactic complexity.

fusiform (18, 19) – regions that are largely peripheral to sentence processing.

Next, consider the “short” versus “long” conditions (columns in Table 6), said to tax Working Memory (WM) differentially. Cooke et al. expected this contrast to activate Broca's region, reasoning that longer trace-antecedent distance requires more WM, sometimes claimed to be supported by this region (Smith & Jonides, 1999). However, a careful scrutiny of the contrasting materials indicates that they did not constitute minimal pairs, built out of sentences in which everything is the same, except distance. A comparison of the structures in (9'a–b) shows that the “padding” with additional words



Indeed, the authors' expectation (that fMRI would tease apart canonicity from distance, and localize around the language regions) did not materialize. To take one comparison as an example, a comparison along the “canonicity” dimension on the “short” sentences (9a) versus (8a), resulted in a collection of clusters, including the left posterior temporal-occipital (BA 19), bilateral lingual/fusiform (BA18, BA19), and right lingual/

affected tree geometry, number of nodes, node labels, and consequently their meanings, both lexical and compositional, and likely, in their phonology (and note that many additional tree details are suppressed for clarity). This comparison, thus, is a multiply confounded.

No wonder, then, that when the condition that contained “short” object relatives (9–9'a) was subtracted from the “long” one

Table 6 – Cooke et al.’s design with 4 relative clause types.

		Dependency length	
		<i>Short</i>	<i>Long</i>
Gap position in R	<i>Subject</i>	(8a)	(8b)
	<i>Object</i>	(9a)	(9b)

(9-9'b), activations in multiple loci were found, not necessarily in agreement with what we know about WM (left pSTG/MTG [-64 -56 8]; right pSTG/MTG [52–68 16], [60 -20 -8]; left Inf Frontal [-52 28 -8]; left hippocampus [-32 -20 -20]; bilateral lingual/fusiform [0–92 -8]). It is quite likely that many, if not most, of the activations listed above are due to the multiple confounds inherent in the study design that are reflected in the fMRI signal. Yet, their results have been used to bolster a position that MOVE is not localizable in Broca's regions (e.g., Rogalsky, Almeida, Sprouse, & Hickok, 2015).

We can conclude that Cooke et al.’s study had a good design matrix, and its implementation met reasonably high standards for the time it was conducted. Unfortunately, crucial syntactic details were neglected, casting serious doubts on the validity of the authors' conclusions. These deficiencies went undetected, and this paper has, thus, long been cited as a study that pitted gap location against WM load.

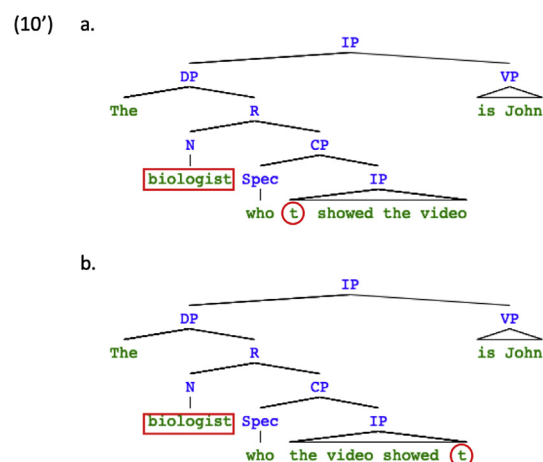
4.3.3. More current studies

With these problems in mind, we now turn to studies of MOVE in relative clauses, which have a fairly straightforward design. First among these is a study by Constable et al. (2004). These authors compared subject versus object relatives (with words drawn out of the same bag), in an experiment that featured non-reversible center-embedded sentences that were plausible (10) and implausible ones (11)⁵ (see 10' for tree structures associated with (10a,b)). It required participants to judge plausibility on both visual and auditory presentations (where each modality was tested separately):

- (10) a. The biologist who showed the video studied the snake.
 b. The biologist who the video showed studied the snake.
 (11) a. The thief who chased the policeman was slow.
 b. The man who the dolphin loves eats seafood.⁶

⁵ Earlier, Ben Shachar and her colleagues tested the \pm MOVE contrasts, using Hebrew relative clauses with embedded clauses as a baseline (Ben Shachar et al., 2003), and Hebrew topicalization structures (Ben Shachar et al., 2004). Their results (activations in Left IFG and left STS were only obtained by ROI analyses. In keeping with our current policy, we restrict discussion to studies that produced results in corrected whole brain analyses.

⁶ Note that the “implausible” condition includes sentences which, unlike the “plausible” ones, do not seem to be made up of the same words. We leave the lack of control here open: it may have created noise, but it does not affect the main comparison (8) in which the pair of sentences contrast in their syntax but are built out of the exact same inventory of words.



No behavioral data (error rates, RTs) were reported. Given the well-controlled experimental design, the authors were in position to analyze the loci for MOVE across modalities. The subtraction of effects stemming from both viewing and listening to sentences of types (10a,11a) from effects stemming from (10b,11b) uncovered multiple loci: in the left IFG (44/45) [-49 11 13], Premotor cortex (6/4) [-36 4 46]; STG/Parietal (39) [-36 -64 31]; Posterior Parietal (40) [-51 -58 3]; Anterior cingulate (6/24) [-2 6 33]; and Thalamus [-3 -24 15]; and in the right IFG (44/45) [44 6 2] and Premotor (6) area [43 14 23]. This large number of clusters is not unusual when examining main effects in such subtractions. However, the authors note that: “using the most conservative criterion, that the site must be similarly activated in both modalities and must show comparable effects of complexity for both modalities, the strongest candidate site appears to be BA 44/45 in left IFG” (p. 18).

An experiment with virtually the same 2×2 design was carried out by Rogalsky et al. (2008). As part of a more complex experiment that explored cross-modal effects of syntactic complexity, their Exp. 2 deployed a plausibility judgment task. Their results were not dissimilar from Constable et al.’s: the same contrast (across \pm plausibility) showed activation in the pars triangularis [-41 38 14] and pars opercularis [-42 13 23] of the left IFG.

Next, Meltzer, McArdle, Schafer, and Braun (2010) similarly used reversible and irreversible subject- and object-gap relative clauses, this time in a sentence-to-picture matching

excluded from analysis). A single brain location distinguished between the two effect types – the left IFG (–50 32 6), localized mostly in BA 45, and to some extent in BA 44 by the Amunts et al. (1999) map.

Finally, we turn to Santi and Grodzinsky (2010), already discussed in the context of MERGE. It is the only study to date to have used all four types of relative clauses in (1), hence able to pit both sources of complexity – MERGE and MOVE – against one another. They conducted a neural adaptation (repetition suppression) experiment that used a secondary, (lexical monitoring) task with all 4 sentence types, replicated standard behavioral measures, and found that MOVE exposed a single activated cluster, whose peak in the left IFG [–48, 29, 15] localized to BA 45 by the Amunts et al. probabilistic map.⁷

4.3.4. Related results from English

Before ending this discussion of MOVE in Wh-movement structures, we briefly mention fMRI studies that have contrasted other subject/object asymmetries in relative clauses: subject-versus object-cleft sentences, that have long been thought to be related to relative clauses (cf. Mokrosz, 2015 for a recent review). Admittedly, the subject/object contrast in clefts is not as “pure” as the one in relative clauses, due to syntactic and semantic complications. Most notably, cleft constructions contain an anaphoric “existence presupposition”: the subject cleft sentence *it is the woman who touched the man* presupposes a context in which somebody touched the man, whereas its object counterpart *it is the man who the woman touched* presupposes a context in which the woman touched somebody. These presuppositions are not identical in content, a difference that may be confounded with MOVE, and is never easy to control for. Nevertheless, the results we present are relatively stable, and contribute to the generality of our conclusion regarding the localization of MOVE. Europa, Gitelman, Kiran, and Thompson (2019) – a study that otherwise met our criteria as it carried out a whole brain analysis - compared activation patterns for these constructions (e.g., *it is the woman who touched the man* vs *it is the man who the woman touched*). They found a left-lateralized network, that included the IFG [–51,21,0], [–54, 18, 18]].

Finally, we turn to several studies of MOVE which are naturally relevant to our review, yet are more difficult to carry out and to interpret, as they contain different “bags of words”,

⁷ Another study by Rogalsky et al. (2015) set out to test the MOVE contrast. It tested the interaction between this structural contrast and the linear distance of the MOVE operation. The authors claimed to uncover “a main effect of movement in the left hemisphere superior temporal gyrus (STG), middle temporal gyrus (MTG), putamen, and thalamus, as well as bilateral post-central gyrus; a main effect of distance in the left STG, bilateral MTG, bilateral claustrum, and right cingulate gyrus” (p. 3). However, it reported a failure to obtain an effect in Broca's region. Their failure, as well as their success to find a Distance X MOVE interaction, led them to argue that “the fact that non-movement sentences, particularly the short variants, activated this region at least as well as long movement sentences argues strongly against a movement-specific explanation of the response properties of this region as a whole” (p. 3). In keeping with our basic approach, we refrain from discussing this paper in the text, as all of its results were obtained through analyses that were uncorrected for multiple comparisons.

which may lead to confounds and complications. At issue are well known instantiations of the so-called NP-movement relation; in English, prominent among these are the passive, unaccusative, and Raising constructions (Adger, 2003; Martinović, 2019).⁸ The linguistic and psycholinguistic literature is replete with debate on the status of these (e.g., Collins, 2005), and as we seek to adhere to safe grounds, and to steer clear from such debates, we point out briefly that the active/passive contrast in English has been tested in neuroimaging several times; once in PET (reported in Caplan, 2000) with little evidence for a signal intensity difference, and in two more recent fMRI studies (Europa et al., 2019; Mack et al., 2013) that succeeded in measuring such a difference.⁹ In the former, results were mixed, as the IFG was significantly activated bilaterally: left [–36, 4, 32]; right [56,24,28]. Hence left Broca's region was implicated, but not singled out. In addition, significant activation was found in left pMTG/occipital gyrus [46,–76, 4]. Europa et al. (2019) combined the active/passive construction with object- and subject-cleft structures. A whole-brain analysis found activations in the left IFG [–48,22,22], MFG [–50,16,38], and pMTG [–52,–36,0].

Collectively, studies of MOVE conducted in English consistently have found activation in the IFG, particularly in the pars opercularis and pars triangularis, which by most accounts jointly constitute Broca's region. This region is, without a doubt, most crucially involved in human syntactic processing. Finally, we note that much is still missing from the experimental MOVE literature. Specifically, we are not aware of any study of wh-questions (whether matrix or embedded), Left Dislocation, and related structures. In the next section, we briefly review studies in languages, other than English, that use instances of MOVE for cross-linguistic explorations of the neural mechanisms of syntactic processing.

4.4. Special instances of MOVE in Japanese and in German

MOVE is a generalization regarding the relation between elements in a representation of a string. As noted above, it has many instantiations, some of which do not feature in English. Scrambling is a general term for the process that derives non-canonical word order in languages with “relatively free word-order” such as German, Dutch or Japanese. In such languages, constituents can occur in a variety of syntactic permutations, where deviation from the “canonical” form preserve the core meaning of the sentence, but add Focus (see below). Here is an

⁸ Raising in English is another instance of NP-movement in the syntax (e.g., *The man seemed to John [t to be falling]*). As no fMRI studies of such constructions exist, we will not discuss them any further.

⁹ The active/passive contrast involves inherent confounds. That is, the *-en* morpheme only features in passive, not its active counterpart; the passive contains a by-phrase which the active does not; as well, controlling for the presence of an auxiliary forces a progressive active (ia) but not passive (ib), whose progressive counterpart would be *The sister was being pushed*. (i) a. [_{IP} [_{DP} The [_Nbrother] [_{VP} was pushing] [_{DP} the sister]]] (active). b. [_{IP} [_{DP} The [_R sister] [_{VP} was pushed t] [_{PP} by the brother]]] (passive). These and other differences have led some to doubt the MOVE analysis of passive.

Table 8 – Three Japanese studies of “canonicity” and other factors.

Study	Design	Participants/Task	analyses	Peak locations as reported (Tal/MNI)	Unified Peak locations		
					MNI Coords	ANATOMICAL	JuBrain areas
Hirotsani et al., 2011	<i>Active vs. Causative</i> A. Adv [DP] _{NOM} [DP] _{DAT} [DP] _{ACC} V <i>Active</i> B. Adv [DP] _{NOM} [DP] _{DAT} [DP] _{ACC} V+CAUS <i>Active+Caus</i>	16 subjects, Auditory, 20% questions.	Whole brain: B>A	MNI <i>Left</i> LIFG pars triang. (-54 27 6), dorsal premotor area (-42 3 18) putamen (-12 6 3), STG (-42 -57 21) Heschl gyrus (-63 -18 6) <i>Right</i> STG (66 -21 9) ACC (9 21 48) putamen (18 12 0) cerebellum (36 -60 -30)	<i>Left</i> -54 27 6 -42 3 18 -12 6 3 -42 -57 21 -63 -18 6 <i>Right</i> 66 -21 9 9 21 48 18 12 0 36 -60 -30	LIFG pars triang. Dorsal premotor area Putamen STG Heschl gyrus STG ACC Putamen Cerebellum	Broca-45-L Operculum-OP5-L Gapmap-Temporal-to-Parietal-L TE22-L, TE3-L TPJ-R, TE3-R Gapmap-Frontal-I-R, PreSMA-R
Kim et al., 2009	<i>“Scrambling” vs. Active</i> A. [DP] _{NOM} [DP] _{ACC} V <i>+canonical</i> B. [DP] _{ACC} [DP] _{NOM} V <i>-canonical (“scrambled”)</i>	36 subjects, read, speeded plausibility (RT _B >RT _A)	B vs. A	Tal LIFG (-54 26 20) LDPFC (-42 0 50)	-57 30 16/-54 26 20 -42 0 50	LIFG LDPFC	Broca-45-L Gapmap-Frontal-II-L
Kinno et al., 2008	<i>Quasi-symbolic “Scrambling” vs. Active</i> A. [DP] _{NOM} [DP] _{ACC} V <i>+canonical</i> B. [DP] _{NOM} [DP] _{DAT} V-pass <i>-canonical (passive)</i> C. [DP] _{ACC} [DP] _{NOM} V <i>-canonical (“scrambled”)</i>	14 subjects, read (long exposure times) and verify against an image	B vs. A C vs. A	MNI LIFG (-48 24 21) LIFG (-52 21 21) LpSTG/LMTG (-54 -54 3)	-48 24 21 -52 21 21 -54 -54 3	LIFG LIFG LpSTG/LMTG	Broca-45-L, IFS-IFJ2-L Broca-44-L, Broca-45-L Gapmap-Temporal-to-Parietal-L

example from a simple sentence in Japanese, a verb-final language (12a), and its scrambled variant (12b):

- (12) a. [CP_{IP}[NP Mary-ga][VP_{DP} sono hon-o][V yonda]] (koto)
Lit.: *Mary*_{NOM} *that book*_{ACC} *read (fact)*
(the fact that) ‘Mary read that book’
b. [CP_{DP} sono hon-o][IP_{NP} Mary-ga] t [V yonda]] (koto)
Lit.: *that book*_{ACC} *Mary*_{NOM} *read (fact)*
(the fact that) ‘Mary read that book’

In this example, we see that the accusative object *that book* may cross the nominative subject *Mary*. Critically, this syntactic change preserves meaning (though certain properties of the displaced element must be carefully selected to guarantee meaning preservation). The relation between the scrambled object and its original position is widely considered an instance of MOVE (e.g., Grewendorf & Sabel, 1999; Mahajan, 1990). Scrambling may be short- or long-distance (i.e., where an element is scrambled across clause boundaries). Here, we only look at instances of short-distance Scrambling, in which the object crosses the subject position of the same clause. As reviewed in Table 7, in the three Japanese Scrambling studies we identified all three activated the left IFG, and one also found activation in the left STG.¹⁰

¹⁰ We note that studies of passive have also been conducted with Japanese-speaking participants. In Japanese, passive predicates are morphologically marked (i.e., by the morpheme *rare*), whereas active verbs are uninflected. Thus, the IFG activation for passive sentences in Japanese studies may be attributable to morphological complexity, rather than movement operations. Japanese also is a verb-final language and, therefore, the thematic and syntactic reanalysis processes take place after both noun phrases are presented (see Yokoyama, Okamoto et al. (2006) for discussion).

Another language that famously features Scrambling is German, another verb-final language. The accusative object *the fridge* (13a) can scramble over the nominative subject *the father* (13b, some nodes are suppressed for simplicity):

- (13) a. (Ich glaube dass) [IP_{DP} der Vater] [VP_{DP} den Kühlschrank] zu reparieren versprochen hat]]
Lit.: *I think that the father*_{NOM} *the fridge*_{ACC} *to fix has promised*
'I think that the father has promised to fix the fridge'
b. (Ich glaube dass)[DP den Kühlschrank][IP_{DP} der Vater] [VP t zu reparieren versprochen hat]]
Lit.: *I think that the fridge*_{ACC} *the father*_{NOM} *to fix promised has*
'I think that the father has promised to fix the fridge'

Although Scrambling shares only a subset of its properties with other instances of MOVE, there is little doubt that it is an instance of syntactic displacement. The processing of such relations must be supported by neural tissue, which raises the important question of whether the neurolinguistics of MOVE is uniform across its sub-species. A number of neuroimaging investigators have explored this question in German. These studies feature minimal pairs and report corrected results in a variety of well-accepted tasks. Therefore, a detailed review of this set of studies seems redundant. The German studies and their relevant results are presented in Table 8, in which the characteristics of the conditions in each study are specified. Notably, across all studies, the left IFG emerged as crucial for MOVE. In two thirds of the studies, the left STG or STS also was activated. Yet notice that in 4/5 German studies, and 1/3 Japanese studies, RH loci are reported as well (see Table 9).

Table 9 – Five German studies of “Scrambling” and other factors.

Study	Design	Participants/Task	analyses	Peak locations as reported: (Tal/MNI)	Unified Peak locations		
					MNI Coords	ANATOMICAL	JuBrain areas
Friederici et al., 2006	“canonicity parameter” from 0 to 2 ((±Scrambling) 1. Adv Aux [DP] _{NOM} [DP] _{ACC} [DP] _{DAT} V +Can, 0 2. Adv Aux [DP] _{ACC} [DP] _{NOM} [DP] _{DAT} V -Can, 1 3. Adv Aux [DP] _{DAT} [DP] _{NOM} [DP] _{ACC} V -Can, 1 4. Adv Aux [DP] _{ACC} [DP] _{DAT} [DP] _{NOM} V -Can, 2	13 participants; phrase-by-phrase reading	Linear effect (4>3>2>1)	Tal LIFG 44 (-49 10 4) preSMA; (7 22 44)	-51 12 0/-49 10 4 9 28 43/7 22 44	LIFG preSMA	Broca-44-L, Operculum-OP9-L Gapmap-Frontal-I-R
Bahlmann et al., 2007	“canonicity” (±Scrambling) X “case ambiguity” 1. [DP] _{M-NOM} V [DP] _{M-ACC} ... +Can,-Amb 2. [DP] _{M-ACC} V [DP] _{M-NOM} ... -Can,-Amb	12 participants; read word by word, indicate if stim appeared previously	2>1	MNI LIFG [-40, 28, 8]	-40 28 8	LIFG	Operculum-OP9-L
Bornkessel-Schlesewsky et al., 2012	“canonicity” (±Scrambling) X Clause-type (±embedded) A. [DP V ₁][dass [DP] _{NOM} [DP] _{ACC} V ₂ Aux] +Can,+V _{final} B. [DP V ₁][dass [DP] _{ACC} [DP] _{NOM} V ₂ Aux] -Can,+V _{final} C. [DP V ₁][DP] _{NOM} [DP] _{ACC} V ₂ Aux] +Can,-V _{final} D. [DP V ₁][DP] _{ACC} [DP] _{NOM} V ₂ Aux] -Can,-V _{final}	18 participants; speeded acceptability	word order contrast (B+D) – (A+C)	Tal LIFG, IFS/IFJ/PMC (-47 14 6) R. IFS/IFJ/PMC/IFG (34-1 30) L. ACC (-8 20 39) L. STS/STG (-47 -43 12) L./R. thalamus (medial nucleus) (-5 -25 12) L./R. thalamus (anterior nucleus) (11 -16 3)	-49 16 2/-47 14 6 38 3 29/34 -1 30 -7 26 37/-8 30 39 -49 -44 14/-47 -43 12 -4 -24 11/-5 -25 12 13 -15 0/11 -16 3	LIFG, IFS/IFJ/PMC RIFS, IFJ, PMC, IFG LACC LSTS, STG L thalamus, medial nucleus R thalamus, anterior nucleus	Broca-44-L, Operculum-OP6-L Gapmap-Frontal-II-R, IFS-IFJ2-R Gapmap-Frontal-to-Occipital-L Gapmap-Temporal-to-Parietal-L, TPJ-L
Bornkessel et al., 2005	“canonicity” (±Scrambling) X “case ambiguity” X V-type (Act/Exp) A. ...dass [DP] _{NOM} [DP] _{DAT} V _{act} ... +Can,+Amb B. ...dass [DP] _{DAT} [DP] _{DAT} V _{act} ... -Can,+Amb C. ...dass [DP] _{NOM} [DP] _{DAT} V _{exp} ... +Can,+Amb D. ...dass [DP] _{DAT} [DP] _{DAT} V _{exp} ... -Can,+Amb E. ...dass [DP] _{NOM} [DP] _{DAT} V _{act} ... +Can,-Amb F. ...dass [DP] _{DAT} [DP] _{NOM} V _{act} ... -Can,-Amb G. ...dass [DP] _{NOM} [DP] _{DAT} V _{exp} ... +Can,-Amb H. ...dass [DP] _{DAT} [DP] _{NOM} V _{exp} ... -Can,-Amb	15 participants; read word by word, 20% comprehension questions, (>50% accuracy)	No Main effect of any factor “Canonicity” X V-type interaction (collapsing over ±Ambig)	MNI LIFG pars opercularis (-45, 18, 15) L pSTG (-55, -42, 21) L pSTS (-49, -58, 29) L IFJ (-36, 10, 34) L ventral PMC (-36, 5, 52) L IPS (-28, -56, 44) R IPS (46, -39, 55)	-45 18 15 -55 -42 21 -49 -58 29 -36 10 34 -28 -56 44 46 -39 55	LIFG pars opercularis L pSTG L pSTS L ventral PMC LIPS RIPS	Broca-44-L TPJ-L, IPL-PFCM-L IPL-PFM-L, IPL-PGA-L Gapmap-Frontal-II-L, IFS-IFJ1-L, IFS-IFJ2-L AIPS-IP3-L AIPS-IP2-R, IPL-PFM-R
Fiebich et al., 2005	“canonicity” (±Scrambling) X position of adverbial PP A. ... Wh _{NOM} [long PP] [DP] _{ACC} V +Can,+PP _{final} B. ... Wh _{ACC} [long PP] [DP] _{NOM} V -Can,+PP _{final} C. ... Wh _{NOM} [long PP] [DP] _{ACC} V +Can,-PP _{final} D. ... Wh _{ACC} [long PP] [DP] _{NOM} V -Can,-PP _{final}	14 participants, phrase-by-phrase reading, verification of answers to the question probe;	Obj vs. Subj Long vs. short Obj questions Long vs. short Subj questions	Tal ns LR IFG (-44, 21 11), (45, 21 10), (-46 17 4), LR STS, MTG (-54 -27 -1), (-52 -46 6),(45 -18 -3) LR parieto occipital sulcus	-46 24 7/-44 21 11 49 25 5/45 21 10 -48 19 -1/-46 17 4 -57 -28 -2/-54 -27 -1 -54 -47 -7/-52 -46 6	LIFG RIFG LIFG LSTS LMTG RMTG	Operculum-OP8-L, OP9-L Broca-45-R, Broca-44-R Broca-44-L, Operculum-OP8-L STS1-L, STS2-L Gapmap-Temporal-to-Parietal-L TI-L, TEI-L
Grewe et al., 2005	Canonicity (±Scrambling) A. N-SO Dann hat der Lehrer dem Gärtner den Spaten gegeben then has [the teacher] _{SUBJ} [the gardener] _{IOBJ} [the spade] _{DOBJ} given B. N-OS Dann hat dem Gärtner der Lehrer den Spaten gegeben then has [the gardener] _{IOBJ} [the teacher] _{SUBJ} [the spade] _{DOBJ} given	16 participants, acceptability judgment of visually displayed - read - stimuli	B-A	Tal LIFG/aInS (-32 20 3) LIFG (-52 14 15) L pre-SMA/BA8 (-2 32 30) L inf. frontal junction (-38 8 38) R inf. frontal sulcus (44 26 18) RIFG/aInS (38 20 6) RIFG (46 11 9)	-33 22 -2/-32 20 3 -54 17 12/-52 14 15 -1 37 26/-2 32 30 -39 13 37/-38 8 38 48 30 13/44 26 18 42 23 0/38 20 6 50 14 4/46 11 9	LIFG/aInS LIFG L preSMA, BA8 L inf. frontal junction R inf. frontal sulcus RIFG, aInS RIFG	Inusual-ID7-L Broca-44-L, Broca-45-L, Gapmap-Frontal-to-Occipital-L Gapmap-Frontal-II-L, IFS-IFJ1-L Broca-45-R Operculum-OP9-R, Broca-45-R Broca-44-R, Operculum-OP8-R

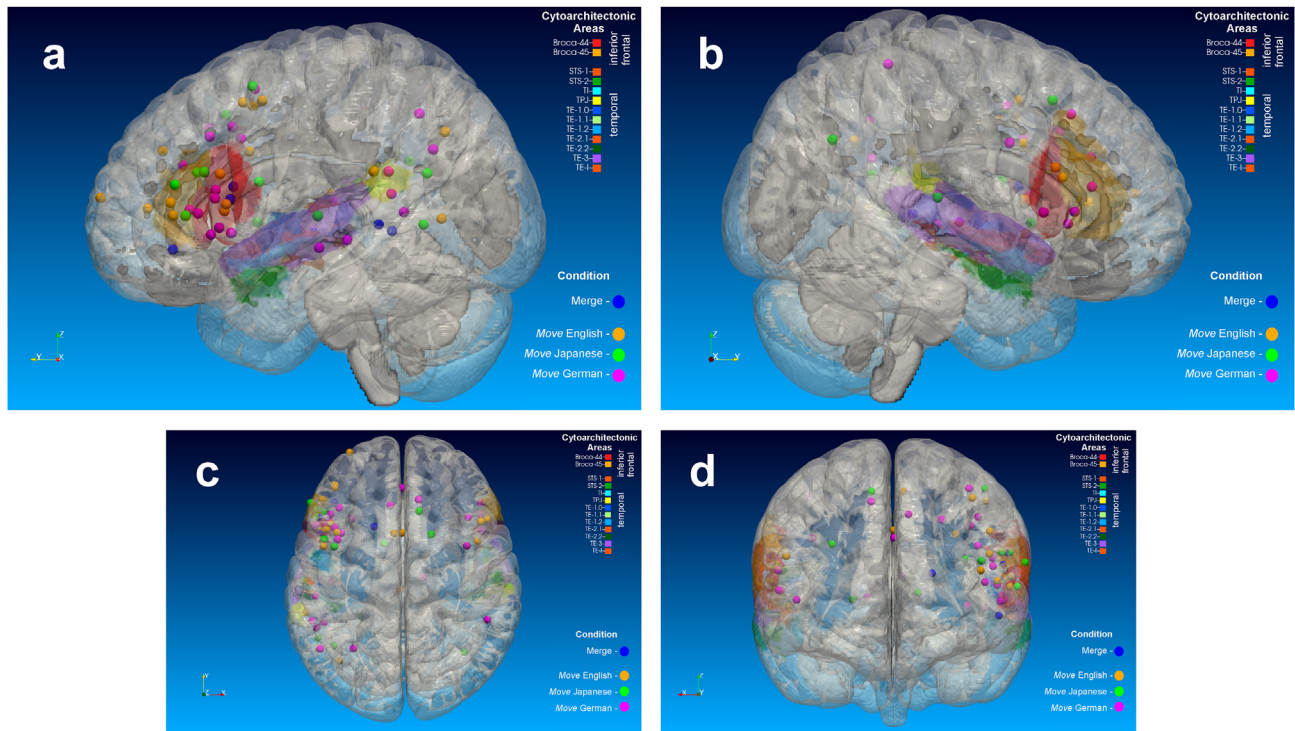


Fig. 1 – Surface images with all maxima and relevant cytoarchitectonic areas.¹¹ Maxima are marked for MERGE studies (blue), and for MOVE in the respective languages (orange, green and pink, see legend). In the background, selected JuBrain cytoarchitectonic areas are superimposed: on the frontal lobe, the Broca's region portion of the Inferior Frontal Gyri are marked in both hemispheres by areas 44, 45 (red, orange); in the temporal lobes, a host of areas is involved (enlarge to see legend). (a) left hemispheric surface image; (b) right hemispheric surface image; (c) top surface image; (d) rear surface image.

To understand the involvement of the RH, we return to the meaning of scrambled sentences. Scrambling is invariably invoked to convey a focused meaning via emphatic intonation on the scrambled/focused element. To illustrate, consider the German examples in (12): the non-scrambled (12a) delivers the speaker's belief that the father has promised to fix the fridge. Yet the scrambled (12b) delivers a slightly different meaning, namely that among all possible alternatives (that the father promised to fix the car, that he would promise to fix the oven, etc.), the speaker's belief is that the father promised to fix *the fridge*, and no other appliance. Scrambling, then, is confounded with focus, which evokes a set of alternatives to the focused element

¹¹ The coordinates of all fMRI-maxima in this meta-analysis were reported either in MNI-space or Talairach-space. Those in Talairach-space were transformed into the MNI-space by using the inverted affine transformation offered by the Brainmap database (<https://brainmap.org/icbm2tal>). These locations are visualized on a transparent reconstruction of the MNI template ("icbm152asym2009c", <https://www.bic.mni.mcgill.ca/ServicesAtlases/ICBM152Nlin2009>) (Fonov, Evans, McKinstry, Almlí, & Collins, 2009) by using the visualization software "ITKsnap" (<http://www.itksnap.org>) (Yushkevich, Piven et al., 2006). In addition, several regions of the Julich-Brain-Atlas (<https://www.ebrains.eu/service/human-brain-atlas>) (Amunts et al., 2020) which are related to auditory or speech functions, are visualized on the surface of the template in order to assign the functional locations to anatomical regions. The regions mapped in the Julich-Brain-Atlas are based on a parcellation of the human brain by cytoarchitectonical criteria.

(Fox, 2000; Rooth, 1992). Focus in German is conveyed by a special intonational contour (similar effects are found in Japanese, albeit with a weaker emphasis). Thus, the RH activation in these studies (4/5 of the German studies above, and 1/3 of the Japanese studies) is likely attributable to the focus component of Scrambling, in which MOVE goes along with intonation-expressed Focus. Nevertheless, across all studies of Scrambling, we see converging left LIFG, and to some extent, left STG activation.

5. Visualization, summary and conclusions

Our review sifted through dozens of studies, and found those that met the criteria we set early on. It is now time to look back. In the tables, we localized study maxima by transforming them to JuBrain – the Jülich brain atlas. This is visualized in Fig. 1, with the relevant cytoarchitectonic areas marked in the background. The clustering of peaks in the left IFG and STG/STS is clear:

The images and tables help us tally up the numbers:

- A. Three fMRI studies of MERGE contrasts (in French, German and English) with a total of 76 healthy participants were reviewed.¹² Of these, one (17

¹² The study by Matchin et al., 2017, is not included, as its whole-brain analyses were not corrected for multiple comparisons.

participants) found no activation clusters, whereas the other (with 58 participants) led to 3 activation peaks in the left IFG, one activation in the left pSTS, and one in the right IFG.

- B. All five fMRI studies with English MOVE contrasts in relative clauses that were reviewed (91 healthy participants) found activation in the left IFG; two of these studies (with 35 participants) found activation in the STG. Three of these studies also found activation in other brain regions. There was no between-study overlap in these additional clusters, some of which localized to the right hemisphere. It should be kept in mind that these are the cleanest studies, as all conditions were created out of the same bag of words, and featured no syntactic or semantic differences other than MOVE.
- C. Of the English MOVE studies, two (35 participants) found right hemisphere activations.
- D. All eight studies of MOVE as instantiated in Japanese (66 participants) and German (72 participants) Scrambling contrasts, with a total of 138 healthy participants, found activation clusters in the left IFG. Of these, three also found activation clusters in the left STS or STG, among other clusters.
- E. Five of these studies (79 participants) found activation clusters in the right hemisphere.

The picture that emerges for MERGE is a bit murky: MERGE shows some involvement of the left IFG, and STS/STG. MOVE produces highly consistent results and a very sharp picture: the left IFG is activated across-the-board and unambiguously, and to a somewhat lesser extent, the STG/STS. These data indicate that MOVE and to a lesser extent MERGE are supported by the left IFG.

In conclusion, we described our review of numerous fMRI studies of complex syntactic processes, from which we carefully distilled the relevant set of core studies, on the basis of fairly stringent criteria that we established and justified at the outset. This core of studies gave us a fairly broad empirical basis to localize the neural substrate of complex syntactic processes. We found it to be consistent and replicable. Importantly, [Zaccarella, Schell, & Friederici, 2017](#), reached similar conclusions, albeit not on the same empirical grounds. On this basis, we can conclude the left IFG, and to a lesser extent the left STG/STS, are reliably implicated in complex receptive syntax, and that the rumors about the death of Broca's and Wernicke's area ([Tremblay & Dick, 2016](#); [Matchin & Hickok, 2020](#)) seem to have been vastly premature. Our review shows, we hope, that despite the difficulties, the neural bases for syntactic processing in the human brain evince remarkable stability.

Credit author statement

All three authors contributed equally to the paper.

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