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Syntactic Dependencies as Memorized Sequences in the Brain

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I would like to consider a unification of two areas in cognitive neuroscience: Investigations of working memory (WM), and the study of syntactic representation and processing. I would like to think about the functional neuroanatomy of these seemingly unrelated systems, and entertain the possibility that they may be much more closely related than previously supposed. Think of dependency relations in syntax: It is clear that their computation requires a memory. A sentence like (0), to take an extreme example, requires several memories, each with different properties:

(0) [**Which of the papers that he₁ gave to Ms. Brown₂**]₃ did every student₁ hope *t*'₃ that *she*₂ will read *t*₃

Here, not only does each pronoun relate to a different antecedent { 1:(*every student, he*), 2:(*Ms. Brown, she*)}, but also, the parenthesized expression to the left must be linked to two different positions 3:(***Which of the papers that he gave to Ms. Brown, t', t***). This is a truly complex structure, aspects of which will be ignored here (like quantifier scope, precedence relations among syntactic operations, etc., cf. Fox, 1999). Suffice it to note that we have at least three separate links, each with its own structural properties, each requiring a memory to hold linked parts temporarily during processing. Perhaps, I will propose, there are several WMs, each entrusted with a different linguistic function. My attempt to argue for this position begins with an observation regarding a co-occurrence that has not been given sufficient attention: On the one hand, components of working memory (WM) reside in Left Inferior Frontal Cortex (LIFG), parts of which are known as Broca's region (or Brodmann's Areas 44, 45 and their vicinity); on the other hand this

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area, when lesioned, manifests in disruptions to the ability to analyze certain intra-sentential dependencies (somewhat similar to those in (1)) in comprehension. Arguably, this anatomical juxtaposition is not accidental. It is possible, then, that the scope of WM is wider than current accounts would have it, and that it spans over syntactic computations. I will explore this possibility, and try to unify considerations regarding WM (which receive empirical support from a variety of memory tasks monitored in fMRI and PET) with a strictly syntactic approach to Broca's region, based on experimentation with Broca's aphasics. This is an approach that views this region as housing mechanisms that compute transformations, and no other syntactic relation. The attempt to unify these two major approaches is an intellectual exercise that requires the reader to put disciplinary preconceptions aside: A linguist is asked to temporarily suppress certain grammatical considerations, and a cognitive neuroscientist - to take grammar as a serious object of psychological inquiry. I will propose that this adventure is worthwhile, as it helps discover new facts, and refine our understanding of the representation, neural implementation and localization of language. It also underscores, in my view, the prospects of a cognitive neuroscience of syntax.

1. Two approaches to Broca's region: TDH and WM

The role of Broca's region in the processing of sentences has been studied quite extensively. I focus on two explicit attempts to characterize its functional role: The Trace-Deletion Hypothesis (TDH), and the recent proposal that this region houses components of working memory (WM). These proposals have more in common than initially meets the eye, as we shall see. Our tour will take us to an unusually broad collection of linguistic and cognitive theoretical considerations, and of experimental results that range from normal grammaticality judgments, to sentence comprehension and judgment by aphasic patients, to the time-course of sentence processing, and to a range of tasks carried out inside hi-tech neuroimaging instruments (PET and fMRI).

1.1 A Movement Approach To Broca's Region (LIFG)

The starting point of the TDH is the observation that movement is the line dividing impaired and preserved structures in Broca's aphasia. The idea is that traces of movement are invisible to the syntactic system in this syndrome.

(1) Trace-Deletion Hypothesis (TDH)

Delete all traces from agrammatic representation.

Any task that recruits traces is bound to fail, and the shape of the failure depends on phrasal geometry, certain semantic properties the predicate, and task specifications. The TDH has far-reaching implication regarding the role of Broca's area in sentence reception in aphasia as well in health.

The manner by which this account (coupled with an augmentative interpretive strategy) captures a massive body of comprehension and real-time performance data, including a host of cross-linguistic phenomena, has been described in detail elsewhere (see Grodzinsky, 1986, 1995, 2000). Here, I would like to initially focus on the way the TDH handles the deficit as manifested in grammaticality judgment, a task that might in fact probe the patients' abilities – and through them the role of Broca's area – in a way that is more informative than comprehension. Later, I will explore the consequences of the lesion-based TDH to the normal brain. Consider, first, the contrasts in (2)-(3). In (2), movement of a phrase is licit (2a-e) as long as it does not cross a like element (NP), in which case ungrammaticality follows (2f). A similar principle holds in (3). A question can be formed only if a *wh*-element does not cross another. Both sets of facts have been claimed to fall under the same constraint – Relativized Minimality (RM), which requires that the distance between an antecedent and a trace be minimal relative to antecedent type. In other words, the presence of a potential antecedent that intervenes between a moved element and its trace blocks linking between the latter two. (cf. Rizzi, 1990). In the examples below, an RM violation is apparent only in (2f) – *it* – and in (3b) – *whom*, which are indeed the sole ungrammatical strings in the paradigm:

- (2)
- a. It is likely that [Mary will win]
 - b. *Mary* is likely [t to win]
 - c. It seems that Mary is a fool
 - d. *Mary* seems [t a fool]
 - e. *It* seems that *Mary* is likely [t to win]
 - f. **Mary* seems that *it* is likely [t to win]

- (3) a. *Whom* did John persuade *t* [to visit *whom*]
 b. **Whom* did John persuade *whom* [to visit *t*]

Knowledge of the position of the trace is crucial for judgment in these cases, since RM (or whatever other constraint on movement one might imagine) must be formulated over trace-antecedent relations. When RM and the TDH are coupled, it follows that Broca's aphasics would be unable to judge grammaticality of strings which violate this constraint, because in order for it to be computed on a representation, the location of the trace must be known, and it is exactly that which is inaccessible to the Broca's aphasic, by the TDH. This prediction is borne out. When asked to judge contrasts such as in (2)-(3), patients made 30-50% errors, compared to a set of controls, in which error rates were significantly lower, 15% and under (Grodzinsky & Finkel, 1998). I will return to these issues below.

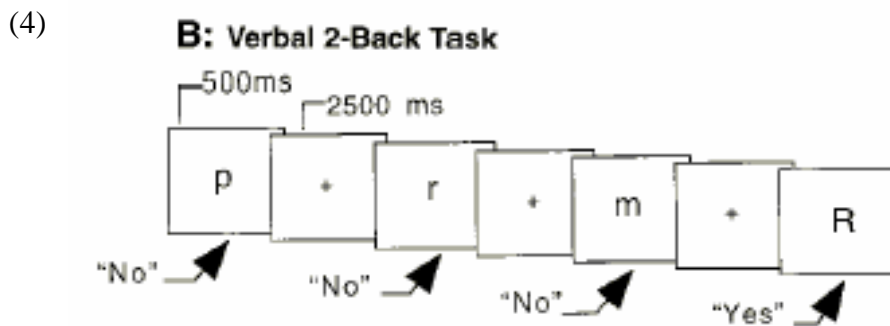
1.2. A Working Memory Approach To Broca's Region (LIFG)

What could the cognitive underpinnings of this deficit be? One could, perhaps, imagine a disruption that is directly linked to knowledge of traces of movement. Still, could the observed failures be linked to an identifiable, independently motivated processing unit? Such a move, if possible, would not only unify a broad range of data under one account, but also bridge a gap between psychological and linguistic perspectives on language processing in the brain. It may therefore be worthwhile to give this possibility a fair hearing. One idea that I would like to explore is that of rigging the aphasic deficit to Working Memory (WM), since the latter is a construct said to be closely linked to language processing, and some of its components are claimed to reside in Broca's area. It therefore seems reasonable to entertain the possibility that the range of results described by the TDH can be explained by appealing to WM. The TDH, in other words, could be a mere consequence of a WM failure. Before considering this possibility, let us examine the characterization of WM, and some empirical arguments for its localization in Broca's region. This will lead to a direct comparison between a TDH and a WM approach to Broca's area.

The notion of WM is not new: It was proposed a while ago as a specialized unit, aimed at holding things in temporary store during processing. Baddeley's (1986) model posits separate storage buffers for verbal and visual-spatial information. Verbal storage is

decomposed into a buffer for short-term maintenance of information (which Baddeley claims to be phonological) and a subvocal rehearsal process that refreshes the contents of the buffer. A central concept in this approach is that of load, which is a linear property of stimuli, for which there are identifiable, linearly related cognitive and cerebral correlates. As WM load grows, so grows effort, and the experimenter devises ever more sophisticated methods to measure it. Smith, Jonides and their colleagues (See Smith & Jonides, 1999; Carpenter, Just & Reichle, 2000 for recent reviews) have been using such a method, with the goal of localizing components of this system in the frontal lobes. They have explored this issue through extensive testing of neurologically intact subjects in PET and fMRI. Two central claims emerge: 1. WM is localizable, and some of its central components are in the Left Inferior Frontal Gyrus (LIFG), or Broca's area. 2. WM is incremental: the more load a task involves, the more intensely is the neural tissue of these regions harnessed to its service (rather than expanding to other regions).

The most direct evidence comes from experiments that use the *n*-back task. A subject is presented with a sequence of single letters separated by 2.5 seconds; for each letter s/he has to decide whether it is identical to the letter that either was mentioned in the instructions (0-back), or appeared one, two or three items earlier in the sequence (by pushing a yes/no button). The structure of a 2-back experiment is in (4) (taken from Smith & Jonides, 1999):



A comparison with a set of controls suggests to the authors that this experiment isolates a frontal “rehearsal” circuit.² Other PET and fMRI studies have used 0-, 1-, 2- and 3-back

² This experiment uses two different controls. In one, participants also see a sequence of letters, but here they decide whether each letter matches a *single* target letter, rather than a non-adjacently presented one. The difference between this and the 2-back condition and should identify the localization of a component dedicated to temporary storage and maintenance of an item in a string for the purpose of immediate use.

tasks. All found activation in Broca's area and the premotor cortex, among other loci, although Broca's area and its vicinity seem the most stable in exhibiting activity across experiments (e.g., Awe *et al.*, 1996; Cohen *et al.*, 1994; Braver *et al.*, 1997; Cohen *et al.*, 1997; Jonides *et al.*, 1997). Importantly, when spatial relations constitute the task, other areas light up, indicating that there may be distinct WMs, and that the current one may be specialized for the "verbal" domain.

As stated, the connection between these claims, which focus mostly on the phonological shape of elements presented in lists, and considerations pertaining to grammatical structure, seems rather tenuous. Still, despite the absence of structural constraints of the type familiar in linguistics, it is tempting to inquire whether this processing component is linked to abilities that implicate structured linguistic materials. There are two reasons for such a move, *anatomical* and *functional*: First, certain WM circuits are in LIFG, namely Broca's area and its vicinity³; second, tasks in receptive language in which Broca's aphasics fail require a temporary store. Perhaps there is a connection, after all, and the notions entertained by psychologists could be reformulated, so as to make direct contact with linguistic considerations⁴. Next I will argue that there are also important and precise *geometric* similarities between the description of WM as it emerges through the above experiments, and movement, which may bring the aphasia data and the WM account closer than a first blush would suggest.

1.3. Geometric Similarities between Movement and 2-Back

What is the form of strings whose grammatical status is unknown to aphasics? In (2)-(3) we saw violations of RM, which abide by the following schema:

Indeed, the subtraction of this control from the 2-back condition yielded many of the areas of activation that have been obtained in item-recognition tasks, including the left frontal speech regions and the parietal area. A second control required participants to rehearse each letter silently. Subtracting this rehearsal control from the 2-back task should remove much of the rehearsal circuitry since rehearsal is needed in both tasks; indeed, in this subtraction, neither Broca's area nor the premotor area remain active. Hence, this experiment is considered to have isolated a frontal rehearsal circuit.

³ Smith *et al.* attempt to identify a region smaller than Broca's area. We are not sure that this level of precision is possible, given the variation in the locus of BA 44,45. Cf. Amunts *et al.*, 1999 for a detailed neuroanatomical analysis of this issue, and a new perspective regarding this variation.

⁴ Indeed, there have been attempts to link this perspective to sentences – Smith and Geva (2000) extend their account to this domain. They cite a correlation that has been repeatedly found between severely reduced digit span and "poor sentence comprehension", and suggest that the scope of WM is likely wider than phonology. While this proposal is not readily interpretable in linguistic terms, the attempt to think about the relationship between WM and syntactic movement is certainly commendable.

- (5) a. ...*X*...*t*...*Y*...
 └───┘
 b. *..*Y*...*X*... *t*...
 └───┘

In these structures, movement is licit (5a) if the moved element *X* does not cross a like element *Y* (as are, obviously, structures that contain no movement at all – [...*X*...*Y*...]). Yet if a moved element *Y* is separated from its trace by *X*, an element sufficiently similar to it (in a sense that is explicated), namely, if movement results in crossing a potential antecedent, the structure is ungrammatical (5b).

Reflect for a moment on the kind of resource necessary for this relation to be computed during sentence analysis: At the very least, some memory system is needed, one that keeps track of a “free” constituent which is encountered as parsing proceeds, so that later, when an appropriate position is identified downstream, a connection can be established between it and the memorized constituent⁵. It takes no more than a modicum of imagination to see how this constraint might emanate from the same system recruited for the *I*-back task, where an element must be stored and held in memory until an additional item is input, so that a comparison between it and the memorized one can be made. Moreover, a lesion to the system computing RM occurs in Broca’s area, the alleged anatomical locus of the temporary WM store.

1.4. *I*-back vs. 2-back in Broca’s Aphasia and normal WM

The similarity actually goes further. Violations of RM involve an element (*X* in (5b)) that interferes between another and an empty position (*Y* and *t* in (5b)). Reinterpreted in memory terms, RM might mean that a (moved) element will not be held in memory for later linking to a trace, if a like element is encountered on the way. Making the trace-antecedent connection is blocked in such cases. When other structural considerations are suppressed, this appears to be the very situation encountered in the 2-back task: Two positions (*r* and *R* in Smith & Jonides’ schema in (4)) must be matched across an intervening third (*m*). Aphasic patients, lesioned in LIFG, then, fail on an analog of a 2-back task. However, when asked to check a relation between two adjacent positions, namely, where requirements of case (6)-(7) or grammatical agreement (Spec-N or SV –

⁵ As Edwin Williams points out correctly, there are probably multiple WMs operating concurrently in sentence processing, for the analysis of sentences with multiple dependencies.

(8)) are violated, they readily detect these violations, where the relevant adjacent elements are bolded.⁶

(6) **They/*them were** chased by the police (Linebarger *et al.*, 1983)

(7) a. Seljak **obradjuje polje/*poljem**

The farmer is cultivating the field (ACC/*INST)

b. Seljak **trci polje/poljem** (*ACC/INST)

The farmer is running through the field (Lukatela *et al.*, 1988)

(8) a. *The banker noticed that **two customer** deposited the checks late

b. *The baker told the help that **the bread were** rising (Shankweiler *et al.*, 1989)

In all three judgment experiments, Broca's aphasics performed well, in contrast to their diminished abilities in judging RM violations (Mikelic *et al.*, 1995, present more relevant evidence). Performance, then, seems to drop rather sharply when Broca's aphasics move from the *1-* to the *2-back* task. This sharp drop would run contrary to the incremental nature of WM, had the story not had a twist: A careful reading of the neuroimaging literature reveals something special about the step from *1-* to *2-back* task: The change in intensity of reaction in Broca's area monitored for neurologically intact people – as observed in fMRI – is much steeper when one moves from a *1-back* to a *2-back* task than anywhere else in this setup. (Cohen *et al.*, 1997; see Jonides *et al.*, 1997 for the same result obtained in PET). This result is unexpected from the standard WM perspective. As Cohen *et al.* acknowledge, their conception of WM predicts that increased neural activity should be linearly related to increase in memory load. This is not the case⁷. The non-linearity of the reaction measured in Broca's area in the *2-back* task correlates with the deficit in Broca's aphasia, where sensitivity to RM, prohibiting interventions in movement, is compromised: This is precisely what one would expect after the destruction of an isolable component whose participation in processing is obligatory. Cohen *et al.* themselves consider the possibility that there is a qualitative difference between the *0-* and *1-back* tasks, and the *2-* and *3-back*, which may be responsible to the “the step function observed within PFC [pre-frontal cortex].” On this view, the *2-* and *3-back* tasks may “depend on the maintenance of information about the

⁶ I am aware of no data pertaining to sensitivity to case and agreement violations in non-adjacency, although these would clearly be a crucial test for this account.

sequential order of stimuli, whereas the θ - and I -back conditions do not.” (Cohen *et al.*, pp. 605-6). This comment brings the aphasia data immediately to mind, suggesting that the WM unit whose activity was monitored in LIFG for the 2-back task, is exactly the component wiped out by damage to Broca’s region that results in Broca’s aphasia.

The discussion has centered on results from grammaticality judgment in Broca’s aphasia. It is important to emphasize, albeit in brief, that the WM account works in a similar way for the broad array of comprehension results available for Broca’s aphasia. The patients fail to link a θ -role properly to a moved antecedent, and in most instances, there is another potential antecedent intervening between the trace and the moved element. A failure here, too, is what a 2-back disruption would predict⁸.

Similarities should not obfuscate important differences. The time course of sentence processing tasks and the n -back task are not the same: While in natural speech, words come in at a rate of about 3-4 per second, the n -back task is presented at a slow rate – some 2.5 seconds elapse between every two items. This difference, however, does not necessarily diminish the force of the similarity, as it is reasonable to assume that WM works more efficiently when harnessed to service sentence processing, aided and abetted by structural considerations that may help it operate faster than it does with lists.

To recapitulate, the idea is that dependency relations in sentence comprehension are computed by the same Broca’s area WM component probed by the 2-back task. Of yet, there has been no direct investigation of this hypothesis (whether in neurologically intact or aphasic subjects), but there are several results that might bear on it. Whether or not this WM component is on a par with the memory invoked to explain effects of difficulty in processing embeddings (e.g., Gibson, 1998) remains an open question.

2. Four constraining results

Let me now review more recent evidence from sentence-level tasks that might distinguish between a general, non-linguistic WM-based account, and a linguistic account that attributes the computation of movement to LIFG. It comes from error-inducing (comprehension and grammaticality judgment) tests in aphasia, and from somewhat

⁷ Cohen *et al.* cite another experiment which did not obtain the step function, but rather, monotonicity (Braver *et al.*, 1997). These results may be less stable than one would desire them to be.

⁸ One potential exception is passive, but there, too, an implicit argument, known to be active in Broca’s aphasia (cf. Balogh & Grodzinsky, 1999) may be the intervening potential antecedent.

parallel fMRI experiments that monitor regional activation in the healthy brain. Here is the logic behind these empirical endeavors.

Aphasia first: If Broca's aphasics suffer from a WM deficit, they would fail on tasks that involve the analysis of sentences with intra-sentential dependency relations, in which the distance between the two co-dependent elements is increased. Success and failure would only depend on distance (i.e., the number of interveners), and not on grammatical constraints. The syntactic account (TDH) says the opposite – syntactic movement, rather than distance, is the sole predictor of success and failure. The WM-related and a syntax-related account can be distinguished empirically: On the former view, the failure should be independent of the grammatical properties of the dependency, and would occur as long as the sequential properties make it on a par with the respective n-back task. On the grammatical view, by contrast, the deficit should be constrained to movement, so that sentences containing other dependency relations would not lead to a deficit, even if sequentially, the dependency relation at issue is on a par with an error-inducing n-back sequence. On this latter view, for example, aphasic patients would fail to detect violations of grammaticality in sentences in which an NP intervenes between a moved NP and its trace (violations of Relativized Minimality) not because they cannot link two non-adjacent positions in a *sequence*, but rather, because of the relevant grammatical constraint.

In fMRI in health, the logic is similar, modulo the dependent measure – regional activations that correlate with properties of stimuli. Precisely the cases for which the WM account would expect errors in aphasia are the ones that would lead to fMRI-monitored activations in Broca's region. The TDH, by contrast, would expect Broca's region to be activated only by sentences that contain movement.

Below, I briefly present results from error-monitoring experiments in aphasia, and Blood Oxygen Dependent Level (BOLD) response monitored in fMRI in health, which indicate that syntactic movement resides in Broca's region:

1. Grammaticality judgment of structures that contain violations of Relativized Minimality, in which Broca's aphasics fail to detect NP- and Wh-movement violations, but succeed in head-movement (Grodzinsky & Finkel, 1998).

2. Tests of comprehension, in which the distance (# of words) between gap and antecedent is parameterized. No effect of increased distance is observed for Broca's aphasic patients (Friedmann & Gvion, 2004).
3. fMRI tests of grammaticality judgment and comprehension in healthy subjects, in which movement activates Broca's region (Ben Shachar et al., 2003, 2004).

I proceed to show that, contrary to the expectations of the WM account, the deficit does not generalize to all dependency relations:

4. Tests of comprehension in Broca's aphasia, where the sentences contain a dependency relation but not movement. These are sentences with bound reflexives. The patients successfully comprehend these structures (Grodzinsky *et al.*, 1993).
5. Tests of grammaticality judgment in Broca's aphasia, where sentences contain a movement relation and/or binding. Broca's aphasic patients exhibit differential behavior (Santi & Grodzinsky, 2004, forthcoming).
6. fMRI tests that pit Movement vs. Binding. Movement activates Broca's region, thereby replicating previous results, and binding activates frontal regions in the right hemisphere (Santi & Grodzinsky, 2004, forthcoming).

2.1 Grammaticality Judgment in Head Movement

We begin by returning to the grammaticality judgment experiment discussed above. Recall that two sets of constructions from that study were presented: NP-movement (2) and Wh-movement (3). The patients performed rather poorly on both, unable to detect violations of grammaticality. One control was a set of sentences that contained head-movement, which in English involves auxiliary verbs (traditionally known as "Affix Hopping"). These were cases of the following form:

- (9) a. They could have left town
 b. **Could** they *t* have left town?
 └──────────┘

- (10) a. John **did** not *t* sit
 └────────┘
 b. John **has** not *t* left the office
 └────────┘

Observe that, similar to auxiliary movement in English is barred from crossing a like element – another auxiliary in this case, as evidenced by (11):

(11) a. ***Have** they **could** *t* leave town?
 └──────────┘

b. *John **did** not **have** *t* left the office
 └──────────┘

Rizzi (1990) has proposed that this type of movement, while different from the standard type in certain respects, also falls under the same generalization, and is constrained by Relativized Minimality. If Relativized Minimality is impaired in Broca's aphasics, or, alternatively, if a WM deficit impairs their ability to carry out 2-back tasks, a deficit in this set of structures is expected as well. Our test included the cases in (9)-(10), and their ungrammatical counterparts as in (11)⁹. The table in (12) shows, however, a sharp contrast between the patients' abilities in to detect violations of movement constraints in phrasal constituents (2)-(3), where they performed miserably, and their relative agility in detecting violations of head-movement (9)-(11):

(12)

<i>CONDITION</i>	<i>X' (% error)</i>
a. NP movement (2)	28.2
b. Superiority (3)	40.9
c. Auxiliary (9), (11a)	15.9
d. Negation (10), (11b)	13.4

Performance on (12a-b) was not different from chance, whereas performance on (12c-d) was well above chance; in addition, the two sets of conditions were significantly different from one another. Unlike movement of phrasal constituents, head movement is relatively preserved in Broca's aphasia. And, while certain analytic issues regarding these results need consideration that is beyond the scope of this presentation (cf. Grodzinsky & Finkel, 1998 for detailed discussion), two conclusions follow: First, this relation is distinct from phrasal movement at least at some level, a distinction that might have potential implications to generalizations such as Relativized Minimality (cf. Chomsky, 2000 for some discussion of this point). Secondly, this result leads to a reformulated TDH, that is, to a restrictive account of the involvement of Broca's region in the computation of dependency relations: It supports operations involved in establishing dependencies in which the antecedents are phrasal constituents (cf. Grodzinsky, 1995, 2000).

⁹ There was a set of controls that contained no movement, but violations of lexical requirements. Patients made less than 10% errors on these conditions.

Consequently, the LIFG WM is constrained by the grammar, permitted to engage only phrasal constituents. Head movement, while having the same geometric features as the rest of the cases from the WM perspective, has different grammatical properties, and is unaffected by damage to Broca's area¹⁰. The computation of this relation is therefore separate, and since it must rely on memory, we are forced to the conclusion that it is a memory of another type.

This view is more focused and precise than before, yet there it has an obvious missing part: Dependency relations typically involve an antecedent and a referentially dependent element. In the case of NP antecedents, the latter may either be a trace, or an anaphoric expression. The TDH contends that traces are involved. But does the deficit extend to anaphoric relations? An answer to this question will be given below. But first, we might examine the WM hypothesis from a different direction, that is, from the perspective of the linear distance between traces and their antecedents.

2.2. Parameterized distance between antecedent and gap

Friedmann & Gvion (2004) derived a clear prediction from the WM account: If the distance (i.e., the number of words) that separates a trace from its antecedent is increased, performance should be affected. Initial hints to that effect already existed (Schwartz, Linebarger, Saffran & Pate, 1987; see Grodzinsky, 2000, for discussion), yet Friedmann & Gvion conducted a systematic study, parameterizing the distance between traces and their antecedents. Their aphasic subjects were presented with Hebrew subject- (13) and object (14) relative clauses, while variable (2 to 9 words) trace-antecedent distance. Some examples are as follows:

(13) *Subject Relatives*

a) distance 2:

Ze **baxur**_i im zakan she-**t_i**-malbish et ha-xayal

This guy with beard that dresses Acc the-soldier

'This is a guy with a beard that dresses the soldier.'

b) distance 5:

Zo ha-**baxura**_i im ha-mixnasaim ha-xumim ve-ha-xulca ha-levana she-**t_i**-mexabeket

'et ha-yalda

This the-woman with the-pants the-brown and-the-shirt the-white that hugs Acc the-girl

'This is the woman with the brown pants and the white shirt that hugs the girl'

¹⁰ Interestingly, Wernicke's aphasics performed in a way that was hardly distinguishable from Broca's. See Grodzinsky & Finkel (1998) for discussion.

(14) Object Relatives

a) distance 2:

Ze ha-**baxur**_i she-ha-yeled tofes **t**_i

This the-guy that-the-kid catches

'This is the man that the boy catches'

b) distance 5:

Ze ha-**xayal**_i she-ha-rofe im ha-xaluk ha-lavan mecayer **t**_i

This the-soldier that-the-doctor with the-robe the-white draws

'This is the soldier that the doctor with the-white robe draws.'

The result they obtained was clear: the comprehension abilities of Broca's aphasics did not change with distance. That is, Subject-gap relatives were comprehended at above-chance levels, regardless of distance, and Object-gap relatives yielded chance performance. Friedmann & Gvion thereby replicated previous results to that effect (e.g., Grodzinsky, 1984, 1989), and extended them, lending further support to the TDH: We now know that increasing the distance (when distance is defined as the number of intervening words) does not affect comprehension, contrary to the prediction of the WM memory account.

2.3 fMRI Studies of Movement in Health

I reviewed evidence regarding the movement deficit in Broca's aphasia. Recent results from fMRI experiments in health complement the picture. The relevance of these experiments is clear: As pathological data show that Broca's area is critically needed for the calculation of Movement, the fMRI technique should monitor activation in this region as these operations take place in health. There are by now a number of such experiments, featuring several receptive tasks with sentence-pair stimuli. These studies evince a Blood Oxygen-Level Dependent (BOLD) response pattern that is unique to syntactic movement operations. I will briefly review one series of studies that presented healthy subjects minimal pairs of sentences, one involving syntactic movement, the other not *ceteris paribus*:

(15) ± Movement (other "complexity" held constant)

a. I told John that the nurse slept in the living room (–Movement)

b. *I helped **the nurse** that John saw ___ in the living room* (+Movement)

(16) ±Topicalization

a. Danny gave the book to the professor from Oxford (–Movement)

b. *To the professor from Oxford Danny gave the book ___* (+Movement)

(17) **±Wh-movement**

- a. The waiter asked if the tourist ordered avocado salad in the morning (–Movement)
- b. *The waiter asked **which salad** the tourist ordered ___ in the morning (+Movement)*

In all instances, activation was observed in left Broca’s region, and in Wernicke’s region bilaterally (Ben Shachar *et al.*, 2003, 2004). While the results above were obtained in Hebrew, similar effects have been observed in English (see Caplan, 2001), and in a variety of experiments in German (mostly from scrambling, Fiebach *et al.*, 2001; Friederici *et al.*, 2003, Röder *et al.*, 2001). These studies, then, provide further support for the TDH.

2.4 Comprehension of Reflexive Binding

A way to pit the TDH and the WM theories is to test the role of Broca’s area in processing dependency relations other than movement. Naturally, anaphoric dependencies are the first relation that comes to mind. In Grodzinsky *et al.*, 1993, we tested Broca’s aphasics on a variety of constructions involving binding relations in a sentence verification test. Relevant to the present context is their test of reflexives and their antecedents.¹¹ The stimuli were of the following form:

(18) *This is A. This is B. Is A touching herself?*

The preceding short sentences were put in to satisfy discourse requirements. Each sentence was presented twice, once along with a “Match”, a picture with two characters, A and B, where A was touching herself (correct response “yes”). A second presentation was along with the “MisMatch”, that had the same two characters, except now A was touching B (correct response “no”). Stimuli were mixed with others that contained pronouns (“her”) in the same positions, which counterbalanced the experiment.

(19) This is A. This is B. Is A touching herself?

<i>Match (%error)</i>	<i>MisMatch</i>	<i>X'</i>
19.4% (7/36)	8.3% (3/36)	13.89%

While the patients made multiple errors elsewhere, exceeding 50% in certain cases which are not currently relevant, they were almost error-free, and significantly above chance in the reflexive condition, as (19) shows.

Given this finding, one might be tempted to conclude that the deficit in Broca’s aphasia does not pertain to all dependency relations. Rather, it is restricted to movement,

as the patients' performance in antecedent-reflexive binding seems near-normal. Yet this conclusion is premature, as the result itself is less decisive than one would like it to be. First, as pointed out by Grimshaw & Rosen (1990), this type of experiment features a perfect correlation between the locality of a reflexive and reflexive action. On this view, all subjects have to do is associate the character who performs an action on herself with the antecedent in order to get at the correct answer. This criticism is testable, through the introduction of an additional response option in a picture that associates the reflexive action with a non-local antecedent. Such a test was carried out with children, who gave clear cut positive results, and demonstrated knowledge of the locality of reflexive binding (see Grodzinsky & Kave, 1994). With aphasics, however, this experiment was not conducted, leaving open the possible interpretation entertained by Grimshaw and Rosen. A second problem with this study is the number of antecedents and their position. Although there were two potential antecedents in each stimulus, only one of them (A) was intra-sentential. As a consequence, patients' ability to check binding with a local antecedent were tested, but not their ability to reject intra-sentential non-local ones. This makes the comparison between sentence-level tasks and the *n*-back task less direct.

These conclusions all set the stage to a set of experiments on binding relations and movement, which aimed at solving these problems, and providing a clear answer to the question above. I will sketch the theoretical context, and proceed to describe these experiments and their results briefly.

3. Experiments that Contrast Binding and Movement

3.1. Movement and Local Binding

A well-known syntactic puzzle, one which syntacticians love to pull out of their bag of tricks, documents a locality constraint imposed on the relationship between reflexives and their antecedents (20), and then proceeds to show how this constraint must be violated

(21):

- (20) a. [Pierre Likes himself]
b. *[Pierre likes herself]
c. Pierre believes[Natasha likes herself]
d. *Pierre believes [Natasha likes himself]

¹¹ Blumstein *et al.*, 1983, tested aphasics on pronouns and reflexives, but their study does not bear directly on the current issue. See Grodzinsky *et al.*, 1993, for discussion.

The examples in (20) suggest that a reflexive must have an antecedent (or must be bound) within its local domain – that is the explanation for the ungrammaticality of (15b,d), in which the (masculine) reflexive has either no antecedent within the sentence, or one that is too far – outside the parentheses (since the only potential local one is feminine). Yet observe how the judgments seem to be reversed in (21):

- (21) a. *Which heiress does Pierre believe likes himself
 b. Which heiress does Pierre believe likes herself

Sacrificing accuracy for simplicity of exposition, we will replace the notion “local antecedent” with “nearest potential antecedent”. Thus *Pierre* in (21), the nearest potential antecedent for the reflexive in (16a) cannot bind it, even though they are of the same gender, whereas in (16b) *which heiress*, not the “nearest potential antecedent” but rather the farthest one, must. This is exactly the opposite of (20): What appears nearest may not be; and what appears far behaves as if it is near. The result is an apparent paradox.

It is important to note that the fact that the sentences in (21) are questions is not the reason for this puzzle. That this is indeed so is shown in (22), which makes (20c-d) into questions without changing their grammatical status:

- (22) a. Which prince believes [Natasha likes herself]?
 b. *Which prince believes [Natasha likes himself]?

And yet, in the questions in (21) the situation is reversed. How can we find our way out of this paradox? In what sense is (21) different from (20) and (22)? As we have seen, saying that the sentences in (21) are questions is insufficient. What seems to distinguish (21) from (22) is that while in (21) the question is about *Pierre*, the subject of the main clause, in (22) it is *Natasha* – the subject of the embedded clause – that the question is asked about. This difference seems crucial, because sentences containing questions, as everyone knows, are said to contain a transformational relation between two positions – the extraction site and the site where the question expression is found. On this basis, we can annotate the sentences in (21)-(22) thus:

- (23) a. ***Which heiress_i** does Pierre believe [**t_i** likes himself]
 b. **Which heiress_i** does Pierre believe [**t_i** likes herself]
- (24) a. ***Which prince_i t_i** believes [Natasha likes himself]
 b. **Which prince_i t_i** believes [Natasha likes herself]

Now we see that the wh-antecedent in (23) changed its serial position relative to its declarative counterpart in (20), which is not the case in (24). A potential resolution of the puzzle in (20)-(21) thus looms large: Observe that the extraction site in (23), replaced by the silent category *t*, is now the closest NP to the reflexive (compare to (20)), and crucially, is closer than the overt NP (*Pierre*). Suppose the silent category counts as a potential antecedent for the reflexive. Suppose further that silent categories preserve the gender of their moved elements. The effects in (21) follow: Empty antecedents – traces – are subject to the locality constraint as in (20), hence in both cases (16a-b) they bind the reflexive. Now, the gender on the trace in (21a) is feminine but the reflexive is *himself*, and the mismatch results in ungrammaticality. In (21b), the opposite happens. In a sense, then, (21) is the apparent reverse of (20): What appears to be local is not; and what appears to be non-local is. And this is precisely what we sought to understand. We have accounted for the phenomena (though somewhat sketchily), and resolved the paradox.

3.2. Modularity: The Distinctness of Binding and Movement

The solution of the paradox is not without consequences, even for the extremely narrow range of facts we have considered. For there is another, more comprehensible and parsimonious way of stating the solution: To establish an intrinsic ordering between the two dependencies, and say that movement “takes place” *after* the locality constraint on reflexives and their antecedents is satisfied. On this view, the underlying (pre-movement) representation of (21) is (25):

- (25) a. *Pierre believes [**Which heiress** likes himself]
 b. Pierre believes [**Which heiress** likes herself]
- (26) a. ***Which heiress_i** does Pierre believe [*t_i* likes himself]
 b. **Which heiress_i** does Pierre believe [*t_i* likes herself]

Given this representation, the facts in (20)-(21) follow: Within the local domain, only a feminine antecedent can bind a feminine-marked reflexive to give a matching grammatical result. It is only after binding requirements are satisfied that movement applies, to yield (23), reproduced as (26). But for this view to hold, the two relations – binding and movement – cannot be the one and the same. They are ordered. They are also subject to different constraints. This implies distinctness. Thus, trace-antecedent relations, and the relation between reflexives and their antecedents, while sharing

important properties – both are structural dependencies among (potentially) non-adjacent constituents – cannot be reduced to one rule. Not all dependency relations in the syntax are one and the same. Obviously, more support is needed to make this conclusion compelling, but at the present context we will not go any further. For us, suffice to say that the standard linguistic view (for which more evidence can be adduced) is that movement and binding are distinct.

The contrasts we just saw are explained through the postulation of ordering of syntactic operations: Locality conditions of the binding of reflexives apply first, prior to extraction, and movement applies second. Advantage of this set of phenomena was taken, to investigate how processes that underlie these rule systems – how algorithms that implement them in language use – are represented in the language regions of the left cerebral hemisphere. I will try to show that the distinction between these two rule systems is reflected very clearly in brain structure, and explore the consequences of this result to the WM view of LIFG.

Recall that reflexives depend on another NP within the sentence for reference. Grammatical conditions determine whether this dependence is possible: First, the antecedent NP must be local; second, reflexive and antecedent must agree in person, gender and number; third, for a non-local NP to be a proper antecedent, it must originate in a local position, even if it moves later. In a sentence that has two full NPs and one reflexive, all these considerations apply: As long as there is an open path linking the reflexive to an NP antecedent, the sentence is grammatical.

The two sentence pairs in (27) contain the same NPs, and differ only in that their overt order is switched by a question in (c)-(d) relative to (a)-(b). Note that grammaticality is orthogonal: (a), (c), but not (b), (d) are grammatical:

- | | | |
|------|---|-------|
| (27) | a. [_{NP1} The woman] believes [_{NP2} the man] likes himself | “Yes” |
| | b. [_{NP1} The woman] believes [_{NP2} the man] likes herself | “No” |
| | c. [_{NP1} Which man] does [_{NP2} The woman] believe <i>t</i> likes himself | “Yes” |
| | d. [_{NP1} Which man] does [_{NP2} The woman] believe <i>t</i> likes herself | “No” |

Consider now how this paradigm works: In (22a), NP₁ – *the woman* cannot link to the reflexive due to excessive distance; NP₂ – *the man* – links to the reflexive as it is local and agrees with it in gender and number. Result: The sentence is grammatical; correct answer “Yes”. In (22b), NP₁ – *the woman* – cannot link to the reflexive due to excessive

distance; NP₂ – *the man* – cannot link to the reflexive due to an agreement mismatch. Result: The sentence is ungrammatical; correct answer “No”. In (22c): NP₁ – *which man* – though non-local, links to the reflexive through a double link: first, a local link between the reflexive and the trace of movement; second, a movement link from the trace to the NP. Agreement is satisfied; NP₂ – *the woman* – cannot link to the reflexive due to an agreement mismatch, as well as excessive distance. Although it is the closest overt NP, the trace, which counts as an NP for syntactic purposes, is closer. Result: The sentence is grammatical; correct answer “Yes”. Finally, in (22d), NP₁ – *which man* – a link between the (local) trace and the reflexive cannot be established due to an agreement mismatch. Thus, even though a second, movement link is established between the trace and the NP, the agreement mismatch remains and linking fails; NP₂ – *the woman* – cannot link to the reflexive due to excessive distance. Although it is the closest overt NP, the trace, which counts as an NP for syntactic purposes, is closer. Result: The sentence is ungrammatical; correct answer “No”.

3.3. The Experiment as a TDH-Related Task

We constructed a grammaticality judgment test of a set of cases, similar to those in (27), which contain a reflexive, two potential antecedents, and considerations of locality and movement enter into the determination of the grammatical status of sentences. The same sentences feature in two sets of conditions, featuring the two dependency relations for which we seek to characterize the aphasics’ abilities: Binding and movement. This set of cases allows for a direct comparison between the two dependency relations, hence an evaluation of the scope of the TDH. As stated, it predicts that only cases involving movement (22c-d) would cause problems to the patients, where (22a-b) would not, even though they contain a dependency relation, since this relation is not movement.

3.4. The Experiment as an *n*-Back Task

Now, consider the cases in (27) from a WM perspective, as discerned through the 2-back task: in (22a), a 1-back suffices to decide that the sentence is grammatical, because the nearest potential antecedent permits a grammatical reading. The situation changes, however, in the other cases: The sentence in (22b) can be deemed ungrammatical only after both potential antecedents had been examined, and rejected (each on different grammatical grounds). This requires both a 1-back and a 2-back comparison. In (22c), the

correct antecedent in the farthest, hence again, both a 1-back and a 2-back comparisons are necessary, but more importantly, perhaps, the determination of grammaticality presupposes the ability to carry out a movement analysis of this sentence. Finally, (22d) is rejected on a computational and knowledge bases similar to those that lead to acceptance of (22c). Thus, although all cases look the same serially, each pair (22a-b)/(22c-d) appeals to a different piece of knowledge, and requires, perhaps, a different set of structure-sensitive processes. If WM is involved in the aphasic deficit in a way that makes no structural distinctions, it is expected to make no distinction between binding and movement, since from a WM perspective, both seem to require the same processing resources. I will now briefly present results from two recent experiments that pitted the TDH against the WM hypothesis.

3.5. The Aphasia Experiment

We tested 6 Broca’s aphasics, all diagnosed on the basis of clinical neurological findings, neuroimaging, and the BDAE. Anatomically, they all had lesions that included Broca’s area. They all performed above-chance in comprehension of actives and subject relatives, and around chance on object relatives and passives. We tested them in a grammaticality judgment task, using a procedure that previous demonstrated is understood (and doable) by the patients (Grodzinsky & Finkel, 1998). Our test thus consisted of grammatical and ungrammatical instances of NP- and Wh-movement, all crossed with binding, where the violations always involved an incorrect gender on the reflexive. The question was whether or not the patients would be able to detect distant violations, and if so, would their ability be diminished by the presence of a trace. Thus the resulting structure of the test was as follows:

(28)	+Grammatical	– Grammatical
-MOV	a. It seems to Sally that the father rewards himself b. The man think that Mary likes herself	c. It seems to Sally that the father rewards herself d. The man think that Mary likes herself
+MOV	e. The father seems to Sally ◀ to reward himself f. Which man does Mary think [t likes himself]	g. The father seems to Sally ◀ to reward herself h. Which man does Mary think [t likes *herself]

We obtained very clear results (Santi & Grodzinsky, submitted): Broca’s aphasics were quite good at accepting grammatical sentences, and detecting violations (reflexive/antecedent gender mismatches) without movement. The presence of movement

diminished performance. Interestingly, right hemisphere damaged patients (n=3) were nearly at ceiling on all conditions.

3.6. The fMRI experiment

We also conducted an fMRI study with healthy subjects (Santi & Grodzinsky, submitted). The materials here were slightly different, reflecting constraints that are imposed by this technology. The sentences either contained Movement (MOV), or a Binding relation (BIND), or both. As the task was grammaticality judgment, each sentence types had an ungrammatical counterpart, leading to the design in (29):

(29)

a. -MOV-BIND	+GRAM	The girl supposes the cunning man hurt Christopher
	-GRAM	*The girl supposes the cunning man swam Christopher
b. -MOV+BIND	+GRAM	The girl supposes <i>the cunning man</i> hurt <i>himself</i>
	-GRAM	* <i>The girl</i> supposes the cunning man hurt <i>herself</i>
c. +MOV-BIND	+GRAM	<i>Which older man</i> does Julia suppose ◀ hurt the child
	-GRAM	* <i>Which older man</i> does Julia suppose ◀ swam the child
d. +MOV+BIND	+GRAM	<i>Which older man</i> does Julia suppose ◀ hurt <i>himself</i>
	-GRAM	*Which older man does <i>Julia</i> suppose ◀ hurt <i>herself</i>

Here, too, the results were clear: a Movement effect was obtained for the posterior part of left Broca's area (Brodmann Area 44), and for parts of left Wernicke's area. A \pm Binding contrast was obtained in distinct cerebral loci: First and foremost, deactivation for -Binding was monitored in the right Middle Frontal Gyrus; second, activation for +Binding was monitored in the left anterior portion of Broca's area (Brodmann Area 45), in a locus more anterior and markedly distinct from the one for which the Movement effect was recorded. While the Binding contrast is subtle and requires further thought and testing (cf. Santi & Grodzinsky, submitted, for discussion), its distinctness from the Movement effect is clear. Support for the TDH is obtained – Broca's area is Movement-modulated, and although it undoubtedly hosts certain WM mechanisms, there is a portion of it whose behavior is structure dependent.

4. Implications and remaining questions

4.1. A structure-sensitive WM

It is always difficult to convince people to cross disciplinary boundaries, which is what I tried to do in this paper. But if some preconceptions can be set aside, then linguistic and cognitive neuroscience can meet mid-way. Here, we seem to have gone a full circle: Beginning with a non-structural hypothesis, we ended up with a result that ties Broca's region strongly to grammar. We have identified a WM whose only role is keeping track of moved phrasal constituents. It plays a critical role in the processing of movement, but not other dependencies; and it makes contact with phrases, and excludes heads. Of the multiple memory systems required for sentence analysis in real-time, we seem to have isolated one which is located in LIFG, whose activity is manifest in 2- but not 1-back tasks in the intact brain.

This is a generalized, yet restrictive characterization of a WM, possibly one of many such devices. It should come as important news to linguists and cognitivists alike. For linguists, this is major corroboration from neurology to the view that movement is distinct from other dependency relations, and that head movement is to be set apart from the rest. Moreover, it is a demonstration that underlying syntactic mechanisms can be tapped in tasks that are outside sentential context. To cognitivists, this result sets a new constraint on WM, and shows how results from imaging studies converge on lesion data. Thus, not only does it cast a new spin on its character, but also suggests new ways of studying it.

4.2. Ruling out another Non-Structural Explanation

One seemingly possible explanation for the results of the BAM study relies on simple proximity. On this view (versions of which are known as the Minimal distance Principle (MDP) proposed by Chomsky, 1969 for children and espoused by Blumstein *et al.*, 1983 for aphasics, or more specifically as the Most Recent Potential Filler strategy (Frazier, Clifton & Randall, 1983), only the closest potential antecedent is checkable. If it cannot serve as an antecedent, the aphasic patient rules it out, without looking at more distant ones. This principle would account for the patients' performance on the single-antecedent cases, and for the cases of binding without movement (23a-b). In this latter set of cases, if the closest antecedent is not a potential binder, the sentence is indeed ungrammatical.

Yet, observe the prediction of an MDP-based approach for the binding plus movement sentences (28f,h), repeated below as (30). In these, the patients should always reject the grammatical case (30a), while accepting the ungrammatical (30b), because in the absence of considerations that pertain to dependencies, what matters is whether or not the closest potential antecedent, *the woman*, agrees with the reflexive. In (30a) it does not, hence the patients are expected to say “no” all the time, whereas in (30b) the opposite should occur:

- (30) a. [_{NP1}**Which man**] does [_{NP2}Mary] think [_{NPt}] likes himself “Yes”
 b. [_{NP1}**which man**] does [_{NP2}Mary] think[_{NPt}] likes herself “No”

Performance should thus be below chance in both cases, which does not happen. As the table in (31) demonstrates, Broca’s aphasics, while being above chance on the –movement cases (upper row), are around chance on both the grammatical the ungrammatical cases of movement (lower row):

(31) Movement vs. Grammaticality in performance (%correct, SD):

	+ <i>Gram</i>	- <i>Gram</i>	<i>X'</i> (±)
– MOVE	87 (8.23)	67 (16.36)	77 (16.25)
+ MOVE	66 (20.11)	53 (20.57)	57.5 (20.9)

4.3. Further Predictions

As a general point, it should be clear that the conclusions of this report have crisp and wide reaching predictions for normal functional imaging and for aphasia. Two cases come immediately to mind: a. Broca’s area is expected to be very active not just in *n*-back tasks, but also in tasks involving sentence processing with movement, but not binding; b. Aphasics are expected to fail the 2-back task. To judge by Smith and Geva’s report on digit span, this might be found.

It is time to note an important limitation of the foregoing discussion: It has ignored issues pertaining to hierarchical relations, and focused only on the sequential nature of dependencies in strings. Hierarchy, a central property of syntactic objects, must interact with WM in intricate ways. This, however, is beyond the scope of this preliminary report. I should just mention a few relevant constructions that need to be tested.

Two such cases (also relevant to the MDP) regard the contrast between hierarchically local but linearly non-adjacent binding of a reflexive, apparent in the case

of a complex NP binder (32). Another pertains to the complex issue of reflexives in double objects (33):

(32) An uncle of Mary's adores himself/*herself

(33) John showed Mary to herself/himself in the mirror

4.4. Processing Load and Broca's Area

Finally, the results speak to the notion of processing complexity in language. The non-incremental nature of the activity as monitored in neuroimaging devices, and more saliently, the sharp drop in performance in aphasia and the dissociation between performance on different types of dependency relations, casts doubt on the centrality of notions that make no direct contact with structure. The results thus show that conceptions of processing complexity, load, and capacity limitation, which have been introduced to describe the role of Broca's area in language (Just *et al.*, 1996, carpenter *et al.*, 2000) may be valid just in case they are equated with grammatical concepts (such as syntactic movement). That is, they must have a syntactic character.

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