VARIATION IN BROCA'S REGION: PRELIMINARY CROSS-METHODOLOGICAL COMPARISONS

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Your run-of-the-mill linguist, the one engaged in playing with syntactic principles and such, usually uses intuitions about grammaticality, ambiguity, synonymy, coreference and meaning as the stuff from which linguistic facts are carved. To many, these are *bona fide* biological phenomena: responses to grammaticality quizzes count as behaviors, we humans are organisms, biology is about behaviors of organisms (among other things), hence linguistics is biology. This in a nutshell seems to be the logic behind Chomsky's oft-cited saying that "linguistics is part of psychology, ultimately biology". Yet to non-linguists, or at least to those whose intellectual development was not strictly within the generative community, this view is somewhat difficult to digest. I am not even talking of die-hard radicals, for whom to think that language is part of our biology is to make a "category mistake"; I am thinking about the moderates, for whom the division between biology, psychology and linguistics is not a mere bureaucratic happenstance, an arbitrary division made by university administrators and librarians. Biology is about the "hard facts" of life on earth, they say, and language *per se* is not necessarily such a thing; thus for the field to count as a true part of life science, linguists must try harder.

It is in this context that *The Genetics of Language* conference was set, I think. But it is not the only backdrop. It was also set in light of seemingly "harder" empirical evidence, amassed over the past 30 years or so by psychologists, neurologists, and perhaps geneticists, that provides important hints that language is a truly biological entity, hints that come from varied, sometimes unexpected empirical angles. New approaches, novel experimental methods and advanced scientific instruments have yielded new sources of empirical evidence, which will, one hopes, not only play a central role in future linguistic theorizing, but also help bridge the gap between disciplines. In this brief paper I would like to go over a couple of such approaches.

I don't know much about genetics, but for a while, I've dabbled in representational and neural aspects of syntax. My comments will be thus confined to the neurological underpinnings of human syntactic ability. I will tell you in brief what we now know about these, and how we came to know it.

1. Modularity in Anatomy and Linguistics

Linguists often talk about the modular structure of linguistic theory. Jerry Fodor's monograph (1983) emphasized modularity as an issue in cognitive science as well. Less known is the long history of this concept in anatomy. Paul Broca – a founding father of aphasiology – was engaged in a fierce debate on this matter already in the 1860s. His (rather compelling) case for a distinct anatomical region for language, met a fierce opponent, Pierre Flourens, who put forth the argument that the brain makes neither functional nor structural distinctions (and who also beat Victor Hugo in a contest for a seat in the Académie Française). The notion they debated was quite similar to present day modularity, and like now, the debate was empirical in nature – both Broca and Flourens referred to pathological data, discussing the relation between selectively impaired behaviors of brain-damaged patients, and lesion sites as revealed by post-mortem operations. Broca observed selective loss of expressive language capacity subsequent to focal damage to the left frontal lobe (or more accurately, the foot of the 3rd gyral convolution thereof), to which Flourens retorted with counter-evidence (if somewhat dubious) to show that damage to other regions had similar consequences (cf. Zeki, 1993, ch. 2, for an insightful and amusing review). Later, John Hughlings-Jackson, Sigmund Freud and others from the French school (Hughlings-Jackson, 1878; Freud, 1895; cf. Kandel *et al.*, 2000, ch. 1, for a review) joined in, further promoting a "Holistic" view that permitted no distinctions among types of mental capacities and likewise denied the claim that brain areas specialize. For them, language was part of a general symbolic ability, which resided virtually everywhere in the brain.

This debate on Modularity marked the first round in a series, to be continued throughout the years to come. For just before the turn of the 20th century, the modularist position returned, this time from a micro-anatomical, rather than clinical, angle. Up to that time it was believed that the brain is not composed of cells, but is, rather, an undifferentiated part of the organism (at least at the microscopic level). Golgi devised new methods for the staining of neural tissue, which Ramón y Cajal used to produce the first microscopic evidence for the existence of basic building blocks – neurons. Without the Neuron Theory – a clearly modular notion, it is difficult to see how any physiological justification could be given to a modular theory of cognition. Brodmann subsequently carried out a microscopic morphological analysis of the brain, his findings further supporting a modularist position. He succeeded in distinguishing among cortical regions on the basis of differences in the spatial arrangement, density, shape and connectivity of cells within these regions. His

work culminated in a famous partitioning and numbering of the human cortex into cytoarchitectonically defined regions, as in Figure 1 (see Amunts & Zilles, 2001, for a recent review).
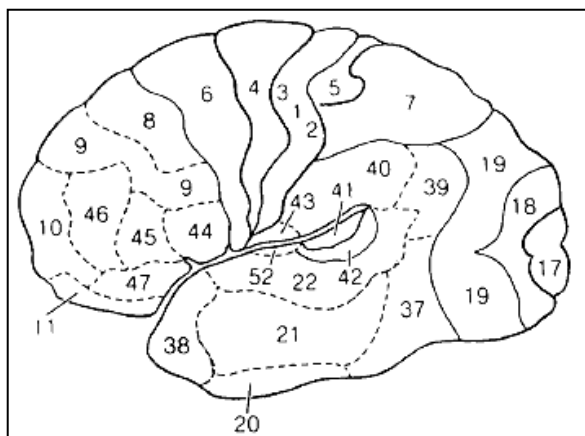

Figure 1: Brodmann's division of the left cortical surface into numbered areas (Broca's region is BA 44, 45)

Golgi, Ramón y Cajal and Brodmann are credited with much of the solid foundation on which current Functional Neuroanatomy is now based. Their ideas, methods, and speculations on functional divisions in cortex, and their views on structure/function relations, paved the way to current thinking. And still, this was not enough. The compelling empirical evidence these anatomists presented did not suppress the opposing view, championed by Karl Lashley (e.g., 1951). On the contrary, the anti-modular position, that language was nothing special – a mere reflection of a general sequencing skill – prevailed for most of the 20th century in both psychology and neurology (hints of it can still be found in current textbooks).

Yet since the 1960s, it was becoming increasingly clear that Broca was right: language (or at least important parts thereof) lives in the left hemisphere (see Geschwind, 1965). The main source of evidence was lesion data – mostly aphasic deficits. Geschwind, reiterating Broca, Wernicke, and Lichtheim (cf. Lichtheim, 1885, for a famous presentation) claimed that language centers exist. As clinicians, he and his followers emphasized communicative skills, viewing language as a collection of activities, practiced in the service of communication: speaking, listening, reading, writing, naming, repetition, etc. The characterization of the language centers derived from this intuitive theory, as a cerebral center per activity is posited. The resulting theory of localization uses these activities as building blocks, taking them to be the essence of human linguistic capacity (cf. Geschwind, 1979, Damasio, 1992 for clinical perspectives).

2. From Neurology to Neurolinguistics

The birth of a sub-discipline is not just an intellectual, but also a social event, and should be reported as such. It is difficult to grasp the evolution of neurolinguistics outside its historical context, and it is for this reason we should approach current thinking as an interim ending of an ongoing historical tale. So, the appearance of modern linguistic theory did not pass unnoticed. Inspired by *Zeitgeist*, psycholinguists in the 1970s began using theoretical and experimental tools borrowed from linguistics and psycholinguistics (e.g. Blumstein, 1972; Zurif & Caramazza, 1976). Not denying the relevance of activities humans engage in during communication, they began devising experiments that focused on linguistic distinctions that emanate from the

new theoretical apparatus. Language was now seen as a piece of knowledge *about* structure, one that is organized in distinct components. The new experiments were fashioned accordingly: they aimed to test aphasics' abilities in phonology, morphology, syntax, and semantics. Soon thereafter, new findings were obtained, indicating that the brain distinguishes between types of linguistic information. These results could not be couched in the activity-based view, and the centers had to be "redefined" (Zurif, 1980): Each anatomical center was now said to contain devices used for the analysis and synthesis of linguistic objects. Roughly, Broca's region (Brodmann's Area BA 44,45,47, see Fig. 1) was said to house syntax (for both receptive and productive language), while semantics was to reside in Wernicke's area (BA 22, 42, 39). This shift marked a new kind of debate: while earlier ones were about Modularism vs. Holism, at issue now was the proper unit of analysis of brain/language relations.

Yet as findings accumulated – from different tasks, languages, stimulus types, and laboratories – new contradictions began to surface: in some cases, Wernicke's aphasics showed syntactic disturbances; Broca's patients, on the other hand, while failing certain tasks that probed syntactic abilities, succeeded in others. Serious doubts were cast on the new model, in which Broca's (but not Wernicke's) area supports receptive syntactic mechanisms. Finer linguistic concepts had to be introduced. At long last, linguistics and neuroscience were beginning to come closer, and harbingers of a new discipline – Neurolinguistics – were appearing, with the goal of mapping linguistic abilities onto cerebral cortex in a manner that takes linguistic theory as a central tool to describe behavior; at the same time new methods, techniques, and concepts to study the brain were put to use. The next section briefly reviews the main sources of neurological evidence that are currently available.

3. A Quick Typology of Experimental Neurolinguistic Arguments

3.1. Lesion/aphasia studies through the measurement and analysis of errors: focal brain damage may selectively impair the linguistic system, and the resulting pattern of impairment and sparing may be gleaned from linguistically-guided investigations into the patients' aberrant language behavior. Impairment to a particular rule system is isolated and linked to the damaged brain region. This is the "new localization" of grammar in the brain. Conversely, the lesion-based method provides an insight to the way the brain carves out linguistic ability, thereby providing critical neurobiological information as to the internal structure of linguistic rule systems.

Since Roman Jakobson's famous study (1941) of language deficits in childhood and aphasia and the their implications to phonological theory (see Grodzinsky, 1990, ch. 6, for a reconsideration), a number of linguistic claims have been made, based on aphasia data (in phonology, Blumstein 1972; in morphology, Badeker & Caramazza, 1998; in syntax, Avrutin, 2000; 2001; Friedmann, 1994, 1998; Grodzinsky, 1984; 1990; 2000a; Grodzinsky *et al*., 1993; Lonzi & Luzzatti, 1993). These works have also benefited from studies of the (deviant) time-course of sentence comprehension in aphasia (cf. Shapiro *et al*., 1993; Zurif, 1995 for prominent examples).

3.2. Electrophysiological correlates of cognitive activity through ERP and MEG: cognitive activity has certain electrophysiological reflexes, monitored by EEG, or by changes to the magnetic field that these reflexes induce. This type of response can be evoked (ERP) and investigations have linked certain patterns to specific types of stimuli. Distinctions among types of phonological and syntactic information are found

in both time and space. MEG experiments, for example, have shown that phonological analysis takes place remarkably early on. Phillips *et al*. (2000) used MEG to record brain activity while subjects were listening to a "phonetic" versus a "phonological" condition. A finding of an all-or-nothing property of phonological category membership, as opposed to phonetic stimuli, indicated that early analytic processes operate over discrete categories.

In ERP studies of syntax, electrophysiological response is typically recorded while subjects listen to ungrammatical strings that contain violations of different syntactic principles. Recorded brain responses differ in direction (positive vs. negative), timing (200, 400 or 600msec after stimulus presentation), and general location in space (as mapped by scalp electrodes), thereby making the dissociation of syntactic processes possible. While the spatial localizing value of this method is relatively low, its temporal resolution is remarkable, and has led to the discovery of important distinctions among syntactic rule types (Neville *et al*., 1991; Kluender & Kutas, 1993; Fiebach *et al*., 2002).

3.3. Blood Oxygenation Level Dependent (BOLD) signal as monitored in PET and fMRI: Brain regions engaged in cognitive activity demand higher oxygen levels, increasing blood flow into these regions (albeit with some delay). Change in blood flow is detected by advanced instruments: fMRI measures minute changes in magnetic field that increased blood flow causes; when molecules with unstable isotopes are injected into the circulation, PET can detect their radioactive mark in cerebral areas in which their concentration increases due to oxygen demands. These techniques provide good spatial (but poor temporal) resolution, and the experimenter can carry out comparisons between stimulus types in terms of the location and intensity of the signal they evoke. Syntactic stimuli of various sorts can be thus investigated (Just *et al.*, 1996; Stromswold *et al.*, 1996; Embik *et al*., 2000; Ben Shachar *et al*., in press; Röder *et al*., 2002).

Below I present two neurolinguistic arguments in some detail, and describe some interesting problems that ensue, each presented with an outline of a solution. I focus on cross-linguistic deficit analyses in aphasia, and on recent studies in the functional imaging of syntax, in an attempt to seek convergence among seemingly disparate sets of findings. I argue that the two methodologies produce highly consistent results, all leading to the conclusion that the Left Inferior Frontal Gyrus (LIFG, also known as Broca's region) is critically involved in the computation of phrasal movement in receptive language.

4. Damage to LIFG Results in a receptive Deficit to XP-movement
4.1. Trace-Deletion: The Basics
Left Broca's region is topographically the triangular and opercular parts of the left inferior frontal gyrus (LIFG), or Brodmann's areas (BA) 44,45, respectively (see Fig 1). Focal insult to the vicinity of this region impairs linguistic ability in highly specific ways. The aetiology of this condition may be stroke, hemorrhage, protrusion wound, tumor or excision of tissue. Work carried out in many laboratories, through varied experimental methods and on several languages, has indicated that the receptive abilities of Broca's aphasic patients in the syntactic domain are compromised in that they are unable to link traces to (phrasal) antecedents, whereas other syntactic abilities remain intact. The various formulations of this claim have become known as the Trace-Deletion Hypothesis (TDH, Grodzinsky, 1984; 1986;

1995; 2000a). The basic observation has been that Broca's aphasics suffer comprehension difficulties only when phrasal movement takes places, that they fail to determine the grammatical status of sentences once traces are critically necessary, yet that they are quite successful in both comprehension and judgment of other constructions. When asked to match sentences to pictures in a binary choice experimental design (i.e., on tasks that require the matching of 2 arguments in a sentence to 2 actors in a scene, which amounts to a θ-role assignment task), their performance on the structures in (1) is at chance level (as measured by tests that consist of 10-20 trials per construction type), yet they are well above chance in comprehending the controls in (2), whose representations contain no movement (for the moment, I ignore movement of the subject from [Spec,VP] to [Spec, IP] and other string vacuous movement; see below; see also Grodzinsky, in preparation a). Further, their ability to link reflexives to their antecedents is intact; they also correctly rule out the binding of a pronoun to a local antecedent (3) (except when the antecedent is an R-expression, hence subject, perhaps, to constraints that go beyond the binding conditions, as well as beyond the scope of this paper, see Grodzinsky *et al.*, 1993), indicating that their deficit is restricted to movement (and is not a result of a generic "working memory" deficit, or an overall linking failure, e.g., Caplan & Waters, 1999). Also, upon being asked to judge the grammaticality of sentences as in (4), they vacillate. Thus, they fail to consistently accept the (i) cases, and conversely, to detect the ungrammaticality of the (ii) cases – violations of *SuperRaising, that-trace*, and *Superiority* (4). By contrast, they are quite agile when request to determine the grammatical status of constructions whose status does not depend on traces of XP-movement (5). Finally, they successfully determine the status of constructions that involve head-movement (6) (Grodzinsky & Finkel, 1998; see Lima & Novaes, 2000 for a replication in Brazilian Portuguese).

Chance comprehension
(1) a. The man that the woman is chasing is tall
    b. Show me the man who the woman is chasing
    c. It is the man that the woman is chasing
    d. The man is chased by the woman
Above-chance comprehension
(2) a. The woman who is chasing the man is tall
    b. Show me the woman who is chasing the man
    c. It is the woman that is chasing the man
    d. The woman is chasing the man
(3) a. This is Goldilocks. This is Mama Bear. Is Mama Bear touching herself?
    b. This is Goldilocks. This is Mama Bear. Is every Bear touching her?
Failed Determination of Grammatical Status
(4) a. (i)   John seems likely to win
      (ii) *John seems that it is likely to win
    b. (i)   Which woman did David think saw John?
      (ii) *Which woman did David think that saw John?
    c. (i)   I don't know who saw what
      (ii) *I don't know what who saw
Successful Determination of Grammatical Status
(5) a. (i) Who did John see?   (ii) *Who did John see Joe?
    b. (i) The children sang   (ii) *The children sang the ball over the fence
    d. *The children threw   (ii) *The children threw the ball over the fence

(6) a. (i) Could they have left town? (ii) *Have they could leave town?
    b. (i) John did not sit   (ii) *John sat not

This pattern of performance is rather intricate. The TDH claims that traces of XP movement are deleted from the patients' representations, receiving independent support from on-line processing investigations (cf. Zurif, 1995). Note that all traces are referred to in the traditional way, and that considerations pertaining to the copy theory of movement are suppressed (Chomsky, 1995; Bobaljik , 2002; Fox, 2002). On the cases thus far tested, the two approaches are indistinguishable. Thus, rather than dwell on this mater, I will focus on the central, robust result – a movement failure, which cuts across construction types, tasks, laboratories, and languages.

4.2. Mapping Representations onto Performance
Assuming trace-deletion, albeit limited to XP-traces, predicts the pattern of success and failure that the patients exhibit in grammaticality judgment: they fail when an ability to represent traces of XP-movement is critical (4), and succeed in detecting other violations (5)-(6). Yet, in the domain of comprehension, trace deletion does not predict the data. Such results cannot follow from linguistic distinctions in the usual way, because a syntactic distinction cannot in itself map onto performance level in an experiment that is aimed to detect errors. Thus, an explicit mapping from structural deficiency to behavior (=error rate) is necessary, in the form of a set of premises from which actual performances can be deduced. Mere trace-deletion, then, does not elucidate the chance performance on the constructions in (1). Moreover, as already noted, the patients' success in constructions that involve the movement of the VP-internal subject to [Spec, IP] is also left unaccounted for. Hence additional tools are needed, from which this intricate pattern would follow. As θ-assignment is the main task used in the above experiments, the solution derives the patients' aberrant performance from abnormal thematic representations they are said to possess. The main idea is to say that chance performance in a binary choice θ-selection task actually follows from a θ-conflict. That is, the patient is receiving thematic information that indicates that both NPs in the sentence have the same θ-role, and hence can each be matched to any of the actors in the sentence. The task of the theoretician, then, is to specify the conditions that would bring about this representation. I.e., to create a situation in which the patient has to decide on agent and patient, yet in his or her mind, both candidate NPs are linked to the same θ-role. This situation should lead to a θ-conflict, which would lead to guessing on the task at issue. We might want to characterize the desirable scenario a bit more generally: Guessing behavior might follow when any 2 (potentially different) θ-roles were assigned to 2 NPs in a sentence, as long as both θ-roles are on a par on some universal thematic hierarchy. Here is how this result is obtained.

        The interpretation of moved constituents depends crucially on traces; without traces, the semantic role of a moved constituent cannot be determined. Under the TDH, moved constituents (*italicized* and **bolded** below) are uninterpretable. Assume that in such a situation, a non-linguistic, linear order based cognitive strategy is invoked, in an attempt to salvage those uninterpreted NPs. The strategy links θ-roles to (θ-less) serial positions thus: <NP_1=agent; NP_2=theme>. In English, the strategy will force moved constituents in a clause-initial position to be agents: They are moved, hence linked to a trace; trace-deletion hinders θ-assignment, and these NPs fall under the scope of the strategy. The idea is to view aphasic sentence interpretation as a composite process – an interaction between an incomplete (traceless) syntactic

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representation that may lead to a partial thematic representation, and a compensatory cognitive strategy. In certain cases, for example, subject questions (7) or subject relative clauses (8), the default strategy should compensate correctly for the deficit:

(7) a. **Which man** *t* touched Mary?   *Above chance*
     b. **Which man** did Mary touch *t*?   *Chance*
(8) a. **The man** who *t* is touching Mary is tall   *Above chance*
     b. **The man** who Mary is touching *t* is tall   *Chance*

In the subject relative (8a), the object of the relative clause (*Mary*) is assigned the theme role without the mediation of a trace. The head of the relative (***the man***)*,* is moved, and receives its semantic interpretation (or thematic role) via the trace. A deleted trace render this process impossible in Broca's aphasia. Thus only the object ends up with a grammatically assigned role; to save the uninterpretable subject of the relative (***the man***), the strategy is invoked, assigning it the agent role. This interaction between (deficient) grammar and (non-grammatical) strategy yields the correct semantics: NP_1(***the man***)=agent by strategy, and NP_2(***Mary***) =theme by the remaining grammar. The same considerations hold of *which* subject questions (7a). By contrast, the TDH system predicts error in the object question (7b) and relative (8b): In these cases, an agent role is assigned to the subject of the relative or question (*Mary*), yet another agent role is assigned by the strategy to the moved object (acting subsequent to trace-deletion). Now the interaction between grammar and strategy gives rise to a misleading representation: NP_1(***the man***)=agent by strategy, and NP_2(***Mary***)=agent by the grammar. The result is a semantic representation with 2 potential agents for the depicted action, which predicts guessing behavior.

These assumptions lead to predictions that are borne out, confirmed once experiments are set up correctly so that they satisfy discourse requirements (although some of the data have been ignored here, for the sake of simplicity and focus, cf. Hickok and Avrutin, 1995; Grodzinsky, 1989). The TDH thus captures the selective nature of the comprehension deficit in Broca's aphasia.

We have ignored movement of subjects from [Spec,VP] to [Spec,IP]. Consider now a schematic solution to this problem: as the subject does not change its linear position relative to other major constituents in the string (at least in the cases for the data reviewed), the strategy compensates correctly, and above chance performance in active sentences is expected, as is indeed the case. A broad range of experimental results is derived, and with it a conclusion: Broca's region is critically involved in the representation of traces of movement.

4.3. Cross Linguistic Variation
It may be important to show that the comprehension problem in Broca's aphasia is not tied to a particular construction type (object relative, object question, passive, etc.), but is rather best accounted for by a to trace deletion cum default, i.e., the TDH. To show that, we bring up 3 arguments: 1. We show that despite their success in comprehension tasks with subject relatives (due to their use of the default strategy), there are tasks in which their problems surface, namely such tasks in which the strategy is of no use, or cannot be invoked. This is observed in real-time processing tasks. 2. We show that aphasics have comprehension problems in subject relatives in languages whose phrasal geometry is different from English.

Consider real-time processing in the healthy brain. It has long been known that neurologically intact subjects access the antecedents to traces at the gap position in real-time. This is demonstrated by Cross-Modal Priming tests, in which subjects listen

to sentences such as (9a), and watch a screen, onto which a visual probe of the types in (b-d) may be projected at points 1, 2 or 3 in the sentence. Their task is to make a lexical decision on the visually presented item:

(9) a. The passenger smiled at **the baby**[1] that the woman[2] in the pink jacket fed[3] __
     at the train station
    b. Diaper (related)
    c. Horse (unrelated)
    d. Strile (non-word)

At position (*1*) – immediately after the prime – access to the related target (9b) is obviously facilitated, and reaction times are shorter; at position (*2*), there is a decay to this effect, yet surprisingly, at (*3*), there appears to be facilitation – the prime gets reactivated at the gap position (Love & Swinney, 1996).

     When Broca's aphasics perform this task, they do not show normal priming at the gap (Zurif *et al*., 1993). This is in line with the TDH: If traces are deleted, they should not facilitate access to antecedents at the trace position. With that in mind, we can look at subject-gap relatives. If comprehension of such structures is intact, traces in subject position should be reactivated, and the normal reaction-time patterns should follow; otherwise, in this case, too, performance should be aberrant. Indeed, Broca's aphasics evidence abnormal performance in this case, indicating that their impairment is not construction-specific.

With this in mind, we can now move on and consider languages whose structural properties differ from English in ways that interact with the deficit in Broca's aphasia. Results obtained from a variety of language types lend support to the TDH in a surprising way. Consider Chinese, an otherwise SVO language, where heads of relative clauses (annotated by the subscript **h**) follow the relative (10a), (11a), unlike English in which they precede it (10b), (11b):

(10) a. [*t* zhuei gou] de **mau**$_h$ hen da   *Chance*
       chased dog that cat very big
    b. **the cat**$_h$ that [*t* chased the dog] was very big   *Above chance*
(11) a. [mau zhuei *t*] de **gou**$_h$ hen xiao   *Above chance*
       cat chased that dog very small
    b. **the dog**$_h$ that [the cat chased *t*] was very big   *Chance*

This structural contrast leads to a remarkable prediction regarding performance in Broca's aphasia: Opposite English/Chinese performance patterns are expected. In English subject relatives, (repeated as (10b)), the head of the relative (*cat*) moves to the front (for concreteness, I assume a head-internal analysis of relative clauses, yet the analysis could be recast in other terms as well), lacks a role by the TDH, and is assigned agent by the strategy, which leads to a correct representation in which the cat indeed chases the dog. In Chinese (10a), the head (*mau*) also moves, yet to sentence-final position, and the linear strategy assigns it the theme role. This representation has now two themes (*dog* and *cat*), and guessing follows. Similar considerations hold in object relatives (11a-b), and are left to the reader. This prediction is confirmed: The results in Chinese are a mirror-image of the English ones (Grodzinsky, 1989; Su, 2000; Law, 2000). The mirror-image results correlate with a relevant syntactic contrast between the two languages – the position of the relative head. The *θ*-conflict now becomes a generalization, deriving chance performance from an agent/agent conflict in English relatives, and from theme/theme conflict in Chinese.

Further intriguing cross-linguistic contrasts exist as well. Japanese scrambling, for example, results in 2 configurations:

(12) a. *Taro-ga Hanako-o nagutta*   ***Above chance***

        Taro hit Hanako

        Subject Object Verb,

     b. ***Hanako-o*** *Taro-ga **t** nagutta*   ***Chance***

       Object Subject *t* Verb.

As expected, Broca's aphasics are above-chance in comprehending (12a), and at chance level on (12b), in keeping with the TDH (Hagiwara & Kaplan, 1990). This result is robust, supported by a host of replications: it has also been obtained in Hebrew (Friedmann, 2000), Spanish, Korean (Beretta *et al*., 2001) and German (Burchert *et al*., 2001). These results are important: they indicate that scrambling and cases of XP-movement form a neurological natural class. Below, some neuroimaging results to the same effects will be discussed.

Further cross-linguistic contrasts are also documented. Passive, for one, does not always generate chance performance: Dutch aphasics by and large perform above chance (e.g., Friederici & Graetz, 1987). The TDH has been recently modified to account for the difference between the English and the Dutch patients' performance on this construction, a modification that carried over to account for some other related phenomena (Grodzinsky, 2000b). I will not dwell on this matter here.

4.4. Individual Variation and Quantitative Syntax

The broad cross linguistic data coverage, and the variety of constructions handled by the TDH, do not resolve a nagging problem – that of individual variation. It has been the perception in aphasiology, that replication of comprehension test results is difficult. It has been pointed out that the evidential basis claim to support the TDH is shaky, because most experimental results cited above are non-replicable: Performances on passive have been found to vary greatly among patients in different studies, ranging from 30 to 100 percent correct; likewise, comprehension levels on actives have varied from 50-100% (Berndt et al., 1996). These observations have been used in support of the claim that Broca's aphasia does not characterize a homogeneous group, and should not be studied as such (Caramazza *et al*., 2001).

These claims are important. If the data are as dispersed as they appear, we should be very worried: That is, if behavioral aberrations among patients with the same lesion location vary arbitrarily, then there must be something fundamental that we are failing to understand about brain/behavior relations. We better check our basic assumptions, or try to devise new methods that would expose the reasons for the variation that is presumably observed. Perhaps we can find the right distance from which one must view these phenomena to discern regularity.

My colleagues and I embarked on a two-pronged investigation, which I will briefly describe (see Grodzinsky, in preparation b, for details). First, we critically reviewed past replication failures for test design, patient diagnosis, test administration, and data analysis (Zurif & Piñango, 1999); in parallel, we devised a new quantitative approach to syntactic error analysis (Grodzinsky, Piñango, Zurif & Drai, 1999), in an attempt to understand the variation.

The first issue that needed to be tackled is that of patient selection. As there are several aphasic syndromes, patients must be selected. In the absence of theoretically motivated diagnostics, the efficacy of a selection procedure can only be evaluated after the fact. The proof of the pudding, that is, is in the eating: So, while standard clinical selection procedures may not always be done on theoretically

principled ground (as Caramazza, 1984, has correctly argued), do seem to work. The study of clinically diagnosed Broca's aphasia, for one, seems to have produced consistent results across patient groups, laboratories, experimental approach and language. We thus used the Boston Diagnostic Aphasia Examination (Goodglass & Kaplan, 1983) or corresponding measures as the basic selection tool.

Next, we turned to patients' errors. Careful error analysis can discern robust patterns only in fairly large datasets. Complex logistics typically restrict aphasia experiments to small sample sizes (in terms of both number of subjects and trials per subject). We thus collapsed many studies together, charting construction type by percent correct in binary choice designs as detailed above (recall that the task is 2-arguments-to-2-actors matching, or a θ-selection task, hence it is binary; recall also that each construction type has 10-20 tokens, hence the data come in the form of percent or proportion correct per construction type). Above chance performance means being near perfect; chance scores are equivalent to the scores of an unbiased coin that is tossed n times, n the number of trials (=token sentences) per patient. A sample of k series (=patients) of n tosses (=responses), plotted as a frequency curve, should yield a normal (or binomial on certain assumptions) distribution, with a mean $\mu=n/2$. In our case, a *# of patients* by *% correct* graph should yield a Gaussian with $\mu=50\%$. The results of our compilation (currently consisting of scores for $k=77$ Broca's aphasics) are rather striking. Figure 2 contains frequency curves for aphasics' performance on 2 groups of constructions, arranged by the performance level that the TDH attaches to them. The broken line plots the performance levels of aphasic speakers of several languages on constructions that the TDH predicts to be above chance – actives, subject relatives, subject questions, subject clefts etc. (ac-TDH items). The black line plots the rest: verbal passives, object relatives, object questions, object clefts, scrambled actives (in German, Spanish, Hebrew, Korean) and some more – all yielding at chance performance levels (c-TDH).
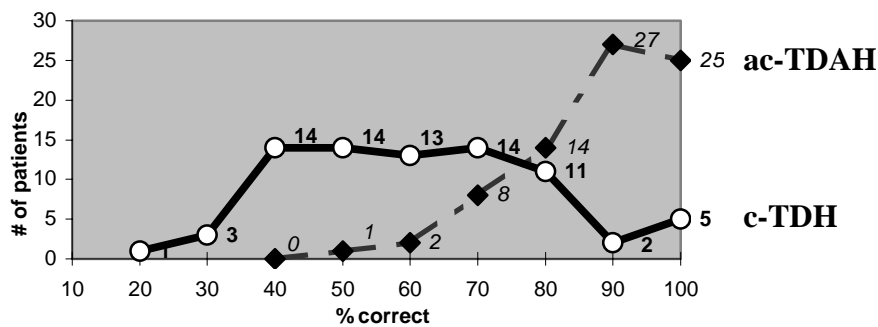

Figure 2: Frequency curves for the comprehension
performance of 77 Broca's aphasics on 2 groups of structures

The broken line ($\mu=84.1\%$) contains individual scores that are mostly over 80% correct (66/77 patients), that is, the patients are well above chance. The full line ($\mu=57.6\%$) tells a different story: Most scores (55/77) are 40-70% correct. Statistical analysis indicates that the two curves are significantly different from each other, and that the full curve is not distinguishable from chance (the broken line is, of course, see Drai & Grodzinsky, 2000a). We may now be coming close to understanding why the shapes of the 2 curves are so different, and why the range of variation on the c-TDH structures is greater than the ac-TDH items: The latter approaches 100% quasi-asymptotically, while the former appears to have a bell-shaped distribution, with a mean around 50%, thereby reflecting chance performance, meaning that the patients behave as if they toss a coin before responding. If this is true, then the TDH is

vindicated, as this is precisely what it predicts. But we are not there yet: the precise shape of the c-TDH curve needs to be studied numerically. We thus embarked on a more detailed study of the properties of this curve.

As noted, there was in fact an independent motive to our investigation: The seemingly broad range of variation documented by the c-TDH curve has given rise to claims that it actually reflects a *mixed* group of performances, hence a non-uniform collection of subjects. The patients that were pooled together, on this view, do not suffer from the same illness, and as such cannot be considered a group (Caramazza *et al*., 2001). A numerical study of our curve enables an empirical test of this claim: We can now ask whether the distribution it describes has a single mode or is, rather, multi-modal. Unimodality would indicate a single group of performances; multi-modality would open way to other interpretations, perhaps along the line of Caramazza *et al*.'s proposals – that the patients exhibit a mixed bag of symptoms, one of which is their performance on these constructions, and hence they can be grouped according to the different types of performance patterns they exhibited. To decide between these possibilities, a formal test is necessary. What is needed, then, is a method that determines whether a graph represents one group or more. Yet, as any *n*-modal Gaussian curve can be described as consisting of *n+1* components (=modes, or groupings in the data), the question is not whether a move from an *n* to *n+1* modes is possible, but rather, whether it is *justified*. As basic scientific principles always call for maximal generalization, *ceteris paribus*, the increase in the number of modes (components) that an empirical curve is analyzed into must be done for a reason. In the present case, the reason could be empirical, that is, if numerical tests would indicate that an (*n+1*)-modal curve provides a better approximation of the data than an *n*-modal one.

To determine that, we used a Gaussian Mixture Model analysis. This method starts off by checking whether the best approximation to a curve is a unimodal Gaussian, and does so by moving up: The actual number of components of a model is determined by comparing the maximum likelihood value of an *n+1*-components mixture with that of an *n*-component mixture, until the increased number of components ("peaks" in the curve) increases the likelihood only marginally. When that happens, the addition of another mode is spurious. We carried out this analysis with an Expectation Maximization algorithm, borrowed from electrophoresis, and developed by Dan Drai for the analysis of rodent exploration of 3D-space (Drai, Benjamini & Golani, 2000). Our calculations showed that the addition of a mode to a unimodal curve (a move from 1 to a mixture of 2 Gaussians) in our case was spurious (improvement in fit of this addition being insignificant – $p < .51$). The patients constitute a single group (read: syndrome), and their performance is uniformly at chance, in keeping with the TDH. Performance variation in Broca's aphasia is apparent, not real.

4.5. Summary
Before concluding, it should be noted that there are other aspects of aphasia other than trace-deletion, where patterns of impairment and sparing interact with theoretical issues in interesting ways (e.g., Friedmann, 1994; 1998; Friedmann & Grodzinsky, 1997; 2000 on split inflection; Grodzinsky, 1984; Grodzinsky, Pierce & Marakovitz, 1991 on the representation of passive; Grodzinsky *et al*., 1993 on the formulation of Condition B; Lonzi & Luzzatti, 1993 on verb movement; Hickok & Avrutin, 1995 on D-linking and chain types; Avrutin, 2000 on DRT).

Returning to the main, there are three ideas that pertain to the mapping from deficient syntactic representation onto performance rates in experiments that measure errors, and collude to yield a uniform account of the receptive patterns in Broca's aphasia: 1. Traces are deleted; 2. θ-assignment to moved NPs is augmented by a linear strategy; 3. Deviations from the expected pattern follow from the nature of chance-level performance: grouping patients' performances together yields a (corrected) Gaussian, whose unimodal nature confirms (in fact for the first time) group uniformity, that is, provides a formal argument in favor of the syndrome-based approach to Broca's aphasia. Next, when this observation is translated into a localizing claim, the conclusion is clear: **Broca's region is critically involved the computation of XP-movement in receptive language.** Having established that, we can proceed to view Broca's region from the angle of the healthy brain, as evidenced through functional imaging of movement. The TDH seems to have a fairly straightforward translation from the pathological to the normal functioning of left Broca's region: If the ability to compute movement is wiped out by damage to this area, then in the healthy brain, LIFG should be activated by syntactic movement.

5. Finely Tuned Receptive Syntactic Operations in the Healthy Brain: Role of LIFG in Movement

5.1. Anatomical Variation: A Caveat

Lesion data have received a bad name not only due to the apparent variation in scores; it has also been argued that as natural experiments, they produce lesions whose size is so large and variable that it prevents accurate localization. These problems have led some to shy away from aphasia research. The advent of the new imaging technologies – PET and fMRI – has given people the feeling that these problems are solved, and that the past can be left behind, never to be revisited (see Grodzinsky, 2002 for a critical appraisal). I have participated in this shift to imaging as well, yet somewhat cautiously. Let me tell you why.

Neuroimaging techniques have undergone impressive development. Analytic methods have managed to rid the observer from considerable amounts of noise; image distortion has gone down, the number of slices, and the speed of data acquisition have gone up significantly. Resolution, speed and accuracy of images will no doubt improve further, as this field has been attracting not only huge amounts of research funds, but also the best and brightest young minds in neuroscience. Yet certain problems will not go away: the human brain exhibits large variability at both the topographic and cytoarchitectonic levels. This complicates precise anatomical maps of function, as it sets an upper bound on resolution. The shape of Broca's region has been shown to be variable at both levels (Tomaiuolo *et al*., 1999; Amunts *et al*., 1999), and the correspondence between cytoarchitectonic boundaries and topography is both poor and variable. These studies are based on large samples (50 subjects in Tomaiuolo *et al*., 10 subjects in Amunts *et al*.), enabling the construction of probability maps that attach a number to a point in the reference space (Tallairach & Tournoux, 1988), which represents the number of subjects whose Broca's region touched that point, hence the probability that this particular anatomical structure is part of Broca's region. The process begins by normalizing all brains to a single template, and then superimposing the relevant region on it. Anatomical variation, which is rather high, leads to poor inter-brain overlap, which means that these probability maps cover large cortical areas. That is, the union of all Broca's regions in all brains results in a volume substantially greater than any Broca's region in a single brain.

It is here that a comparison between lesion and imaging data is in order: Given that sentence processing depends on relatively large chunks of neural tissue, it is not at all clear (and in any case, has not been demonstrated) that for language investigations, the spatial resolution of images is any higher than that obtained through lesion studies. This is an important caveat to bear in mind as we get to the home stretch: A review of some preliminary work on the imaging of syntactic movement in the healthy brain.

5.2. Step I: Imaging "Sentence Complexity"
Beginnings are always difficult, and thus the first studies of sentence comprehension were less syntactically detailed than one would have wished. Early efforts looked at the putative "processing difficulty" of different sentence types (Stromswold *et al*., 1996; Just *et al*., 1996), claiming that signal intensity in left and right Broca's and Wernicke's regions increases with "difficulty"; later, it turned out that anatomical overlap among studies was fairly poor (see Ben Shachar *et al*., in press, for a critique). Experience with the linguistic interpretation of lesion data leaves one with a gnawing sense that the anatomically blurred picture may well be due to the fact that linguistic complexity (and subsequent "difficulty") is not a well defined notion, and its varying interpretations may influence the way experimental materials are selected, and hence may affect experimental results. Building on the aphasia data, we looked for stronger links between movement and the primary language areas of the brain.

5.3. Step II: Movement activates Broca's region in fMRI
When you tease movement apart from (whatever you construe as) complexity, and test it in fMRI, a fairly clear picture emerges: Michal Ben-Shachar has conducted a series of tightly controlled fMRI experiments that probe various aspects of movement in Hebrew, pitted against a fairly simple notion of complexity. Based on the aphasia data, we expected Broca's region to be activated when the ±Movement contrast is tested. First, relative clauses (13a) were compared to sentences with CP complements (13b). The idea was to construct minimal pairs in which several straightforward complexity measures are kept constant (i.e., number of words, propositions, embeddings, verbs, ratio of functional to lexical categories, and more), and contrast object relative clauses (13a) with sentences that have main verbs which take CP complements (13b), so that the resulting minimal contrast would be movement (Ben Shachar *et al*., in press):

(13)   a. 'azarti   la-**yalda**   [Se-Rina pagSa *t* ba-gina]
           helped-I to-the-girl that-Rina met   *t* in-the-garden
           *I helped **the girl** [that Rina met **t** in the garden]*
       b. 'amarti le-Rina [Se-ha-yalda yaSna ba-gina]
          told-I to-Rina that-the-girl slept in-the-garden
          I told Rina [that the girl slept in the garden]

Complexity, in fact, to the extent that it entered into play, was pitted against our expectations. That is, the only potential difference in complexity between the conditions was the number of arguments of the predicate pairs in each sentence type. When this figure is calculated, the sentence type that does not involve movement (13b) has more argument slots. If anything, it should cause a conservative bias, increasing activation in the -Movement case.

Subjects made grammaticality judgments (each sentence had an ungrammatical counterpart, created by the switching of the verbs in the embedded

sentences in (13) – *meet* for *sleep*). We analyzed the grammatical sentences separately. We found a movement effect: (13a) produced a higher BOLD signal that (13b) in left Broca's region (LIFG, or BA 44, 45) and to a lesser extent, in Heschl's gyri (BA 22, see figure 1) of both hemispheres. Thus the core computational resource for Movement structures is in areas 44,45 of the left cerebral hemisphere, in keeping with the lesion data as described by the TDH. Auxiliary computations occur in temporal areas bilaterally. LIFG (seen in Figure 3) was not only the region with the highest signal intensity, but also, the only region that exhibited left/right asymmetry:

R   **L**

Figure 3: A statistical map associated with movement.
Left IFG is the most activated region (Ben-Shachar *et al.*, in press)

An intriguing finding noted above – that scrambling patterns with movement in aphasia – actually converges on results from an experiment by Röder *et al.* (2001). This group has conducted an fMRI experiment in German, that looked at different types of embedded clauses with double-objects. The comparison they report gives a coherent (if partial) picture: When sentences in which both objects of an embedded double-object verb are scrambled with the embedded subject (14b), and compared to their non-scrambled counterparts (14a), activation is detected in the very same areas for which we found activations in the Hebrew fMRI experiments, that is, mostly in LFG, with some bilateral temporal activation.

(14) a. Jetzt wird der Astronaut dem Forscher   den Mond beschrieben
        Now will the astronaut [to] the scientist the moon   describe
      b. Jetzt wird **dem Forscher den Mond** der Astronaut *t t* beschrieben

Finally, additional studies in Hebrew (Ben Shachar *et al.*, in preparation) have indicated that this effect is not only localized, but also very robust, generalizing over tasks (comprehension and grammaticality judgment), and over two additional contrasts in Hebrew: a. Embedded wh-questions vs. yes/no questions, b. Object topicalized vs. non-topicalized main clauses ((15a-b) vs. (15c-d)). All contrasts activate overlapping regions. These findings provide an imaging perspective that converges on the TDH. Namely, the same brain regions that implicate disorders in syntactic movement analysis, are the most activated ones in the healthy brain, when syntactic movement operations are called for.

5.4. Step III: Double Objects
The experiments above provide an imaging perspective on the localization of movement operations. Despite the fact that this research program is just at its beginning stages, we have attempted to take this perspective a step further. That is, we

tried to see whether it is possible to use the location and intensity of the fMRI signal as a tool for the examination of specific linguistic hypotheses. Ben-Shachar & Grodzinsky (2002) report a study of Hebrew double objects, aimed to get an imaging perspective on the linguistic analysis of this construction. As a first pass, we have focused on 2 main questions regarding this construction (e.g., Larson, 1988; Aoun and Li, 1988):

(I) What type of movement (if any) is involved?
(II) Which complement order (dative or double object) is base generated and
     which is derived?

We tried to answer these questions by constructing an activation map. As the materials in (15) crossed dative shift with topicalization, we compared datives and double objects (15c-d) on the one hand, and their topicalized counterparts (15a-b) on the other hand.

(15)   a. 'et ha-sefer ha-'adom Dani natan la-professor me-Oxford
             Acc the-book the-red Dani gave to-the-professor from-Oxford
        b. la-professor me-Oxford Dani natan 'et ha-sefer ha-'adom
            To-the-professor from-Oxford Dani gave Acc the-book the-red
        c. Dani natan 'et ha-sefer ha-'adom la-professor me-Oxford
            Dani gave Acc the-book the-red to-the-professor from-Oxford
        d. Dani natan la-professor me-Oxford 'et ha-sefer ha-'adom
            Dani gave to-the-professor from-Oxford Acc the-book the-red

Regarding issue (I), an activation-by-region interaction between the dative-shift contrast (15c-d) and the topicalization contrast (15a-b) would imply two distinct operations, while anatomical overlap in activation would suggest that a similar process is invoked in both cases. As to issue (II), following the same logic as in our previous experiments, the relative intensity of the signal in (15c-d) should indicate which is the derived order. Our study thus utilized 2 types of empirical argument: the anatomical locus of the fMRI signal as reflecting uniformity or distinctness of operations (topicalization vs. dative shift); and the relative intensity of the fMRI signal within an anatomical region as reflecting more mental computation (double object vs. dative).

The dative shift contrast yielded two important results: first, it indicated a spatial pattern quite different from that for the relative/complement clause comparison, and the topicalization contrast (to which it was compared directly). Specifically, the comparison between (15c) and (15d) activated two frontal regions in the *right cerebral hemisphere*, and not any of the topicalization-related regions. This difference not only suggests that a different type of operation is involved, but also, and quite surprisingly, it provides a preliminary indication against the commonly held belief that syntax is exclusively in the left hemisphere, and that none is represented on the right side of the brain (see Grodzinsky, 2000a, for a review of this literature).

Moreover, when the relative intensity of the BOLD signal is measured in the two right frontal regions that are sensitive to the dative-shift contrast, it is significantly higher for double objects (15d) than for datives (15c), suggesting that Hebrew double objects are more demanding than datives, and providing an indication of their derived nature.

6. An afterthought

This paper provides a selective review of empirical reasons to believe in the neural modularity of syntax in the domain of receptive language. The brain seems to be

making fine-grained syntactic distinctions, gleaned through investigations of errors aphasics make, and BOLD responses monitored in the brains of healthy subjects through fMRI. Many questions remain unanswered (others are discussed elsewhere), yet the claim that left Broca's region handles movement of phrasal constituents seems to be massively supported. Cross methodological research programs such as the one just presented, that combine behavioral lesion studies with neuroimaging of healthy language point to the great potential in neurolinguistics: They allow refined testing of modular linguistic as well as anatomical hypotheses.

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REFERENCES
Aoun, J., and Li, Y. A. (1989). Scope and constituency. *Linguistic Inquiry 20*, 141-172.

Amunts, K., A. Schleicher, U. Bürgel, H. Mohlberg, H.B.M. Uylings & Zilles, K. (1999). Broca's region revisited: Cytoarchitecture and intersubject variability. *Journal of Comparative Neurology, 412*: 319-341.

Amunts K. and K. Zilles. (2001). Cytoarchitectonic mapping of the human cerebral cortex. In Naidich T. Yousry T., Mathews V., eds., *Neuroimaging Clinics of North America on Functional MR Imaging*. New York: Harcourt.

Avrutin, S. (2000) Comprehension of Wh-questions by children and Broca's aphasics. In Y. Grodzinsky, L.P. Shapiro, & D.A. Swinney (Eds.), *Language and the Brain: Representation and Processing.* Academic Press, San Diego, 295-312.

Avrutin, S. (2001). Linguistics and agrammatism. *GLOT International, 5,* 3-11

Badecker, W., and A. Caramazza. (1998). Morphology in aphasia. In Zwicky, A., and Spencer, A. (eds.). *Handbook of Morphology*. Oxford: Blackwell.

Ben-Shachar, M., Hendler, T., Kahn, I., Ben-Bashat, D., and Grodzinsky, Y. (in press). The Neural Reality of Syntactic Transformations: Evidence from fMRI. *Psychological Science.*

Ben Shachar, M. & Y. Grodzinsky. (2002). On the derivation of Hebrew double objects – a functional imaging investigation. Paper presented at NELS 33, MIT.

Ben Shachar, M., T. Hendler and Y. Grodzinsky. (in preparation). Functional imaging of questions.

Beretta, Alan, Cristina Schmitt, John Halliwell, Alan Munn, Fernando Cuetos and Sujung Kim (2001). "The effects of scrambling on Spanish and Korean agrammatic interpretation: why linear models fail and structural models survive." *Brain and Language, 79,* 407–425.

Berndt, R. S., Mitchum, C. C., & Haedinges, A. N. (1996). Comprehension of reversible sentences in ''agrammatism'': A meta-analysis. *Cognition, 58,* 289–308.

Blumstein, S. (1972). *A Phonological Investigation of Aphasia*. The Hague: Mouton.

Bobaljik, J. D. 2002. A-Chains at the PF interface: Copies and covert movement. *Natural Language and Linguistic Theory* 20:197-267.

Broca, P. (1861) Remarks on the Seat of the Faculty of Articulate Language Followed by an Observation of Aphemia (trans. G. von Bonin), in *Some Papers on the Cerebral Cortex* (Springfield: Thomas, 1960).

Brodmann, K. (1909). *Vergleichende Lokalisationslehre der Grosshirnrinde in ihren Prinzipien dargestellt auf Grund des Zellenbaus*. Verlag von Johann Ambrosius Barth, Leipzig [published as *Brodmann's 'Localisation in the Cerebral Cortex'*, translated and edited by L.J. Garey, 1999].

Burchert F., R. de Bleser & K. Sonntag. (2001). Does case make the difference? *Cortex* 37, 700-703

Caplan, D. & G. Waters. (1999). Verbal working memory and sentence comprehension. Behavioral and Brain Sciences, 22, 77–126.

Caramazza, A., Capitani, E., Rey, A., & Berndt, R. S. (2001). Agrammatic Broca's aphasia is not associated with a single pattern of comprehension performance. *Brain and Language, 76,* 158-184.

Chomsky, N. (1995). *The Minimalist Program*. Cambridge, MA: MIT Press.

Damasio. A. 1992. Aphasia. *New England Journal of Medicine, 326*, 531-539.

Drai D., Benjamini Y. & Golani, I. (2000) Statistical discrimination of natural modes of motion in rat exploratory behavior. *Journal of Neuroscience Methods, 96,* 119-131.

Drai, D. & Y. Grodzinsky. (1999). Syntactic regularity in Broca's aphasia: there's more of it than you ever imagined. *Brain & Language, 70*, 139-143.

Drai, D., Y. Grodzinsky & E. Zurif. (2001). Broca's aphasia is associated with a single pattern of comprehension performance. *Brain & Language, 76*, 185–192.

Embick, D. Marantz, A., Miyashita, Y., O'Neil, W., and K. Sakai A (2000). Syntactic Specialization for Broca's Area. *Proceedings of the National Academy of Sciences* 97:11, 6150-6154.

Fiebach, C., M. Schlesewsky & A. Friederici. (2001). An ERP investigation of syntactic working memory during the processing of German wh-questions. *Journal of Memory and Language.*

Fodor, Jerry. (1983). *The Modularity of Mind.* Cambridge, MA: MIT Press.

Fox, D. (2002). Antecedent contained deletion and the copy theory of movement. *Linguistic Inquiry, 33*, 63-96.

Freud, S. (1891) On Aphasia: A Critical Study (trans. E. Stengel) (New York: International Universities Press, 1953).

Friederici, A. & P. Graetz. (1987). Processing passive sentencesin aphasia: Deficits and strategies. *Brain and Language, 30*, 93-105.

Friedmann, N. (1994). *Morphology in agrammatism: A dissociation between tense and agreement.* M.A. thesis. Tel Aviv University.

Friedmann, N. (1998). *Functional categories in agrammatic production: a cross-linguistic study.* Doctoral dissertation, Tel Aviv University.

Friedmann, N. (2000). Agrammatic comprehension of OVS and OSV structures in Hebrew. *Behavioral and Brain Sciences, 23*, 33-34.

Friedmann, N., & Grodzinsky, Y. (1997). Tense and agreement in agrammatic production: pruning the syntactic tree. *Brain and Language*, **56***, 397-425.*

Friedmann, N., & Grodzinsky, Y. (1999). Split inflection in neurolinguistics. In L. Rizzi and M.-A. Friedemann (Eds.) *The Acquisition of Syntax: Studies in comparative developmental linguistics.* Longman Linguistics Library Series. Geneva: Switzerland.

Geschwind, N. (1965). Disconnexion syndromes in animals and man. *Brain* 88:237-294; 585-644.

Geschwind, N. (1979). Specializations of the human brain. *Scientific American*, September.

Grodzinsky, Y. (1984). *Language Deficits and Linguistic Theory.* Doctoral dissertation, Brandeis University.

Grodzinsky, Y. (1990). *Theoretical Perspectives on Language Deficits.* Cambridge, MA: MIT Press.

Grodzinsky, Y. (1995). A restrictive theory of agrammatic comprehension. *Brain & Language, 51*, pp. 26-51.

Grodzinsky, Y. (2000a). The neurology of syntax: language use without Broca's area. *Behavioral and Brain Sciences, 23.1,* 1-71.

Grodzinsky, Y. (2000b). Anatomical variation and grammatical variation: A comparative approach to movement operations in the brain. Paper presented at the 31th meeting of the North Eastern Linguistic Society's special session on neurolinguistics, Washington, DC.

Grodzinsky, Y. (2002). Neurolinguistics and Neuroimaging: Forward to the Future, or is it Back? *Psychological Science, 11*, 188-193.

Grodzinsky, Y., A. Pierce & S. Marakovitz. (1991). Neuropsychological reasons for a transformational analysis of verbal passive. *Natural Language & Linguistic Theory, 9*, 431-453.

Grodzinsky, Y. (In preparation a). Trace Deletion, interpretive principles, and the Copy Theory of Movement.

Grodzinsky, Y. (In preparation b). Quantitative error analysis in syntax.

Grodzinsky, Y. & L. Finkel. (1998). The neurology of empty categories. *Journal of Cognitive Neuroscience, 10.2,* pp. 281-292.

Grodzinsky, Y. M. Piñango, E. Zurif & D. Drai. (1999). The critical role of group studies in neuropsychology: comprehension regularities in Broca's aphasia. *Brain & Language, 67*, 134-147.

Grodzinsky, Y., K. Wexler, Y.-C. Chien, S. Marakovitz & J. Solomon. (1993). The breakdown of binding relations. *Brain & Language, 45.3*, pp. 396-422.

Hagiwara, H. and P.Caplan. (1990). Syntactic Comprehension in Japanese aphasics: Effects of Category and Thematic role order. *Brain & language, 38*, 159-170.

Hickok, G. and S. Avrutin. (1995). Comprehension of Wh-questions by two agrammatic Broca' aphasics. *Brain & Language, 51*, 10-26.

Hughlings-Jackson, John. (1878). *Selected Writings of John Hughlings Jackson*, ed. James Taylor (London: Hodder and Stoughton Limited, 1931-1932), Vol. 2: Evolution and Dissolution of the Nervous System and Speech, pp. 154-204.

Jakobson, R. 1941. *Kindersprache, Aphasie und algemeine Lautgesätze* [translated as *Child Language, Aphasia, and Phonological Universals*. The Hague: Mouton, 1968].

Just, M. A., Carpenter, P. A. , Keller, T. A. , Eddy, W. F. , Thulborn, K. R. (1996). Brain activation modulated by sentence comprehension. *Science*, *274*, 114-116.

Kandell, T. Jessell & J. Schwartz . (2000). *Principles of Neural Science.* New York:Appleton & Lange.

Kluender, R. and Kutas, M. (1993). Bridging the Gap: Evidence from ERPs on the Processing of Unbounded Dependencies. *Journal of Cognitive Neuroscience, 5:2*, pp. 196-214.

Larson, R. K. (1988). On the double object construction. *Linguistic Inquiry, 19*, 335-391.

Lashley, K. S. (1951). The problem of serial order in behavior. In *Cerebral Mechanisms in Behavior.* New York: Wiley, pp. 112-136.

Law, S.-P. (2000). Structural prominence hypothesis and chinese aphasic sentence comprehension. *Brain and Language, 74***,** 260–268.

Lichtheim, L. (1885). *Über Aphasie.* Deutsches Archiv für klinische Medicin, Leipzig, 1885, 36: 204-268. [translated into English as *On Aphasia*].

Lima R. & C. Novaes. (2000). Grammaticality judgments by agrammatic aphasics: Data from Brazilian-Portuguese. *Brain and Language, 74***,** 515–551.

Love, T. & Swinney, D. (1996). Coreference Processing and Levels of analysis in Object Relative Constructions; Demonstration of Antecedent Reactivation with the Cross Modal Paradigm. Journal of Psycholinguistic Research, 25, 5-24.

Lonzi, L. and Luzzatti, C.(1993). Relevance of adverb distribution for the analysis of sentence representation in agrammatic patients. *Brain and Language,45,* 306-317.

Neville, H., Nicol, J., Barss, A., Forster, K. & Garrett, M. (1991). Syntactically based sentence processing classes: Evidence from event-related potentials. *Journal of Cognitive Neuroscience, 3,* 151-165.

Phillips, C., Pellathy, T., Marantz, A., Yellin, E., Wexler, K. McGinnis, M., Poeppel, D., Roberts, T., 2000, Auditory cortex accesses phonological categories: An MEG mismatch study, *Journal of Cognitive Neuroscience.*, 12:1038–1055.

Röder, B. O. Stock, H. Neville, S. Bien, and F. Rösler. (2001) Brain Activation Modulated by the Comprehension of Normal and Pseudo-word Sentences of Different Processing Demands: A Functional Magnetic Resonance Imaging Study. *NeuroImage, 15*, 1003-1014.

Stromswold, K., Caplan, D., Alpert, N. and Rauch, S. (1996). Localization of syntactic comprehension by positron emission tomography. *Brain and Language 52*, 452-473.

Su, Y.-C. (2000). Asyntactic Thematic Role Assignment: Implications from Chinese Aphasics. Paper presented at the LSA Meeting, Chicago.

Talairach, J. & Tournoux, P. (1988). *Coplanar stereotaxic atlas of the human brain*. Stuttgart: Thieme.

Tomaiuolo, F., J.D. MacDonald, Z. Caramanos, G. Posner, M. Chiavaras, A.C. Evans and M. Petrides. (1999). Morphology, morphometry and probability mapping of the pars opercularis of the inferior frontal gyrus: an *in vivo* MRI analysis. *European Journal of Neuroscience, 11*, 3033-3046.

Zeki, S. (1993). *A Vision of the Brain*. Boston: Blackwell

Zurif, E.B. (1980). Language mechanisms: a neuropsychological perspective. *American Scientist*, May.

Zurif, E.B.,(1995). Brain regions of relevance to syntactic processing. in L. Gleitman and M. Liberman (eds.), *An invitation to Cognitive Science*, Vol. I,. Cambridge, MA: MIT Press [2nd edition].

Zurif, E. B. & A. Caramazza. (1976). Linguistic structures in aphasia: Studies in syntax and semantics. In H. Whitaker and H. H. Whitaker, (eds), S*tudies in neurolinguistics, Vol. 2.* New York: Academic Press.

Zurif. E.B. & M. Piñango. (1999). The existence of comprehension patterns in Broca's aphasia. *Brain & Language, 70*, 133-138.

Zurif, E.B., Swinney, D., Prather, P., Solomon, J., & Bushell, C. (1993). An On-line Analysis of Syntactic Processing in Broca's and Wernicke's Aphasia. Brain and Language, 45, 448-464.