

On the Biological Foundations of Language: Recent Advances in Language Acquisition, Deterioration, and Neuroscience Begin to Converge

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In this paper, experimental results on the study of language loss in prodromal Alzheimer's disease (AD) in the elderly are linked to experimental results from the study of language acquisition in the child, via a transitional stage of Mild Cognitive Impairment (MCI). Recent brain imaging results from a pilot study comparing prodromal AD and normal aging are reported. Both, behavioral results and their underlying neural underpinnings, identify the source of language deficits in MCI as breakdown in syntax–semantics integration. These results are linked to independent discoveries regarding the ontogeny of language in the child and their neural foundations. It is suggested that these convergent results advance our understanding of the true nature of maturational processes in language, allowing us to reconsider a “regression hypothesis” (e.g., Ribot 1881), wherein later acquisition predicts earliest dissolution.

Keywords: Language acquisition; language loss; brain; maturation; Prodromal Alzheimer's disease

1. Introduction

Since Lenneberg's (1967) landmark work on the *Biological Foundations of Language*, the fields of language acquisition, language deterioration, neuroscience (including study of the brain's “language network”), as well as the linguistic theory of a language faculty, have all developed exponentially. At the same time, we are still far from fulfilling Lenneberg's fundamental challenge, that is, “we must try to understand the nature of the maturational processes” (Lenneberg 1967: 126). Now, however, through converging recent interdisciplinary advances, we are poised for new advances in our understanding of maturational processes involved in language acquisition; not only new advances in developmental theory of language acquisition but new advances in realization of brain–behavior relations in the area.

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In this paper, we provide one example of such recent interdisciplinary convergence. We link recent discoveries from experimental results on our study of language loss in prodromal Alzheimer's disease (AD) in the elderly to comparable early experimental results from our study of language acquisition in the child. We report recent brain imaging results from a pilot study comparing prodromal AD and normal aging. Our brain imaging results cohere with our behavioral results documenting language loss in prodromal AD, allowing us to adumbrate selected brain-behavior relationships in language dissolution and to begin to identify the nature of language loss in prodromal AD. We then link these results to new independent discoveries on the ontogeny of the neural foundations for language in the child that are emerging from research led by Angela Friederici at the Max Planck Institute for Human Cognitive & Brain Sciences (e.g., Friederici 2016, 2017, this issue). Although such new results have begun to reveal the neural basis for language development and its impairment, until now there has not been clear principled mapping of language acquisition facts or theory to these precise neurobiological results, especially with regard to later language acquisition (although see Friederici 2006, 2016, 2017, Friedrich & Friederici 2005, 2010, Skeide et al. 2014, Vissiennon, Friederici, Brauer & Wu 2017).

Here, we suggest that our recent results on language acquisition and language loss cohere with what has now been independently discovered regarding underlying maturation of the language network. In doing so, these results suggest an expanded approach to the study of language across the lifespan. They allow us to reconsider a *regression hypothesis* (RH; Ribot 1881/2012, 1881, Lust et al. 2015b) as an explanation of the relation between the ontogeny and dissolution of language knowledge. Although our previous results had disconfirmed a version of RH with regard to the acquisition of syntax, our present results invite us to reconsider this hypothesis with regard to syntax–semantics integration. Together, our results advance our understanding of the true nature of maturational processes in language.

2. Comparing Language Loss in Prodromal AD to Language Acquisition in the Child

In our recent work, we have tested language production in populations (ages 58–98) with *mild cognitive impairment* (MCI). In what is now appreciated as a continuum in the development of AD, MCI is a stage of increased risk for AD diagnosis. Individuals at this stage demonstrate a cognitive decline from baseline that is not at the level of dementia (Petersen 2003, 2004, Wicklund & Petersen 2014). Individuals with a diagnosis of MCI are known to convert to AD at a higher level than cognitively normal individuals (Morris & Cummings 2005, Talbert et al. 2006, Dickerson et al. 2007, Chapman et al. 2010, Roberts et al. 2014). We compared language in MCI to *healthy aging* (HA; 62–87 years), *healthy young* (HY; 20–29 years), and children (ages 3;5 to 7;6 in years;months) with matched experimental designs. Through an inter-institutional collaborative infrastructure we compared 51 MCI subjects to 24 HA to

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10 HY across a series of linguistic experiments testing various forms of sentence formation (relative clauses, coordinate sentences, adjoined clause sentences), using an elicited imitation (EI) task. The EI task has been shown to require reconstructive analysis of both syntax and semantics in sentence structure (e.g., Lust et al. 1996). Used with controlled and standardized experimental designs, results are shown not to depend solely on memory but on analytic sentence reconstruction (Blume & Lust 2017). The EI experiments were complemented by two other tests of language knowledge, and by a general cognitive assessment (Addenbrook's cognitive exam revised; ACE-R; see Mioshi et al. 2006) and a test of working memory, the Brown-Petersen test (also referred to as the Auditory Consonant Trigram Test; Brown 1958, Belleville, Chertkow, & Gauthier 2007), as well as by a general sociodemographic background assessment.

For example, one such experiment compared production of complex sentences with varied forms of relative clauses across these groups, using an experimental design that had been previously used with children. All sentences within each study were controlled for structural variables, as well as length and lexical frequency, in conjunction with an EI task. The children had been tested earlier with this experimental design using sentences such as exemplified in Table 1a. Data, methodology, and results from this child study were archived in the Cornell Language Acquisition Lab Virtual Center for Language Acquisition.¹ Results from the child study had revealed a developmental progression in the first language acquisition of relative clause structure (Flynn & Lust 1980).

Determinate Head	S	Big Bird pushes the balloon which bumps Ernie.
	O	Ernie touches the balloon which Big Bird throws.
Headless	S	Cookie Monster hits what pushes Big Bird.
	O	Cookie Monster pushes what Big Bird throws.
(a)		
Determinate Head	S	The attorney presented the evidence which freed the defendant.
	O	The shopkeeper discounted the merchandise which the customer bought.
Headless	S	The state policeman discovered what troubled the private detective.
	O	The philosophy teacher pondered what the research scientist said.
(b)		

Table 1: Example Sentences for elicited imitation for children in (a), for adults in (b).

¹ Experimental design, methods, and results from this early study are banked in the web-based Virtual Center for Language Acquisition Database, DTA tool (Data Transcription and Analysis tool) and are available on request. See Pareja-Lora, Blume, & Lust (in press), as well as Blume, Flynn, & Lust (2012).

Adult populations, including HA, HY, and MCI, were more recently tested on structurally matched sentences such as exemplified in Table 1b (Lust et al. 2015). MCI participants were assessed at Massachusetts General Hospital (MGH) through neurologic evaluations and a battery of standardized neuropsychological and clinician evaluations. Subjects' diagnoses of MCI were based on neurological evaluation including Clinical Dementia Rating scores (CDR; Morris 1993) and performance on neuropsychological tests from the Uniform Data Set (UDS; Morris et al. 2006, Weintraub et al. 2009, Monsell et al. 2012), as well as additional standardized neuropsychological measures. HA participants were recruited from MGH and administered the same tests as the MCI population to provide a control HA population.² HY adults were recruited at the Massachusetts Institute of Technology from the student and administrative population. Based on a sociodemographic questionnaire, all participants in this study reported no history of neurological disorders or events.

Results from this comparative study were surprising. The relative clause structure that was last developed by the child and most difficult in language production through childhood to approximately 7 years of age was the lexically headed type; that is, those with a determinate lexical noun head such as *balloon* in the examples in Table 1a. We have argued that this English lexically determinate headed relative clause represents complex language-specific computation, explaining its later acquisition (Flynn et al. 2005). However, it was this determinate lexically headed relative clause structure that was best retained in the MCI subjects. The headless

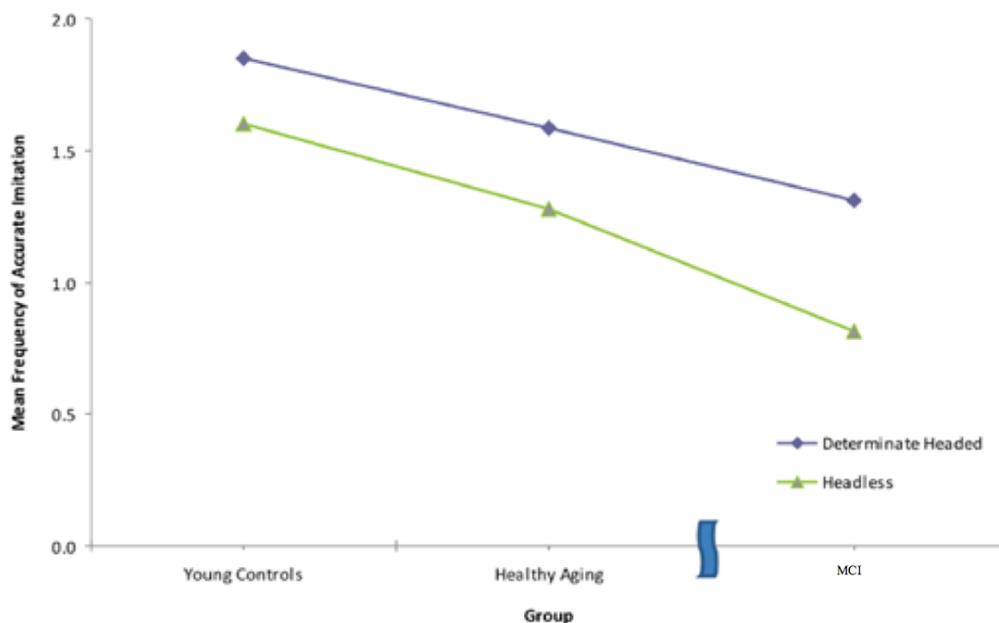


Figure 1: Frequency of accurate imitation for each type of relative for each adult group. (See Lust et al. 2015b for details.)

² A subset of 13 HA were tested at Cornell, and self-declared cognitively normal, i.e., although they presented as non-impaired, they did not receive the same diagnostic tests as did the clinical MGH subjects and the MGH tested HA controls.

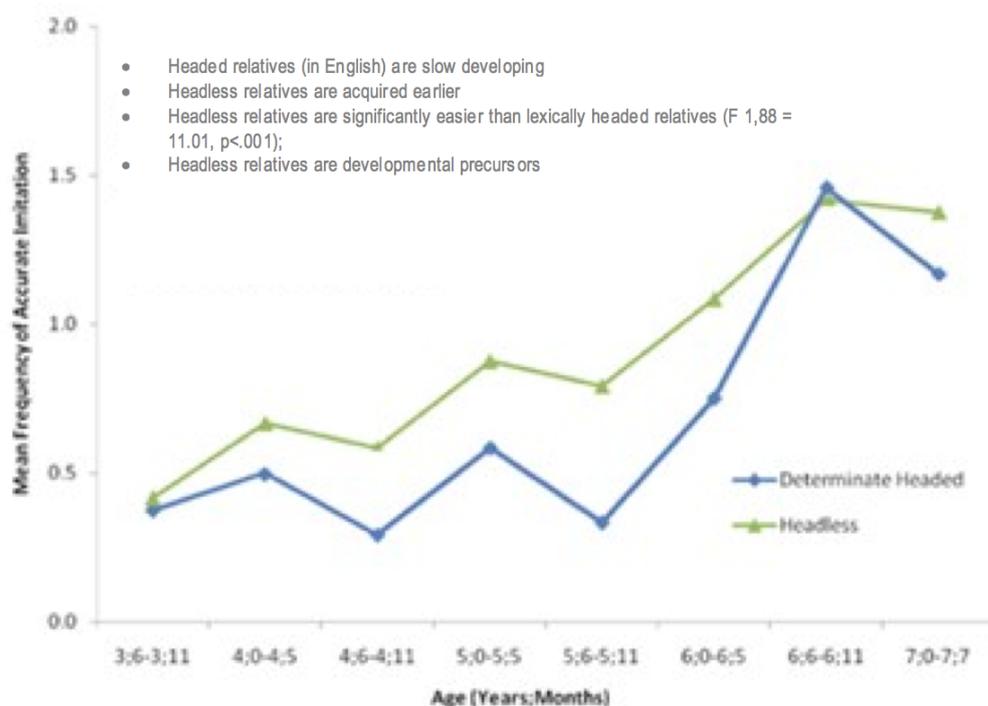


Figure 2: Frequency of accurate imitation by children for each type of relative for each age group. (See Flynn & Lust 1980 for details. The total N of 96 children was divided to eight 6-month age groups.)

relative clause type that was predominant in child language production early and throughout development was the “headless relative”, e.g., the *what*-headed structure in the examples in Table 1a. Yet, it was this headless relative type of structure that posed significantly greater difficulty for the MCI. As we have argued (Lust et al. 2015b, 2017), these results disconfirmed a RH (“Ribot’s hypothesis”) with regard to the acquisition of syntax. It was not true that what was last acquired by the child was first lost by the adult in language deterioration (see Figures 1 and 2).

At the same time, results from this study also began to provide evidence on the fundamental nature of language deterioration in prodromal AD. MCI subjects differed significantly from HA and HY in their overall language production. However, this was not the case with regard to their production of the determinate headed relatives, the complex syntactic structure that is last acquired by the child. In spite of the syntactic complexity of headed relatives, MCI subjects produced these with significantly greater facility than they did the headless relative. The MCI subjects failed in production especially of the headless relative, the very structure that had been developmentally prominent. Example of imitation performance by an MCI individual is shown in (1a) and (1b). In a randomized set of EI sentences, the individual correctly reproduced lexically headed relatives such as in (1a), without change, while distorting headless relatives as in (1b).

- (1) a. *Headed Relatives EI (TS033): Successful imitations (no change)*
The attorney presented the evidence which freed the defendant.

The shopkeeper discounted the merchandise which the customer bought.
The physician formulated the therapy which cured the patient.

- b. *Headless Relatives EI (TS033): Unsuccessful imitations (changes from stimulus sentences)*
- i. Target: The state policeman discovered what troubled the private detective.
Response: The st. . . policeman something discovered what.
 - ii. Target: The philosophy teacher pondered what the research scientist said.
Response: The pondered what the philosopher said.
 - iii. Target: The peace activist protested what the vice president suggested.
Response: The peace activist suggested other someone suggested.

This distinction in EI performance (summarized in Figure 1) held in spite of the experimental controls on length (all 17 syllables), general structure, and lexical frequency that characterized all sentences across the design.

An example of the structure of an MCI production error on a headless relative is shown in Figure 3.

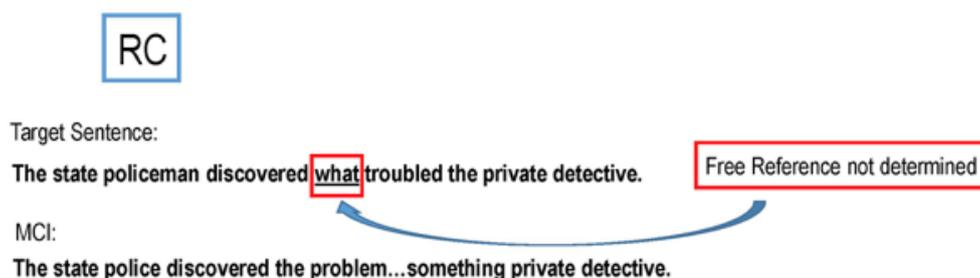


Figure 3: Example of structure of MCI subject's (GC533) production of a headless relative clause (RC).

3. The Nature of Language Deterioration in MCI

These results not only verified language deterioration in prodromal AD (MCI), but also began to provide evidence on the nature of this language deficit. It appeared that the complex syntax of a well-formed lexically headed relative clause was relatively well retained in MCI language. What was impaired was a case where the subject must specify an undetermined reference (e.g., whatever it was that troubled the detective in the example in Figure 3 above) and link it to the sentence structure. The difficulty that these sentences demonstrate appears to concern the integration of syntax, necessary for sentence production, with the semantics of the sentence,

especially the computation of external reference, necessary for sentence interpretation. Specifically, this was a case when the subject had to compute an interpretation of indeterminate reference reflected in the headless relative and then integrate this semantic and pragmatic computation with computation of the syntax of the sentence. Although all sentences require an integration of syntax and semantics, the headless sentences appear to provide a particular challenge to this integration, which must be involved in all sentence processing.

These results suggest that language deterioration in prodromal AD targets the syntax–semantics interface in the language faculty (Figure 4; see Berwick et al. 2013) and suggests that this interface is the locus of this early language breakdown, rather than core syntactic computation. Subsequent experiments with other types of complex sentences which vary indeterminate reference (e.g., coordinate and adverbial subordinate sentences with or without free pronouns that are indeterminate in reference), and experiments with other tasks, confirmed this area of language breakdown (e.g., Lust et al. 2014, Lust et al. 2015a, Sherman et al. 2015a,b, Sherman 2017).

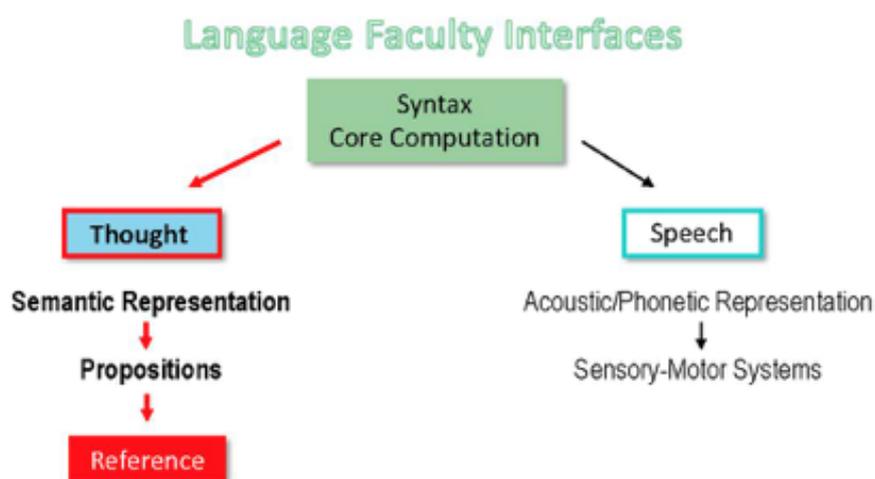


Figure 4: Schematic of the language faculty and its interfaces with other systems. (Illustration based on Berwick et al. 2013.)

3.1. Dissociating Memory and Language

Although memory and language performance are inextricably linked, it is clear from a comparison of headed and headless sentences in our controlled design, for example, (1a) and (1b), where headed sentences of equal length and general syntactic complexity are imitated significantly better than the headless sentences in (1b), that memory alone cannot explain these results in our MCI population. This conclusion was supported by our regression analyses of memory tests against linguistic performance. Both the ACE-R and the Brown Petersen tests did show that

the groups significantly differed, with MCI showing significantly deficient performance. However, performance of subjects on the ACE-R memory subcomponent did not significantly predict linguistic performance on the RC sentences overall groups (regression estimate = .06577, $p = .19$) or within any group. More specifically, the Brown Petersen test of Working Memory also did not, not overall groups (regression estimate = .00141, $p = .81$) or within any group, including MCI (regression estimate = .002819, $p = .79$). These results would appear to cohere with independent psycholinguistic research which has failed to find effects of working memory on online processing, suggesting its alternative role on post interpretive processing (Caplan et al. 2011; also see Waters, Caplan, & Rochon 1995 for generalization to studies of Alzheimer's disease populations).

Thus we conclude that the nature of language deterioration that has been discovered in MCI is language-related, rather than determined simply by domain-general cognitive deficits, such as memory.

4. Pursuing Biological Foundations

Recent advances in neuroscience with regard to the biological foundations of a language network in the brain have allowed us to begin to test a hypothesis regarding the neurobiological foundations for language dissolution in MCI, which was suggested by our linguistic behavioral results.

Independent analyses of language processing have yielded a model wherein sentence processing involves distinct, incremental sequential components serially ordered such that syntax–semantics integration is distinct from earlier phonological and syntactic sentence computation. Integration of syntax and semantics occurs finally, as a late and distinct stage in serial processing within the dominant (i.e. left) hemisphere, as suggested in Figure 5. This model sketches the neural underpinnings of the temporal process of sentence comprehension as schematized in the illustration. The final integration step is focused on a posterior portion of the superior temporal gyrus (STG), an area of the language network that merges with the angular gyrus and supramarginal gyrus of the inferior parietal lobule (IPL; Friederici 2002, 2011, 2012, Friederici & Kotz 2003). Integration takes place at a later phase of language comprehension—in a neural network implicating the IPL/STG hub at later phases (Fengler et al. 2016).

Recent studies from independent labs have begun to map psycholinguistic data to the neural foundations of processing. For example, semantic processing in AD patients has provided evidence for the contribution of superior temporal and inferior parietal regions of the left hemisphere (Grossman et al. 1997). Studies of pronoun reference resolution have suggested a “two component model for resolving a pronoun's reference” and observe inclusion of inferior parietal cortex (IPC) activation to account for an “integration of probabilistic and value information” in resolving a pronoun's reference (McMillan et al. 2012: 674, 685).

Independent advances have also identified the IPL as a critical integrative hub in a network of functionally connected brain regions referred to as the Default Network (DN). The DN is generally implicated in internalized or associative processing and is typically suppressed during externally directed attention tasks (Bar et al. 2007, Buckner et al. 2008, Andrews-Hanna, Smallwood, & Spreng 2014). The

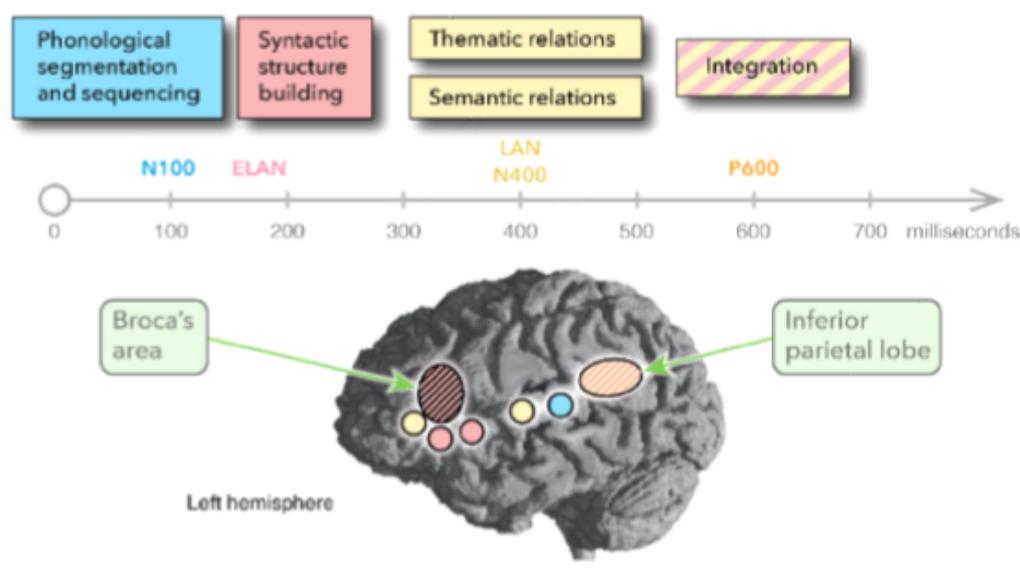


Figure 5: Schematic of the Serial Sentence Processing Model. (Adapted from Friederici 2002, Friederici & Kotz 2003.)

IPL, part of the DN, provides a cross-modal integrative hub, with connectivity to both the Posterior Cingulate Cortex (PCC), a core hub of the DN, and also to frontal and temporal regions involving classic Broca's and Wernicke's areas. The default-aligned node, left IPL, has been observed to facilitate modulation (i.e. suppression) of the DN (Menon and Uddin 2010, Spreng et al. 2013: 83; also see Friederici 2011). Recent research is investigating the degree to which the DN underlies cognition (Marguiles et al. 2016).

It has been suggested that loss of functional and structural integrity of the DN and its interactions with other brain networks occurs in older adulthood and may have clinical significance (Greicius et al. 2004, Seeley et al. 2009, Anticevic et al. 2012: 586, Turner & Spreng 2015, Spreng et al., in press). In AD, DN is disrupted "early as the disease progresses" evidencing "hypometabolism" and accelerated atrophy in DN connectivity hubs (Buckner et al. 2005, 2008: 28, Andrews-Hanna et al. 2014).

The linguistic behavioral evidence we found regarding the nature of the language difficulties in our MCI subjects suggests deterioration in the integration of external reference and the syntax of sentence construction, the last phase in the Serial Sentence Processing Model described above, targeting the IPL area in language connectivity. This deficit would be consistent in general with DN disruption and with deterioration in the DN connectivity hub involving the left IPL. We may assume that the syntactic composition of sentence structure must comprise internal cognition; and that some form of suppression of such internal computation must be involved in the cognitive computation involved in determining semantic and pragmatic reference to the external world.

Thus, both linguistic and neurocognitive foundations lead us to the hypothesis that damage in the IPL area would cohere with deterioration of the integration

of syntax and semantics, which our behavioral language data have suggested is compromised in MCI. Our linguistic behavioral results, which characterize prodromal AD in MCI, suggest that cortical degeneration may occur early in this area, at the MCI phase, even before AD is clinically diagnosed. Independent studies have shown that the IPL appears to deteriorate early in the course of neural degeneration in prodromal AD, evidenced by relatively early atrophy of cortical grey matter in this area (e.g., Greene et al. 2010: 1304, Jacobs et al. 2011, Hanggi et al. 2011; the finding of early prodromal temporo-parietal involvement with frontal areas relatively spared is also indicated with other methodologies, e.g., position emission tomography [PET]; Minoshima et al. 1997, Small et al. 2006). This early atrophy of the IPL differentiates from Broca’s area (i.e. Brodmann areas 44 and 45), for example. Atrophy in prodromal AD is not global: ‘[E]ven in end stage AD, distinct language-associated gyri are spared while others show severe atrophy’ (Harasty et al. 1999: 682).

Since our linguistic behavioral data suggest good retention of syntax per se (e.g., as reflected in the relatively good performance on lexically headed relatives) in the MCI population, both our language data and neuroscientific data, as well as current sentence processing and cognitive modeling, predict that we may find relatively damaged IPL area in our MCI subjects, in contrast to relatively spared Broca’s area (i.e. inferior frontal gyrus) which is generally associated with syntax (e.g., Friederici, this issue).

4.1. Hypothesis

On the basis of the neuroscientific results discussed above as well as our linguistic behavioral results regarding language deterioration in MCI, we hypothesized that, in our MCI subjects, the IPL area, critical to syntax–semantics integration, would show significantly more grey matter deterioration in contrast to HA than Broca’s area as a frontal area implicated in syntactic processing.

4.2. Participants

In a first pilot study, we have now conducted volumetric analysis of brain images of six MCI subjects from the total group who participated in our experimental linguistic tests (Lust et al. 2015b) and compared them to a sample of HA. Structural MRI scans of this subset of MCI subjects were acquired during clinical diagnostic testing (Siemens 3T TIM Trio). Their scans were compared to healthy control matched templates derived from ADNI (Alzheimer’s Disease Neuroimaging Initiative; Mueller et al. 2005, Weiner et al. 2010, adni-info.org 2016). Three ADNI scans were matched

Group	n	Age: Mean	Age: Range	Males	Yrs. Education: Mean	Yrs. Education: Range	Handedness (% Right)
MCI	6	77	68–88	6	17.33	14–20	83.33 %
Healthy Aging (ADNI)	18	78–79	65–88	18	15.78	8–20	100 %

Table 2: Participants—MRI scanning. Note: One scan was eliminated in linguistic analyses because of missing linguistic data.

to each MCI participant in age, sex, and education, providing a total of 18 healthy aging scans for comparison with the selected MCI subjects.

Five of the six MCI subjects were diagnosed as MCI amnesic, single domain; one as multi domain, non-amnesic. MCI subjects had MMSE scores ranging from 23 to 29, mean 26.8, while ADNI subjects all had perfect scores of 30.

4.3. *Methods*

Volumetric analysis was conducted on the structural MRIs of the MCI subjects using Voxel Based Morphometry (VBM) methods (Kurth et al. 2015). Volumetric data were compared to the 18 HA matched scans (derived from ADNI). Regions of Interest (ROIs) of IPL and Broca's area were created to assess regional specificity. We examined the relation between cortical volume in these two left hemisphere (LH) ROIs linked to linguistic processing with the goal of initiating a test of our hypothesis and a prototype methodology for identifying neural correlates of observed linguistic behavior.

All scans involved structural T1-weighted images obtained on a 3-tesla (T) scanner. Scanning of MCI subjects took place at MGH Radiology division as an independent component of diagnostic clinical testing. Deidentified scans were provided by MGH to study investigators (per IRB) for research purposes. ADNI dataset participants were scanned using 3-T GE Medical Systems scanners. The scanners collected T1-weighted (T1w) 3D anatomical spoiled gradient echo (SPGR) sequences (256×256 matrix; voxel size = $1.2 \times 1.0 \times 1.0$ mm³; TI = 400 ms; TR = 6.98 ms; TE = 2.85; flip angle = 11°).

4.4. *Analyses by VBM*

MRI scans (deidentified structural T1 scans) were imported into SPM in DICOM format and transformed to NIFTI. Scans were corrected for left/right orientation. Scans were then segmented into grey, white, and cerebral spinal fluid using the VBM toolbox in SPM8. Next, grey matter sections were quality controlled for homogeneity of variance again using VBM, then coregistered to MNI space using a FSL "152T1-avg" template.

All subject scans were preprocessed using SPM8 and the protocol specified in Kurth et al. (2015). Segmented and smoothed grey matter masks were linearly aligned to a DARTEL template that was manually created from 20 HA and 20 MCI ADNI subjects. Left and right IPL volumes were taken from Harvard-Oxford Cortical Atlas (HOA) masked and binarized using FSL Maths. Subsequently, masked IPL regions from subjects were extracted from the HOA and ROI volumes were calculated for each subject. Using FSL, ROIs of left Broca's area and left IPL were created using HOA, with a threshold at 50 % and binarized using FSL Maths. Thereafter mean values of voxels in each ROI were extracted and tabulated using FSL Stats by applying the mask to scans and isolating mean voxel values.

4.5. *Statistical Analyses*

We examined two types of models. The first model looks at brain volume as a function of brain area and MCI status in the sample of 30 subjects. IPL versus

Broca's area is a repeated measure on each individual, a fixed classification factor denoted ROI. Group (HA vs. MCI) is a second fixed classification factor. The model includes these two factors and their interaction; individuals are included as levels of a random classification factor. Analysis was by a general linear mixed model. Brain volume for IPL and Broca's area is the proportion of grey matter relative to a template for healthy aging.

To study the relation between cognitive status as measured by brain imaging and status as measured by linguistic tests, the second type of model examined RC (relative clause experiment) scores for proportion correct as the dependent variable, with the repeated measures for that task, TR (type of relative) and FC (functional role, i.e., subject or object in relative clause), as fixed classification factors; a brain volume measure as a covariate, with regressions specified separately by TR \times FC; and individuals as levels of a random classification factor. Separate models were analyzed for each of IPL and Broca's area volume measures. This analysis was carried out on MCI individuals only. The key test is of homogeneity of regressions of RC scores on brain volume variables by TR and FC subclasses. An alternative model that had greater numerical stability specified the IPL and Broca's area regressions separately only for the 3 levels of TR, pooling across FC. Analysis was by a logistic-linear mixed model with binomial error assumption and a logit link function. Degrees of freedom were computed by a first-order Kenward-Rogers method.

4.6. Results

The analyses described above revealed:

1. Lower IPL grey matter integrity in MCI than HA; similar Broca's area integrity between them.
2. Greater mean difference between IPL (DN connectivity hub) and Broca's area (syntax related) neurodegeneration in MCI than HA scans (significant Group \times Area interaction: $p = .03$).
3. The regressions of syntactic performance on ROI IPL were significantly different for structures requiring reference resolution and syntax integration (determinate headed vs. headless relative clauses; see Table 3). Test of homogeneity of regressions: $p = .011$.

Results from initial brain scan analyses suggest that a significant pattern of biomarking may link to an observed pattern of behavioral linguistic deficits. MCI may involve significant early neural degeneration in an area central to syntax- semantics integration in sentence processing and an integration hub of the DN, including the IPL. This area appears to be significantly more compromised in prodromal AD (MCI) compared to that in inferior frontal gyrus or Broca's area (Brodmann areas 44 and 45). This may indicate correlation with the linguistic pattern we have found

Sentence Type	ROI IPL	
	Estimate	
Relative Headed	Estimate	-.118
	SE	5.376
	P	.983
Relative Headless	Estimate	4.701
	SE	6.549
	P	.476

Table 3: Results of regression analysis: Relative clause type and ROI IPL.

in the language deterioration of MCI: deficit in syntax-semantic integration, compared to relatively spared basic syntactic computation (cf. Payne et al. 2016).

Linguistics behavioral results cohere with current structural and functional connectivity models of language knowledge and processing, as well as with observed neurodegeneration patterns in progressive development of prodromal AD.

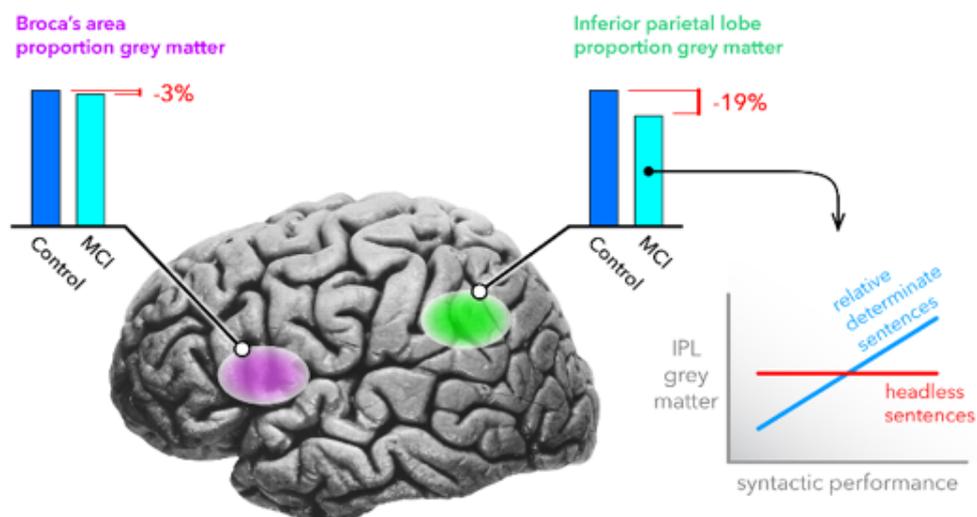


Figure 6: Proportion grey matter (relative to template) in Broca's area and inferior parietal lobe (IPL).

5. The Neurobiology of Brain Development

Independently, results from study of the neural bases of language development (analyzing both grey and white matter; Friederici 2006, 2012, 2016, see Friederici et al. 2017 for a review) have now provided evidence that “brain systems underlying language processing are in place already early in development” (Friederici 2006: 949). Connectivity of the language network (involving both white and grey matter connectivity) develops over time, taking until 7 years of age (or even adolescence) before completion. Specifically, it is proposed that although ventral systems of language network connectivity are in place even at birth, aspects of the dorsal system “connecting the temporal cortex to Broca's area” develop “much later and [are] still not fully matured at the age of seven” (Friederici 2012: 1; also see Friederici 2017, this issue). This connectivity implicates the posterior area of the language network, which is focal in syntax–semantics integration, as an area of final late development of the architecture of the language network in the child. Given the language processing model we reviewed above, this delayed brain development may involve not the acquisition of syntax per se, but of syntax–semantics integration.

5.1. Convergence of the Neurobiology of Brain Development and the Neurology of Language Loss in Prodromal AD

The results from the brain development studies and our initial studies of cortical loss with dementia suggest a correlation. The area of functional connectivity in the

language network that has been discovered in early pilot imaging studies to underlie language deterioration in early prodromal AD generally corresponds to the area Friederici and collaborators have identified as the last developing in normal maturational development, viz., the posterior area of the language network and the default network converging on the IPL. If so, these data and this neurobiological model would appear to support a form of a RH regarding lifespan maturation of language. An area lost early in the course of dementia matures later in childhood.

5.2. *The Nature of Language Acquisition Over Time: Pursuing the Nature of maturational processes*

The challenge now for the development of a full maturational theory is to understand why neurobiological development of the language network appears to take the time it does (until age 7, or even later, adolescence), while much of basic syntax is generally acquired by the age of 3 (see, e.g., Lust 2006 for a review). Here we suggest that a coherent theory may be possible. When we look back to the evidence from language acquisition, we find that acquisition of complex syntax in the headed relative clause was late acquired, while another form of relativization, that is, headless forms (the ones we have argued to be more universally available given cross-linguistic typology; Flynn et al. 2005), is accessible early (Flynn & Lust 1980). This evidence was derived from analyses of language production in the child; and in Lust et al. (2015b) it was compared to production data from the prodromal MCI group in dispute of a regression hypothesis of language maturation. However, when we consider the comprehension data from the same child subjects we see that headless relatives are in fact always, across development until 7 years of age and beyond, recognized as semantically difficult. In this case, the child is performing an act-out task where they demonstrate their interpretation of a sentence by moving dolls (see Blume & Lust 2017). The child is naturally challenged to determine the unnamed reference of the head of the relative, that is, the referent of *what* in *Cookie Monster pushes what Big Bird throws*, in the face of several possible referents in the pragmatic context presented to the child.

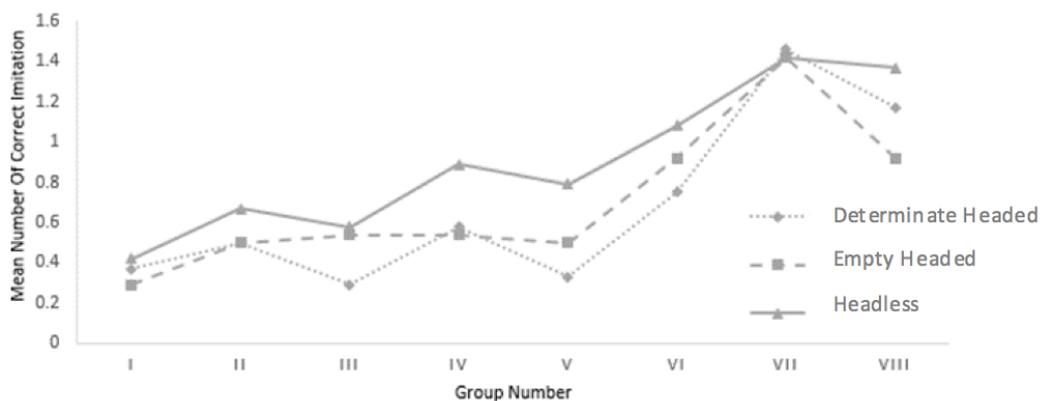


Figure 7: Mean number correct imitation for each head type by age group divided into eight 6-month age groups, ranging from 3.6–3.11 to 7.0–7.7; see Figure 2.

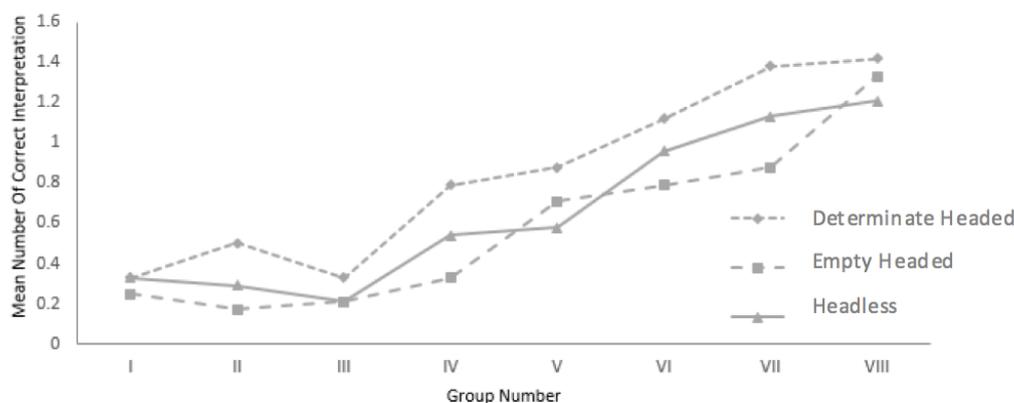


Figure 8: Mean number correct comprehension for each head type by age group. (Figures 8 and 7 result from a full experimental design in which Determinate (concrete headed) relatives are compared both to Headless relatives (cf. Table 1) and also to “empty headed” relatives with the noun head “thing”. This ‘thing’ condition was tested in order to try to dissociate the syntactic property of ‘head’ vs the semantic property of indeterminacy. See Flynn & Lust 1980.)

Results from comparison of the development of children’s production (Figure 7) and comprehension (Figure 8) in this study suggest that syntactic development (more clearly demonstrated in the production task) and semantic development (more clearly demonstrated in the comprehension task) are distinct. Even while comprehension of a headless relative is necessarily challenging semantically to children of all ages, it precedes the headed relative clause in development in the production task; it is only for ages 6.05–6.11 (group 7) and 7.0–7.7 (group 8) that comprehension and production appear to cohere in the integrated production and comprehension of the syntax and semantics in these sentences.

Thus, evidence may suggest a new hypothesis: Just as syntax–semantics integration is compromised in language loss with cerebral deterioration in prodromal AD, so syntax–semantics integration may develop only over time in normal first language acquisition, requiring a more protracted course of development than syntax per se. If so, these developmental results would converge with the neuroscientific evidence suggested by Friederici and collaborators, both for language processing and for language development.

6. Toward A New Developmental Theory

Our results lead us to support the view that in some ways “the brain basis of language develops continuously over time” (Friederici 2006: 941). At the same time, however, we argue that our results do not support a proposal that in language maturation “syntax gradually segregates from semantics in the developing brain” (Skeide, Brauer and Friederici 2014: 1), and “mastery of complex syntax is delayed” in the child. Rather, our results, including converging evidence from language acquisition and language loss, would suggest that syntax and semantics are to some degree independent continuously through development. The child does not show dominance of semantics, for example, in the case of relative clause acquisition,

but development of production of syntactically complex sentence formation proceeds even while semantics continues to develop independently. What “matures” or develops is the integration of syntax and semantics. That is, the older child and the adult, including the young and HA adult, efficiently integrate the independent knowledge of syntax and semantics, exemplifying efficient computation at the “language faculty interface” between these in sentence processing. In contrast, language deterioration, as in the case of prodromal dementia with cerebral degeneration, begins to sever this integration, leading to specific deficits where the syntax–semantics integration is most challenging; not in syntax itself. The MCI subjects first begin to fail not in syntactic structures that do not require more indeterminate semantic computation but where semantic computation challenges syntax–semantics integration (as in the computation of indeterminate reference in the case of headless relatives, for example).

This conclusion regarding language maturation coheres with both Friederici’s proposed serial processing model for sentence comprehension and the neuroscientific results regarding brain development during language maturation. At the same time, it coheres with our language acquisition studies as well as with our preliminary pilot neuroscientific results in language deterioration in MCI reported here.

Our results also argue for a re-interpretation of the “regression hypothesis” or “Ribot’s hypothesis”, which seeks to link acquisition with loss in a comprehensive developmental theory. We have seen that this RH does not hold in the case of acquisition of syntax per se (Lust et al. 2015b). The most complex, last-developed syntactic forms of relative clause structures are not the first lost in prodromal AD (MCI). In fact, in contrast to the RH, these are the structures that are best retained. However, based on results from the converging evidence reviewed here, there is new support for the RH hypothesis, at a more general level of analysis: If as we have seen,

- (i) neural structures involved in syntax–semantics integration are in fact the last to be developed,
- (ii) child language acquisition continuing post age 3 does involve a protracted development of integration of syntax and semantics, and
- (iii) first signs of language deterioration and neural degeneration in developing dementia do involve deterioration of the syntax–semantics integration component of language processing,

then, based on our findings and analysis, it can be argued that what takes the most time in the process of language acquisition, and is last developed in the child (i.e. the integration of syntax and semantics), is the most vulnerable and first lost in language deterioration. This would suggest that in a more comprehensive theory of language maturation, the RH deserves new examination.

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