Functional Connectivity of Brain Regions in Good and Poor Readers

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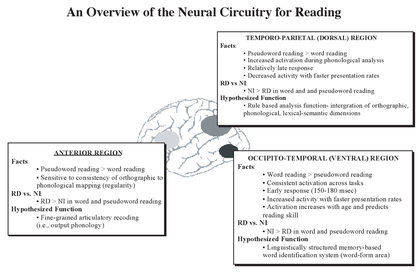
INTRODUCTION

Developmental dyslexia is characterized by an unexpected difficulty in reading in children and adults who otherwise possess the intelligence, motivation, and schooling considered necessary for accurate and fluent reading.[1] A large body of research has converged to implicate a specific processing deficit in dyslexia, namely, phonologic assembly, referring to an analytic decoding process associated with context-sensitive grapheme-to-phoneme mapping routines.[2,3] During development, nonimpaired readers learn to perform phonologic assembly in a nearly automatic fashion, yet dyslexic readers continue to exhibit labored, attentionally demanding, and error-prone decoding.

A Neurobiological Model

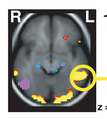
We have proposed a neurobiological model[4] of single-word word reading that identifies three important cortical sites:

- **the inferior frontal gyrus** (Broca) involved in recoding linguistic information into phonetic-gestural information, as a precursor to overt production;
- **the temporoparietal region** angular gyrus (AG) and supramarginal gyrus important for mapping from the orthographic to the phonological form;
- **the occipitotemporal region** (OT) acts as a developmentally modifiable fast word recognition system.

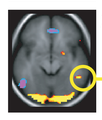


BACKGROUND

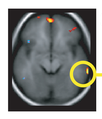
We previously reported[5] an fMRI study of good readers (N=74) and dyslexic readers (N=70) while they made semantic relatedness judgments on word printed pairs. We identified an area in left ventrolateral occipitotemporal cortex that showed a striking pattern of effects:



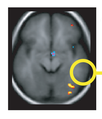
1) in good readers: activates strongly during reading;



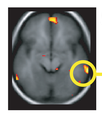
2) in dyslexic readers: activates minimally during reading;



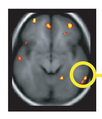
3) in good readers: correlates positively with age;



4) in dyslexic readers: no correlation with age;



5) in good readers: correlates with reading ability;



6) in dyslexic readers: correlates weakly with reading ability.

This pattern strongly suggests that the left OT develops, in good readers, to support fast and accurate word identification. In poor readers, additional frontal and right hemisphere areas correlate with skill.

Other studies have indicated that this area activates rapidly (~170ms) in response to words[6]; is roughly homologous to a site that supports expertise in visual object recognition[7]; and is affected by phonological[8] and semantic[9] manipulations.

Here, we examine the interactions of this area with other language sites, and how these interactions change as a function of age and reading ability.

METHODS

Functional Connectivity

The initial analysis examined effects within localized areas of the brain but did not assess the language network as a distributed neural system. Here, we assess relationships among brain regions, or functional connectivity. This is operationalized as region-to-region correlations, computed across subjects and seperately for each group. Differences in correlations across groups are used as an index of the difference in functional linkage of those regions.[10,11]

Subjects

In order to asesss connectivity changes associated with both development and reading ability, we split the original sample into four groups: young vs. old, and nonimpaired vs. dyslexic:

	Nonimpaired		Dyslexic	
	Young	Old	Young	Old
N	47	27	24	46
Age				
mean	9.4	13.5	10.1	14.9
min	7.6	11.5	7.9	11.5
max	11.5	17.8	11.5	18.4
Woodcock-Johnson Word Attack				
mean	507	519	476	493

Regions of Interest

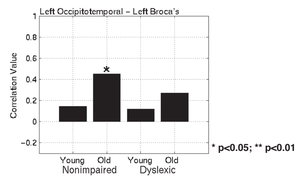
We selected a set of 8 regions of interest based upon our activation analysis and the literature:

#	hem	name	abbrev	Tal x	y	z
1	L	lateral occipitotemporal	LOT	-59	-40	-5
2	R	lateral occipitotemporal	ROT	60	-36	-5
3	L	Broca's area	LBR	-45	17	23
4	R	Broca's homologue	RBR	47	18	23
5	L	angular gyrus	LAG	-37	-62	41
6	R	angular gyrus	RAG	42	-60	41
7	L	medial occipitotemporal	LFU	-40	-48	-5
8	M	anterior cingulate gyrus	ACG	-4	41	5

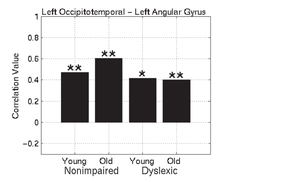
RESULTS: SINGLE CORRELATIONS

First, we examined connectivity among the three main reading sites: the occipitotemporal area, Broca's area, and the angular gyrus.

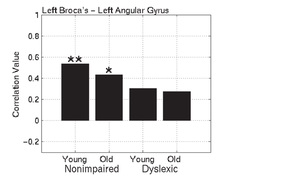
Occipitotemporal Area <-> Broca's Area:
- strong connectivity only in older good readers
- trend suggests an age-related increase



Occipitotemporal Area <-> Angular Gyrus:
- significant connectivity within each group
- numerically stronger in older good readers



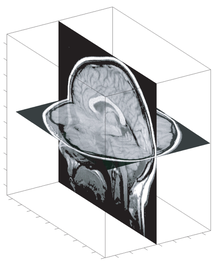
Broca's Area <-> Angular Gyrus:
- strong connectivity for good readers
- trend suggests an age-related decrease



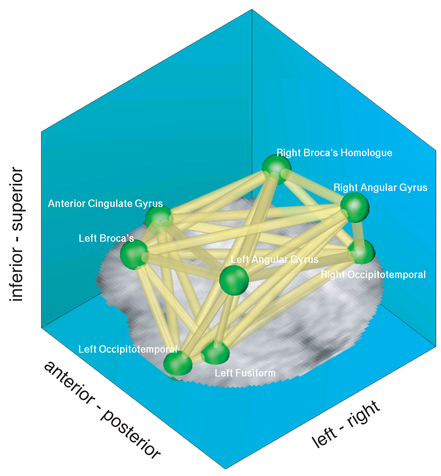
RESULTS: ALL CORRELATIONS

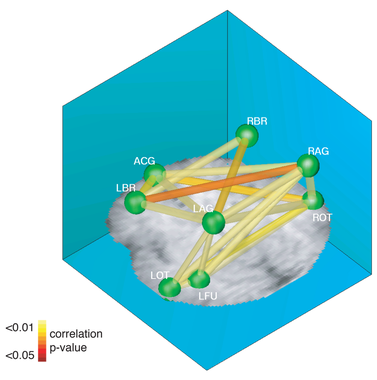
Second, we examined the correlations among a larger set of regions to visualize the larger network employed by each group.

Viewpoint is from behind the left hemisphere:

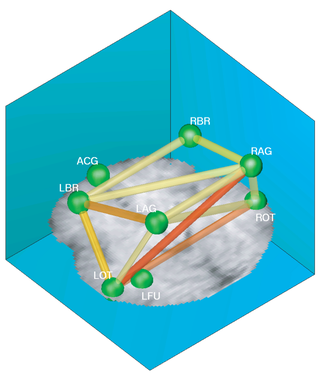


Regions of interest are shown with green blobs and correlations are shown with connecting lines (here, all possible correlations are shown):

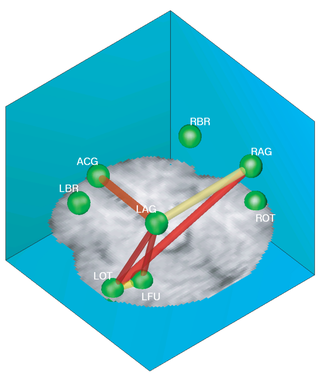




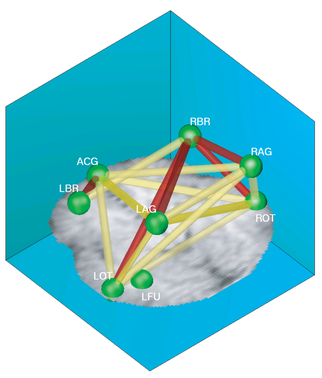
Younger good readers (7-11.5 years) show a set of significant correlations, including:
- Broca <-> left AG;
- left AG <-> left OT.



Older good readers (11.5-18 years) also show many significant correlations, including:
- Broca <-> left OT;
- Broca <-> left AG;
- left AG <-> left OT.



Younger dyslexic readers (7-11.5 years) show a more restricted set of correlations, including:
- anterior cingulate gyrus <-> left AG;
- left AG <-> left OT.



Older dyslexic readers (11.5-18 years) again show a wide set of correlations, including:
- anterior cingulate gyrus <-> left AG;
- left AG <-> left OT;
- anterior cingulate gyrus <-> left OT.

RESULTS: MULTIVARIATE ANALYSIS

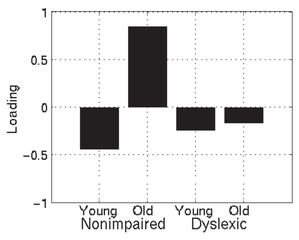
Third, we applied Partial Least Squares analysis (PLS)[12] to identify sets of correlations that change with age, or as a function of reading ability. PLS extracts a set of multivariate components, where each represents a pattern of region-to-region connectivity that differs among the groups.

Components are described by two sets of loadings:

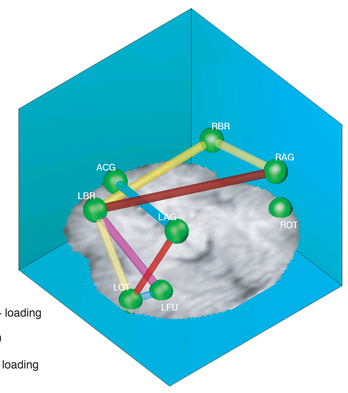
Group Loadings indicate which groups express the correlational pattern:

Brain Loadings indicate the correlational pattern:

Component 1

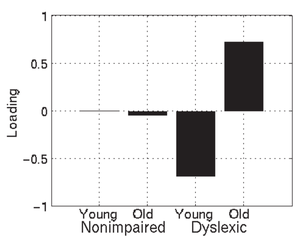


Group loadings indicate a correlational pattern that is more strongly expressed for older good readers, relative to the other groups.

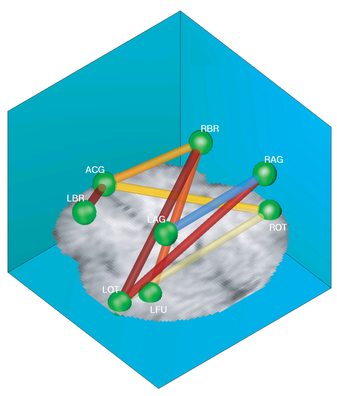


Brain loadings identified a set of region-to-region correlations, including:
- left Broca <-> left OT;
- left AG <-> left OT;
- left Broca's <-> right Broca.

Component 2

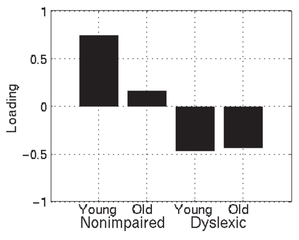


Group loadings indicate a correlational pattern that is more strongly expressed in older dyslexic readers, relative to younger dyslexics.

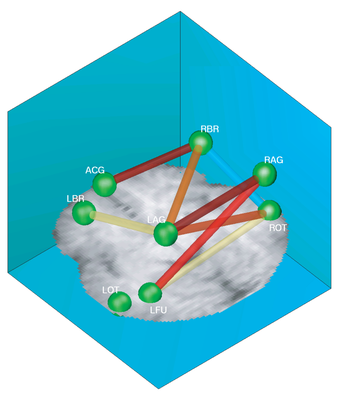


Brain loadings identified a set of region-to-region correlations, including:
- left OT <-> right Broca & right OT & right AG;
- anterior cingulate <-> left Broca & right Broca;
- anterior cingulate <-> right OT.

Component 3



Group loadings indicate a correlational pattern that is more strongly expressed in younger good readers, relative to the other three groups.



Brain loadings identified a set of region-to-region correlations, including:
- left Broca <-> left AG;
- anterior cingulate <-> right Broca.

DISCUSSION

With age, good readers develop a particular set of functional connections among the areas in the reading network. Connections between the left occipitotemporal area and Broca's area are strengthened, and connections between the left angular gyrus and Broca's area are weakened. This is consistent with the hypotheses that

(i) initial development of reading is supported by decoding processes involving the angular gyrus; and

(ii) later development of skilled reading is supported by the occipitotemporal site, serving as a trainable, linguistically structured word-form identification area.

In contrast, dyslexic readers strengthen different functional connections with development. In particular, the left occipitotemporal area increases connectivity with right hemisphere sites, homologous to the LH sites more typically associated with linguistic function. We suggest that compensatory strategies, such as recognition based upon the whole-word visual form, are supported by the additional recruitment of these RH sites in dyslexics. We additionally observed increased connections among the anterior cingulate gyrus, a site associated with attention and cognitive control, and Broca's area, Broca's homologue, and the OT homologue. This is consistent with the more effortful, attentionally demanding processing characteristic of dyslexia.

Conclusions

Functional connectivity, the interaction of brain regions, shifts during development and differentiates good and poor readers. Results support the notion that fluent, skilled reading is supported by the development of a word identification area located in occipitotemporal cortex. Ongoing studies will continue to assess functional connectivity among these sites, and its modification by training and intervention in developmental dyslexia.

Acknowledgments

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