The Reading Brain as a Statistician: An fMRI Study of the Artificial Grammar Learning Paradigm in Young Good and Poor Readers

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INTRODUCTION

Developmental dyslexia has been associated with implicit (e.g. Pavlidou et *al.*, 2009; 2010; 2014) /procedural learning (e.g. Nicolson & Fawcett, 2007; see Lum et *al.*, 2013 for a review) difficulties. Whether such difficulties are the cause or consequence of the disorder (or whether they are specific to developmental disorders) is still an open question. Based, therefore, on the proposed relationship between implicit learning and reading (e.g. Arciuli et *al.*, 2012; Frost et *al.*, 2013), we aimed to examine the neural signature of implicit learning in children using the AGL paradigm.

Most fMRI studies have examined the neural response at test (i.e. outcome) (e.g. Forkstam et *al.*, 2006; Lieberman et *al.*, 2004; Yang & Li, 2012) rather than acquisition (i.e. process) based on the untested assumption that learning unfolds uniformly over time. Thus, we developed a design that enables the investigation of the neural substrates underlying the process as well as the outcome of implicit learning for the first time in young children; putting at test the assumption that the process of learning and the result of learning are interchangeable.

Our findings contribute significantly to the understanding of the potential role implicit learning may play in fluent and dysfluent reading.

METHODS I

Participants

	N	CA*	IQ*
TD	18	8.8 (SD = 1.1)	≥ 70
DD	11	8.8 (SD = 1.1)	≥ 70

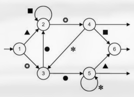
*CA = chronological age, *As measured by WASI

Materials

A. Behavioral Measures:

WASI; CTOPP; WJ III; TOWRE

B. The AGL Task:



Christiansen *et al.*, 2010 experimental grammar.

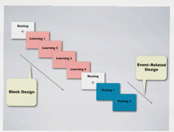
structured item:

unstructured item:

φ φ φ φ φ φ
ψ ζ φ δ ξ
ξ φ ψ

METHODS II

MRI Task Design



Learning: 2 stimulus conditions: *randomly* ordered *unstructured* trials (Greek letters) and *structured* trials (shapes). 4 functional runs: 3 blocks (2 str-1 unstr/ 2 unstr-1 str).

Testing: 40 items (*20 items per run*), which were balanced for: 1) Grammaticality; 2) Chunk Strength; 3) Anchor strength; 4) Novelty; 5) Novel fragment position; 6) Global similarity; 7) Length.

RESULTS I

Behavior (in scanner) at test:

We run *t*-tests to explore whether children's test performance after passive exposure was above chance.

TD: no learning at group level

One-Sample Test

	Test Value = 20					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference: Lower	Upper
InScanner_AGL_Total	-1.829	17	.085	-1.6667	-3.589	.256

DD: no learning at group level

One-Sample Test

	Test Value = 20					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference: Lower	Upper
InScanner_AGL_Total	-1.227	10	.248	-1.0909	-3.071	.890

Participants cross-tabulation based on AGL above chance performance

Group1TD2RD * AGLLLearnerNLNotLearner Crosstabulation

Count

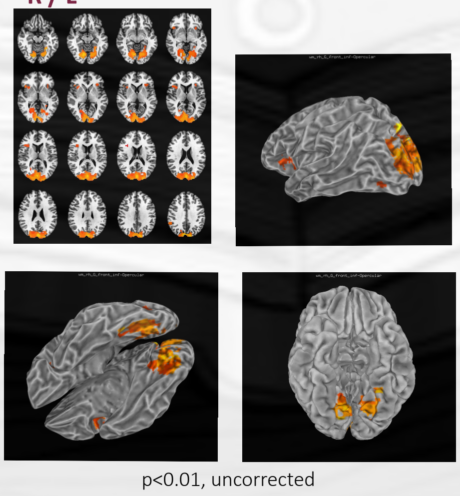
		AGLLLearnerNLNotLearner		
		L	NL	Total
Group1TD2RD	1.0	3	15	18
	2.0	5	6	11
Total		8	21	29

RESULTS II

Brain (learning process):

We extracted the learning effect from the MRI images as the difference between structured blocks, and unstructured blocks, excluding the first block before learning occurs. Our first analysis looked across the whole sample.

Structured-Unstructured
[blocks: 2+3+4+5+6]



p<0.01, uncorrected

Key Areas of Activation:

Cuneus; Insula; Inferior Occipital Gyrus/Fusiform

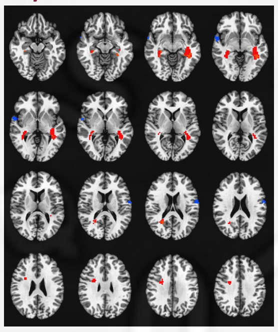
RESULTS III

Average BOLD signal response based on functionally defined clusters that show up in the [**Structured** - **Unstructured**] map (see **Results II**).

RESULTS IV

Next, we split the sample based on whether participants showed significant learning (N=8) or not (N=21).

Learner vs Non-Learner
[Structured - Unstructured]



p<0.05, uncorrected

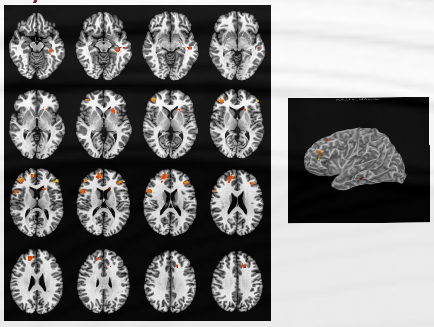
Key Areas of Activation:

Parahippocampal areas; Hippocampus

RESULTS V

Next, we split the sample based on whether participants had reading difficulties (N=11) or not (N=18).

Dyslexic vs Control
[Structured-Unstructured]



p<0.01, uncorrected

Key Areas of Activation:

Putamen; Inferior Frontal Gyrus; Medial FG

CONCLUSIONS

Overall, our data on passive learning (process) confirms findings from adult AGL studies implicating similar areas of activation during test (outcome) such as bilateral **Cuneus**, **MFG** and **PL** (see Karuza, Emberson & Aslin, 2014 for a review): we observed increased activity throughout the occipital, parietal, and prefrontal cortical areas, reflecting the complex nature of the task (visually presented stimuli, decision processes about the stimuli etc.) and suggesting that such areas maybe recruited early to facilitate and optimize test (i.e. outcome/ grammaticality decisions) performance.

Frontostriatal networks such as the MFG as well as the **Insula** and **Basal gaglia** (e.g. **Putamen**) are regularly reported to subserve procedural learning. It has also been proposed that the striatum could play a role in optimizing behavior over time. However, based on TD adult data, it is proposed that these areas become less activated/engaged for overlearned materials: our data shows an increased engagement of such areas at initial stages of learning but a decrease in activation over time for structured items.

MTL (Hippocampal/ Parahippocampal) response pattern maybe attributed to potential similarity-based learning, which appears to govern the initial state of learning in AGL and which is no longer used once the 'rules' have been acquired (e.g. Bahlmann et *al.*, 2009) and hence a shift is expected to the left IFG during the later part of the task. However, given that we appear to have accidentally sampled more AGL learners with DD, our data on DD vsTD and L vs. NL needs to be revisited.

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