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Title : Developing Language Abilities by a non-verbal training : A fMRI study.

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Abstract

Introduction

The language ability is a critical aspect of experimental design in functional imaging studies. Today, it is commonly accepted that the brain structures underlying the language are more distributed than the traditional Broca's and Wernicke's areas. Currently, some other areas as the premotor cortex, the supplementary motor area, the cerebellum or subcortical structures, notably, are recognised. However, a lesser studied question is to define if it is possible to observe a reorganisation of the activation observed during language tasks when the subjects have been trained to develop non-verbal abilities. Particularly, Bates and Ellman (1996) claim that probabilistic regularities are the basis of the language acquisition processing.

Objectives : Then, our goal was to test wether if it is possible to develop some activations in areas implicated during language tasks by specific non-verbal probabilistic activities.

Subjects : 10 subjects have been trained to develop their probabilistic abilities by using specific tools : the Concrete Representations of Formal Systems. 10 others subjects composed a control group.

Results : Results show a greater activation in subcortical structures (in basal ganglia) during a verb generation task, particularly in the anterior part of the caudate nucleus for the experimental group.

Conclusion : It might thus be possible that this area represents a "crossroad" between verbal and non-verbal activities.

Keywords: basal ganglia. cerebral reorganisation. language development. non-verbal learning. probabilistic learning. syntactic processes.

Running head : Non-verbal learning and neuronal activity of language

Introduction

It is now commonly accepted that the brain structures underlying the language are well distributed in the brain. Notably, some activations can be observed in the superior motor area or premotor cortex during phonological perception tasks (Fiez, Raife, Balota, Schwarz & Raichle, 1996 ; Zatorre, Meyer, Gjedde & Evans, 1996), phonological production tasks (Gelfand and Bookheimer, 2003 ; Heim, Opitz, Muller & Friederici, 2003) or manipulation of sentences (Homae, Hashimoto, Nakajima, Miyashita & Sakai, 2002 ; Indefrey, Brown, Hellwig, Amunts, Herzog, Seitz & Hagoort, 2001). Wildgruber, Ackermann & Grodd (2001) also observe an implication of the precentral gyrus, the anterior part of the insula, the right cerebellum and the basal ganglia. All of these results tend to prove that the language activity implies the activation of different parts of the cortex, sometimes not specifically attributed to the language itself. Similar arguments have been proposed recently by Ullman (Ullman, 2001, 2004; Ullman, Corkin, Coppola, Hickok, Growdon, Koroshetz & Pinker, 1997) who claimed in his Declarative/Procedural Model that **some parts of the brain are involved both in language activities and in non-verbal activities**. He highlights two principal areas during a language task: the left superior temporal gyrus underlying the semantic part, and the left inferior frontal gyrus and the basal ganglia, activated when subjects use grammatical structures. Interestingly, these structures are also activated during many non-verbal cognitive tasks, as the implicit procedural learning (Echenbaum & Cohen, 2001), probabilistic rule learning (Knowlton, Mangels & Squire, 1996 ; Poldrack, Prabhakaran, Seger & Gabrieli, 1999) or sequence learning (Aldridge & Berrigdge, 1998 ; Peigneux, Maquet, Meulemans, Destrebecqz, Laureys, Degueldre, Delfiore, Aerts, Luxen, Franck, Van der Linden & Cleeremans, 2000).

Interestingly, a similar hypothesis has been proposed in a completely different context. Notably, in developmental psychology, Saffran, Aslin and Newport (1996, see also Saffran,

2001) observed that 8 months-old children are able to discriminate pseudowords providing from an artificial language on the basis of the probabilistic structures of this language only. Seidenberg (1996) interpreted this observation as the proof that the probabilistic constraints in the learning processes can favour the development of cognitive structures. According to these authors, an individual must discover the regularities of his environment to acquire the language ability.

The present study goes one step further in that direction: we postulate that these regularities can be provided by non-verbal examples, and that it is possible to develop the activation of the cortical structure underlying them (i.e. basal ganglia).

To test this hypothesis, we choose to propose some logical probabilistic problems presented by a concrete tool : a Concrete Representation of a Formal System (CRFS). “A CRFS is a set of tools which is furnished with technical constraints. These constraints make certain actions possible and others impossible: from these facts a logical structure is suggested” (Lowenthal, 1991). During the manipulation of these objects, subjects must discover the regularities providing from the material. More precisely, subjects must discover some sequences inside complex streams of letters (ex: AABAABAAB).

Previous research with CRFSs has shown that these tools favour language learning in normal children and develop the formulation, testing and adaptation of hypotheses (Lowenthal, 1992). We also observe a development of the visuospatial analysis (Lefebvre, 2002) and reading abilities (Lowenthal, 1986). Another set of clinical studies has shown that the manipulation of these materials offer the possibility for subjects having lost cognitive functions to reacquire them, at least partially. Some interesting results have been observed in patients with focal brain injuries, particularly for redeveloping some language functions (Lowenthal & Saerens, 1982 ; Mauro, 1990).

Objectives

On the basis of these previous results, we formulate the hypothesis that an intensive non-verbal training based on the detection of probabilistic regularities in a situation with few simple but specific rules (i.e. hereafter called microworld), could lead to a functional reorganisation of language-related activations, which could be detected by fMRI. Dominey and his collaborators (Hoen et al., 2003) have already shown the specific learning should transfer between non-linguistic and linguistic domains via a common neural basis. Notably, they studied effects of non-linguistic perceptual sequence training on syntactic comprehension of six left-hemisphere damaged aphasic patients and discovered a link between non-verbal sequences and grammatical ability.

Another set of studies (Houdé, Zago, Mellet, Moutier, Pineau, Mazoyer & Tzourio-Mazoyer, 2000 ; Houdé, Zago, Crivello, Moutier, Pineau, Mazoyer & Tzourio-Mazoyer, 2001) has shown that the expertise gained by some specific learnings can induce changes in the activation pattern associated with a given task (i.e. a reasoning task in these studies). The goal of this paper is to define if it is possible to observe a same type of switching for cerebral activations underlying the language, comparing activations observed by training subjects at a post-test versus control subjects without any training.

Methods

General study design and subjects

Twenty healthy French-speaking volunteers (14 females and 6 males, 18-20 years of age) participated in this study. All subjects were right handed by self-report and scored between 75 and 100 on the modified Edinburgh handedness scale (Ransil and Schacter, 1994). Subject selection took place about one week before the pretest, and selected subjects gave their informed consent. This study was approved by the Ethical Comity of the University of Mons-Hainaut (Belgium).

During a pretest, each subject was tested to evaluate his language by a spelling-grammatical test (Doutriaux et Lepez, 1980). This test evaluates the spelling and grammatical ability degree, and allows to define a “behavioral” score for each of our subjects. These results were used to divide a 20 subjects population into two ten-subjects groups of equivalent grammatical ability. Also, the men/women proportion was the same in both groups. Each participant has been confronted to a language fMRI protocol. After this evaluation, an experimental group (EG) has been submitted to an experimental training, based on the perception of environmental regularities presented by CRFS, while the control group (CG) had no activities during the experimental phase. Finally, each participant (experimental and control) had to undergo a second fMRI evaluation.

Experimental training

The « Experimental Group » (EG), composed by 10 subjects, has been submitted to four one-hour training sessions (Lefebvre, 2005), one per week, where they were confronted individually with logical exercises presented by a CRFS material: the Dynamical Mazes.

Dynamical Mazes represent a construction set where subjects must elaborate a network on a base-board with small pieces (see Figure I).

Fig I

This material has built-in constraints which restrict the possible actions carried out by the subjects. During the manipulation of this object, subjects must discover the regularities inherited in the material. In fact, our CRFS is a finite automaton consisting of “a control block capable of assuming various states, an input channel and an output channel” (Trakhtenbrot & Bardin, 1973, p.1). The bricks of a Dynamical Maze are fundamental elements which allow to simulate small mechanical computers (Lowenthal, 1986). Subjects have two activities when they manipulate this tool: a “construction” activity (where subjects have to elaborate a network on their boards) and an “exploitation” activity (where subjects have to discover the regularities provided by the network for elaborating a general rule based on the exits regularities).

In fact, switches (the complex mechanisms on the Figure I) can be opened on the left or on the right. In figure I, both switches are opened on the right, and if a mobile is inserted at the bottom of the network, it goes out through output B. Our switches have the characteristics that if a mobile goes throughout them, a mechanism moves the two squares and the small triangle and opens the circuitry on the other side. In our example, after the way of the mobile, the two switches are opened on the left, and a second mobile should go out through output A. During the “exploitation” activity, subjects must elaborate a synthesis table for elaborating hypotheses about the exits. For example, the table 1, which corresponds to the table related to the Fig. 1, allows to observe that the trains 1-5-9-…go out through the outpout B. Then, subjects can conclude that the train 101 goes also out through output B as all trains "4 X+1". Elaborating this kind of generic rules implies to perceive that circuitry have a specific regularity : "BAAA".

Trains	Mechanisms		Output
	Mechanism 1	Mechanism 2	
1	R	R	B
2	L	L	A
3	R	L	A
4	L	R	A
5	R	R	B
6	L	L	A
7	R	L	A
8	L	R	A
9	R	R	B
10			

Table 1: An example of synthesis table elaborated by subjects.

"Mechanisms" represent the state of the circuitry mechanisms when "the train" is introduced in the network. L : (open on the) left ; R : (open on the) right.

The discovering of the regularities, but also the built-in constraints of the tools (some pieces have characteristics which imply that subjects discover the environmental constraints of the microworld by themselves), allows to present a probabilistic component for all of our exercises.

MRI sequences

MRI scans were performed on a 1.5T Philips Intera System equipped with a standard quadrature head-coil. Functional images were obtained with the blood oxygenation level-dependent (BOLD) contrast method, using a gradient-echo single-shot EPI sequence with the following parameters: repetition time 3000ms, echo time 50 ms, field-of view 200mm, matrix 64x64, 32 slices of 4.85mm thickness with no gap (whole brain coverage). An anatomical reference scan was acquired for each subject using a T1-weighted 3D gradient-echo sequence with an isotropic resolution of 1.3mm.

fMRI Protocol

The fMRI experiment involved a visual presentation of thirty nonsense drawings (see Picture II), thirty writing pseudowords and thirty writing words.

Fig II

The subject was instructed:

1) to look at the forms (rest condition) ;
2) silently read pseudowords ;
3) silently generate a verb associated with each word.

The drawings were designed to globally simulate the visual load of a word. The pseudowords were chosen to present only “Consonant-Vowel-Consonant-Vowel” combinations to simplify the task. Finally, to ensure that words were sufficiently simple to generate a verb within 3 seconds, we first tested fifty 6 to 8 years-old children. For all stimuli chosen, 80% of the children had to be able to generate a verb within the 3 seconds while the rhythm of the presentation of stimuli was the same as the rhythm used during the fMRI experiment. The number of letters of pseudowords and words was correlated.

The total session lasted 4 minutes and 30 seconds divided in nine 30 seconds blocks, each consisting of ten nonsense characters, ten pseudowords and ten words. Stimuli were presented at a rate of one per three seconds (i.e. one per dynamic scan). Each subject underwent two such sessions before and after (non-)training.

fMRI Data analysis

The acquired images were analysed off-line by means of the statistical parametric mapping tool SPM2 (University College London, UK). Pre-processing steps included (Friston, Ashburner, Frith, Poline, Heather and Frackowiak, 1995) realignment of functional images, coregistration between anatomical and functional scans, normalization of all scans to the Talairach atlas (Talairach and Tournoux, 1988), and Gaussian spatial filtering (smoothness = 10 mm, full-width at half maximum). Single-subject analyses were performed using a fixed-effect box-car model convolved with an estimate of the hemodynamic response. For each subject and session activation clusters were defined by applying the threshold $t = 4.5$ (p uncorrected <.0001; p corrected <.001 at the cluster level). Since no significant differences were found between the first and second sessions, both sessions were averaged in the analysis. A random-effects analysis was also performed to assess significant activations among the control population, using the previously obtained contrast images as input for a one-sample t-test (Friston, Holmes and Worsley, 1999). Same statistical thresholds were used in the single-subject analysis. Moreover, averaged activation maps obtained during the language tasks were contrasted before (prestest) and after (post-test) experimental training. The threshold for activation significance was the same as for the one sample t-test.

Results

Behavioral tests

Linguistic Modalities Mean Score (Standard Deviation)	Experimental Group (N = 10)	Control Group (N = 10)	p. values
Grammar	29 (SD=4,6)	27,5 (SD=5,4)	p = .777 (t = .288)
Spelling	29,6 (SD=4,7)	27,8 (SD=5,3)	p = .611 (t = .518)

Table 2: Means, Standard deviations and p. values for comparison of the behavioral Scores of experimental and control groups

The results of the behavioral pretest are presented in Table 2. Results show that our groups are equivalent at Grammar and Spelling levels at the beginning of this study.

Imaging Findings

Three modalities are compared : pseudowords-rest (P-R), verb generation-rest (V-R) and verb generation-pseudowords (V-P) for experimental group (see Table 3) and for control group (see Table 4) at two different times : before (i.e. pretest) and after (i.e. post-test) the training.

For experimental group

	Pseudowords - rest						**Verb Generation - rest**						**Verb Generation - Pseudowords**					
	Pretest			**Posttest**			**Pretest**			**Posttest**			**Pretest**			**Posttest**		
Region (Brodmann's Area)	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Frontal Lobe																		
SMA (6)	-3	-1	50	-10	12	48	-4	0	60	-12	14	56	-8	10	52	-8	16	46
Premotor Area (6)				-50	8	26				-46	36	24	-35	-3	56	-27	5	59
Inferior Frontal Gyrus (44)	-53	2	11	-58	18	2	-44	20	4	-47	20	10						
Temporal Lobe																		
Superior Temporal Gyrus (22)										-60	-42	-1						
Occipital Lobe																		
Lingual (17)	-5	-89	-1	-8	-99	2	-1	-79	-10	-8	-98	-10						
Dorsal Extrastriate (18)							-7	-96	11									
Subcortical Areas																		
Anterior Cingulum (24/32)	-8	-16	44	-8	16	30	-8	22	38	-10	20	32	-8	20	44	-8	22	34
Putamen + globus pallidus *Left*							-11	-5	4	-13	4	6						
Right										21	15	0						
Cerebellum							33	-63	-30	30	-80	-42	6	-76	-22	18	-59	-38

Table 3: Talairach coordinates of centers of gravity of significant activations for the experimental group – random effect analysis, one-sample t-test (X = Left (-)/ Right (+); Y = Posterior (-)/Anterior (+); Z = Feet (-)/ Head (+))

For Control group

	Pseudowords - rest						**Verb Generation - rest**						**Verb Generation – Pseudowords**					
	Pretest			**Posttest**			**Pretest**			**Posttest**			**Pretest**			**Posttest**		
Region (Brodmann's Area)	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Frontal Lobe																		
SMA (6)	-6	10	49				-12	6	58	-2	8	52	-18	4	56	-4	14	38
Premotor Area (6) *Left*	-50	4	25	-52	-2	39	-44	18	36	-38	1	44	-44	20	38			
Right	48	5	51															
Inferior Frontal Gyrus (44)				-53	8	9				-39	13	-1						
Temporal Lobe																		
Superior Temporal Gyrus (22)										-50	-44	-1						
Occipital Lobe																		
Lingual Gyrus (17)	-16	-84	-4	18	-86	-12	0	-78	-4	6	-72	-9				-4	-78	5
Subcortical Areas																		
Anterior Cingulum (24/32)							10	28	32	8	18	38				10	18	36
Posterior Cingulum (30)	9	-55	-24													8	-22	32
Putamen + Globus Pallidus							-16	7	5									

Thalamus							-7	-22	3				-4	-7	7			
Cerebellum							46	-60	-38	13	-81	-39	37	-64	-40	29	-54	-34

Table 4: fMRI coordinates of significant activations for the control group

Discussion and conclusions

The goal of this research was to observe if a specific training, based on the manipulation of a concrete tool allowing to present regularities, develops specific activations on the language parts of the brain. More precisely, we postulated that basal ganglia, activated during grammar activity and perception of regularities, can be influenced by this kind of technique.

Cortical Activity

General observations

Both groups present left hemisphere dominance for language tasks, as evidenced by the number of activations in the left part of the brain, compared to the other side. Large hemispheric activities are seen particularly in frontal (supplementar motor, dorsal premotor and Broca's areas) and in the occipital (lingual) areas, but also in the right cerebellum.

Broca's area is activated during a pseudowords reading task as well as during a generating verbs task. This result confirms some observations describing Broca's area as the centre of the phonological production (more particularly, the pars opercularis (Houdé, Mazoyer and Tzourio-Mazoyer, 2002)) and of the graphemic-phonemic conversion. Moreover, the left-prefrontal network is involved in inner speech (Houdé, Zago, Mellet, Moutier, Pineau, Mazoyer & Tzourio-Mazoyer, 2000; Jonides, Smith, Marshuetz, Koeppe & Reuter-Lorenz, 1998; Price, 1997; Price, Wise & Frackowiak, 1996).

Finally, the right cerebellum activation confirms its implication in language tasks, probably in its motor aspects (Gebhart, Petersen & Thach, 2002; Papathanassiou et al., 2000; Riva & Giorgi, 2000). More precisely, we observe that the right cerebellum is only activated during V-R and V-P tasks in both groups, before and after training. This result is consonant with a semantic implication of this structure (strongly implicated in verb generation tasks), but not phonologic (specific to the pseudowords tasks) and can adequately complete the Desmond and Fiez's (1998) observations who have proved the influence of the right cerebellum in the language activity.

A more subtle result is observed in the experimental group, where the premotor cortex is only activated after our treatment (P-R and V-R), as already observed by Duffau, Capelle et al. (2003). This result seems to indicate that this area, involved during some language tasks, can be more activated after a non-verbal training. This activation reflects a state of preparedness for selecting the motor response, necessary to formulate the response (Petit, Courtney, Ungerleider & Haxby, 1998). If, at the beginning, this ability is not correctly acquired by subjects, it seems to be possible that manipulating CRFS can help subjects to develop their faculties to select correct motor sequences.

Subcortical Activity

The activations of subcortical structures are relatively subtle. First, we observe that these structures are involved when subjects produce verbs but are not activated during the pseudowords task. It indicates that the left Basal Ganglia tend to be particularly used during a word selection task process.

We found a subcortical activation during the pretest for all of our subjects (Experimental and Control) when they must generate verbs. But, after our treatment, we observe a great increase in the left Putamen and in the Globus Pallidus for our Experimental Group (Table 5). However, at the post-test for the control group, no subsequent significant activation was highlighted.

	Experimental Group								**Control Group**							
	Pretest				Posttest				Pretest				Posttest			
	X	Y	Z	CS	X	Y	Z	CS	X	Y	Z	CS	X	Y	Z	CS
	-11	-5	4	1,75	-13	4	6	10,4	-16	7	5	0,86				

Table 5: Comparison of the putamen and globus pallidus’activities between EG and CG

Note: CS in cm^3 : Cluster Size

We clearly observe a greater activation in the bilateral caudate nucleus and the Globus Pallidus structures after the experimental phase as shown on the slices presented in the following (See Figure II). If we have 1,75 cm^3 cluster size at the pretest of our EG, a 10,4 cm^3 cluster is observed during the posttest analysis. In contrast, we have not great specific activations at the posttest for the CG.

Fig III

A single-subject analysis of the subcortical activity shows that half of our experimental group presents greater Caudate nucleus activation (i.e. a bigger cluster size after the training) at the post-test than at the pretest, and only two subjects have a weaker activation after the training. By comparison, anyone in the control group shows an activation at the post-test, when we carry out a single-subject analysis, as shown in Table 6.

Subjects	**Pretest**	**Post-test**
Experimental group		
D.T.	0	0
L.E.	0,55	0
L.A.	0	0
R.D.	0	0
L.J.	0	4,42
G.O.	2,27	0,66
A.V.	0	1,2
P.J.	1,14	6,7
P.S.	0	1,55
F.S.	0	0,7
Control group		
C.O.	0	0
T.P.	1,99	0
D.T.	0	0
B.M.	0,12	0
F.A.	0	0
L.S.	1,07	0
V.A.	0	0
L.L.	0,38	0
D.D.	0	0
D.P.	0	0

Table 6: Comparison of the clusters sizes (cm^3) between pretest and post-test in the caudate nucleus; single-subject analysis

While the comparison between groups is non-significant at the pretest (Z = .177, α = .912), a significant difference is highlighted at the post-test for the experimental group (Z = 2.8, α = .023). Notably, all subjects who present a greater activation at the post-test where submitted to the training phase (N = 5), showing that our training should develop the activation of these specific structures. Duffau, Bauchet, Lehericy and Capelle (2001) have equally shown that this area is implicated in the motor sequences'program, particularly if they are relatively complex. Our training of sequencing activities, based on the perception of regularities presented by the manipulation of concrete tools, seems to develop the activation of the premotor cortex and these subcortical structures. Our results can explain the link, postulated by Saffran et al. (1996), that probabilistic abilities and language are strongly connected. If we refer to Ullman's works (2001, 2004), we can observe that basal ganglia are implicated during verbal activities, but equally during non-verbal activities. We think that the specificity of our tools, which allows learning at a probabilistic level, has developed the faculty of our subjects to elaborate language words. It is possible that non-verbal probabilistic exercises, which stimulate basal ganglia, develop some other cognitive activities, such language, also supported by this structure. An interesting explanation of the link existing between rules application and verb generation task has been highlighted by our subjects. In fact, many of them claim they used the first part of the word presented ("vol-" for "voleur" ; "livr-" for "livre"…) and added a traditional French verb ending ("vol" + er ; "livr" + er, …) to solve the verb generation task. It is clearly a basic rule application.

Another set of investigations needs to be conduced for observing if this increasing activation can be observed in a psychometric way. Moreover, it would be necessary to define if some other specific areas can also be influenced by our tools. Our results clearly indicate that a specific area, the left basal ganglia, is activated during language tasks and that specific exercises can develop this activation. But now, it should be interesting to define if some areas, traditionally accepted as more specific for the language activity, as Broca's area, can be influenced by a non-verbal learning. Further with brain injured patients could establish whether a non-verbal approach can help aphasic subjects, and if we can observe some different activations in their brain when they try to produce a verbal language after our treatment.

Developing Basal Ganglia activity might also be interesting to prevent the loss of activation caused by some neurodegenerative diseases, as Parkinson disease. Notably, further researches will have to investigate if developing the perception of environmental regularities can prevent some symptoms and maintain a correct degree of activity by this type of patients.

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Figure I : a Dynamical Maze – Switches are composed by two squares and one small triangle.

Figure II : Examples of nonsense drawings

Figure III: Comparisons between activations of the subcortical structures before and after the training, for experimental and control groups

Figure I:

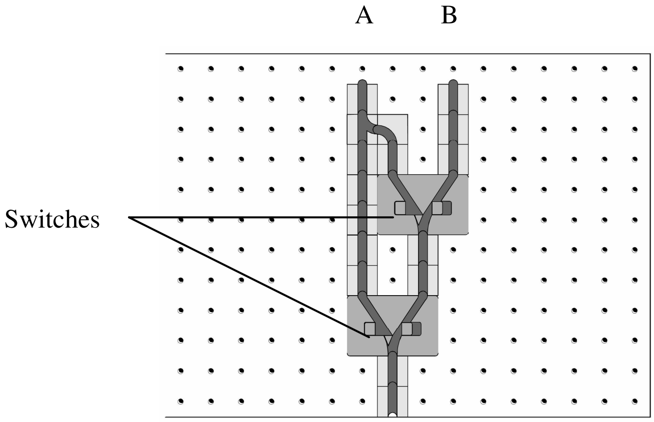


Figure II:

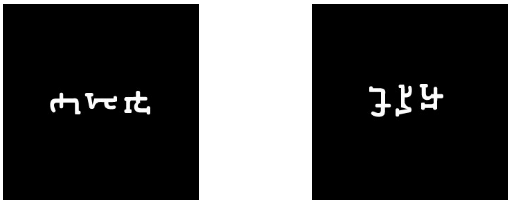
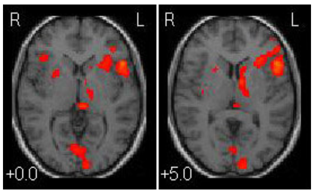
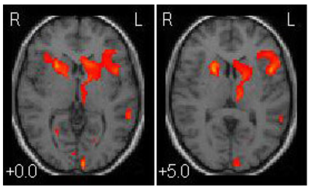


Figure III:

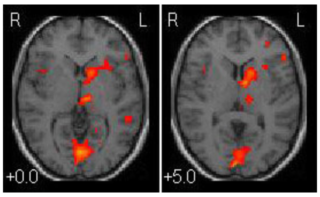
Experimental Group Pretest



Experimental Group Posttest



Control Group Pretest



Control Group Posttest