ORIGINAL ARTICLE

THE JOURNAL OF NEUROBEHAVIORAL SCIENCES
NÖRODAVRANIŞ BİLİMLERİ DERGİSİ

Year : 2015
Volume : 2
Issue Number : 2
Doi Number : 10.5455/JNBS.1433794984

Article history:
Received 14 June 2015
Received in revised form 2 September 2015
Accepted 7 September 2015

AN INVESTIGATION OF NEURAL CORRELATES IN ADULTS WITH DEVELOPMENTAL DYSCALCULIA USING FMRI

GELİŞİMSEL DİSKALKULİ SAHİBİ YETİŞKİNLERDE NÖRAL BAĞLANTILARIN FMRI İLE İNCELENMESİ

E. Seylan Şahin*[1]

JNBS 2015 Published by Üsküdar University www.jnbs.org

Abstract

Developmental dyscalculia is a specific learning difficulty which reflects deficits in arithmetical skills. The cause behind this disorder is not known. Recent studies provide evidence in favor of believing that the disorder is somehow tied with specific brain regions' roles. These regions include the intraparietal sulcus (IPS), the angular gyrus (ANG) and the supramarginal gyrus (SMG) in developmental dyscalculia. The present study investigates the role of these regions in adults with developmental dyscalculia. Brain images were collected from 10 participants with developmental dyscalculia and 10 control participants using fMRI while conducting number comparison, multiplication and subtraction tasks. The results revealed the activation of the intraparietal sulcus during number comparison and the activation of both the angular gyrus, the supramarginal gyrus, and the intraparietal sulcus during calculation tasks. These results suggest that the IPS activation was not less than the developmental dyscalculia group than in the control group when conducting the number comparison task; and that there were activation in the ANG, SMG and IPS regions of the brain in participants' brains during both the multiplication and subtraction tasks.

Keywords: cognitive neuroscience, developmental dyscalculia, fmri, angular gyrus, supramarginal gyrus, intraparietal sulcus.

Özet

Gelişimsel diskalkuli matematik yeteneğini etkileyen bir özel öğrenme güçlüğü formudur. Bu bozukluğa neden olan faktörler kesin olarak bilinememektedir. Son çalışmalar, diskalkulinin ortaya çıkmasında beyindeki spesifik bölgelerin etkili olabileceği yönünde kanıt ortaya koymaktadır. Bu beyin bölgeleri arasında; intraparyetal oluk, angular girus ve supramarjinal girus yer almaktadır. Bu çalışma, bu bölgelerin gelişimsel diskalkulideki rollerini araştırmaktadır. Çalışmaya 10 gelişimsel diskalkuli sahibi yetişkin, 10 da kontrol grubu olmak üzere 20 katılımcı dahil olmuştur. Katılımcılar sayı kıyaslama, toplama ve çıkarma işlemlerini yaparken fMRI ile beyin aktiviteleri görüntülenmiştir. Sayı kıyaslama esnasında intraparyetal olukta beyin aktivasyonu tespit edilmiştir. Toplama-çıkarma esnasında intraparyetal oluk, angular girus ve supramarjinal girusda beyin aktivasyonu tespit edilmiştir. Sayı kıyaslama esnasında IPS de gözlenen aktivasyon diskalkulik grupla kıyaslandığında kontrol grubunda daha az saptanmamıştır. Ayrıca, toplama-çıkarma esnasında da ANG, SMG ve IPS'de de aktivasyon gözlenmiştir.

Anahtar Kelimeler: *kognitif nörobilim, gelişimsel diskalkuli, fmri, angular girus, supramarjinal girus, intraparyetal oluk*

Introduction

The term "Developmental Dyscalculia" refers to a specific learning difficulty which affects mathematical abilities and mathematical learning. Individuals with developmental dyscalculia may have difficulties in understanding simple number concepts, acquiring mathematical skills, and learning number facts and procedures (Hannell, 2013).

In recent years, there is an increasing agreement that developmental dyscalculia has a neuropsychological basis which is characterized by deficits in basic numerical skill; for instance, number comparison and number sense, such as to be able to calculate mathematical problems in your head and number fluency (Landerl, Bevan & Butterworth, 2004; Rubinsten & Henik , 2005; Butterworth, 2005; Gersten & Chard, 1999). Even research on developmental dyscalculia has increased recently, the causes of which are still not known. On the other hand, there are two different hypotheses which try to explain the cause of such deficits; the first suggests an abnormally developed specialized brain system and deficits in number sense (Butterworth, 1999; Dehaene et al., 2003; Aster and Shalev, 2007) while the second suggests general deficits in cognitive abilities (Geary, 1994).

According to Dehaene (2001), every person is born with number sense. This refers to an ability to quickly understand basic numerical concepts, the ability to approximate and manipulate numerical quantities, and the ability to acquire and represent numerical quantities. Further, it is suggested that a specific cerebral system which is located in the intraparietal cortex of both hemispheres is responsible for number sense and number processing. Especially, the intraparietal sulcus (IPS) has an importance for number

*[1] Address for Correspondence: University of Ahi Evran, Psychology Department, Kırşehir. E- mail: seylan şahin [seylansahin@yahoo.com]

processing, particularly for processing numerosity when arraying things (Butterworth, Varma, & Laurillard, 2011) and for number comparison (Kadosh et al., 2005). Due to early damage to their inferior parietal cortex, children with developmental dyscalculia might have defects in the number sense which results in their inability to grasp numbers intuitively (Butterworth, 2005). A great deal of research has supported this hypothesis by using a range of tasks (Hanich eet al., 2001; Jordan & Hanich, 2003; Landerl, Bevan, & Butterworth, 2004). In addition, neuropsychological studies conducted on patients with left parietal lesions as well as normal subjects support that calculation or number comparison tasks activated the horizontal segment of IPS (Cappelletti, Butterworth & Kopelman, 2001; Dehaene and Cohen 1997; Dehaene et al., 1999). Moreover, in their study, Molko et al. (2003), found out that, a number of comparison tasks caused the bilateral activation of the intraparietal sulcus.

On the other hand, the second hypothesis suggests a non-numerical explanation which focuses on general cognitive deficits, such as those with regards to to working memory (Geary, 1993; 1994). According to Geary (1993), children with developmental dyscalculia might have computational and memory-retrieval errors which might be related to their using working-memory resources. Indeed, working-memory might have a central role in developmental dyscalculia. This is evidenced in several studies, all of which indicate that working memory functions have an essential role in cognitive arithmetic in children and adults (De Rammelaere & Vandierendonck, 2001; LeFevre et al., 2005) as well as well as in children with developmental dyscalculia (Geary & Brown, 1991; Gray, 1991).

1.1. Neural Basis of Developmental Dyscalculia

It has been found that the ability to understand and manipulate numerosities has a direct relationship with the parietal lobes, mainly with the IPS (Piazza et al., 2002; Dehaene et al., 2003; Castelli, Glaser, & Butterworth, 2006). This is because activation was detected in the parietal lobes, including the horizontal segment of the IPS when healthy adults were solving mathematical problems (Dehaene et al., 2003; van Eimeren et al., 2010). In addition, the superior parietal lobule (SPL), the angular gyrus (ANG) and the supramarginal gyrus (SMG) regions are the other brain regions that were found to have a relation with number processing and mathematical abilities (Grabner et al., 2009; Wu et al., 2009). The supramarginal gyrus (especially the left SMG) showed activation in the studies using a calculation task (Rivera et al., 2005); likewise, the SMG with ANG have been found to be activated in mental mathematic tasks (Rickard et al., 2000).

On the other hand, the results found from healthy adults have been found to be similar with those retrieved from children with developmental dyscalculia in terms of the relationship between IPS and numerical distance (Ansari, 2008). Neuroimaging studies have shown that the parietal cortices, including the IPR and SMG, have abnormal activity related with the number's size and difficult tasks (Molko et al., 2003; Rivera et al., 2002). Evidence in favor of IPS activation modulated by numerical distance was provided by the study by Price et al. (2007). According to the results of this study, non-symbolic number processing led to a stronger activation in the right IPS of the control group than in the children with developmental dyscalculia.

According to Kucian et al. (2006), arithmetical problems in children with developmental dyscalculia are related with defects in the parietal areas. Further, a significant blood flow increase in the prefrontal and parietal cortices, as well as bilateral activation in the ANG, were found during subtraction tasks (Roland & Friberg, 1985). Grabner et al. (2007) found a relation between brain activation in the left ANG and complex multiplication tasks in their study with adults who had lower and higher mathematical-numerical skills. Furthermore, Lee suggested that the left SMG and ANG were responsible for single digit multiplication facts.

The present study investigates the neural correlates of developmental dyscalculia in adults based on fMRI data. For this purpose, adults with developmental dyscalculia were scanned while conducting tasks testing number comparison, multiplication and subtraction. The aim was to examine the brain activations related to the tasks being tested for in adults with developmental dyscalculia and the differences between the developmental dyscalculia group and the controls. It was predicted that adults with developmental dyscalculia would show less brain activation than in the control group in the IPS with relation to the tasks that tested for number comparison, more activation than in the control group in the ANG and in the SMG during the tasks that tested for multiplication, and bilateral IPS activation during the tasks that tested for subtraction.

2. Methods

2.1. Participants

Twenty adults aged between 19 and 36 (15 females and 5 males, mean age= 22.17, SD= 3.4, range= 19-36) voluntarily participated in this study. All subjects were undergraduate and postgraduate students from the University of York. All 20 subjects were both native speakers of English and right-handed. None of the subjects had any history of psychiatric or neurological illnesses.

All participants were assessed using behavioral tests including general cognitive ability (Wechsler Abbreviated Scale of Intelligence; Wechsler, 1999), arithmetic skill (Wide Range Achievement Test 4; Wilkonson & Robertson, 2006), reading skill (Test of Word Reading Efficiency; Torgesen, Wagner, & Rashotte, 1999) and speed calculation tests in order to identify whether they had low arithmetic skills. Clinical diagnoses of the participants were not made by the investigators. After behavioral test section, brain image data was collected from all participants by using fMRI while they were having fMRI tasks.

10 of participants constituted the developmental dyscalculia group (6 females and 4 males, mean age= 21.79, SD= 1.7 years, range= 19-24). Participants met the present research criteria for developmental dyscalculia only if they had an IQ at or above 90, a Wide Range Achievement Test (WRAT) arithmetic score below 85, and

JNBS 2015 Published by Üsküdar University www.jnbs.org

Table 1: Background variables for participants with developmental dyscalculia and controls

	DD			Control			Effect Size	
	Mean	*SD*	*N*[a]	*Mean*	*SD*	*N*[a]	*t*	*p**
Age	21.50	1.650	10	22.70	4.945	10		
Cognitive ability (IQ)	115.10	9.608	10	125.80	8.664	10	-2.615	.018*
Sight Word Reading Efficiency (TOWRE)	100.30	10.100	10	100.80	12.246	10	-.100	.922
Phonemic Decoding Efficiency (TOWRE)	110.20	8.817	10	107.40	13.501	10	.549	.590
Reading (WRAT)	113.30	7.675	10	113.30	6.413	10	.000	1.000
Spelling (WRAT)	108.40	4.351	10	110.50	4.994	10	-1.003	.329
Arithmetic (WRAT)	86.30	3.020	10	110.20	7.983	10	-8.855	.000*
Handedness	68.89	27.25	9	64.70	25.95	10	.343	.736

Note: DD= Developmental Dyscalculia, TOWRE = Test of Word Reading Efficiency. WRAT = Wide Range Achievement Test.
[a] Number of participants varies due to technical problems with participants' medical situations and experimenters' errors.
* Bonferroni-corrected significance level; p < .05, independent-samples t test, two-tailed.

a difference between their IQ and WRAT arithmetic scores of at least 10 points.

The other 10 participants constituted the control group (9 females and 1 male, mean age= 22.7 years, SD= 4.9 years). Control participants were matched as far as possible with regards to the IQ, age and gender of the experimental groups. Control participants met the present research criteria if they had an IQ at or above 90 and a WRAT arithmetic score of above 100.

2.2. Procedure

Participants were tested usually during one—maximally two—sessions. All subjects were assessed in the Numerical Cognition Laboratory of the Psychology Department of the University of York. The tests were conducted in the following order: first, reading and arithmetic skills tests; second, handedness inventory; finally, general cognitive ability measurement.

2.3. fMRI Tasks

The fMRI scanning part of the study consisted of a motor cortex localizer task, a number comparison task, a multiplication task and a subtraction task.

2.3.1. Motor cortex localizer

The paradigm which was used in the study was a finger-to-thumb opposition paradigm. The image of the task was shown to the participants on the screen during the scanning. The image included two hands with a red dot being projected on the fingers of the image. Participants were asked to touch their left or right thumb synchronously in correspondence with the finger on which the red light was being projected on. The stimuli included white hands placed on a black background.

2.3.2. Number comparison

The number comparison task consisted of white double-digit Arabic numbers (31-99, never 65; Arial, font size 60; number 65 presented in Arial, size 24) which were demonstrated centrally on a black screen one by one. Participants were required to determine whether the demonstrated number was smaller or larger than 65. This is called a distance effect and was used to compare a set of target numbers with a fixed standard number in order to reflect participants' reaction times (Zhang & Wang, 2005).

Participants pressed one of two response buttons so as to give their decisions; while the left index finger was to be used for smaller numbers, the right index finger was used for larger numbers. According to Aster & Shalev (2007), while making judgements about numbers, the left hand is quicker for smaller numbers and the right hand is faster for larger numbers; this is known as the "spatial numerical association of response codes" (SNARC) effect.

2.3.3. The rationale behind the inter-stimulus interval (ISI) randomization:

(Also applies to both multiplication and subtraction tasks)

The purpose of using the make_random_timings.py command from the AFNI suite was in order to choose stimulus timings within a particular block. For each set of parameters, 100 timing randomizations were applied. The stimulus block which had lengths of 75, 150, 240, 300, 450 and 600 seconds were assessed. While the ISI was jittered, the timing of the stimuli presentation remained stable.

JNBS 2015 Published by Üsküdar University www.jnbs.org

Several conditions were used, such as Multiplication/ Subtraction correct (Mc, Sc), Multiplication/Subtraction incorrect (Mi, Si), Number Comparison Close (C)/Far (F) were used within a block. In order to assess the design matrix, a gamma convolution was used. Afterwards, custom scenarios were used in order to obtain the sets of randomizations from a single block and to combine them into the full experimental design using multiple blocks. The 3dDeconvolve command from AFNI was used for this purpose.

2.3.4. Multiplication

The multiplication block consisted of presenting a multiplication problem with single digit operands and a suggested response (e.g. 2 × 8 = 16) to participants. White digits (Arial, size 30) placed on a black background were used. The stimuli included fifty per cent incorrect answers (e.g. 2 × 8 = 14) and fifty per cent correct answers. Participants were asked to decide if the equation was solved correctly and respond by pressing one of two response buttons (right index finger for correct items, left index finger for incorrect items). Half of the incorrect equations were table-related (e.g. 2 × 8 = 14) while the other half were unrelated (e.g. 2 × 8 = 15).

2.3.5. Subtraction

The subtraction block consisted of presenting a subtraction problem with a suggested response (e.g. 16 – 9 = 7) to participants. White digits (Arial, size 30) placed on a black background were used. In the first part of the block, the stimuli included fifty per cent double digit equations ranging from 11 to 19 and presented first, and fifty per cent single digit equations ranging from 3 to 9 and presented second. The other half of the block consisted of fifty per cent double digit equations ranging from 52 to 91 and presented first, while the other fifty per cent were double digit equations ranging from 23 to 76 and presented second. The first half had a small problem size that could be solved by fact retrieval (e.g. 16 - 9 = 7) while the other half had a large problem size that needed to be calculated (e.g. 88 – 35 = 53). Participants were asked to decide if the equation was solved correctly and respond by pressing one of two response buttons (right index finger for correct items, left index finger for incorrect items).

2.3.6. fMRI Procedure and Design

Before the scanning session, there was a training period in which participants had a chance to exercise the tasks by receiving full instructions. In the training period, participants could see a shorter example of the tasks on a computer screen. They were asked to make decisions about the stimuli and respond by pressing response buttons on the keyboard quickly. This was an exact copy of the process that would take place during the scanning. After completing the training period, participants completed a motor cortex localizer task, a number comparison task, a multiplication task, and a subtraction task during the scanning period.

For all fMRI tasks, the Presentation 13.1 program was used in order to present and control the stimuli as well as acquiring reaction times (RTs). A mirror which was placed to the head coil helped participants to see the stimuli which was shown on a screen. Before each block, the upcoming task was announced on the screen. The fMRI scanning session consisted of two consecutive parts which took approximately 40 minutes for each and a 10 min break between these two parts. Each part included either a motor cortex localizer task or a number comparison task, two blocks of multiplication and two blocks of subtraction. The presentation order was randomized.

2.4. Data acquisition

Imaging data were collected at the York Neuroimaging Centre (YNiC) using a 3 Tesla Signa HDx Excite MRI system (General Electric) with an eight channel phased array head coil (GE Signa Excite 3.0T, High Resolution Brain Array, MRI Devices Corp., Gainesville, FL). In order to reduce head movement, a foam insert was placed in the scanner.

The following functional imaging parameters were used to obtain the functional MR imaging in the present study: a T2*-weighted gradient echo EPI sequence (echo time (TE) = 34.3 ms, repetition time (TR) = 3 s, flip angle = 90°, field of view (FOV) =256 mm, matrix = 128 x 128). 38 para-axial slices (which were parallel to the corpus callosum), each with a thickness of 3.5 mm thickness, were obtained per volume with no inter-slice spacing. The voxel size of the images was 2 x 2 x 3.5 mm.

The following functional imaging parameters were used to obtain high resolution anatomical images in the present study: a T1-weighted sequence (TE = 3.6ms, TR = 9.0ms, flip angle=8°, FOV = 256mm, matrix = 256 x 256). The voxel size of the structural images was 1 x 1 x 1 mm.

2.5. Data Analysis

2.5.1. Behavioral Data

Performance measures on accuracy and the RTs of the cognitive ability, reading skills, handedness and the arithmetic skills tests, the motor localizer, the number comparison, the multiplication and the subtraction tasks were analyzed using descriptive statistics firstly. Then, individual trials of each task were analyzed using independent t-tests for between-group differences. In addition, for each task, the effects of trial types (close/ far, correct/incorrect, correct large & small/incorrect large & small) were analyzed using repeated measures analysis of variance (one-way within-subject ANOVA).

2.5.2. fMRI Data

Pre-processing and statistical analyses were carried out using FEAT (FMRI Expert Analysis Tool version 5.98) which is part of FSL (the software library of the Oxford Centre for Functional MRI of the Brain (FMRIB); www. fmrib.ox.ac.uk/fsl). At the first-level analysis, irst-level analysis, MCFLIRT (Jenkinson, 2002) was used in order to apply motion corrections. Pre-statistics processing

JNBS 2015 Published by Üsküdar University www.jnbs.org

JNBS 2015 Published by Üsküdar University www.jnbs.org

included slice-timing correction using Fourier-space time-series phase-shifting and non-brain removal using the BET Brain extraction tool, version 3.3 (Smith, 2002).

In order to smooth the images spatially, a Gaussian kernel of FWHM 5mm and a grand-mean intensity normalization of the entire 4D dataset with a single multiplicative factor were used. To take away the low frequency drifts, a high-pass temporal filter (Gaussian-weighted least-squares straight line fitting, with sigma of 25.0s for multiplication/subtraction and 30.0s for both motor cortex localizer and number comparison tasks) was used. FLIRT (FMRIB's Linear Image Registration Tool; Jenkinson & Smith, 2001) was utilized in order to register high-resolution structural images of a standard brain (MNI 152).

During the second-level analysis, in order to perform group analysis for mixed-effects across participants, FLAME (FMRIB's Local Analysis of Mixed Effects; Beckmann, 2003; Woolrich, 2004) was used. Trials with inaccurate responses for Subtraction/Multiplication blocks were not analyzed.

Both single- and second-level analyses were done at single-subject-level and images were thresholded using clusters settled in Z> 2.3 and a corrected cluster significance threshold of p = 0.05.

The contrasts, as well as whole brain analyses of each contrast, were analyzed at single-subject-level. This was done in order to determine the brain areas involved in the mathematical processes.

3. Results

3.1. Number Comparison

Four clusters were detected for participants with developmental dyscalculia and the controls in the close distance contrast (numerical distance to 65 was small, as mentioned in fMRI section), encompassing areas in the angular gyrus in the left hemisphere, intraparietal sulcus in the both hemisphere and in the superior frontal gyrus. Similarly, this activation pattern was identical for the far distance contrast (numerical distance to 65 was large, as mentioned in fMRI section); five clusters

Brain areas	Voxels	Z-MAX	Peak Coordinates In MNI X (mm)	Y (mm)	Z (mm)
Close					
Angular Gyrus	1723	5.13	-6	6	42
IPS	1158	5.04	42	-46	38
IPS	11463	5.06	-40	-6	8
Superior Frontal Gyrus	2134	4.76	38	18	10
Far					
Angular Gyrus	3270	4.56	-2	-66	-22
Angular Gyrus	2397	4.89	-44	-4	8
Angular Gyrus	1845	4.09	34	-28	38
IPS	696	4.2	22	4	8
IPS	671	4.26	-44	-40	36

*Only first three peak activations of each contrast can be seen (the first three is close > far contrast, the second three is far > close contrast).
Z= 2.3

were detected encompassing areas in the angular gyrus in the left hemisphere and intraparietal sulcus in the left hemisphere (see Figure 1, Table 2). The IPS activation was stronger in the close distance contrast than in the far distance contrast and stronger in the left hemisphere than in the right hemisphere.

3.2. Multiplication

Multiplication correct items activated the bilateral network of the brain regions, including the angular gyrus, supramarginal gyrus, neighboring areas of the intraparietal sulcus and also, the inferior frontal gyrus in the left hemisphere and the superior frontal gyrus (see Figure 2, Table 3). Similar activation patterns were observed when multiplication incorrect items were considered, with bilateral activation in the intraparietal sulcus, the angular gyrus, the supramarginal gyrus and also, the superior frontal gyrus and the inferior frontal gyrus in the left hemisphere (see Figure 2, Table 3). Activations were more extensive in the left hemisphere compared to the right in both tasks.

Table 2: Number comparison (close distance, far distance and close versus far contrasts), showing cluster index, number of voxels within each cluster, maximum z-score and peak cluster coordinates for the two groups.

Table 3: Number comparison (close distance, far distance and close versus far contrasts), showing cluster index, number of voxels within each cluster, maximum z-score and peak cluster coordinates for the two groups.

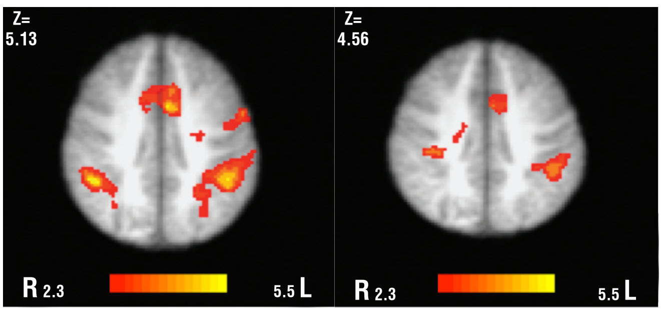

Figure 1. Brain activation in the close distance contrast (left image) and the far distance contrast (right image) in the number comparison task for participants with dyscalculia and the controls.

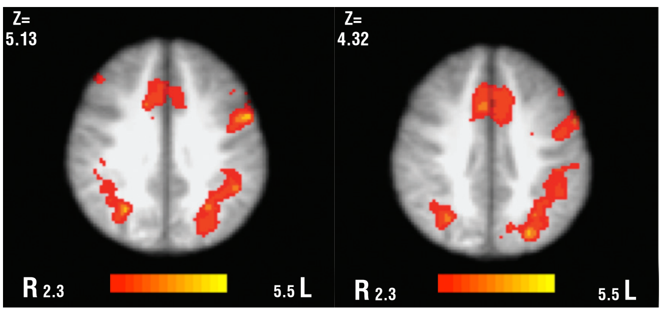

Figure 2. Brain activation in the incorrect item contrast (left image) and the correct item contrast (right image) in the multiplication task for participants with dyscalculia and the controls.

			Peak Coordinates In MNI		
Brain areas	Voxels	Z-MAX	X (mm)	Y (mm)	Z (mm)
Correct					
Angular Gyrus	8781	4.32	-26	24	0
Supramarginal Gyrus	4290	4.58	44	-86	-12
IPS	7011	4.81	-22	-92	-16
Inferior Frontal Gyrus	2883	4.46	-48	24	20
Incorrect					
IPS	3273	5.1	-32	26	-4
Angular Gyrus	2227	4.56	32	20	-4
Supramarginal Gyrus	6618	4.88	24	-88	-8
Inferior Frontal Gyrus	3743	5.09	-46	20	24

Z= 2.3

3.3. Subtraction

As with the multiplication task, subtraction task's correct items led to bilateral activation in the angular gyrus, the supramarginal gyrus, neighboring areas of the intraparietal sulcus and also, the superior frontal gyrus as well as the inferior frontal gyrus in the left hemisphere (see Figure 3, Table 4). A similar pattern of activation was observed when subtraction incorrect items were considered, with bilateral activation in the intraparietal sulcus, the angular gyrus, the supramarginal gyrus and also activation in the superior frontal gyrus and the inferior frontal gyrus (see Figure 3, Table 4). Likewise, activations were more extensive in the left hemisphere when compared to the right in both tasks.

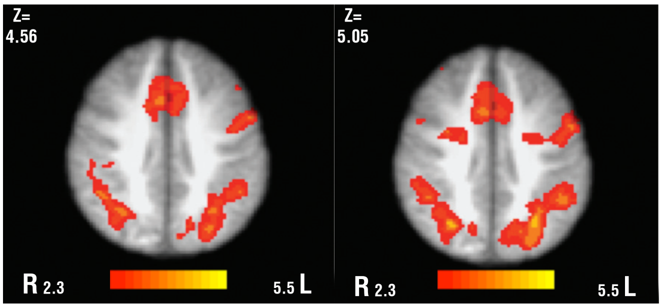

Figure 3. Brain activation in the correct item contrast (left image) and the incorrect item contrast (right image) in the subtraction task for participants with dyscalculia and the controls.

Table 4: Subtraction (correct and incorrect item contrasts), showing cluster index, number of voxels within each cluster, maximum z-score and peak cluster coordinates for the two groups.

			Peak Coordinates In MNI		
Brain areas	Voxels	Z-MAX	X (mm)	Y (mm)	Z (mm)
Correct					
Angular Gyrus	3273	5.1	-32	26	-4
Supramarginal Gyrus	2127	4.56	32	20	-4
IPS	3743	5.09	-46	20	24
Incorrect					
IPS	29543	5.05	-26	20	0
Angular Gyrus	2777	4.98	28	-64	36
Supramarginal Gyrus	39996	5.48	-24	-92	-16

Z= 2.3

4. Discussion

The present study examined the neural correlates in adults with developmental dyscalculia during number comparison and calculation (multiplication and subtraction) tasks. The results confirmed IPS, ANG and SMG activity in subjects when they exercised their mathematical skills. This supports previous studies' results (Grabner et al., 2009; Wu et al., 2009; Ansari, 2008).

We predicted that the IPS activation would be less in developmental dyscalculia during the number comparison task. The results support the role of the IPS during number comparison and agree with previous studies (Pesenti et al., 2000). However, there was no activation when the two groups were compared. It was found that close and far distance led to a similar activation pattern. However, the activation was stronger when the number was close to the comparison number. In addition, the activation was stronger in the left hemisphere. A series of studies indicate that the IPS holds the representation of number distance (Dehaene et al., 2003; Dehaene, Dehaene-Lambertz, & Cohen, 1998). In their study, Pinel et al. (2001) examined the examined the relation between numerical distance and brain activity in the comparing of two-digit numbers and found that numerical distance affected IPS activity. In addition, it was discovered that the distance had an inverse relation with activation; i.e. when the distance was small, the activation was stronger. Other studies have found differences between the controls and the developmental dyscalculia group with regards to the activation of IPS (Price et al., 2007; Kucian et al., 2006; Ansari et al., 2005). However, these studies either compared children with other children or children with adults. Only a few studies were done with adults. This is the major contribution of the study. Even though the IPS region of the brain was activated during the number comparison task, there is still a debate about their role. This study tried to find a solution to this debate by underlying the role of IPS in the number comparison task.

Furthermore, we predicted that there would be activation in the left ANG and the left SMG during multiplication. Multiplication led to the activation in the ANG, SMG and IPS regions of the participants' brains. Correct and incorrect items did not show a difference in the activation pattern and the activation was stronger in the left hemisphere for both items. When the two experimental groups were compared, no activation was observed. These results show similarities with the literature which suggests that the left ANG activates during multiplication tasks (Chochon et al., 1999; Dehaene et al., 1999). In their study, Ischebeck et al. (2006) examined the examined the learning process of multiplication and subtraction. Half of the participants took multiplication/subtraction training before fMRI scanning. The results showed that trained multiplication led to higher activation in the IPS and the left inferior frontal gyrus which were presumed to have a role in quantity processing (Fias et al., 2003; Piazza et al., 2002; Ischebeck et al., 2006) and verbal working memory (Ischebeck et al., 2006). On the other hand, untrained multiplication led to activity in the left ANG which was related with mathematical fact retrieval (Lee, 2000). Moreover, the SMG was found to be related with

JNBS 2015 Published by Üsküdar University www.jnbs.org

THE JOURNAL OF NEUROBEHAVIORAL SCIENCES
NÖRODAVRANIŞ BİLİMLERİ DERGİSİ

multiplication in children with developmental dyscalculia (Mussolin et al., 2009). It can be said that over-activation in the ANG and SMG regions was not examined in adults with developmental dyscalculia. This study tries to fill this gap in the literature by examining the ANG and the SMG activation in adults with developmental dyscalculia by using several multiplication tasks (correct-incorrect, table related-unrelated).

In addition, we predicted that there would be bilateral activation in the IPS during subtraction. The results confirmed this prediction. Additionally, the same brain regions that were found to be activated during multiplication were active during subtraction and there was no difference between the two groups. The final analysis compared subtraction and multiplication in order to find differences in activation patterns; however, no activation was detected. Thus, the prediction, which suggested that we would find different activation patterns between the two groups, was not confirmed. Brain imaging studies provided evidence in favor of different representations in the brain for different mathematical operations due to different types of knowledge (Dagenbach & McCloskey, 1992; Dehaene & Cohen, 1995) and different number mechanisms (Lemer et al., 2003; Dehaene et al., 2004). According to Dehaene et al. (2004), damage in the ANG region resulted in multiplication deficits while damages in the IPS region caused subtraction deficits. However, subtraction tasks showed a similar activation pattern and did not show a difference when subtraction and multiplication tasks were compared.

The study included some weaknesses. The main limitation was that the data from participants with developmental dyscalculia belonged to the previous project while the control data belonged to a project conducted during the 2012-2013 academic year. Even though the data collection procedure was the same, it was not known whether there were conditions that could affect the data. In addition, 4 or 5 participants with developmental dyscalculia also had reading difficulties which could affect the results. The bottom line is, however, that more research on investigating neural correlates is needed.

To conclude, neural correlates in developmental dyscalculia were investigated in this study. It was predicted that the IPS region of the brain would show less activation during the number comparison task in the adults with developmental dyscalculia. However, the findings showed that adults with developmental dyscalculia did not show less brain activation than in the control group in the IPS with relation to the tasks. Additionally, it was discovered that the activation of the left ANG, as well as the left SMG, during the multiplication task while there was activation in the bilateral IPS during the subtraction task.

References

Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. Nature Reviews Neuroscience, 9(4), 278-291.

Ansari D, Garcia N, Lucas E, Hamon K, Dhital B. (2005) Neural correlates of symbolic number processing in children and adults. Neuroreport, 16, 1769–1773.

Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. Developmental Medicine & Child Neurology, 49(11), 868-873.

Beckmann, C., Jenkinson, M., & Smith, S.M. (2003). General multi-level linear modelling for group analysis in FMRI. NeuroImage, 20, 1052 – 1063.

Butterworth, B. (1999). The Mathematical Brain. London: Macmillan.

Butterworth, B. (2005). The development of arithmetical abilities. Journal of Child Psychology and Psychiatry, 46(1), 3-18.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: from brain to education. Science (New York, N.Y.), 332(6033), 1049–53. doi:10.1126/science.1201536

Cappelletti, M., Butterworth, B., & Kopelman, M. (2001). Spared numerical abilities in a case of semantic dementia. . Neuropsychologia, 39, 1224-1239.

Castelli, F., Glaser, D. E., & Butterworth, B. (2006). Discrete and analogue quantity processing in the parietal lobe: A functional MRI study. Proceedings of the National Academy of Sciences of the United States of America, 103(12), 4693-4698.

Chochon, F., Cohen, L., van de Moortele, P.-F., & Dehaene, S. (1999). Differential contributions of the left and right inferior parietal lobules to number processing. Journal of Cognitive Neuroscience, 11, 617–630.

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and the central executive involved?. Memory & Cognition, 29(2), 267-273.

Dagenbach, D., & McCloskey, M. (1992). The organi- zation of arithmetic facts in memory: Evidence from a brain-damaged patient. Brain and Cognition, 20, 345–366.

Dehaene, S. (2001). Précis of the number sense. Mind & Language, 16, 16-36.

Dehaene, S., and Cohen, L. (1995). Towards an anatomical and func- tional model of number processing. Math. Cognit. 1, 83–120.

Dehaene, S., & Cohen, L. (1997). Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic.Cortex, 33, 219–250.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract rep- resentations of numbers in the animal and human brain. Trends in Neurosciences, 21, 355–361.

Dehaene, S., Spelke, E., Stanescu, R., Pinel, P., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. Science, 284, 970–974

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. Cognitive Neuropsychology, 20, 487-506.

Dehaene, S., Molko, N., Cohen, L., Wilson, A.J. (2004). Arithmetic and the brain. Curr. Opin. Neurobiol. 14 (2), 218–224.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. Journal of Cognitive Neuroscience, 15(1), 47-56.

Geary, D. C. (1993). Mathematical disabilities: Cognition, neuropsychological and genetic components. Psychological Bulletin, 114, 345-362

Geary, D.C. (1994). Children's mathematical development. Washington, DC: American Psychological Association.

Geary, D.C., & Brown, S. (1991). Cognitive addition: strategy choice and speed-ofprocessing differences in gifted, normal, and mathematically disabled children. Developmental Psychology, 27, 398-406

Gersten, R., & Chard, D. (1999). Number Sense: Rethinking Arithmetic Instruction for Pupils with Mathematical Disabilities. Journal of Special Education, 33(1), 18-28.

Grabner, R. H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. NeuroImage, 38, 346–356. doi:10.1016/j.neuroimage.2007.07.041

Grabner, R.H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., & Neuper, C. (2009). To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. Neuropsychologia, 47(2), 604-608.

Gray, E. M. (1991). An analysis of diverging approaches to simple arithmetic: Preference and its consequences. Educational Studies in Mathematics, 22(6), 551-574.

Hanich, L.B., Jordan, N.C., Kaplan, D., & Dick, J. (2001). Performance across different areas of mathematical cognition in children with learning difficulties. Journal of Educational Psychology, 93(3), 615-626.

Hannell, G. (2013). Dyscalculia: Action Plans for Successful Learning in Mathematics. Routledge.

JNBS 2015 Published by Üsküdar University www.jnbs.org

Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstätter, F., Benke, T., Felber, S., & Delazer, M. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction. NeuroImage, 30(4), 1365–75. doi:10.1016/j.neuroimage.2005.11.016

Jenkinson, M. & Smith, S.M., 2001. A global optimisation method for robust affine registration of brain images. Med. Image Anual. 5 (2), 143–156.

Jenkinson, M., Bannister, P.R., Brady, J.M., & Smith, S.M. (2002). Improved optimisation for the robust and accurate linear registration and motion correction of brain images. NeuroImage, 17 (2), 825- 841.

Johansen-berg, H., Behrens, T., & Rushworth, M. F. S. (2004). Response-Selection-Related Parietal Activation during Number Comparison. Journal of Cognitive Neuroscience, 16(9), 1536–1551.

Jordan, N. C., & Hanich, L. B. (2003). Characteristics of children with moderate mathematics deficiencies: A longitudinal perspective. Learning Disabilities Research & Practice, 18(4), 213-221.

Kadosh, R. C., Henik, A., Rubinsten, O., Mohr, H., Dori, H., van de Ven, V., ... & Linden, D. E. (2005). Are numbers special?: the comparison systems of the human brain investigated by fMRI. Neuropsychologia, 43(9), 1238-1248.

Kucian, K., Loenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006). Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. Behavioral and brain functions : BBF, 2, 31. doi:10.1186/1744-9081-2-31

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. Cognition, 93(2), 99-125.

Lee, K. M. (2000). Cortical areas differentially involved in multiplication and subtraction: A functional magnetic resonance imaging study and correlation with a case of selective acalculia. Annals of Neurology, 48(4), 657-661.

LeFevre, J.A., DeStefano, D., Coleman, B., & Shanahan, T. (2005). Mathematical cognition and working memory. In J. I. D. Campbell (Ed.), Handbook of mathematical cognition (pp. 361-377). New York: Psychology Press.

Lemer, C., Dehaene, S., Spelke, E., Cohen, L., 2003. Approximate quantities and exact number words: dissociable systems. Neuropsychologia 41, 1942–1958.

Molko, N., Cachia, A., Rivière, D., Mangin, J. F., Bruandet, M., Le Bihan, D., ... & Dehaene, S. (2003). Functional and structural alterations of the intraparietal sulcus in a developmental dyscalculia of genetic origin. Neuron, 40(4), 847-858.

Mussolin, C., Volder, A. De, Grandin, C., Schlögel, X., Nassogne, M., & Noël, M. (2009). Neural Correlates of Symbolic Number Comparison in Developmental Dyscalculia. Journal of cognitive neuroscience, 22(5), 860–874.

Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: A PET study. Journal of Cognitive Neuroscience, 12, 461–479.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. (2002). Are subitizing and counting: implemented as separate or functionally overlapping processes? NeuroImage, 15(2), 435-446.

Pinel, P., Dehaene, S., Riviere, D.,andLeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. Neuroimage 14, 1013–1026.

Price, G., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. Current Biology, 17(24), R1042-R1043.

Rickard, T.C., Romero, S.G., Basso, G., Wharton, C., Flitman, S., & Grafman, J. (2000). The calculating brain: an fMRI study. Neuropsychologia, 38(3), 325-335.

Rivera, S.M., Menon, V., White, C.D., Glaser, B., & Reiss, A.L. (2002). Functional brain activation during arithmetic processing in females with fragile X Syndrome is related to FMR1 protein expression. Human Brain Mapping, 16(4),206-218.

Rivera, S. M., Reiss, A. L., Eckert, M. A. & Menon, V. (2005). Developmental changes in mental arithmetic: evidence for increased functional specialization in the left inferior parietal cortex. Cerebral Cortex 15, 1779-1790.

Roland, P.E., Friberg, L., (1985). Localization of cortical areas activated by thinking. J. Neurophysiol. 53 (5), 1219–1243

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: a study of developmental dyscalculia. Neuropsychology, 19(5), 641.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). Test of Word Reading Efficiency. Austin, TX: Pro-Ed.

Van Harskamp, N. J., Rudge, P., & Cipolotti, L. (2002). Are multiplication facts implemented by the left supramarginal and angular gyri? Neuropsychologia, 40, 1786–1793.

Wechsler, D. (1999). Wechsler Abbreviated Scale of Intelligence. San Antonio, TX: Psychological Corporation.

Wilkinson, G. S., & Robertson, G. J. (2006). Wide Range Achievement Test 4 professional manual. Lutz, FL: Psychological Assessment Resources.

Woolrich, M., Behrens, T., Beckmann, C., Jenkinson, M., Smith, S., (2004). Multi-level linear modelling for FMRI group analysis using Bayesian inference. NeuroImage 21 (4), 1732–1747.

Wu, S.S., Chang, T.T., Majid, A., Caspers, S., Eickhoff, S.B., & Menon, V. (2009). Functional heterogeneity of inferior parietal cortex during mathematical cognition assessed with cytoarchitectonic probability maps. Cerebral Cortex, 19(12), 2930-2945.

Zhang, J., & Wang, H. (2005). The effect of external representations on numeric tasks. The Quarterly Journal of Experimental Psychology Section A, 58(5), 817-838.

JNBS 2015 Published by Üsküdar University www.jnbs.org