A Neuropsychological Approach of Developmental Dyscalculia and a Screening Test Via a Web Application

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Abstract—Traditional definitions of Developmental Dyscalculia state that a child must substantially underachieve on mathematical abilities tests relative to the level expected for the given age, education and intelligence. However, current cognitive developmental neuropsychological studies suggest that not only the core numerical but also the cognitive skills of children with developmental dyscalculia present deficits. The main aim of the proposed research protocol was to construct a battery of six tests that can be delivered by computer in order to screen children's arithmetic and cognitive skills. The hypothesis of the study was that children that are already diagnosed by paper and pencil tests as dyscalculic will present lower scores and larger time latencies not only in mathematical but also in cognitive tasks. A total of 134 right handed children (74 male and 60 female, age range 8 – 12 years) participated in this study. The students with disorders in mathematics (N= 67, 37 male and 30 female age range 8 – 12 years M= 10.15 SD=1.10) had a statement of dyscalculia after assessment at a Centre of Diagnosis, Assessment and Support, as it is required by Greek Law. A comparison group without any learning disabilities was individually matched with the dyscalculic group according to age, sex and grade (N=67, 37 male and 30 female, age range 8 – 12 years old, M=10.24 SD=1.12). Statistical analysis revealed that children with dyscalculia had statistically significant lower mean scores of correct answers and larger time latencies in all tasks compared to their average peers that participated in the comparison group. These findings suggest that children with dyscalculia present several deficits on cognitive systems apart from the core numerical ones. The results are discussed in relation to the use of computers as screening tools for children with learning disabilities.

Keywords—Developmental Dyscalculia, cognitive abilities, computer based screening

1 Introduction

The International Classification of Diseases (ICD 10) and the Diagnosing and Statistical Manual of Mental Disorders (DSM – IV TR) suggest that the main defining criterion of Developmental Dyscalculia is a significant discrepancy between specific mathematical abilities and general intelligence [1,2]. Specifically, Developmental Dyscalculia is a neurodevelopmental disorder that affects the ability of a child to learn arithmetic, despite normal intelligence, proper schooling, adequate environment, socioeconomic status, emotional stability and necessary motivation [2]. Children with dyscalculia are characterized by difficulties in learning and remembering arithmetic facts [3] as well as differences in executive calculation procedures and poor problem solving strategies [4]. Furthermore, dyscalculic students may present difficulties understanding simple number concepts, lack an intuitive grasp of numbers and have problems learning numerical facts and procedures [3]. Specific Learning Disabilities involving mathematic skills usually become apparent later than reading and writing problems often at about the age of eight. Children with dyscalculia comprise 4 – 6% of the school population according to estimates [5]. However, there has been rather little research on dyscalculia compared to other Specific Learning Disabilities, such as dyslexia and in much less widely recognized type of disorder [6]. Children, unlike reading which needs to be taught, exhibit a biological based propensity to acquire arithmetic skills [7]. Certain numerical skills such as counting, adding, comparing and understanding quantities, develop naturally without formal schooling [7]. This numerical capacity is thought to be an inherent trait, present as early as infancy, exemplified by the ability of infants to discriminate between small numbers and engage in numerical computation [8, 9].

Two of the most studied neuropsychological models postulate representational and format–specific modules, located in different areas of the left and right cerebral hemisphere that are relevant to adult cognitive number processing and calculation. These models are mainly based on adults with traumatic brain injury that presented dissociations in various aspects of number processing and calculation. The first one is the McCloscey, Caramazza and Basili (1985) model, which was outlined by observations on patients. This model proposed autonomous cognitive systems for number processing and calculation within the number processing it was presented a distinction between number comprehension and number production mechanisms and within each of these subsystems they further distinguished components for processing Arabic numbers. A distinction was also proposed between Arabic numbers, and verbal comprehension along with production components within lexical and syntactic processing mechanisms. Finally, they distinguished among cognitive mechanisms within the calculation system for processing operation symbols or words, the mechanisms for retrieval of basic arithmetic facts and mechanisms for execution of calculation procedures [10]. The second is the "triple code model" of Dehaene (1992). This model positions abilities such as quantification, number transcoding, and calculation or approximation into three clusters according to the format in which numbers are manipulated. First, there are abilities like verbal counting or arithmetic fact retrieval that are positioned on general spoken or written language processing system. Second, there are abilities like multi-digit calculation or parity judgment which require the mastery of a dedicated positional system which is the linguistic competence and literacy system. Lastly, the "triple code model" supports that abilities to compare and to approximate numerical quantities emerge in infants before the acquisition of language.

Therefore, it is assumed to constitute a distinct proverbal system of arithmetic reasoning [11].

There are several neuroimaging studies that suggest that children with dyscalculia present an abnormal anatomy of the perceptible system in the brain. Also, it has been proposed that there is a specialized number processing network in the brain [6] as researchers have suggested that the intraparietal sulci is involved in numerical processing. Functional neuroimaging studies revealed that the parietal lobe, and more specifically the intraparietal sulci, is active in numerical processing and arithmetic [12]. More specifically, bilateral intraparietal sulci activation was identified in enumeration [13] and size congruity [14]. Right intraparietal sulci activation was identified for brightness congruity [15] and left intraparietal sulci activation was identified for non-symbolic and symbolic comparative judgment [16]. Also, there was a region of gray matter in the left inferior parietal lobe that was significantly reduced in size in children who experienced calculation difficulties. The same children experienced very low birth weight. In the study of Rotzer et al., (2008) were examined children with developmental dyscalculia and control group and it was found that children with developmental dyscalculia had reduced gray matter volume in the right intraparietal sulci, anterior cingulate gyrus, left inferior frontal gyrus and bilateral middle frontal gyri [17]. White matter comparison presented clusters with significantly less volume in the left frontal lobe and in the right parahippocampal gyrus in children with developmental dyscalculia. Apart from the intraparietal sulci, a study of adults [18] revealed that number specific activations was also located in the right temporal regions. Lastly a meta-analysis of Kaufmann et al., (2011) suggests that dyscalculia is associated with impairments in brain areas associated with number magnitude processing such as the parietal cortex and to a lesser extend in the frontal cortex [19].

A large amount of studies on the field of cognitive psychology suggests that children with dyscalculia present a number of cognitive difficulties (for review [20]) The most generally agreed feature of dyscalculic children in the field of executive functions is that they find it difficult to remember arithmetic facts (e.g. [21,22,23]). Moreover, memory deficits cause a confusion on mathematic terminology [24], on performing mental calculation [25] and on keeping track on steps on problem solving [26]. Furthermore, several studies suggests [27, 28, 29] that there is a positive correlation between visual spatial perception and mathematical ability. In other words, children that perform better in spatial tasks, perform better in mathematical tests. This link may be based on the fact that the same brain areas are activated for spatial procedures and number tasks [30]. Several researchers reported that children with dyscalculia have attentional problems. In a study that used the Conners' Computerized Continuous Performance Test (CPT) researchers was found that children with dyscalculia presented more commission and omission errors in comparison their average peers [31]. It is worth to highlight that children with dyscalculia face deficits on reasoning such as understanding multiple steps in complex mathematical procedures [24], understanding basic logical principles [32] and deciding on the proper numerical operations in order to solve a mathematical problem [33].

According to Dehaene's model (1992), von Aster and Shalev developed their combined model using suggestions from the cognitive psychological literature along with neuropsychological evidence. More specifically, their model tends as a prerequisite the increasing capacity of working memory and proposes that children from infancy possess a core system of magnitude, which helps them master comparison and approximation supported by the left and the right parietal lobe. During childhood they conquer the verbal number system which supports verbal counting, fact retrieval and counting strategies. The brain area that is responsible for the aforementioned cognitive development is the left prefrontal lobe. Furthermore, the left and right occipital lobes help school-aged children in the acquisition of the Arabic number system which is utilized for written calculations. Lastly, at the same age children also gain the spatial image which helps in ordinality and, therefore, they can present approximant calculations and arithmetic thinking. Bi-parietal lobe is responsible for these functions [34].

Genetic studies propose a role of heredity in dyscalculia. Family studies support a genetic basis in at least some cases. A twin study showed that for dyscalculia probands, 58% of monozygotic co-twins and 39% of dizygotic co-twins were also dyscalculic and that the concordance rates were .73 and .56, respectively [35]. A family study [36] found that approximately half of all siblings of children with dyscalculia were also dyscalculic, with a 5–10 times greater risk than the general population. Children with Williams Syndrome, show abnormalities on simple numerosity tasks such as number comparison, and are also much worse on simple numerical tasks such as seriation, counting, and single digit arithmetic than chronological-age and mental-age matched controls [37]. Some abnormalities of the X chromosome appear to affect numerical capacities more severely than other cognitive abilities. This is particularly clear in Turner's syndrome where subjects can be at a normal or superior level on tests of IQ, language and reading, but severely disabled in arithmetic [38].

There are three well–documented paper pencil methods for diagnosing dyscalculia. The first is the administration of a standardized assessment designed to measure the child's achievement of age appropriate mathematical skills [23]. The second refers to observing child's arithmetic behavior (for review [39]). However, both methods may identify incorrectly non-dyscalculic children as dyscalculic. The third acceptable method for diagnosing dyscalculia is standardized arithmetic tests. In Greece a well-established and validated paper-and pencil test in order to assess children with dyscalculia is the "Mathematical Proficiency Criterion" [40]. This battery of test was constructed in 2008 in order to assess the mathematical competency of children aged from 7.06 to 15.05 years old. It is consisted from three subtests that assess the three aspects of school mathematical knowledge. The facets that compose the mathematical ability are vocabulary, calculation and problem solving test.

The last few years there have been some attempts to develop software for the assessment of learning disabilities. A software program that is constructed in order to assess the mathematical abilities of children aged from 6 to 14 years old is the "Dyscalculia Screener" [41]. "Dyscalculia Screener" consists of a series of item timed tests. This battery is designed to measure the children's level of immanent arithmetic ability through computer delivered tests such as dot enumeration, number comparison (8 is larger than 7) and arithmetic achievement in mathematical operations. The essential aspect of the software test is the speed that the child responds to each question.

The computer, also, collates the subject responses, automatically analyzes the sum of the data and, finally, calculates the score. The way the scores are computed on each subtest, include the median reaction time of correct answers, which is then adapted by the median simple reaction time. A web application screener in order to determine whether a student has a handle on numeracy skills is the "Two–minute numeracy screener". This test is delivered to children that attend senior Kindergarten to Grade 3. The numeracy screener test assesses the children's ability to judge which of two numbers is larger. Numbers are presented symbolically (Arabic numerals) or non–symbolically (dot arrays). Children are given a time limit, which is depended on the class that they attend, in order to complete as many items as they can [42]. Another web based test has been used for screening adults and learners in post–6 education for mathematical disabilities. It is effective in both further and higher education and also, for screening adults in their workplace. This web based application is based on a model which is built in two principal objectives. Firstly, to establish the learner's understanding of numbers and secondly their understanding of the application of numbers to other systems. The model outlines six areas: number conceptual, number comparative, graphical, symbolic abstraction, spatial temporal and operational [43].

Most of the literature on students with developmental dyscalculia and the tests, in any form, that have already been established and validated, assesses children's core number skills. However, the main aim of the present research protocol was not only to construct mathematical procedures that can be delivered by computer in order to screen children's arithmetic skills but also to screen cognitive abilities of children with dyscalculia. Furthermore, the web application was designed in order to deliver three arithmetical tasks and three tasks that assesses children's cognitive abilities. The second aim of the study was to develop a web application for dyscalculia that screens children from 8 to 12 years old (3rd, 4th, 5th and 6th Grade of Greek Primary School), and which to the best of our knowledge, does not exist in any form. This kind of software can be easily be deployed in a server and be accessed, through a web browser, practically from anywhere. In the event of an update, there is no action that needs to be taken from the user. Furthermore, a web application has a fast development cycle, meaning that it can be built and deployed in less time than the average desktop application, and does not require proprietary software that locks it to a specific platform.

Tasks that have been most effective in discriminating dyscalculics from other pupils were chosen to be incorporated in this web application. Furthermore, new tasks were implemented in order to examine the executive functions of dyscalculic children as it is already mentioned several researches supports that children with developmental dyscalculia present lower scores than their average peers. More specifically, we included in the application a go/no-go task, a visual discrimination task, and a working memory task. A calculation task was also embedded, given the fact that pupils with dyscalculia present difficulties in performing mathematics calculations of certain types [44]. Given that dyscalculia learners have often difficulty in understanding simple number concepts [4] a task that evaluated their understanding of mathematical terminology was also added. Additionally, given their unexpected difficulty in dealing with mathematical problems [45] a mathematical problem solving task was included.

The hypothesis of the present study was that Greek students that are already diagnosed by paper-and-pencil tests as dyscalculic, will also present lower performances and higher time latencies in both mathematical and cognitive tasks of the aforementioned web application screener.

2 Methods

2.1 Participants

A total of 134 right handed children [74 male and 60 female, age range 8–12 years) participated in this study. The students with disorders in mathematics (N= 67, 37 male and 30 female age range 8 – 12 years M= 10.15 SD=1.10) had a statement of dyscalculia after assessment at a Centre of Diagnosis, Assessment and Support, as it is required by Greek Law. A comparison group without any learning disabilities was individually matched with the dyscalculic group according to age, sex and grade (N=67, 37 male and 30 female, age range 8 – 12 years old, M=10.24 SD=1.12). It was formed by pupils who attended the same classes with dyscalculics. They presented typical academic performance according to their teachers' ratings. Additionally, all children that participated in the present study did not have a history of major medical illness, psychiatric disorder, developmental disorder, Attention–Deficit/Hyperactivity Disorder or significant visual or auditory impairments according to their medical reports available at their schools.

2.2 Materials and Procedure

Arithmetic skills of children with dyscalculia and typically achieving children were examined, using a battery that consisted of three tasks that evaluates critical skills relevant to mathematics disorder assessment through the use of a web application. Before the main test procedure, children performed a training task in order to familiarize with the testing procedure by clicking on a picture. During the main test procedure, six tasks were used for evaluating children's arithmetic ability and individual skills were measured through the number of correct responses: (1) a go/no-go task. Children had to select the target picture over a number of five pictures that was presented randomly (see figure 1). (2) A visual discrimination task. This assessment was made up of a series of diagrams or patterns with a part missing and children were expected to select the correct part to complete the designs from a number of options (see figure 2). (3) A working memory task of sequences. Twenty two sequences of numbers were presented, where the first sequence included three numbers; the second four numbers; the third five numbers; the fourth six numbers; the fifth seven numbers; the sixth eight numbers. Participants were asked to report the numbers with the use of a 0-9 num pad that was displayed. (4) A calculation task that examined their ability for mental arithmetic calculation skills in which participants had to decide if the result that was presented was correct or incorrect. (5) A task that evaluated their understanding skills of mathematical terminology, in which the child had to define correctly numerical concepts, and (6) an arithmetic problem solving task in order to examine their comprehension of mathematical problems, in which children had to decide whether to do addition, subtraction, multiplication or division in order to solve it (see figure 3). The last three tasks are modified computer versions of the "Mathematical Proficiency Criterion" [40]

Time latency was not measured during the go/no-go task and during the working memory task. However, it was measured during the four other tasks of the aforementioned web application. Furthermore, it is worth to mention that all children succeeded in running the program independently. They were able to run the program easily and effortlessly from the training task till the last testing procedure, as before the assessment tasks it is presented an example that guides the children on the demands of the process that follows. The researchers interfered only on technical issues, such as to type URL of the web application.

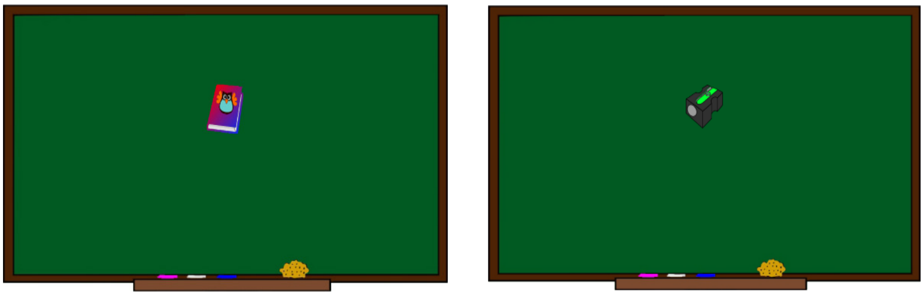

Fig. 1. The left side of the figure presents the target stimuli and the right sight presents one out of five non target stimuli.

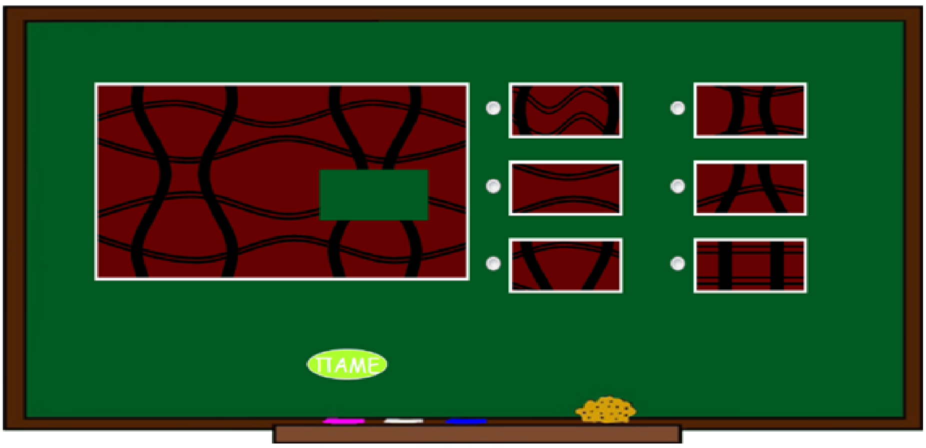

Fig. 2. Visual discrimination task. The child had to select one out of six possible answers in order to complete the large pattern on the left.

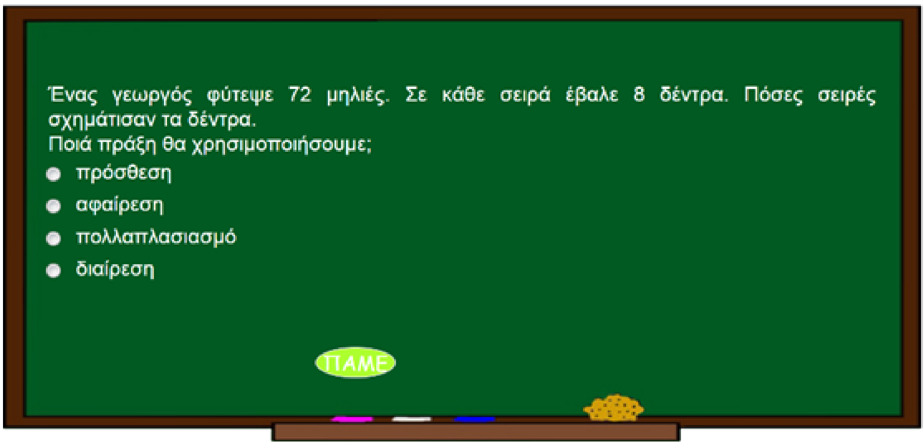

Fig. 3. A problem solving tasks. The child had to decide whether to do addition, subtraction, multiplication or division by selecting the appropriate of the four "buttons".

2.3 Implementation

In our effort to enhance the aforementioned procedure and make it accessible to a larger ensemble of students in the future, we created and deployed a client-server web application that implements its core characteristics. The main focus concerning the technology used was the selection of the appropriate web technologies for the development and implementation of the application and the proper depiction of the interactive environment concerning the user's browsing experience. Our application requires constant communication between a client and the main server that hosts it. Every time a test is finished the user's results are saved for future inspection. Based on this we chose to use a minimum set of basic, timeless and swift, concerning web development, technologies taking into account the reuse of the code and our ability to maintain and expand functionality to suit any future needs. More specifically we used HTML5, CSS3, JavaScript and MySQL.

HTML5 which is the core technology markup language of the World Wide Web was used for the structuring of each page and the appropriate presentation of the content. HTML5 is the immediate successor of HTML and incorporates a plethora of features that are required for the implementation of a web platform as the one we present. It supports the latest multimedia codecs, error handling so that old browsers can ignore any new HTML5 constructs, cross-document messaging for implementing communication between documents across different domains and DOM storage for storing data in the web browser either permanently or for the duration of each session. Multimedia features overhead, like audio and video illustrations has been reduced since in HTML5 multimedia elements are tagged without the support of third party plugins. HTML5 also provides portability, without complexity overhead, to a plethora of devices which is a key issue to our application.

CSS was used for the beautification of each available web page. The graphical representation of each test is of utmost importance. The user, at any given time must be undistracted in his/hers effort to complete the tests. Particular emphasis was placed in the use of a color palette, which changes depending on the sex of the user, that contain a few subtle color changes to avoid making the test a tedious ordeal. CSS3 was also selected for performance optimization since it reduces file time requests and downloads time by using fewer images. CSS3 provides animation features and text-shape effects which in conjunction with browser compatibility makes our application user friendlier.

Application functionality was implemented using the JavaScript programming language. JavaScript is a dynamic programming language and is a key component of modern browsers which in turn have the ability of implementing client-side scripts that can interact with each user's particular choices and change the document content while it is displayed. The communication between client and server was handled by Java servlets that run over the HTTP protocol (HTTP servlets). The main advantage of JavaScript is that it enables users to interact with the application without server intervention. Sending a message to the server and waiting for a reply is usually a time consuming and cost inefficient process especially in a cloud environment. Finally, CSS3 limitations on dynamic and reactive aspects have been overcome using JavaScript.

Moreover, a database was created using MySQL. Through this database the examiner has the ability to check and process past results for each student, come to conclusions based on a larger scale of results and dynamically compute averages concerning every trial that is contained in the overall process.

Google Cloud Engine (GCE) was selected to host the application. GCE provides high-performance virtual machines which can be easily deployed as web servers. West Europe zone was selected to host our experiments. Choosing a region which is close to our point of service might decrease network latency. The intuition behind this move is that a Cloud environment provides elastic scaling. Our primary concern is to deploy Cloud application services (SaaS) which will use the web to deliver dyscalculia applications to users. These services will serve the needs of both researchers and academia.

During the development cycle, several security checks were performed in order to ensure confidentiality, integrity and availability. Vulnerability checks resulted in the following: (i) browsable Web Directories have been eliminated, (ii) potential transmission of cleartext credentials has been avoided and (iii) Denial of Service (DoS) attacks have been prevented.

3 Results

Descriptive statistics were performed in order to obtain mean scores and standard deviations of participants in all six tasks, as the training test was excluded from the statistical analysis. Analysis of Variance (ANOVA) was conducted to compare the scores of children with disorders in mathematics and the control group. Table 1 presents the mean scores and standard deviations for the correct responses on the tasks. Moreover, Table 1 presents the statistical significance of the correct answers of children with impaired arithmetic skills and the comparison group. ANOVA revealed that children with dyscalculia had statistically significant (p<0.05) lower mean scores of correct answers in all six tasks compared to their average peers that participated in the comparison group.

Table 1. Mean scores and standard deviations of children with dyscalculia vs. the typically developing group correct responses and the associated statistical significance in all tasks.

Tasks	**Groups**				
	Dyscalculics		***Typically developing***		
	Mean	***SD***	***Mean***	***SD***	***F***
Go/nogo	0.67	1.80	0.03	0.171	8.483*
Visual Discrimination	6.28	2.62	8.49	1.93	30.897**
Working Memory	2.45	1.50	4.24	1.74	40.674**
Calculation	2.36	1.14	3.30	0.80	30.681**
Numerical Concepts	0.40	0.58	1.06	0.78	30.819**
Problem Solving	0.88	0.79	1.72	0.52	52.666**

*p<0.05 **p<0.01

The mean scores and standard deviations of the latency on the four tasks are presented on Table 2. As it can be seen in this Table, ANOVA revealed that task latencies of children with mathematical disorders were significantly larger than those of their average peers in the three mathematical tasks as well as in the visual discrimination task. It is worth to remind that at go/no-go task and working memory task time latency was not measured.

Table 2. Mean scores, standard deviations and statistical significance for the time latency of answers in dyscalculic children vs. the comparison group in all tasks.

Tasks	**Groups**				
	Dyscalculics		***Typically developing***		
	Mean	***SD***	***Mean***	***SD***	***F***
Visual Discrimination	2.20	1.04	1.52	0.72	12.829**
Calculation	1.67	1.06	0.99	0.50	22.269**
Numerical Concepts	2.04	0.90	1.52	0.77	8.033*
Problem Solving	0.55	0.43	0.24	0.24	24.898**

*p<0.05, **p<0.01

4 Discussion

The aim of the present study is twofold. First, we constructed a test battery that can be delivered by computer in order to screen children's mathematical disabilities. Second, using this battery, we attempted to examine arithmetic and cognitive skills of school-aged children who had a statement of dyscalculia with a comparison group without any learning disabilities. The web application screener that was developed and deployed by the present protocol revealed that children with dyscalculia had significantly lower scores of correct answers and larger latencies in comparison to children that were recruited as comparison group in all tasks of the battery. This result verifies our research hypothesis that Greek students that were diagnosed as dyscalculic by paper-and-pencil tests would present lower scores and larger latencies in the tasks of the web application screener.

Furthermore, dyscalculic children presented lower scores of correct answers and larger latencies in cognitive tasks that were delivered by the web application. This result verifies the second half for the main research hypothesis, that children with dyscalculia would present more incorrect answers and would need more time in order to complete cognitive tasks. Additionally, the results of the present protocol supports the findings of cognitive psychology that suggest that children with dyscalculia presents several deficits on cognitive systems apart from the core numerical ones (for review see [20]). These children face difficulties on attention, memory, reasoning and visual spatial discrimination. The statistically significant results of the answers and the time latency between dyscalculic children and comparison group on tasks that were constructed in order to screen the aforementioned abilities supports the multidimensional approach of developmental dyscalculia as they present evidence from other deficits that dyscalculic children has to face apart from comprehending algorithms of addition and subtraction and have a defective number module or number sense. Additionally, supports studies that suggests intervention programs that are focused on executive functions such as spatial training programs [29].

Another important component, was that internet can be used as a tool for delivering a screening procedure for children with dyscalculia. The use of computers in the identification of children with learning disabilities is steadily increasing in psychology and education. The principal advantage of computer based systems over conservative methods of diagnosis is that the assessment of cognitive skills is more precise. Also, since computers can score performance in terms of correct or wrong answers and latency, they can provide significant savings in time and labor [46].

The main benefits of computer based screeners is that they can capture and engage the interest of the user. If they are properly constructed and presented can help minimize the user's frustration and loss of dignity when working on tasks once accomplished with ease. Moreover, the context of learning to use the computer can provide the user with an experience of mastery and a sense of control. The computer can measure multiple dimensions of performance (latency) at levels that are not possible for the clinician, and also provide automated data collection and storage that can free the clinician to focus more on the treatment. Lastly, the computer is efficient at performing tasks that would otherwise require extensive setup and/or preparation time [2].

However, computer based assessment can never replace the diagnosis by an expert professional, or better by a multidisciplinary team of people with different skills, i.e. psychologist, educational diagnosticians, or other professionals qualified to perform evaluations, is desirable for accurate diagnosis of the student's strengths, weaknesses, present level of academic performance and eligibility for special education services. Also, the multidisciplinary team that can provide the assessment may also construct the intervention program that the child with dyscalculia and the school have to follow [47]. The computer based screeners on condition that are valid can only be a supporting tool at the diagnosis.

In conclusion the web application screener for dyscalculia that was constructed and used for the present research protocol can be used as a screening tool in order to provide first – pass service and referral. Furthermore, the present study is in the line of studies that suggests that children with dyscalculia do not only present difficulties in numerical abilities, but also in more core skills such as cognitive abilities. In addition, strict psychometric evaluation of the screening procedure and its validity the results of which are now under elaboration is a necessary condition before its widespread adaptation recommended.

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