COMPUTER BASED SCREENING DYSCALCULIA: COGNITIVE AND NEUROPSYCHOLOGICAL CORRELATES[1]

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ABSTRACT
Mathematical skills are becoming increasingly critical for achieving academic and professional success. Developmental dyscalculia (DD) is a childhood-onset disorder characterized by the presence of abnormalities in the acquisition of arithmetic skills affecting approximately 5% of school age children. Diagnosing students with possible dyscalculia tendencies and giving them relevant extra learning opportunities based on their specific difficulties are critically important for them to go with their peers. One of the human cognition dimensions is number. Two distinct systems of basic numerical capacities have been described: Approximate and exact number systems. Additionally, current brain imaging studies have associated this disease to structural and functional alterations corresponding to parietal and prefrontal cortices. In order to screen dyscalculia tendencies related to these two systems, we have developed five different cognitive tasks. The aim of this paper is twofold. First, a brief description of the software and the cognitive tasks will be presented. Second, a review of the findings about neural correlates of computer based cognitive tasks used for screening of dyscalculia as well as the neuro-structural and neurofunctional imaging findings in DD will be synthesized.
Keywords: Core systems of number, Dyscalculia, Cognitive processes, Neuropsychology, Neural correlates of dyscalculia, ANS, ENS

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INTRODUCTION
Developmental Dyscalculia (DD) is a specific mathematics learning disability affecting 3 to 6% of school age population in different countries (Mussolin et al., 2010). DD is conceived as a brain-based disorder of probable genetic origin, possibly inherited from one's parents (Butterworth, 2005). Students with DD have considerable difficulties in learning numbers and calculations. In terms of mathematical achievement they lag at least 2 years behind their peers. In order for those students to continue their education with their peers in regular classrooms they should have additional education relevant to their individual needs. However, they should be diagnosed first for their mathematical learning difficulties.

DEVELOPMENTAL DYSCALCULIA: THEORETICAL BACKGROUND OF APPLICATIONS
Diagnosing students with possible dyscalculia tendencies and giving them relevant extra learning opportunities based on their specific difficulties are important for them to attend their regular classrooms with their peers. This diagnosis should be done as early as possible because the brain plasticity is very high in early ages (Zamarian, Ischebeck, & Delazer, 2009). Therefore, the earlier we diagnose dyscalculia the more we have the chance to remediate it. Additionally, if early indicators for mathematics learning difficulties can be translated into key components of remediation programs, it may prevent children from failures (Desoete, Ceulemans, Roeyers, & Huylebroeck, 2009).

Diagnosing DD has been a measurement problem for researchers. There are different approaches to the problem. The variability of these approaches and the tools used to assess dyscalculia make it difficult to establish a common assessment framework. One approach to the resolution of the problem is to assess basic capacities of human cognition. Shalev and Von Aster (2008) proposed that testing of DD should tap several dimensions of human numerical cognition and it is considered to be relevant to the number processing and calculations. Therefore, this study attempts to approach the issue from the perspective of basic human cognition systems, in other words from the basic capacities of human brain.

According to Wilson et al. (2006), DD is caused by a "core deficit" in number sense or in the link between number sense and symbolic number representations (Wilson et al., 2006). A better understanding of the foundational competencies that subserve the acquisition of mathematical skills will help design better mathematics education programs for young children as well as intervention programs that are based on scientific results (Ansari, Price, & Holloway, 2010).

COMPUTER BASED SCREENING TASKS FOR DEVELOPMENTAL DYSCALCULIA

Using computerized versions of neuropsychological tests is becoming popular especially in clinical and educational settings for screening and diagnostic purposes. Within this context, a computerized version of DD screening tool was developed within a research project funded by the Scientific and Technological Research Council of Turkey (TUBITAK: *SOBAG 111K545*). In order to mobilize the tool and making it feasible for data collection, it was decided to develop the software for tablets. Using computers for this purpose is thought to provide flexibility and mobility in reaching students at their convenient times.

CORE KNOWLEDGE DIMENSIONS OF HUMAN COGNITION

Spelke and Kinzler (2007) proposed that humans are born with several numbers of separable systems of core knowledge. According to them, these systems serve to represent inanimate objects and their mechanical interactions, agents and goal directed actions, sets and their numerical relationships of ordering, addition and subtraction, and places in the spatial layout and their geometric relationships. In sum, the proposed five systems of core knowledge are objects, actions, social partners, number, and space. New, flexible skills and belief systems are thought to be built on these core foundations (Spelke & Kinzler, 2007). The proposed core knowledge system dimensions are summarized in Figure 1.

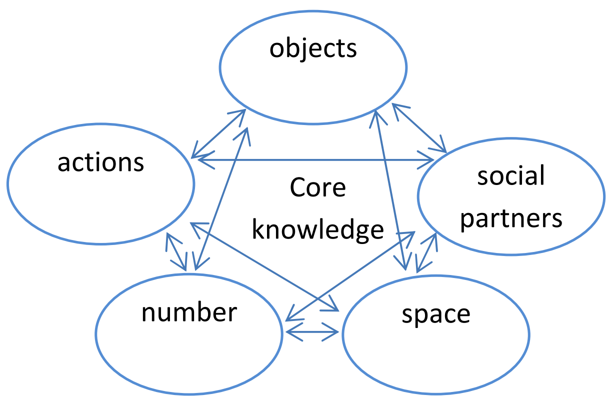

Figure 1: Core knowledge dimensions of human cognition *(This figure was generated by the authors of this paper using the information from Spelke & Kinzler, 2007).*

Although each system has its signature limits to underlie human reasoning about the world (Spelke & Kinzler, 2007), the five systems are possibly interacting with one another in representing and acting on different types of knowledge.

For example, actions might have numerical attributes as well as spatial ones such as traces. Similarly, objects may have both spatial and numerical qualities. Human beings are usually able to attend to three or four separately moving objects, for example, when the objects' boundaries and motions accord with the cohesion and continuity constraints (Spelke & Kinzler, 2007). Similarly a normal human and several other creatures' brain can quickly detect the exact number of dots between 1 and 4 at a glance and determines the number of objects approximately larger than four.

Beyond any doubt, neuropsychological correlates of DD are very important domain for educational applications and for neuroscientists.

NEUROPSYCHOLOGICAL CORRELATES OF DEVELOPMENTAL DYSCALCULIA

Early Studies:

Although poor teaching, environmental deprivation, and low intelligence have been implicated in the etiology of developmental dyscalculia, data indicated that this learning disability is a brain-based disorder with a familial-genetic predisposition, particularly within the left parietotemporal cortex (Shalev & Gross-Tsur, 2001). The neuroanatomic basis of arithmetic has yet to be unrevealed, although application of electrophysiology and brain imaging techniques are yielding encouraging information. Kiefer and Dehaene (1997) used event-related potentials (ERP's) and found that simple multiplication is processed by the left parietal cortex, whereas complex exercises are executed within both centroparietal areas, albeit slightly greater on the left. Neuroimaging studies support these electrophysiologic findings. In normal individuals engaged in arithmetic, functional magnetic resonance imaging (fMRI) reveals bilateral activation of prefrontal and inferior parietal cortices (Rueckert et al., 1996). When the arithmetic task is an exact, language-dependent calculation (e.g., “six times four is … ”), a large area in the left inferior frontal lobe is activated. On the other hand, tasks of number approximation (e.g., “Which is larger, four or nine?”) activate both parietal lobes (Spelke, Pinel, Stanescu, & Tsivkin, 1999).

The “triple-code model” proposed by Dehaene and Cohen (1995) is both neuropsychologically and anatomically based model. These three elements are verbal, visual, and magnitude representation. This model suggests that relatively simple arithmetic operations are processed by the verbal system within the left hemisphere, whereas more complex arithmetic procedures (which require magnitude estimation and visual representations) are bilaterally localized. This model is supported by experimental data from normal individuals performing arithmetic, as well as from case reports of patients with focal brain lesions.

Recent Studies:
According to recent brain studies, the posterior parietal cortex is a region specifically involved with the representation and manipulation of numerical quantity. A left angular gyrus area supports the manipulation of numbers in verbal form. A bilateral superior parietal system supports attentional orientation on the mental number line, just like on any other spatial dimension (Dehaene et al., 2003). Language-independent semantic representation of numerical quantity is related to intra-parietal sulcus (Ansari, 2008; Rosenberg-Lee, Lovett, & Anderson, 2009). Superior parietal lobe, intraparietal sulcus, fusiform gyrus, parahippocampal gyrus and right anterior temporal cortex are releated to DD.

The parietal lobe and more specifically the intraparietal sulcus, has become specialized in the internal representation of quantities, the abstract processing of magnitudes and the relations between them. On the other hand, the angular gyrus takes part in the verbal processing of certain tasks called arithmetical facts (for instance, multiplication tables and additions of small quantities). Prefrontal cortex, posterior part of temporal lobe, cingulate cortex and several subcortical regions are also involved in number processing. Empirical data have provided theoretical and anatomical models for number processing and calculations of which the “Triple Code Model” is currently the most accepted one (Serra-Grabulosa, Adan, Pérez-Pàmies, Lachica, & Membrives, 2010).

In one study, it was shown that white matter volume in right temporoparietal cortex is reduced and there are significant micro-structural impairments in DD. Inferior fronto-occipital areas as key pathways are impaired in DD. Right temporal-parietal white matter is a specific source of vulnerability in DD. White matter differences were primarily localized to the hippocampal region and this region is related to long term potentiation and/or consolidation of knowledge in long-term memory. Recent brain imaging studies suggest that DD in children may be characterized by multiple dysfunctional circuits arising from a core WM deficit. Some researchers also pointed at the structural abnormalities in right hemisphere temporal-parietal white matter and pathways associated with it as key neuroanatomical correlates of DD (Rykhlevskaia, Uddin, Kondos, & Menon, 2009).

OUTCOME AND DISCUSSION
DD screening batteries that could be used in assessing basic numerical capacities should address both approximate and exact number systems. Considering the difficulties children with DD have in mathematics, Shalev and Von Aster (2008) suggested that besides the tasks to measure the knowledge of arithmetical facts and procedures, basic number processing skills such as subitizing (ability to accurately assess size at a glance) a small number of objects and estimating large number of objects, comparing number magnitudes, counting, and the ability to use different notational formats (seven or 7) and spatially representing numbers on a mental number line will be included in order to assess DD throughly.

Mathematical skills are becoming increasingly critical for achieving academic and professional success; but, in Turkey, there is not any standardized dyscalculia screening test. Because of this purpose, attempts to develop a computer based screening DD test for 6-9 years old school age children have been initiated with an interdisciplinary team and approach. Having reviewed the current literature, we developed five different cognitive tasks in order to assess and/or screen the dyscalculia tendencies by utilizing tablets. These tasks are: Dot counting (Subitizing), Number Comparison (Numerical Stroop), Perceptual Quantity Estimation, Number Line Estimation, and Simple Arithmetic tasks. Sample task items are shown in Figure 2. These tasks are sensitive to different cognitive functions and brain structures and/or networks related to numerical capacity.

In order to deliver the tasks, android tablets were chosen for two purposes. First, these tools are flexible and mobile so that they could easily be carried to schools. Secondly, tablet use is gaining popularity among school-age children. Moreover, once the tool is proven to be reliable, more improvement applications could easily be developed and distributed through Android market. The platform included two sections: task trial and task screening. In task trials, participants are given examples of how interaction with the tasks are designed and let them practice before the real tasks. Participants' correct and wrong responses were observed but not recorded in this section. In the screening task, participants' are requested to complete the whole tasks at two sessions, each half an hour duration. Each interaction was transformed into numbers. These data were kept in the tablets and backed up each day regularly.

Finally, brain imaging studies show us, DD included multiple dysfunctional circuits arising from a core white matter deficit, and secondarily a disconnection syndrome. Age, IQ, reading ability, and working memory capacity play important roles in DD. In Table 1 DD screening tasks and cognitive and neuropsychological correlates were summarized.

Table 1: Computer Based Developmental Dyscalculia Screening Tasks and Cognitive and Neuropsychological Correlates.

Task Name	Task Description	Cognitive Function	Related Brain Structure/Area
DOT COUNTING (For example see the item in Figure 2)	In this task, dots will be arranged randomly and/or canonically to reveal the differences in children's enumerating speed in this format.	Knowledge of Number Attention Categorization (for only canonic items) Visual Memory	Posterior parietal cortex Prefrontal cortex Cingulate cortex
NUMBER COMPARISON (For example item see Figure 2)	In this task, subjects were asked to choose either the numerically or the physically larger of the two numbers. Subjects' decisions are interfered with the use of physically incongruent numerals.	Working Memory Executive Functions (Set Shifting, Resistence of Interference Effect) Attention	Prefrontal cortex (bilaterally) Right temporoparietal cortex
PERCEPTUAL QUANTITY ESTIMATION (For example, item see Figure 2)	In this task, numerical context influences their choice of children's representations. Some pictures (different numbers) are shown for 3000 milliseconds then disappear. Students are asked to write their estimates on numerator appeared on the screen.	Working Memory Executive Functions (Abstraction, Planning) Attention	Prefrontal cortex (bilaterally) Intraparietal sulcus
NUMBER LINE ESTIMATION (For example item see Figure 2)	In this task, children are asked to indicate the position of numbers represented in Arabic numerals on number lines that are empty except for the number 0	Working Memory Executive Functions (Abstraction, Planning) Attention	Prefrontal cortex Superior parietal cortex (bilaterally)

	at the left end and a larger number (usually, 10, 20, 100 or 1000) at the right end.	Visuo-Spatial Functions	
SIMPLE ARITHMETIC (For example, item see Figure 2)	In this task, children do basic calculations (addition, multiplication and subtraction operations). Children are asked if the result is correct or not.	Knowledge of Number Working Memory	Left parietal cortex Inferior parietal cortex (bilaterally) Left inferior frontal lobe Left angular gyrus

In Figure 2, sample items developed for computer based developmental dyscalculia screening tasks are presented.

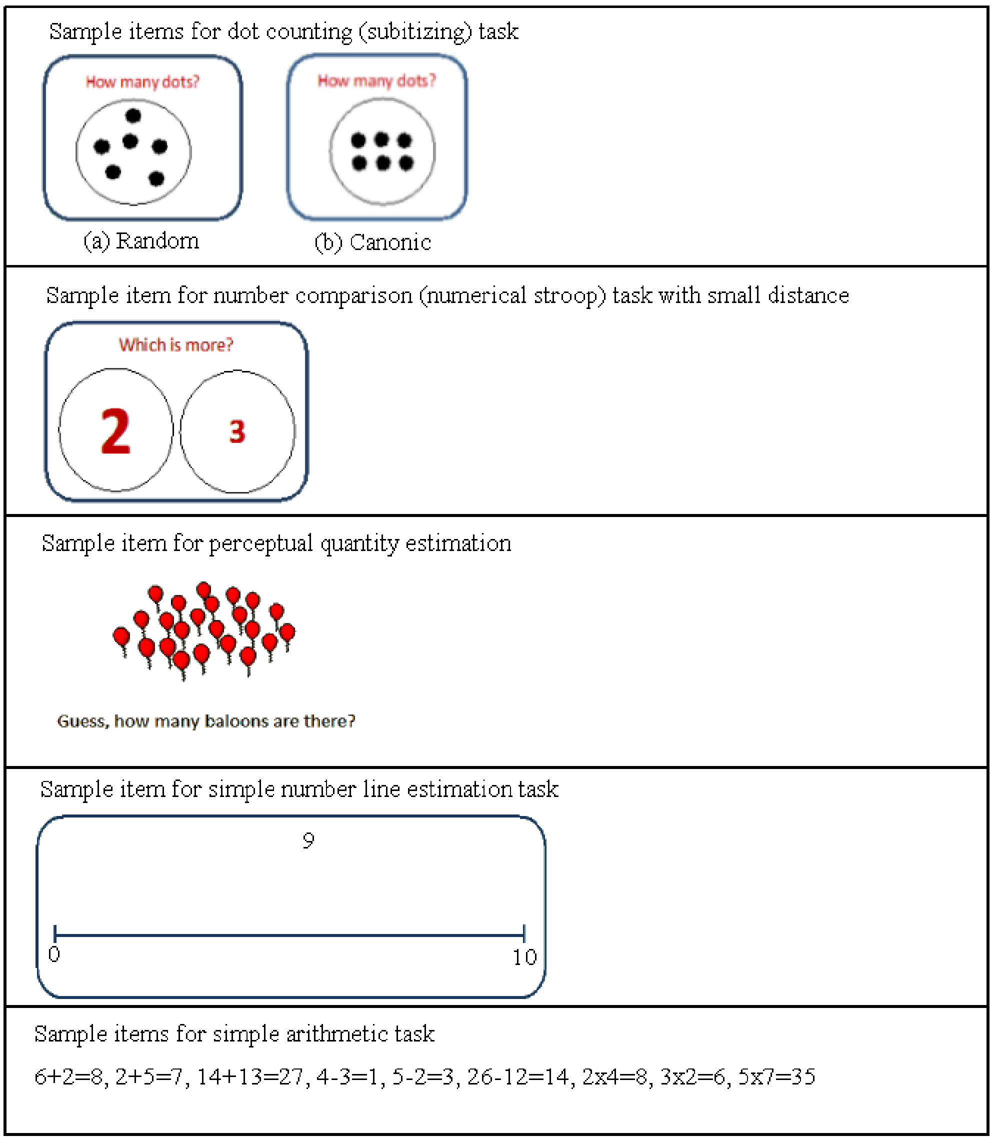

Figure 2: Sample items for computer based developmental dyscalculia screening tasks.

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