Dyscalculia – A Cognitive Approach

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47 students ranging in age from 8 to 16 years have been evaluated for mathematical disabilities. This study shows an indication of certain patterns to be found in the test results. The basic cognitive production involved in solving mathematical problems displays a varied picture, involving executive functions, sequential and simultaneous processing, arousal/attention areas, automation, and cognitive integration. The results from the assessments are discussed from a cognitive point of view.

Introduction

Most studies report the proportion of students with mathematical difficulties to be about 10–15 % (Lunde, Hole & Hansen, 1999). A study conducted in Gothenburg reports mathematical difficulties for about 12–13 % of the total student body (Magne, 1973).

Students with specific mathematical disabilities/dyscalculia have been the target group for this study. The term dyscalculia is used for students whose mathematical achievement is considerably below cognitive level and achievement in other school subjects. The Gothenburg study found this kind of problems in 0,2–0,3% of the students (Magne, 1973). Kosc (1977) found in his study that 6.4 % of all students with normal cognitive abilities do need special adjustment to compensate for difficulties in math. The same results have been reported by Badian (1983). There may be many reasons for this variation in numbers from investigation to investigation. Differences in terminology probably accounts for most. Magne (1998) discusses

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this unclear use of terminology and shows that as many as 59 different definitions are in use within the area of difficulty in mathematics. However troublesome this lack of clarity may be, I still think we may conclude that the number of students with mathematical disability is large and in frequency close to the prevalence of reading disability (Badian, 1983; Tvedt, Johnsen, 2002).

My work has mainly been directed towards students with dyscalculia, but this can have had an inclusive effect leading to the definition being somewhat wider than first assumed. Some students have exhibited problems in both the areas of reading and mathematics. Others could also fit in the more broadly described category of learning difficulties. It seems to be very difficult to establish clear borders. In addition diagnoses like Asperger syndrome, Tourette syndrome, Gerstman syndrome, Nonverbal learning disabilities, Schizotypical conditions, and others, contribute in making a personality with exceptional personal and cognitive features.

The material this article is based on has been gathered the last four years and includes 47 students with great difficulties in math. The age range is from 8 to 16 years (table 1). The students have been recruited from Nordland, Troms and Finmark, the 3 northernmost counties in Norway.

Table 1 Population in study (n = 47), 34 males and 13 females

	Age in years								
	8	9	10	11	12	13	14	15	16
Number	2	5	9	6	3	9	8	3	2

Assessment

This study focuses on specific cognitive features in children with specific difficulties in mathematics and covers an age span of eight years. Children, of course, develop. They change from one year to the other, and the data from different age groups may be compared only to a limited degree. On the other hand, there are personal and cognitive traits that are fairly stable over time and that make it possible to generalize to some extent.

When describing the process of assessment the reader needs to bear in mind that the approach is transdisciplinary, and not limited to an empirical psychometric point of view.

Assessment systems

In assessment of mathematical abilities KeyMath Revised, Ostad's test of mathematics and Test of Early Mathematics Ability (Tema 2) have been applied. Ostad's test of mathematical abilities can be used with all age groups, while KeyMath R has norms established for students aged 7 to 15 years. Still the test, in my experience, has proven to be useful for students with mathematical disabilities up to the age of 16 years. Important aspects of the area are in addition assessed with the aid of systematic observation.

The assessment of the cognitive production process is executed as described below. To understand the underlying production system, like occipital, parietal, temporal, prefrontal and subcortical areas of function, a variety of assessment tools have been applied. Luria's mapping strategies and selected subtests from Halstead-Reitan's Battery (HRB) have been very useful in this process. Identification of hemispheric processes and hierarchy of cognitive functions are included in the diagnostic process.

Mapping of the sequential and simultaneous information processing has been conducted with Kaufmanns Assessment Battery for Children (K-ABC), later on the Cognitive Assessment System (CAS) has been applied. WISC-R, together with others, has been used to assess cognitive level.

Assessment of executive (frontal) functions through systematic observation has been conducted as described by different researchers (Luria, 1969; Luria, 1980; Denckla & Reader, 1993; Lezac, 1994; Grafman, 1994; Das, Kar & Parrila, 1996; Goldberg, 2001). This area has also been mapped by the use of CAS, Category Test, Wisconsin Card sorting Test (WCST), COWAT/FAS, Tower of London (TOL), STROOP, different interview forms, and information extracted from the assessment of mathematical abilities.

In the assessment of attention/arousal functioning Conner's Continuous Performance Test (CPT), STROOP, Wechsler Memory Scale-Revised (WMS-R) and CAS have been used. In addition special test designs have been applied to try to evaluate such aspects as "narrowing problems" and divided/simultaneous attention. Afferent and efferent motor functions have been assessed primarily by using "Lurian" clinical strategies, but also through items from Hallstead/Reitan and K-ABC.

Memory systems have been evaluated by WMS-R, subtests on CAS and K-ABC, part of Luria's clinical strategies and tests of mathematical abilities. In agreement with my supervisor I have used WMS-R down to the age of 12 years, far beyond the age established in the norms (Bosnes, Ellertsen, 2000). The Rivermead Behavioral Memory Test is also part of the assessment.

The imaginative systems have been tested according to a strategy of testing developed by Lunga (1995). Procedural functions have been assessed according to patterns found in the assessment systems mentioned before, as is also the case with primary and secondary automatic functions. When it was necessary to make an evaluation that included social-emotional areas, Personal Inventory of Children (PIC) was used.

The assessment systems listed above are the main tools in the assessment process. In addition, other tests have been used if there have been any questions concerning the areas mentioned. This has been done when judged necessary by clinical experience. For those interested in further details the author has published articles with a functional analytical description of the assessment procedure (Johnsen, 2000; Johnsen, 2001).

Assessment of mathematical abilities

Different tests have been used when evaluating the student's mathematical abilities. They are mentioned earlier in the article. KeyMath has been used with 36 of the 47 students. The test is not normalized for Norwegian students, but has been translated and adapted for use in Norway. This test can be divided into three main areas,

A: Basic concepts. Here the student is required to solve problems concerning the number line, fractions, decimals, percent, and geometry.

B: Operations. Here the student is required to solve problems concerning addition, subtraction, multiplication, division, and mental computation.

C: Applications. Here the student is required to solve problems concerning measurement, time and money, estimation, interpreting data, and problem solving.

Table 2. KeyMath test results (n = 36)

	C > A	C > A and B	A and C > B	A = B
Number	22	21	27	2

22 of 36 students score better on C than on A. 21 students have obtained a better score on C, compared to A and B. No less than 27 score less on B than on A and C. Two students have similar results on A and B.

The elements of KeyMath may be described as follows: A and B represent knowledge while C in principle measures the ability to apply such knowledge. It might seem puzzling that a majority of the students are relatively able in applying knowledge that they, according to the same test, to some extent are lacking.

The different age groups reveal largely the same tendency throughout the material.

The relationship between A and B on the one hand, and C on the other, reflects a number of important aspects. Here I will focus on C as an indicator of the ability to apply knowledge in mathematics that is registered on A and B. A closer look at the questions in C, however, shows a content that to some degree will be learned outside school.

Two modes of learning

The results on K-Math therefore tell us about two different modes of learning mathematics, where acquisition occurs accordingly,

1. Traditional school-based teaching with a theoretical perspective. Here the skills are acquired through the learning of symbols in a formalized setting. This can be described as artificial or scientific cognitive conciliation. Area A and B in KeyMath will reflect this knowledge.

2. Through interaction with the environment and being in a regular language setting, the student acquires mathematical knowledge. This can be described as natural cognitive conciliation. Area C of K-Math will reflect this knowledge.

Vygotsky (1982) discussed this issue in a lecture in The Scientific-Methodological Soviet at The Leningrad Institute in May 1933. The lecture was given under the heading "Development of everyday and scientific concepts during school age". These learning styles will often be held against each other, almost as if they where mutually exclusive. It is more likely that some students are in favor of one way or the other, depending on age and learning abilities.

Looking closer at 1 and 2, I have in my material indications that point to a connection between parietal, mainly bilateral, dysfunction in 9-year-olds and older students and the group that scores higher on C than on A and B. When related to cognitive functions this makes sense. The parietal areas (primarily the inferior) basically produce cognitive integration, and then mainly on a higher conceptual level. The traditional classroom education, with a focus on theoretical teaching, puts a heavy tax on the parietal system's ability to integrate. The learning processes that occur in natural settings do not put such demands on the parietal system. Everyday life itself makes sure this integration process takes place and is probably a good "tool" to compensate for weaknesses in the parietal system.

Based on regular cognitive development, the learning mode described in point 2 will be the best way of learning in preschool and the first years of formal schooling. An interactive teaching approach will probably prevent future mathematical problems for many students. For students with parietal dysfunction point 2 will be the mode of learning throughout life.

A more surprising finding is the fact that about 1/3 of the students score close up to age expected in area C. This strengthens the theory about two alternative modes of learning. It can also be an indication that resourceful students with cognitive dysfunction in posterior tertiary areas will, to a certain degree, be able to achieve results that are at age level in mathematical testing, if learning conditions have been good enough.

One also needs to keep in mind the emotional-motivational aspects. For most students this will be better taken care of under mode 2 compared to mode 1. This might be part of an explanation why the results are as described earlier.

Automation

The second main feature that crystallizes in the material is that area B is clearly below area A and C in 27 of 36 results (Table 2). The basic cognitive production systems being employed while solving problems in area B can be connected to several productions systems in the brain. The most important cerebral functions involved are connected to procedural abilities and ability to automatize. There is a close connection here. If the difficulties in automation are primary, one will often find an overlap with procedural learning difficulties. Probably the premotor cortex, basal ganglia and the cerebellum are primary support systems for motor and cognitive automation, primarily procedural (Luria, 1980; Thompson, 1989; Kunzig, 1998). These functions have independent memory systems (Arnold, 1984; Thompson, 1984).

When the automation problems are of secondary character, as seen in nonverbal learning disabilities (NVL) where repetition reduces recognition and thereby reduces the effect of repetition, the result is automation difficulties of another kind (Rourke, 1989). In this group there will also be found some students with a cognitively based reduction in speed when learning new material and in repetition. An exception here is when a dysfunction in the dominant temporal area causes a need for reduction in tempo to achieve automation (interference) (Tsvetkova, 1972; Luria, 1976).

It is important to assess whether the difficulties in automation are of primary or secondary origin. Secondary difficulties can be almost eliminated when the learning environment is adjusted. For primary difficulties the prognosis seems to be worse, and the need for technical aid (e.g. a calculator) is imminent (Johnsen, 2001). Identifying those areas is possible through the assessment process already described.

Cognitive production

Amongst the 47 students in this study, 39 have been assessed with K-ABC, 8 with CAS and 12 with the complete WISC-R. 12 more have taken selected subtests on WISC-R. Several students have taken two of the three mentioned tests, and a few have taken all three tests.

This study is especially based on K-ABC, since a majority of the students have been assessed with it. In cooperation with other professionals K-ABC has also been used with students outside the age norms. This has primarily been done to evaluate the relation between simultaneous and sequential information processing. Students at age levels above the age norm have also been assessed with WISC-R and/or CAS.

36 of 39 students have a full-scale IQ score below 100; three have a full-scale IQ score above 100. This information is familiar news, confirmed by findings in other studies. The intriguing bit is that some students have dyscalculia, despite high IQ scores as measured through formalized testing. Krutetskii (1976) also found this in his investigation in the schools of Moscow (Johnsen, 1998). A conclusion based on these findings will be that cognitive level does have an influence on mathematical abilities. Cognitive profile is also an influential factor. When a student seems to be unable to learn in the regular school setting or the special education setting an explanation should be asked for. Most likely the explanation will be found in the child's internal environment, the cognitive production system.

Simultaneous and sequential information processing

My reason for choosing Sechenov's (1943) theory for processing of information is dual. 1. I relate to this theory in my clinical practice. 2. As a concept it relates very well to dyscalculia. Simultaneous and sequential information processing can be directly related to research and clinical practice concerning mathematical functions as ordination and cardination.

Simultaneous and sequential information processing are secondary processes and several of the production systems of the brain contribute to these functions. According to Luria, simultaneous functions are associated with the occipital-parietal regions of the brain (Luria, 1974), and the sequential functions with the fronto-temporal systems (Luria, 1966; Luria, 1980). Simultaneous and sequential brain production probably utilizes a much larger production system than Luria proposed (Joseph, 1996). My findings point in the same direction.

When this study began, the K-ABC was the only available tool for assessing this kind of information processing. Later on CAS was developed, with a lot stronger theoretical base. Kaufman has, amongst others, been a contributor to CAS. One of the most significant new developments in K-ABC is that Vygotsky's "zone of proximal development" is implemented in a functional way in the test.

When discussing the results from K-ABC there are some weaknesses one needs to be aware of. Assessment of simultaneous production is to a large extent related to visual-spatial functions and all subtests in the sequential area are demanding on the memory system (Das, 1984). In the sequential area there are subtests that are sensitive to simultaneous interference.

Table 3. Results from K–ABC assessment (n = 39)

	Seque < Simult	Simult < Seque	Seque = Simult
Number	28	9	2

Of a population of 39 there are 28 that have a lower score on sequential processing of information, compared to simultaneous. 9 out of 36 have a higher score on sequential processing; two have an equal score on both areas. When there is a difference, this difference is significant for most results. In the group of 9 that scored lower on simultaneous functions, 5 have been identified to have non-verbal learning disabilities as defined by Rourke (1989). There is not agreement about which of the production systems of the brain contributes most to the different kinds of difficulties found in the area of mathematics. When looking at simultaneous and sequential functions both as single functions and cooperatively, there may be difficulties.

This study has found that weakness in the sequential processing is a main feature for the students with dyscalculia. Based on these results there are two things that need to be addressed in the teaching sessions. One is to put greater emphasis on automation, the other is to work on understanding. Both sequential and simultaneous processes are trainable (Das, Naglieri & Kirby, 1994). It is important to keep the distinctions between nonverbal/verbal and sequential/simultaneous processing of information. The simultaneous and sequential processes take place in both hemispheres of the brain, as does spatial production. Production of language will mostly be located in the dominant hemisphere (Cohen, 1973; Das, Cummings, Kirby, & Jarman, 1979; Goldberg & Costa, 1981).

Executive functions

There is a continually growing research and literature in this area. Together with the more traditional ways of analyzing executive functions, as described by Luria (1974) and Pribram (1990) and others, a more extensive evaluation of this cognitive contribution is achieved through a broader functional analysis of behavior (Goldberg, 1990; Denckla & Reader, 1993; Lezak, 1994; Grafman, 1994; Das, Kar & Parrila, 1996; Goldberg, 2001).

While input and basic processing of information, related to concepts and cognitive schemas, mainly is located in the posterior regions of the brain, executive functions are located in the frontal areas. Factor analysis identifies it as an independent cognitive production (Das, Naglieri & Kirby, 1994). This has been recognized in neuropsychological studies for some time, and recently it has been taken into account also in publications based upon pedagogical and psychological traditions. As an example, what is described as cognitive planning in neuropsychological studies is very similar to what is termed metacognition in pedagogical and psychological studies.

In my study 12 of 47 students exhibit dysfunction in the executive areas to an extent where it can explain the mathematical difficulties. Mathematical abilities rely so heavily on executive cognitive production that one would expect this number to be larger. In the assessment, however, rather stringent criteria for inclusion have been applied. For students under the age of 11, both the results from the formal assessment and the clinical information need to be in agreement for the problems to be related to executive functions.

Relying solely on formal tests of executive functions can be misleading. Executive functions depend on support from other cerebral systems. If any of the support systems fail during testing this will emerge as an executive dysfunction, but in fact it does not need to be an executive function at all.

Dysfunction in the executive system can also influence the results in tests not constructed to assess this function. Tests of mathematical abilities seem to be especially sensitive to executive functions. Systematic interviews and observation of children in everyday situations and during assessment, specific assessment of executive functions, and results from other tests, give information for the drawing of conclusions.

Lunga (1999) has divided executive functions into six subareas,

a. planning/organizing

b. disinhibition/impulsivity

c. working memory

d. evaluation

e. acting in context

f. persistence

Executive dysfunction will result in difficulties in separating important information from trifles (preplanning), setting goals and working towards them, making adjustments while working, and keeping several aspects in focus at the same time. These are cognitive components employed in the working process during mathematical non-routine tasks. The executive area is therefore important to account for when dealing with dyscalculia. If this is the main area of dysfunction, the pedagogical adaptation needs to be different from when the dysfunction can be related to other cognitive areas. The thoroughness with which an assessment needs to be conducted is very necessary from an educational point of view. Different subfunctions have different outcomes when working with mathematical dysfunctions.

Dysfunction in the executive system needs to be addressed especially through pedagogical and social adaptations; often to such an extent that one needs to make a total break with traditional teaching methods (Luria, 1963). But in order to make such adjustments the students need to be identified.

The mathematical functions are in many ways influenced by the executive functions. The cases of dyscalculia identified in this study indicate the need to address the executive functions area to a larger extent.

Arousal/attention function

The arousal/attention functioning is influenced by motivation and other cognitive components (Broadbent, 1984), and the learning opportunities in the environment plays a significant role. Several studies of dyscalculia have found an elevated rate of students with problems with attention. Das, Naglieri and Kirby (1994) divide attention into three main areas,

1. arousal
2. sustained attention
3. selective attention

Arousal is a general condition of activation, while attention is specifically directed towards a goal. Even if the arousal function is somewhat unspecific, it can lead to distinct cognitive difficulties, like problems with narrowing of attention (Easterbrook, 1959).

Sustained attention is the ability to keep the attention directed towards an information source or a goal without losing focus. This type of attention is conceptually comparable to vigilance, and localized in the parietal and frontal areas in the right hemisphere (Posner & Boise, 1971; Das, Naglieri & Kirby, 1994; Posner & Reichle, 1999).

Selective attention can be divided in two areas; attention focused on one source, or attention simultaneously divided and kept focused on two or more elements. Selective attention is mainly located in frontal areas, and is part of the higher executive functions (Denckla, 1993).

Table 4. Arousal/Attention (n = 44)

	Selective attention (only)	Sustained attention (only)	Sustained and selective attention	No indications of attention problems
Number	4	14	15	11

CPT has been used with 44 students, 33 have been tested with STROOP, 7 have been tested with CAS, and 7 have been tested with WMS-R.
As noticed, CPT has been used on the total sample, and therefore has had a pivotal effect on the results. This test has its limitations. Due to the duration, frequency and stimuli of the test, it is only partly useful in assessing sustained attention. Therefore the use of other tests and clinical judgment has been necessary.

14 of the 44 students in this study displayed significant deviation concerning sustained attention. 4 students showed deviation concerning anterior selective attention. 15 students showed significant deviation concerning both sustained and selective attention. 8 of 35 students displayed problems with narrowing.

The tools for the assessment of simultaneous/divided attention were applied only late in this study, and such conclusions cannot be drawn from my material. However, items from CAS, Wisc-R, K-ABC, Halstead/ Reitan and others clearly indicate that this kind of attention problems is present in the population being studied.

As evident in the tables, a large part of the population in this study have difficulties with arousal/attention functioning. In educational settings the approach will be different, depending on where the dysfunction has its origin. To locate the dysfunction in the attention function an assessment needs to be conducted, and the educational approach can be based on this.

A large part of the students in the population showed signs of attentional narrowing problems, where there is too strong figure-ground contrast (Callaway & Dembo, 1958; Agnew & Agnew, 1963). This can result in several difficulties, like socially having reduced abilities for the perception of wholeness, cause and effect. With respect to mathematical functioning it can cause the student to start adding in the middle of a subtraction problem, and vice versa. When working with mathematical problems demanding a solution to be worked out in steps the student is at risk of loosing the overall perspective. A dysfunction like this needs to be compensated for pedagogically.

Extensive dysfunctions in attention/arousal are often combined with dysfunction in memory systems, very often of a global character (Luria, 1976). The population of this study is too limited to draw any conclusions regarding comorbidity between these functions.

Three areas of importance

Memory systems

In this study only 8 students have been tested thoroughly with regard to memory systems. From this sample it is concluded that the memory systems are in concordance with the general cognitive level. K-ABC, WISC-R and CAS together have a substantial amount of subtests assessing different memory functions, and a large proportion of the students has been assessed with these tests. In this population the average results on the memory items fall slightly below general intellectual level – with some variation between different memory functions. It is of special interest that items that tax "working memory" heavily on average fall below other memory functions. My material is too limited for any conclusions to be drawn, but it is a finding that calls for further investigation.

The imaginative system

The assessment of the imaginative system was conducted in ways developed by Lunga (1995). By evaluation and comparison of different subtest from different tests, and with clinical/theoretical experience, one can get an indication of the subject's imaginative processes. In this study 3 of 47 students displayed a significant dysfunction in this system, and several others displayed mild deviations. In the group showing significant dysfunction, not surprisingly, one had a diagnosis of Asperger syndrome, and all three displayed significant levels of dyscalculia. In his recent studies Ostad (1997, 1998) has focused his research on imaginative functions and dyscalculia. Arnold (1984) as well as Holtzman and Kosslyn (1990) have also focused on imaginative functions.

Congenital mathematical ability

Recent research has discovered that humans have an inborn ability to perceive the environment in quantities (quantities up to three or four). If a person lacks or has a weakness in perceiving this quantity there is evidence to indicate developmental dyscalculia (Johnsen, 2000). This insight probably will have great significance in future work with students with mathematical disabilities. Seron, Pesenti, Noèl, Deloche & Cornet (1992), Dehaene (1997), and Butterworth (1999), together with others, have offered substantial contributions to this area.

Summary

This article has evaluated important cognitive functions involved in the development of dyscalculia.

Dividing the different functions into separate areas is somewhat artificial, due to the fact that one overlaps with another in dynamic cooperative processes. Often there are combinations with weaknesses in subsystems, causing learning difficulties, which leads to difficulties in different school subjects. A trait common to several conditions is brought forward – the fact that the dysfunctional system can be difficult to detect due to the outcome of the dysfunction. In order to adapt and adjust the educational approach there is a need to identify the underlying systems of cognitive functions.

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Sammendrag

47 elever i alder fra 8 til og med 16 år er blitt utredet for sine spesifikke matematikkvansker. Artikkelen presenterer utredningsdata på følgende områder: Evnenivå, eksekutive funksjoner, suksessiv og simultan prosessering, aktiverings-/oppmerksomhetsfunksjon, automatisering og kognitiv integrasjon. Utredningsdataene avdekker en elevgruppe med stor spredning i læreforutsetninger. Nøkkelord: Spesifikken matematikk-vansker - årsaker - kognitiv spredning.