IDENTIFYING SUBTYPES AMONG CHILDREN WITH DEVELOPMENTAL COORDINATION DISORDER AND MATHEMATICAL LEARNING DISABILITIES, USING MODEL-BASED CLUSTERING
Abstract

A relationship between motor and mathematical skills has been shown by previous research. However, the question whether subtypes can be differentiated within developmental coordination disorder (DCD) and/or mathematical learning disability (MLD) remains unresolved. In a sample of children with and without DCD and/or MLD, we used a data-driven model-based clustering to identify subgroups of individuals with relatively homogeneous profiles on measures associated with motor and mathematical skills. No subtypes were found based on motor variables (either in combination with mathematical variables or not). Based on mathematical variables only, three emergent groups displayed profiles that conformed to a subtype with number fact retrieval problems, a subtype with procedural calculation problems and a subtype without mathematical problems. Our results raise questions about the usefulness of placing children who have below-average mathematical skills into a single diagnostic category. Furthermore, we inform ongoing debates about the overlap between DCD and MLD, in a way that no phenotype with motor and mathematical problems was found based upon the cluster analysis. DCD seems to be a heterogeneous disability, linked by a diverse way of reasons to MLD.

Keywords: mathematical learning disability, developmental coordination disorder, subtypes

Highlights

- No subtypes were found based upon motor variables
- Mathematical profiles that conformed a semantic memory and procedural calculation subtype
- Questions about one single diagnostic category in DCD and/or MLD
Identifying subtypes among children with developmental coordination disorder and mathematical learning disabilities, using model-based clustering

Previous research has shown that there is a relationship between motor and mathematical skills (Luo, Jose, Huntsinger, & Pigott, 2007; Pagani, Fitzpatrick, Archambault, & Janosz, 2010; Pieters, Desoete, Roeyers, Vanderswalmen, & Van Waelvelde, submitted). In addition, co-morbidity between motor and mathematical problems has been reported (Pieters, De Block, et al., 2012; Pieters, Desoete, Van Waelvelde, Vanderswalmen, & Roeyers, 2012; Vuijk, Hartman, Mombarg, Scherder, & Visscher, 2011). The link between motor and mathematical skills can also be illustrated by the didactical principle applied by clinicians, that one has to start with the manipulation of concrete materials before asking to solve semi-concrete and abstract tasks in a number problem format.

However, for some children, motor skills do not develop according to their age and they may have a developmental coordination disorder (DCD). DCD is a disability characterized by an impairment in the development of motor coordination which interferes with daily living and cannot be explained by a medical condition (American Psychiatric Association [APA], 2000). Children with DCD have common co-morbid disabilities, which seems to be one of the main reasons that complicates research in DCD (Visser, 2003). For instance, mathematical problems are frequently reported in children with DCD (Pieters, Desoete, et al., 2012). This is not unexpectedly, as research has shown that (fine) motor skills predict mathematical skills over time (Luo et al., 2007; Pagani et al., 2010) and the severity of motor problems is related to the severity and the range of co-morbid problems (e.g., Jongmans, Smits-Engelsman, & Schoemaker, 2003; Rasmussen & Gillberg, 2000) including mathematical problems (Pieters, Desoete, et al., 2012).
Mathematical learning disability (MLD) refers to a significant degree of impairment in mathematical skills, including substantially below performances. In addition, these problems remain severe, even with remediation. This is also referred to as a lack of responsiveness to intervention (RTI; Fuchs et al., 2007; Kavale & Spaulding, 2008). Finally, the problems in MLD cannot be explained by impairments in general intelligence or external factors that could provide sufficient evidence for scholastic failure (APA, 2000). Motor problems are frequently co-morbid with learning disabilities, including MLD (e.g., Jongmans et al., 2003; Pieters, De Block, et al., 2012; Pieters et al., submitted; Vuijk et al., 2011).

Given the frequent co-morbidity between DCD and MLD, there is an ongoing debate about the heterogeneity or homogeneity of these two disabilities. In addition, it seems worth investigating if the combination of motor or mathematical problems is helpful to identify subtypes. Cluster analysis has shown to be a useful tool in the identification of subtypes (Macnab, Miller, & Polatajko, 2001). To the best of our knowledge, there is no study investigating subtypes in a population of children with DCD and MLD. However, in an ‘isolated’ way, cluster studies have been conducted in DCD and subtypes in MLD have been proposed.

A few years ago, Visser (2003) described several cluster studies in DCD (Dewey & Kaplan, 1994; Hoare, 1994; Macnab et al., 2001; Miyahara, 1994; Wright & Sugden, 1996) and concluded that, despite the diverse results, one common subtype emerged, characterized by generalized sensorimotor problems. This subtype had an overall impairment on all measured motor related domains and co-morbidity with learning disabilities was frequently reported (Kaplan, Wilson, Dewey, & Crawford, 1998; Macnab et al., 2001; Visser, 2003). Recent studies confirmed this cluster (Green, Chambers, & Sugden, 2008; Tsai, Wilson, & Wu, 2008; Vaivre-Douret et al., 2011). However, most cluster studies in DCD were conducted in rather small samples, ranging from 43 to 178 participants. Furthermore, the link
with mathematics was not made. One exception is the study of Vaivre-Douret et al. (2011),
distinguishing three clusters in a small sample of 43 children with DCD. They found more
mathematical problems in visuospatial and constructional DCD (i.e., characterized by
problems with visual-motor integration, visuospatial structuring, handwriting...) in
comparison to ideomotor DCD (i.e., characterized by problems with crawling, digital praxis,
praxis slowness...). However, the mathematical problems were not differentiated in procedural
and number fact retrieval problems. The problems were based on teacher reports and not on
test results.

Some authors propose at least a procedural and a semantic memory subtype within MLD
(Geary, 1993, 2004; Robinson, Menchetti, & Torgesen, 2002; Temple, 1991). The procedural
subtype would be due to executive dysfunction and characterized by a developmental delay in
the acquisition of counting and counting procedures used to solve simple mathematical
problems. The semantic memory subtype would be due to verbal memory dysfunction and
characterized by errors in the retrieval of number facts (Wilson, Revkin, Cohen, Cohen, &
Dehaene, 2006). The semantic memory subtype in MLD has also been linked to phonetic
problems and dyslexia. The identification of these subtypes was based on cognitive theoretical
models and results on experimental tasks (e.g., Geary, 2004, 2011), no data-driven cluster
analysis has yet been performed in children with MLD.

Since there is a relationship between motor and mathematical skills and since cluster-
analytic studies in DCD are based upon small samples and no cluster-analytic study has yet
been conducted in MLD, we aimed to examine if subgroups of individuals with relatively
homogeneous profiles on measures of motor and mathematical skills can be identified by
means of a data-driven model-based clustering in a large sample of children. Our aim was to
include children with a large range of mathematical and motor skills. Therefore, we included
children with and without DCD and/or MLD. Furthermore, as the semantic memory subtype
in MLD has also been linked to dyslexia, we aimed to investigate the reading and spelling skills of children with MLD, DCD and DCD + MLD and typically achieving children.

**Method**

**Participants**

Four groups of average intelligent children aged 7-12 years participated: 73 children (35 girls) with MLD, 102 children (25 girls) with DCD, 99 children with co-morbid MLD and DCD (44 girls) and 136 children (70 girls) in the typically achieving group without mathematical or motor problems. Typically achieving children were recruited through letters to teachers and parents distributed in mainstream schools. Clinical children were recruited through referral by psychologists, speech therapists and physicians in multidisciplinary rehabilitation, special education and centres for developmental disorders and through newsletter advertisements and letters to teachers and parents distributed in special education schools. All children were typically achieving on intelligence (FSIQ ≥ 80) as assessed with the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991).

Two hundred and one children met the criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV-TR; APA, 2000) for DCD (102 children with DCD and 99 children with DCD and MLD). These children had poor motor coordination substantially below expected, confirmed by a percentile score at or below 16 on the Movement Assessment Battery for Children 2 (M-ABC 2; Henderson & Sugden, 2007; Smits-Engelsman, 2010) for 191 children (for 10 children no recent M-ABC 2 assessment was available). Since all these children received physiotherapy for their clumsiness or scored at or below percentile 15 for writing quality or writing speed on the Systematic Screening of Handwriting Difficulties (Smits-Engelsman, Stevens, Vrenken, & van Hagen, 2005), functional impairment in daily life or in academic achievement was present. A general medical condition or epilepsy was not
the cause of the children’s motor problems, as confirmed by a questionnaire filled out by the parents.

One hundred and seventy-two children were classified as having MLD (73 children with MLD and 99 children with DCD and MLD). All these children scored one standard deviation below the mean on the Arithmetic Number Fact Test (Tempo Test Rekenen [TTR]; De Vos, 1992), the Kortrijk Arithmetic Test Revision (Kortrijkse Rekentest-Revisie [KRT-R]; Baudonck et al., 2006) or the subtest computation of the TEDI-MATH (Grégoire, Noel, & Van Nieuwenhoven, 2004). In addition, they all were non-responsive to the remediation: they received for at least six months therapy and were still having subclinical scores for mathematics after this remediation. Furthermore, these mathematical problems were not due to a lack in education, a sensory deficit or another behavioural or developmental disorder. For 19 children with MLD, we did not have a recent mathematical assessment (TTR: 4 missing and the KRT-R or TEDI-MATH: 15 missing). Nevertheless, they were added to this group as they had a clinical diagnosis of MLD and fulfilled all other criteria described above.

Typically achieving children scored above the 25th percentile on all mathematical and motor tests.

More detailed background information for all groups and the total group is presented in Table 1. As a measure of socio-economic status (SES), the Hollingshead Index score (Hollingshead, 1975) was calculated. Using one-way analysis of variance (ANOVA), significant differences in age, SES, IQ, mathematical, motor, reading and spelling measures between children were found. When comparing the four groups on gender with a Pearson's chi-square test, significant differences between groups were also found, $\chi^2(3) = 19.03, p < .001$.

 Insert Table 1 about here
Tests and materials

Intelligence. Four subtests of the Wechsler Intelligence Scale for Children (WISC-III; Kort et al., 2002; Wechsler, 1991) were used to obtain an estimation of the children’s intellectual capacities. This abbreviated WISC-III is the one recommended by Grégoire (2000) and consists of four subtests: ‘similarities’, ‘picture arrangement’, ‘block design’ and ‘vocabulary’. The reliability and the validity of the abbreviated WISC-III is .92 and .93 respectively.

Mathematics. In order to obtain a complete overview of the mathematical abilities of children and to test for procedural and semantic memory deficits, the following mathematical tests were used: the Arithmetic Number Fact Test (Tempo Test Rekenen [TTR]; De Vos, 1992) for semantic memory deficits and the Kortrijk Arithmetic Test Revision (Kortrijkse Rekentest-Revisie [KRT-R]; Baudonck et al., 2006) or the TEDI-MATH (Grégoire et al., 2004) for procedural deficits. For some of the children, we did not have data from the KRT-R, in that case, the TEDI-MATH was used.

The Kortrijk Arithmetic Test Revision (Kortrijkse Rekentest-Revisie [KRT-R]; Baudonck et al., 2006) is an untimed standardized test on procedural calculations from grade 1 until 6. The KRT-R requires that children solve calculations in a number-problem format (e.g., 39 + 60 = …) or in a word-problem format (e.g., 6 more than 48 is …). The psychometric value of the test has been demonstrated on a sample of 3,246 children and is frequently used in Flemish education and diagnostic assessment.

The TEDI-MATH (Grégoire et al., 2004) is an untimed test for procedural calculation skills for children until grade 3. The TEDI-MATH has been used (e.g., Wilson et al., 2006) and tested for conceptual accuracy and clinical relevance in previous studies (e.g., Desoete & Grégoire, 2006; Stock, Desoete, & Roeyers, 2009, 2010). The psychometric value was
demonstrated on a sample of 550 Dutch speaking children from the second year of kindergarten through the third grade of primary school. The TEDI-MATH has proven to be a well validated (Desoete, 2006) and reliable instrument, values for Cronbach’s Alpha for the different subtests vary between .70 and .97 (Grégoire et al., 2004).

The Arithmetic Number Fact Test (Tempo Test Rekenen [TTR]; De Vos, 1992) is a timed test consisting of 80 (first grade) or 200 (second grade) arithmetic number fact problems. In first grade children have to solve as many additions (e.g., $5 + 2 = \ldots$) and subtractions (e.g., $6 - 5 = \ldots$) in two minutes. Children in the second grade are presented the same additions and subtractions but also multiplications (e.g., $2 \times 8 = \ldots$) and divisions (e.g., $16 : 4 = \ldots$) and a mix of these four operations and have five minutes to solve as many items as possible. The TTR is a standardized test that is frequently used in Flemish education as a measure of number fact retrieval skills. The psychometric value of the test has been demonstrated on a sample of 10,059 children (Ghesquière & Ruijssenaars, 1994).

**Motor skills.** The Movement Assessment Battery for Children 2 (M-ABC 2; Henderson & Sugden, 2007) measures everyday motor competence of children between the ages of 3 to 16 years. As items change with age, the appropriate age bands (7 to 10 years and 11 to 16 years) were applied in this study. The test includes eight subtests across three different domains: ‘manual dexterity’, ‘aiming and catching’ and ‘balance’ and generates an overall motor impairment score besides a score for the separate domains. The M-ABC 2 has good reliability and validity (Henderson & Sugden, 2007). In this study, the Dutch norms were used (Smits-Engelsman, 2010).

The Systematic Screening of Handwriting Difficulties (Systematische opsporing van schrijfmotorische problemen [SOS]) provides an assessment of quality and speed of handwriting by copying a standard text within five minutes on an unruled paper (Smits-
Engelsman et al., 2005). Handwriting quality is evaluated on six domains: fluency in letter formation, fluency in connections between letters, letter height, regularity of letter height, space between words and straightness or regularity of the sentence. Handwriting speed is determined by counting the number of letters written in 5 minutes. Dutch norms were used in this study, which are based upon a reference group of 860 children. The SOS has good test-retest, inter- and intra-rater reliability (Van Waesvelde, Hellinckx, Peersman, & Smits-Engelsman, in press).

**Reading.** Children were tested with standardized Dutch reading measures. Word reading speed or fluency was assessed by the One Minute Test (Eén Minuut Test [EMT]; Brus & Voeten, 1999) and pseudo word reading by the Klepel (Van den Bos, Spelberg, Scheepstra, & de Vries, 1994). Both reading tests consist of lists of 116 unrelated words. Children are instructed to read as many words as possible in one (EMT) or two minutes (Klepel) without making errors. On both tests, the raw scores were the numbers of words read correctly. Both tests were validated in Flanders on 10,059 children (Ghesquière & Ruijsenaars, 1994).

**Spelling.** The PI-dictation (Geelhoed & Reitsma, 2000) is a Dutch standardized test to measure spelling. Children have to write one word of a sentence, which has been repeated. The test consists of nine blocks including 15 words. Each block has an increasing difficulty and the test is stopped when a child made at least seven errors in one block. The test is validated on 3,633 children (Geelhoed & Reitsma, 2000).

**Procedure**

The study was approved by the Ethical Committee of Ghent University and written consent was obtained from the parents. Each child was evaluated individually for several hours by one examiner who was blind to group division.
Data analysis

A model-based cluster analysis (Mclust; Fraley & Raftery, 2003) was conducted using R (R Development Core Team, 2011). This clustering approach is based on the assumption that the observed data come from a population consisting of several subpopulations. Each subpopulation is modelled by a (multivariate) normal distribution. Because we consider this study exploratory in nature, we have fitted several different types of normal distributions (spherical, ellipsoidal or diagonal shape, same or different shape for each component; see the caption of Figure 1 for a full list), each one for a number of cluster solutions, ranging from 1 up to 10 clusters, or up to the largest number of clusters possible for a specific model, given our limited sample size. The Bayesian information criterion (BIC) is used to compare the different models and the different cluster solutions, whereby a higher BIC value indicates a better fit of the model. The BIC value represents a trade-off between the fit of the model (the more flexible the model and the more clusters are allowed, the better the fit) and the number of free parameters that need to be estimated for each model/cluster combination. A BIC plot helps in deciding on the best model. A satisfactory cluster solution is observable by a peak in the BIC plot and a clear separation between the clusters on the scatter plot matrix.

Furthermore, using SPSS Statistics 19 Software Package (IBM, 2010), linear regression with the probabilities of the selected cluster solution was done.

In a first cluster analysis, we aimed to investigate whether the combination of motor (M-ABC 2) and mathematical variables (TTR and KRT-R or TEDI-MATH) would be able to define meaningful clusters. If there is no structure in the sample based upon the combination of these variables, cluster analysis would be done with motor skills (M-ABC 2 domains ‘manual dexterity’, ‘aiming and catching’ and ‘balance’) and mathematical skills (TTR and KRT-R or TEDI-MATH) separately.
Clustering variables were standard scores or $z$-scores (calculated separately for each age, across all groups) if no standard scores were available.

**Results**

**Model-based clustering: Identification of clusters**

*Cluster analysis 1.* We conducted a cluster analysis with the combination of two mathematical variables (TTR and KRT-R/TEDI-MATH) and one motor variable (M-ABC 2 total score). Due to missing values (see Table 1), this cluster analysis was based upon 381 cases. An unconstrained ellipsoidal model (VVV) with three clusters was the best cluster solution. The BIC value for this model was $-4007.78$, the relative BIC difference with a model of two clusters was 4.17% and with a model of four clusters, it was 4.39%. As can be seen in Figure 1, the BIC plots of the ten different models showed no obvious best solution as all plots are flat and there is no observable peak. The fact that this cluster solution was not satisfactory, can also be seen on the scatter plot matrix (showing the three clusters across the three variables) where no clear separation between the clusters can be found (see Figure 2). At first sight, this scatter plot might indicate that the motor variable probably causes noise as the combination of the mathematical variables shows more distinct clusters. As we found no good cluster solution, model-based clustering with the separate domains will be performed.

*Insert Figure 1 and Figure 2 about here*

*Cluster analysis 2.* We conducted a second cluster analysis with the motor variables (i.e., the M-ABC 2 domains ‘manual dexterity’, ‘aiming and catching’ and ‘balance’). Due to missing values (see Table 1), this cluster analysis was based upon 400 cases. An ellipsoidal multivariate normal model (EEE) with one cluster was the best cluster solution. As can be seen in Figure 3, the BIC plots of the ten different models showed no obvious best solution. Only one cluster could be identified; all children were assigned to the same cluster.
Cluster analysis 3. A next cluster analysis on the mathematical variables (TTR and KRT-R/TEDI-MATH) was conducted. Due to missing values (see Table 1), this cluster analysis was based upon 391 cases. The best cluster solution was an unconstrained ellipsoidal model (VVV) with three clusters. The BIC value for this model was -2070.84, the relative BIC difference with a model of two clusters was 15.36% and with a model of four clusters, it was 10.26%. In Figure 4, the BIC plots of the ten different models are outlined. In this figure, an obvious peak can be seen. The scatter plot matrix presented in Figure 5 shows the three clusters across the two variables (number fact retrieval and procedural calculation) indicating a clear separation of clusters.

Three emergent clusters displayed profiles that conformed to respectively a group without mathematical problems and two groups with mathematical problems characterized by different profiles regarding their scores for number fact retrieval (TTR) and procedural calculation (KRT-R/TEDI-MATH).

Cluster 1 included most children ($n = 209$ of whom 84 girls) with the highest scores on both number fact retrieval as well as procedural calculation. These children had average scores for both domains and had no mathematical problems.

Cluster 2 ($n = 112$ of whom 51 girls) manifested a pattern of the lowest scores for both number fact retrieval as well as procedural calculation. These children may be described as having semantic memory problems.

Cluster 3 ($n = 70$ of whom 36 girls) exhibited low scores for procedural calculation but not for number fact retrieval. Their score for number fact retrieval was similar to children in
cluster 1 and the problems with procedural calculation were less severe in comparison to the problems of cluster 2. These children may be described as having procedural calculation problems.

Table 2 provides more detailed information about the mean scores of each cluster on the parameters besides more demographic information. Children in cluster 2 were significantly younger in comparison to children in cluster 1 and cluster 3. Children in cluster 1 were significantly younger in comparison to children in cluster 3. Furthermore, children in cluster 2 and cluster 3 scored significantly lower on intelligence in comparison to children in cluster 1. There were no significant differences in SES between these children allocated to the three clusters.

*Insert Table 2 about here*

The fact that motor skills did not contribute to cluster defining (cluster analysis 1) can also be illustrated by a crosstab in which the assignment to the different clusters comparing cluster analysis 1 and cluster analysis 3 has been outlined (see Table 3). Most children are on the diagonal, indicating that the motor variable did not have added value.

*Insert Table 3 about here*

**Profile of the clusters**

Linear regressions were conducted with the posterior probability of each child belonging to a cluster as an independent variable and motor skills, reading and spelling as a dependent variable (see Table 4 for an overview).

The higher the value for the posterior probability of belonging to cluster 1 (having no mathematical problems), the higher the score in motor skills, reading and spelling. The higher the probability of belonging to cluster 2 (number fact retrieval problems), the lower the score
for motor skills and reading of existing and pseudo words. A higher probability of belonging to cluster 3 (procedural calculation problems) was significantly related to lower motor skills, reading of existing words and spelling.

The standardized coefficients had a more negative value for motor skills and reading of pseudo words in the cluster of children with semantic number fact retrieval problems in comparison to the cluster consisting of children with procedural calculation problems. The standardized coefficients had a more negative value for spelling for the cluster of children with procedural calculation problems in comparison to the cluster consisting of children with number fact retrieval problems.

*Insert Table 4 about here*

Based upon cluster analysis 3, Figure 6 shows a scatter plot matrix with the distribution of children of the DCD group (regardless of the presence of a co-morbid MLD) among the three clusters. As can be seen, children with DCD were present in all clusters.

Respectively 27, 47 and 28 children with severe DCD (i.e., SS ≤ 5 on the M-ABC 2) were present in cluster 1, 2 and 3. It was obvious that around 40% of the children allocated to cluster 2 and 3 had severe motor problems, whereas only 12.9% of the children allocated to cluster 1 had severe motor problems.

*Insert Figure 6 about here*

**Discussion**

Some difficulties remain in identifying subtypes among children with DCD and MLD. Cluster-analytic studies in DCD are based upon small samples and no data-driven cluster-analytic study has yet been conducted in MLD. Therefore, the current study tried to extend the
available studies by means of a data-driven design with two developmental disorders (DCD and/or MLD) and a group of children without motor and mathematical problems.

We found no good cluster solution based on the combination of mathematical and motor variables. Furthermore, we were not able to find a good cluster solution including only the motor variables. We did not find a cluster with motor problems and a cluster without motor problems. The absence of subtypes within the motor variable is in contrast with the findings of other studies in which subtypes were found within a DCD population (e.g., Dewey & Kaplan, 1994; Hoare, 1994; Macnab et al., 2001; Miyahara, 1994; Vaivre-Douret et al., 2011; Wright & Sugden, 1996). This contrasting finding might be explained by the used variables, a larger sample, including both children with DCD as well as MLD and the method used to perform the cluster analysis. In this study, a data-driven way of clustering was conducted and we did not choose a number of clusters that we would aim to find beforehand. The absence of subtypes based on the motor variables (either in combination with mathematical variables or not) suggests that motor skills/problems are not related to the mathematical subtypes that we found. The cluster analysis did not help us to explain the relationship between DCD and MLD. Probably, DCD and MLD are linked by a diverse way of reasons, causes or mechanisms. Further research is definitely recommended.

Particularly interesting was the cluster analysis with the mathematical measures. The best data-driven solution was a model with three clusters (a cluster without mathematical problems and two clusters with mathematical problems). Our findings revealed, in line with Mazzocco, Devlin, and McKenney (2008) and Geary, Hoard, Byrd-Craven, Nugent, & Numtee (2007), that MLD can be considered as a definable disability, differentiating children without MLD from children with MLD. Moreover, two emergent groups of children with MLD displayed profiles, revealing data-driven evidence for a procedural subtype and a semantic memory subtype. This finding is in line with the conceptualisation of MLD subtypes
described by several authors (e.g., Geary, 1993; Geary, 2004; Mazzocco, 2001; Temple, 1991; Wilson et al., 2006). The technique of cluster-analysis, revealed a group of children with problems with procedural calculation. These children with ‘procedural subtype of MLD’ had no problems with number fact retrieval from long term memory. Furthermore, in line with the idea of a developmental delay in the acquisition of mathematical procedures, the problems of these children were not as severe as the problems of children with semantic memory problems (cluster 2). Children with a ‘semantic memory subtype of MLD’ had the lowest expected means for number fact retrieval as well as procedural calculation. In line with Geary (2011) those children with ‘semantic memory MLD’ seem to have a memory dysfunction and are characterized by errors in the retrieval of number facts. Probably, these children have a general memory problem, leading to difficulties to retrieve simple number facts from long term memory and problems to manage more difficult mental computation due to working memory problems or a limited capacity to deal with cognitive load. Further research is definitely needed. Although longitudinal research is needed to be sure of a change over time, children in the semantic memory cluster were significantly younger in comparison to children in the procedural subtype cluster. Our method is unique, as to the best of our knowledge, this is the first time that a cluster analysis was able to confirm the existence of these two subtypes commonly described in mathematics. Furthermore, we can extend the findings of the existence of subtypes in MLD to children with DCD and/or MLD. Replication with diverse samples of developmental disorders would increase our confidence in the reliability of these mathematical subtypes.

These results should be interpreted with care, since the present study has some limitations. First, the current investigation tried to extend the available studies by a model-based cluster study on behavioural measures. However, on the basis of such data, the underlying problem of the identified subtypes remains unclear. Questions arise if it is a matter
of cognitive load, working memory and/or long term memory etc. Additional longitudinal data including not only behavioural but also cognitive measures (i.e., memory) seem indicated. Second, this study should be repeated with more children in all age groups, to look for eventually developmental shifts or stability in subtypes.

These limitations are balanced by several strengths such as the inclusion of children with DCD and/or MLD with well defined criteria according to the literature. We used rather lenient criteria (-1 SD) to include a wide range of mathematical and motor scores. A second strength of this study is the technique of model-based cluster analysis. It provided to be an effective method to investigate the heterogeneity in this sample. Cluster membership was defined as a probability and not as a dichotomous deterministic classification. The clustering was data-driven (with less bias) because it was based upon a goodness-of-fit index (BIC) to determine the optimal number of clusters out of ten different kinds of model structures. More traditional cluster approaches (i.e., k-means clustering which is similar to the EII cluster solution in this model-based clustering) often use a much more restricted underlying model.

Based upon the findings of this study, we can also draw some clinical implications. Clinicians who are involved in the assessment and the remediation of children with mathematical problems should be encouraged to use a mathematical test battery that includes number fact retrieval as well as procedural calculation. Furthermore, as children with DCD were present in all clusters, a multidisciplinary diagnostic evaluation should also include a motor assessment. As the clusters differed significantly in age, it might be that mathematical performance shifts over time. This implies that it is not a good practice to diagnose based upon a one-time assessment and it might be an oversimplification to look for a single domain on which the child has problems with.
References


Hollingshead, A. B. (1975). *Four factor index of social status*. Yale University, New Haven, CT.


Table 1. Means of the four groups and the total group on descriptive and diagnostic measures.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Control children (n = 136)</th>
<th>DCD (n = 102)</th>
<th>MLD (n = 73)</th>
<th>DCD + MLD (n = 99)</th>
<th>complete cases (n)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M (SD)</td>
<td>M (SD)</td>
<td>M (SD)</td>
<td>M (SD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>105.85 b (13.42)</td>
<td>106.84 b (12.13)</td>
<td>109.32 ab (13.18)</td>
<td>112.33 a (13.29)</td>
<td>410</td>
<td>F(3, 406) = 5.33***</td>
</tr>
<tr>
<td>SES(^a)</td>
<td>46.54 a (10.06)</td>
<td>41.62 b (12.65)</td>
<td>42.24 b (11.78)</td>
<td>40.37 b (12.72)</td>
<td>345</td>
<td>F(3, 341) = 5.58**</td>
</tr>
<tr>
<td>IQ</td>
<td>103.96 a (12.94)</td>
<td>95.75 b (11.83)</td>
<td>98.58 b (10.97)</td>
<td>94.62 b (8.93)</td>
<td>410</td>
<td>F(3, 406) = 16.03***</td>
</tr>
<tr>
<td>TTR(^b)</td>
<td>60.18 a (24.54)</td>
<td>29.09 b (24.96)</td>
<td>11.99 c (13.35)</td>
<td>10.77 c (13.43)</td>
<td>406</td>
<td>F(3, 402) = 141.48***</td>
</tr>
<tr>
<td>KRT-R(^b)</td>
<td>67.12 a (22.51)</td>
<td>25.62 b (25.57)</td>
<td>12.14 c (16.20)</td>
<td>8.08 c (11.98)</td>
<td>210</td>
<td>F(3, 206) = 112.94***</td>
</tr>
<tr>
<td>TEDI-MATH(^b)</td>
<td>71.67 a (8.01)</td>
<td>63.06 b (16.08)</td>
<td>64.91 b (12.00)</td>
<td>57.97 c (14.82)</td>
<td>306</td>
<td>F(3, 302) = 18.74***</td>
</tr>
<tr>
<td>M-ABC 2(^c)</td>
<td>11.28 a (2.37)</td>
<td>5.01 c (1.73)</td>
<td>9.91 b (1.45)</td>
<td>5.13 c (1.59)</td>
<td>400</td>
<td>F(3, 396) = 313.56***</td>
</tr>
<tr>
<td>EMT(^c)</td>
<td>9.31 a (3.68)</td>
<td>6.39 b (3.58)</td>
<td>5.20 b (2.82)</td>
<td>5.14 b (3.69)</td>
<td>404</td>
<td>F(3, 400) = 35.40***</td>
</tr>
<tr>
<td>Klepel(^c)</td>
<td>10.09 a (3.21)</td>
<td>7.67 b (3.28)</td>
<td>6.48 b (2.82)</td>
<td>6.83 b (3.51)</td>
<td>394</td>
<td>F(3, 390) = 28.22***</td>
</tr>
<tr>
<td>PI-dictation(^b)</td>
<td>45.15 a (35.73)</td>
<td>14.68 b (26.54)</td>
<td>9.50 b (16.06)</td>
<td>10.96 b (20.20)</td>
<td>391</td>
<td>F(3, 387) = 43.70***</td>
</tr>
</tbody>
</table>

Note. Means with different letters are significantly different by post hoc tests with \( p < .05 \). DCD = developmental coordination disorder; MLD = mathematical learning disability; SES = socio-economic status; IQ = Intelligence Quotient; TTR = Arithmetic Number Fact Test; KRT-R = Kortrijk Arithmetic Test Revision; M-ABC 2 = Movement Assessment Battery for Children 2; EMT = One Minute Test.

\(^a\) based on the Hollingshead index. \(^b\) percentile scores. \(^c\) standard scores

\( ** p < .01. \) \( *** p < .001. \)
Table 2. Cluster analysis 3: Expected means of the clusters.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Cluster 1 ( (n = 209) )</th>
<th>Cluster 2 ( (n = 112) )</th>
<th>Cluster 3 ( (n = 70) )</th>
<th>( F )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( M ) ( (SD) )</td>
<td>( M ) ( (SD) )</td>
<td>( M ) ( (SD) )</td>
<td></td>
</tr>
<tr>
<td>TTR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number fact retrieval(^a)</td>
<td>0.39 (0.78)</td>
<td>-1.18 (0.30)</td>
<td>0.38 (0.92)</td>
<td>-</td>
</tr>
<tr>
<td>KRT-R/ TEDI-MATH</td>
<td>0.47 (0.54)</td>
<td>-1.03 (1.20)</td>
<td>-0.76 (0.79)</td>
<td>-</td>
</tr>
<tr>
<td>Procedural calculation(^a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>108.77 b (9.60)</td>
<td>97.97 c (9.39)</td>
<td>122.26 a (13.16)</td>
<td>( F(2, 388) = 121.43^{***} )</td>
</tr>
<tr>
<td>SES(^b)</td>
<td>44.34 (11.56)</td>
<td>41.18 (12.86)</td>
<td>44.09 (9.96)</td>
<td>( F(2, 336) = 2.35 )</td>
</tr>
<tr>
<td>IQ</td>
<td>101.83 a (12.86)</td>
<td>95.01 b (10.40)</td>
<td>95.54 b (9.47)</td>
<td>( F(2, 388) = 15.74^{***} )</td>
</tr>
</tbody>
</table>

Note. 19 children are not included in this cluster analysis due to missing data on one of the measures. Means with different letters are significantly different by post hoc tests with \( p < .05 \). SES = socio-economic status; IQ = intelligence quotient.

\( ^a \)z-scores. \( ^b \)based on the Hollingshead index.

\( ^{***} p < .001 \).

Table 3. A comparison of the assignment of the children to the different clusters, in cluster analysis 1 and cluster analysis 3.

<table>
<thead>
<tr>
<th>Cluster analysis 3</th>
<th>Cluster analysis 1</th>
<th></th>
<th></th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>167</td>
<td>1</td>
<td>34</td>
<td></td>
<td>202</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>92</td>
<td>13</td>
<td></td>
<td>109</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>69</td>
<td></td>
<td>70</td>
</tr>
<tr>
<td>Total</td>
<td>172</td>
<td>93</td>
<td>116</td>
<td></td>
<td>381</td>
</tr>
</tbody>
</table>

Note. 29 children are not included in this cluster analysis due to missing data on one of the measures.
Table 4. Prediction of the scores for motor skills, reading and spelling based on the probability of belonging to a cluster.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-ABC 2</td>
<td>3.30</td>
<td>-2.83</td>
<td>-1.64</td>
<td>1.65</td>
<td>-1.06</td>
<td>-1.32</td>
<td>1.58</td>
<td>-1.28</td>
<td>-0.89</td>
</tr>
<tr>
<td>EMT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klepel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI-dictation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. B = unstandardized regression coefficient; β = standardized regression coefficient; M-ABC 2 = Movement Assessment Battery for Children 2; EMT = One Minute Test; WISC-III = Wechsler Intelligence Scale for Children.

* p ≤ .05. ** p < .01. *** p < .001.

Figure 1. Cluster analysis 1: Bayesian information criterion (BIC) of different cluster solutions. Note. EII = spherical, equal volume, equal shape; VII = spherical, variable volume, equal shape; EEI = diagonal, equal volume, equal shape; coordinate axes orientation; VEI = diagonal, variable volume, equal shape, coordinate axes orientation; VVI = diagonal, variable volume, variable shape, coordinate axes orientation; EEE = ellipsoidal, equal volume, equal shape, equal orientation; EEE = ellipsoidal, equal volume, equal shape, variable orientation; VEV = ellipsoidal, variable volume, equal shape, variable orientation; VVV = ellipsoidal, variable volume, variable shape, variable orientation.
Figure 2. Cluster analysis 1: Scatter plot matrix showing three clusters.

Figure 3. Cluster analysis 2: Bayesian information criterion (BIC) of different cluster solutions.
Figure 4. Cluster analysis 3: Bayesian information criterion (BIC) of different cluster solutions.

Figure 5. Cluster analysis 3: Scatter plot matrix showing three clusters.
Figure 6. Scatter plot matrix showing the distribution of DCD children among three clusters.