Identifying Subtypes Among Children With Developmental Coordination Disorder and Mathematical Learning Disabilities, Using Model-Based Clustering

Stefanie Pieters, PhD\(^1\), Herbert Roeyers, PhD\(^1\), Yves Rosseel, PhD\(^1\), Hilde Van Waelvelde, PhD\(^1\), and Annemie Desoete, PhD\(^1\)

Abstract
A relationship between motor and mathematical skills has been shown by previous research. However, the question of 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, a data-driven model-based clustering was used to identify subgroups of individuals with relatively homogeneous profiles on measures associated with motor and mathematical skills. One subgroup of children with motor problems was found based on motor variables. Based on mathematical variables, two clinical clusters were found: a subtype with number fact retrieval problems and a subtype with procedural calculation problems. Clustering with motor and mathematical skills revealed two clinical clusters: a cluster with number fact retrieval as well as procedural calculation problems and below average motor and visual-motor integration skills. A second cluster of children had only procedural calculation and visual-motor 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, as below average motor skills were found in both MLD subgroups, although a different motor profile is linked to a different mathematical profile.

Keywords
mathematical learning disability, developmental coordination disorder, subtypes

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, 2012). In addition, motor activities such as counting seem necessary for early mathematics and the development of an adequate mental representation of number concepts (Geary, 1993; Luo et al., 2007). The relationship between motor and mathematical skills has also been explained by the “embodied cognition” theory. This is a theory that argues that cognitive processes are grounded in the interaction of the body with the world. Through the use of neural resources that are also active in bodily perception and action, mathematical cognition is grounded in simulations of sensorimotor processes (Beer, 1995; Soylu, 2011; Thelen & Smith, 1994).

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 that interferes with daily living and cannot be explained by a medical condition (American Psychiatric Association [APA], 2000). The prevalence of DCD has been estimated by the APA (1994) at 6% for children between 5 and 11 years; however, a large range of prevalence rates has been reported, going from 1.7% in the United Kingdom to 15.6% in Singapore (Lingam, Hunt, Golding, Jongmans, & Emond, 2009; van Dellen, Vaessen, & Schoemaker, 1990; Wright, Sugden, Ng, & Tan, 1994).

Children with DCD often have comorbid disabilities, which seems to be one of the main reasons that complicates research in DCD (Visser, 2003). Whereas comorbidity with reading and spelling problems has frequently been

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investigated (e.g., Cheng, Chen, Tsai, Chen, & Cherno, 2009; Fletcher-Finn, Elmes, & Strugnell, 1997; Lingam et al., 2010), mathematical problems have been studied only indirectly in DCD (Alloway & Archibald, 2008). However, mathematical problems are frequently reported in children with DCD (Pieters, Desoete, Van Waelvelde, Vandervsalmnen, & Roeyers, 2012). This is not unexpected, 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 comorbid problems (e.g., Jongmans, Smits-Engelsman, & Schoemaker, 2003; Rasmussen & Gillberg, 2000) including mathematical problems (Pieters, Desoete, Van Waelvelde, 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 (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). The estimated prevalence of MLD lies between 3% and 14% in a school-age population depending on the country of study and the criteria (Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Dowker, 2005; Shalev, Manor, & Gross-Tsur, 2005). Motor problems are frequently comorbid with learning disabilities, including MLD (e.g., Jongmans et al., 2003; Pieters, De Block, et al., 2012; Pieters, Desoete, Roeyers, et al., 2012; Vuijk, Hartman, Mombarg, Scherder, & Visscher, 2011).

Comorbidity is the presence of two or more problems or disabilities in an individual (Piotrowski, 2007). In Flanders, there is a considerable comorbidity of motor problems in MLD (24.8%) and mathematical problems in DCD (31.2%); Pieters, De Block, et al., 2012; Pieters, Desoete, Van Waelvelde, et al., 2012). This association between academic and motor performance was also found in other countries (Vuijk et al., 2011). Given the frequent comorbidity 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 identifying 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 comorbidity 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 with rather small samples, ranging from 43 to 178 participants. Furthermore, the link with mathematics was not established. 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 (e.g., characterized by problems with visual-motor integration, visuospatial structuring, handwriting) in comparison to ideomotor DCD (e.g., characterized by problems with crawling, digital praxis, praxis slowness). However, the mathematical problems were not differentiated in procedural and number fact retrieval problems. In addition, the identification of problems was based on teacher reports and not on test results.

Most authors propose a procedural and a semantic memory subtype within MLD (e.g., Geary, 1993, 2004; Robinson, Menchetti, & Torgesen, 2002; Temple, 1991). The procedural subtype would be a result of executive dysfunction. This subtype is 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 a result of verbal memory dysfunction. This subtype is 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. However, not all studies have found different profiles for these groups (Landerl, Bevan, & Butterworth, 2004; Rousselle & Noel, 2007), and some researchers argue that MLD can be divided into verbal and nonverbal or visuospatial subtypes (Forrest, 2004; Geary, 2004; Kronenberger & Dunn, 2003; Rourke, 1989). At the same time, research on mathematical subtypes has identified children with deficits in word problem solving, who may be distinct from children with computational problems (e.g., Fuchs & Fuchs, 2002; Passolunghi & Mammerella, 2010). However, the identification of these subtypes was often based on cognitive theoretical models and results on experimental tasks (e.g., Geary, 2004, 2011). Until now, no cluster analysis with large samples that include children with varying degrees of math and motor skills has been reported. Since there is a relationship between motor and mathematical skills and since cluster-analytic studies in DCD are based on 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 could 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, with DCD, and with both DCD and MLD and of typically achieving children.

**Method**

**Participants**

Four groups of average intelligence children aged 7 to 12 years participated: 73 children (35 girls) with MLD, 102 children (25 girls) with DCD, 99 children with comorbid MLD and DCD (44 girls), and 136 children (70 girls) in the typically achieving group without mathematical or motor problems. Low achieving and 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 centers 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 (full-scale IQ ≥ 80) as assessed with the third edition of the *Wechsler Intelligence Scale for Children* (WISC-III; Wechsler, 1991).

A total of 201 children met the criteria of the *Diagnostic and Statistical Manual of Mental Disorders* (APA, 2000) for DCD (102 children with DCD and 99 children with DCD and MLD). These children had poor motor coordination, substantially worse than 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. Since all these children received physiotherapy for their clumsiness or scored at or below the 15th percentile for writing quality or writing speed on the *Systematic Screening of Handwriting Difficulties* (Van Waelvelde, Hellinckx, Peersman, & Smits-Engelsman, 2012), 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 their parents. For 10 children with DCD, we did not have a recent M-ABC-2 assessment. Nevertheless, they were added to this group as they had a clinical diagnosis of DCD and fulfilled all other criteria described above.

In all, 172 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 Computation subtest of the *TEDI-MATH* (Grégoire, Noel, & Van Nieuwenhoven, 2004). In addition, they all were nonresponsive to the remediation: They received therapy for at least 6 months and still had at least subclinical scores (or ≤ the 16th percentile) for mathematics after this remediation. Furthermore, these mathematical problems were not the result of a deficit in education, a sensory deficit, or another behavioral or developmental disorder. For 19 children with MLD, we did not have a recent mathematical assessment (TTR: 4 missing; 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.

**Tests and Materials**

**Intelligence.** Four subtests of the 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 are .92 and .93, respectively (Grégoire, 2000).

**Mathematics.** 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 TTR (De Vos, 1992) for semantic memory deficits and the 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* (Subtest 5.2) was used.

The KRT-R (Baudonck et al., 2006) is an untimed standardized test of procedural calculations for Grades 1 to 6. The KRT-R requires children to solve calculations in a number-problem format (e.g., 39 + 60 = ___) or in a word-problem format (e.g., 60...
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>
<th>M</th>
<th>SD</th>
<th>Total Sample (N = 410)</th>
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<tr>
<td><strong>Age</strong></td>
<td>105.85*</td>
<td>106.84</td>
<td>109.32</td>
<td>112.33</td>
<td>112.28</td>
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<td><strong>SES</strong>^a</td>
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<td>38.22^b</td>
<td>37.87</td>
<td>345</td>
<td>43.29</td>
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<td><strong>IQ</strong></td>
<td>103.96*</td>
<td>95.75</td>
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<td><strong>KRT-R</strong>^b</td>
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<td>24.54</td>
<td>19.99</td>
<td>17.35</td>
<td>13.56</td>
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Note. Means with different subscripts are significantly different on post hoc tests at p < .05. **DCD** = developmental coordination disorder; **EMT** = One Minute Test; **IQ** = intelligence quotient; **KRT-R** = Kortrijk Arithmetic Test Revision; **M-ABC-2** = Movement Assessment Battery for Children–2; **MLD** = mathematical learning disability; **SES** = socio-economic status; **TTR** = Arithmetic Number Fact Test.

^aBased on the Hollingshead Index. ^bPercentile scores. ^cStandard scores.

*p < .01. **p < .001.

**Motor and visual-motor integration skills.** To obtain a complete overview of the motor and visual-motor integration abilities of the children, the following tests were used: **M-ABC-2** and the revised **Beery-Buktenica Developmental Test of Visual-Motor Integration.** In addition the **Systematic Screening of Handwriting Difficulties** was given.

The **M-ABC-2** (Henderson & Sugden, 2007) measures motor competence of children between the ages of 3 and 16 years. As items change with age, the appropriate age bands (7 to 10 years and 11 to 16 years) were used 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 and the total scores were used (Smits-Engelsman, 2010). Cronbach’s alpha for the current study was .76 for the young children and .82 for the older ones.

The revised **Beery-Buktenica Developmental Test of Visual-Motor Integration** (VMI; Beery, Buktenica, & Beery, 2004) “copy test” was used to measure visual-motor integration. The VMI has been reported to be a reliable and valid test (Beery et al., 2004). Cronbach’s alpha for the current study was .81.

The **Systematic Screening of Handwriting Difficulties** (Systematische opsporing van schrijfmo- torische problemen) provides an assessment of quality and speed of handwriting by copying a standard text within 5 minutes on unruled paper (Van Waelvelde et al., 2012). 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 on a reference group of 860 children. Cronbach’s alpha for the current study was .62.

**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, 2007) and pseudo-word reading by the *Klepel* (Van den Bos, Spelberg, Scheepstra, & de Vries, 2007). Both reading tests consist of lists of 116 unrelated words. Children are instructed to read as many words as possible in 1 minute (EMT) or 2 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 & Ruijssenaars, 1994). The reliability of the EMT varied from .76 to .94, and for the *Klepel* values between .89 and .96 were found.

**Spelling.** The *Pl-Dictation* (Geelhoed & Reitsma, 2004) 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 increasing difficulty, and the test is stopped when a child makes at least seven errors in one block. The test was validated on 3,633 children (Geelhoed & Reitsma, 2004), with a reliability between .90 and .92.

**Procedure**

Written consent was obtained from the parents. Each child was evaluated individually for several hours by one examiner who was blind to group assignment. Children were tested in a separate and quiet room. Tests were always given in the same order, and breaks were provided as needed. The test leaders all received training in the assessment and interpretation of the tests. For every subtest, instructions and scoring rules were explained. To guarantee reliability of the assessment, each tester had to test one child and score the protocol in advance. This protocol was analyzed and corrected by the main researcher of the study. All responses were entered on an item-by-item basis in SPSS. After completion of the test procedure, all the parents received individual feedback on the results of the tests of their children.

**Data Analysis**

We aimed to let our data determine the number, shape, and volume of the clusters. Therefore, a model-based cluster analysis (Fraley & Raftery, 2003) using a soft partitioning

![Figure 1. Cluster Analysis 1 based on M-ABC-2 variables: BIC values of different cluster solutions.](image-url)

Note. BIC = Bayesian information criterion; EEE = ellipsoidal, equal volume, equal shape, equal orientation; EEV = ellipsoidal, equal volume, equal shape, variable orientation; EEI = diagonal, equal volume, equal shape, coordinate axes orientation; EEV = ellipsoidal, variable volume, equal shape, variable orientation; EVI = diagonal, variable volume, equal shape, coordinate axes orientation; EVV = ellipsoidal, variable volume, variable shape, variable orientation; EVI = diagonal, variable volume, variable shape, variable orientation; EVI = diagonal, variable volume, variable shape, variable orientation.

and cases belonging to all clusters to a certain degree was conducted using R software. This clustering approach is based on the assumption that the observed data come from a population consisting of several subpopulations. Each subpopulation is modeled by a (multivariate) normal distribution (also see Steinley & Brusco, 2011; Vermunt, 2011). Because we consider this study exploratory in nature, we fit different types of normal distributions (spherical, ellipsoidal or diagonal shape, same or different shape for each component; see the note to 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) was 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 19, linear regression with the probabilities of the selected cluster solution was done. First, a cluster analysis was conducted on the different motor subscales of the M-ABC-2. In a second analysis, it was investigated whether a combination of the motor variables (M-ABC-2 and VMI) was able to define meaningful clusters. Moreover, a third cluster analysis investigated mathematical clusters in our data. Finally, it was studied if a combination of motor and mathematical variables could define meaningful clusters.

Since using standard scores from test publisher norm tables adds unwanted variability into the analysis, clustering variables were z scores (calculated separately for each grade, across all groups).

Results

Relationship Between Motor and Mathematical Skills

There was a significant correlation between motor and visual-motor integration skills ($r = .51$, $p < .001$). In addition there was a significant correlation between procedural calculation and number fact retrieval ($r = .56$, $p < .001$). Finally there was a significant correlation between number fact retrieval and motor skills ($r = .49$, $p < .001$), number fact retrieval and visual-motor integration ($r = .30$, $p < .001$), procedural calculation and motor skills ($r = .41$, $p < .001$), and procedural calculation and visual-motor integration ($r = .24$, $p < .001$)

Model-Based Clustering: Identification of Clusters

Cluster analysis 1: Motor variables. A first cluster analysis with the motor variables (i.e., the M-ABC-2 domains of manual dexterity, aiming and catching, and balance) was conducted. Because of missing values (see Table 1), this cluster analysis was based on 400 cases.

An ellipsoidal multivariate normal model (EEE) with one cluster was the best cluster solution (see Figure 1).

Cluster analysis 2: Motor and visual-motor variables. The next cluster analysis was conducted with the combination of two (visual-)motor variables (M-ABC-2 and VMI). Because of missing values (see Table 1), this cluster analysis was based on 397 cases.

A diagonal model with varying volume and shape model (VVI) with three clusters was the best cluster solution. As can be seen in Figure 2, the BIC plots of the 10 different models showed an observable peak for three clusters. The BIC value for this model was $-2071.07$, the relative BIC difference with a model of two clusters was $21.52\%$, and with a model of four clusters it was $2.90\%$.

There was one cluster with clinical children (i.e., Cluster 3) and two clusters of adequate-performing children (i.e., Clusters 1 and 2).

Motor Cluster 1 included most children ($n = 212$, 88 girls) with average or below average motor skills on both M-ABC-2 and VMI. These children had average scores for both domains and had no motor or visual-motor integration problems ($z = -.30$ on VMI and $z = -.18$ on M-ABC-2).

Motor Cluster 2 ($n = 112$, 63 girls) manifested a pattern of well-developed motor skills on both motor measures. These children may be described as above average motor and visual-motor integration performers ($z = 1.25$ on VMI and $z = 0.81$ on M-ABC-2).

Motor Cluster 3 ($n = 73$, 20 girls) exhibited low scores for both motor tests ($z = -1.22$ on VMI and $z = -0.86$ on M-ABC-2). These children may be described as having severe motor and visual-motor integration problems.

Cluster analysis 3: Mathematical variables. A cluster analysis with the mathematical variables (TTR and KRT-R/TEDI-MATH) was conducted. Because of missing values (see
Figure 3. Cluster Analysis 3 based on mathematical skills: BIC values of different cluster solutions.

Note. BIC = Bayesain information criterion; EEE = ellipsoidal, equal volume, equal shape, equal orientation; EEI = diagonal, equal volume, equal shape, coordinate axes orientation; EEV = ellipsoidal, equal volume, equal shape, variable orientation; EII = spherical, equal volume, equal shape; M-ABC-2 = Movement Assessment Battery for Children—2; VVI = diagonal, variable volume, equal shape, coordinate axes orientation; VVE = ellipsoidal, variable volume, equal shape, variable orientation; VII = spherical, variable volume, equal shape, variable orientation; VVV = ellipsoidal, variable volume, variable shape, variable orientation.

Table 1), this cluster analysis was based on 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 3, the BIC plots of the 10 different models are outlined. In this figure, an obvious peak can be seen. The three clusters across the number fact retrieval and procedural calculation variables indicate a clear separation of clusters.

Three emergent mathematical clusters displayed profiles that conformed to 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). There were two clusters with clinical children (i.e., Clusters 2 and 3) and one cluster of adequate-performing children (i.e., Cluster 1).

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

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

Mathematical Cluster 3 (n = 70, 36 girls) exhibited low scores for procedural calculation but not for number fact retrieval. Their score for number fact retrieval was similar to that for 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.

Children in Mathematical Cluster 2 were significantly younger in comparison to children in Mathematical Clusters 1 and 3 (see Table 2). Children in Mathematical Cluster 1 were significantly younger in comparison to children in Mathematical Cluster 3. Furthermore, children in Mathematical Clusters 2 and 3 scored significantly lower on intelligence in comparison to children in Mathematical Cluster 1. There were no significant differences in SES between these children allocated to the three clusters.

Cluster analysis 4: Motor and mathematical variables. We conducted a fourth cluster analysis with the combination of two motor variables (M-ABC-2 and VMI) and two mathematical variables (TTR and KRT-R/TEDI-MATH). Because of missing values (see Table 1), this cluster analysis was based on 378 cases. An ellipsoidal model with equal volume and shape (EEV) with three clusters was the best cluster solution. The BIC value for this model was −4000.24, the relative BIC difference with a model of two clusters was 6.31%, and with a model of four clusters it was 8.46% (see Figure 4).

Nearly the same solution as for Cluster Analysis 3 was found in our data. There were two clusters with clinical children (i.e., Clusters 2 and 3) and one cluster of adequate-performing children (i.e., Cluster 1).

Motor and Math Cluster 1 included most children (n = 191, 84 girls) with the highest scores on both motor and mathematical tests. These children had average scores for both domains (z = 0.39 for procedural calculation, z = 0.41 for number fact retrieval, z = 0.53 for VMI, and z = 0.31 for M-ABC-2).

Motor and Math Cluster 2 (n = 91, 43 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 with below average motor skills (with z = −0.21 on VMI and z = −0.36 on M-ABC-2).

Motor and Math Cluster 3 (n = 96, 41 girls) exhibited low scores for procedural calculation (z = −0.53) but not for number fact retrieval (z = 0.22), similar to the procedural
These children experienced more visual-motor integration problems than the children in Cluster 2 on the VMI ($z = -0.74$) but were better on motor skills tested with the M-ABC-2 ($z = -0.19$). These children may be described as having procedural calculation and visual-motor integration problems.

To conclude, clustering with motor and mathematical skills revealed the same three mathematical clusters. In what follows, we aim to analyze the problems of these math clusters (Cluster Analysis 3).

**Profile of Children in the Mathematical Clusters**

Linear regressions were conducted with the posterior probability of each child belonging to a mathematical cluster as an independent variable and reading, spelling, motor skills, handwriting speed, and handwriting quality as a dependent variable (see Table 3 for an overview).

The higher the value for the posterior probability of belonging to Mathematical Cluster 1 (having no mathematical problems), the higher the score for reading of existing and pseudo-words, spelling, motor skills, handwriting quality (see Note 1), and handwriting speed. The higher the probability of belonging to Mathematical Cluster 2 (number fact retrieval problems), the lower the score for reading of existing and pseudo-words, motor skills, handwriting quality, and handwriting speed. A higher probability of belonging to Mathematical Cluster 3 (procedural calculation problems) was significantly related to lower scores for reading of existing words and spelling skills. The standardized coefficients had a more negative value for reading of pseudo-words, motor skills, handwriting quality, and handwriting speed in the cluster of children with semantic memory problems (Mathematical Cluster 2) in comparison to the cluster consisting of children with procedural calculation (Mathematical Cluster 3) 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.

![Figure 4. Cluster Analysis 4 based on motor and mathematical skills: BIC values of different cluster solutions.](image-url)

Note. BIC = Bayesian information criterion; EEE = ellipsoidal, equal volume, equal shape; EEI = diagonal, equal volume, equal shape, coordinate axes orientation; EEV = ellipsoidal, variable volume, equal shape, variable orientation; EII = spherical, equal volume, equal shape; M-ABC-2 = Movement Assessment Battery for Children—2; VVI = diagonal, variable volume, equal shape, coordinate axes orientation; VVV = ellipsoidal, variable volume, variable shape, variable orientation.
**Discussion**

Some difficulties remain in identifying subtypes among children with DCD and MLD. Cluster-analytic studies in DCD are based on small samples, and no data-driven cluster-analytic study has yet been conducted with large samples that included children with varying degrees of math and motor skills development. 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.

In this study we aimed to let our data determine this number, shape, and volume of the eventual clusters, using a model-based cluster approach based on the assumption that the observed data come from a population consisting of several subpopulations. We fitted several types of normal distributions (spherical, ellipsoidal, or diagonal shape) with the same or a different shape for each component. The BIC was used to compare the models. A satisfactory cluster solution had a peak in the BIC plot and a clear separation between the clusters.

Based on motor variables, we found only one cluster of children with motor problems. These children had severe motor problems. This finding is in line with previous studies in the DCD population (e.g., Dewey & Kaplan, 1994; Hoare, 1994; Macnab et al., 2001; Miyahara, 1994; Vaivre-Douret et al., 2011; Wright & Sugden, 1996).

Particularly interesting was the cluster analysis with the mathematical measures. The best data-driven solution was a model with two clinical clusters (a cluster with number fact retrieval and procedural calculation problems and a cluster with only procedural calculation problems). Our findings revealed, in line with those of Mazzocco, Devlin, and McKenney (2008) and Geary, Hoard, Byrd-Craven, Nugent, and Numtee (2007), that MLD can be considered a definable disability, differentiating children without MLD from children with MLD. Moreover, data-driven evidence was found for a semantic memory and procedural calculation subtype. This finding is in line with the conceptualization of MLD subtypes described by several authors (e.g., Geary, 1993, 2004; Mazzocco, 2001; Temple, 1991; Wilson et al., 2006). So it can be concluded that a significant body of research suggests that mathematical ability, both in typically achieving children and in those with MLD, is made up of several components and that marked discrepancies between them are not uncommon (Cowan et al., 2011; Dowker, 2005; Dowker & Sigley, 2010; Gifford & Rockliffe, 2012; J. A. Jordan, Mulhern, & Wylie, 2009). This is also in line with N. C. Jordan, Blanteno, and Uberti (2003) and Reigosa-Crespo et al. (2012), who discuss important issues relating both to the nature of mathematical disabilities and to their classifications.

Children with “procedural subtype of MLD” had no problems with number fact retrieval from long-term memory.

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### Table 3. Prediction of the Scores for Reading, Spelling, and Motor Skills Based on the Probability of Belonging to a Mathematical Cluster.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Cluster 1</th>
<th>SD of B</th>
<th>t</th>
<th>β</th>
<th>Adj. R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster 1</td>
<td>1.65</td>
<td>0.49</td>
<td>3.41***</td>
<td>.17</td>
<td>.03</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>−1.06</td>
<td>0.54</td>
<td>−1.97*</td>
<td>−.10</td>
<td>.01</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>−1.32</td>
<td>0.64</td>
<td>−2.08*</td>
<td>−.11</td>
<td>.01</td>
</tr>
<tr>
<td>Klepel</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Cluster 1</td>
<td>1.58</td>
<td>0.43</td>
<td>3.64***</td>
<td>.18</td>
<td>.03</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>−1.28</td>
<td>0.48</td>
<td>−2.66**</td>
<td>−.13</td>
<td>.02</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>−0.89</td>
<td>0.57</td>
<td>−1.56</td>
<td>−.08</td>
<td>.01</td>
</tr>
<tr>
<td>Pt-Dictation</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster 1</td>
<td>11.72</td>
<td>3.93</td>
<td>2.98***</td>
<td>.15</td>
<td>.02</td>
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<td>4.42</td>
<td>−1.42</td>
<td>−.07</td>
<td>.01</td>
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<tr>
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<td>5.11</td>
<td>−2.18*</td>
<td>−.11</td>
<td>.01</td>
</tr>
<tr>
<td>M-ABC-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster 1</td>
<td>3.30</td>
<td>0.40</td>
<td>8.26****</td>
<td>.39</td>
<td>.15</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>−2.83</td>
<td>0.46</td>
<td>−6.18****</td>
<td>−.30</td>
<td>.09</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>−1.64</td>
<td>0.55</td>
<td>−2.97**</td>
<td>−.15</td>
<td>.02</td>
</tr>
<tr>
<td>SOS qualitya</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster 1</td>
<td>−0.52</td>
<td>0.13</td>
<td>−3.87****</td>
<td>−.20</td>
<td>.04</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.14</td>
<td>7.00***</td>
<td>.35</td>
<td>.12</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>−0.45</td>
<td>0.17</td>
<td>−2.64**</td>
<td>−.14</td>
<td>.02</td>
</tr>
<tr>
<td>SOS speed</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cluster 1</td>
<td>0.60</td>
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<td>4.59***</td>
<td>.24</td>
<td>.05</td>
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<td>0.12</td>
<td>−13.23****</td>
<td>−.58</td>
<td>.33</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>1.13</td>
<td>0.16</td>
<td>7.09***</td>
<td>.16</td>
<td>.12</td>
</tr>
</tbody>
</table>

*Note. B = unstandardized regression coefficient; β = standardized regression coefficient; Cluster 1 = typical mathematical development; Cluster 2 = semantic memory problems; Cluster 3 = procedural calculation problems; EMT = One Minute Test; M-ABC-2 = Movement Assessment Battery for Children−2; SOS = Systematic Screening of Handwriting Difficulties.

*p ≤ .05. **p < .01. ***p < .001.
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. 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 resulting in errors in the retrieval of number facts. These children likely have a general memory problem, leading to difficulties retrieving simple number facts from long-term memory and managing more difficult mental computation because of working memory problems or a limited capacity to deal with cognitive load. Further research is definitely needed to explore these problems. In addition, it seems that children with semantic memory subtype of MLD had the most (severe) problems on reading of pseudo-words, motor skills, and handwriting quality and handwriting speed in comparison to the procedural subtype, except for spelling. Particularly interesting was the high standardized regression coefficient for handwriting speed in children with semantic memory problems, which indicates that they have difficulties with timed tasks. The procedural subtype in MLD is often described as children having problems in conceptual understanding of procedures (Geary, 1993, 2004, 2011). Since spelling includes a conceptual understanding and application of explicit spelling rules (or procedures), it might be more problematic in children who also have procedural calculation problems. 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 MLD. Furthermore, we can extend 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 behavioral 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, long-term memory, and so on. Additional longitudinal data including not only behavioral but also cognitive measures (i.e., memory) seem to be needed. Second, this study should be repeated with more children in all age groups, to look for developmental shifts or stability in subtypes. Moreover, research also including tests on word problems is recommended since research on mathematical subtypes identified children with deficits in word problem solving, who may be distinct from children with computational problems (e.g., Fuchs & Fuchs, 2002). Finally, a problem might also concern the sample of children assessed in this study since the typically achieving and clinical samples were from different sites ranging in age from 7 to 12 years. In addition, the typically achieving children were those scoring above the 25th percentile, including low achieving and typically achieving children. Moreover, the diversity in the sample was handled by calculating z scores separately for each age for all variables. Additional research is needed with more children in all age groups to study 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 a rather lenient criterion (−1 SD) to include children with 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 (also see Steinley & Brusco, 2011; Vermunt, 2011) 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 on a goodness-of-fit index (BIC) to determine the optimal number of clusters out of 10 different kinds of model structures. More traditional cluster approaches (e.g., 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 on the findings of this study, we can also draw some educational implications. First, it is important not to overlook weak skills leading to a greater demand for professional help and more problems in education and daily life as in comparison to an isolated disability (Albert, Rosso, Maina, & Bogetto, 2008; Brown, Antony, & Barlow, 1995; Shalev et al., 2005). Our research suggests significant comorbidity between motor difficulties and (especially semantic) mathematical difficulties, but this does not mean that all children with motor difficulties must thereby have mathematical difficulties, or vice versa. It is important that educators and clinicians check for additional problems (reading, spelling, motor skills, visual-motor integration skills, and handwriting) in children who demonstrate either type of difficulty. However, it would be doing children with specific learning difficulties a disservice to assume that their difficulties are more pervasive than is necessarily the case. Second, our results raise questions about the wisdom of placing individuals with MLD into a single diagnostic category. This study identified children with deficits in procedural calculation and number fact retrieval skills who may be distinct from children with isolated procedural calculation problems leading to other needs for reasonable adjustments. Therefore, clinicians are encouraged to test
procedural calculations as well as number fact retrieval in children with MLD.

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Note

1. The higher the quality of handwriting, the lower the score.

References


