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formal und inhaltlich überarbeitete Version der Originalveröffentlichung in:
formally and content revised edition of the original source in:
International journal of disability, development and education 65 (2018) 5, S. 509-525

This is an Accepted Manuscript of an article published by Taylor & Francis in International Journal of Disability, Development and Education on 01/01/2018, available online: http://www.tandfonline.com/10.1080/1034912X.2017.1419555.

Development of Working Memory from Grade 3 to 5: Differences Between Children With and Without Mathematical Learning Difficulties

Abstract

Previous research on the development of working memory (WM) in children indicates that WM functioning improves with age. Based on the finding that children with mathematical learning difficulties (MLD) have deficits in WM, the question arises as to whether these children differ from typical learners only in the level or also in the developmental trajectories of WM functioning. To this end, the WM of 80 children with MLD and 71 typical learners was assessed longitudinally in third, fourth, and fifth grades. Preliminary analyses revealed that typical learners outperformed children with MLD in the phonological, visuospatial, and central executive WM functioning in third grade. Latent change analyses indicated that both phonological and central executive WM functioning developed in a linear pattern from third to fifth grades and also was parallel in children with MLD and in typical learners. In contrast, visuospatial WM functioning revealed a linear development across testing waves only in children with MLD whereas typical learners reached a developmental halt from the second testing wave on. Overall, these results indicate that the gap in WM between children with MLD and typical learners does not increase but rather remains constant or even decreases over time. Despite starting at a lower level, the WM functioning in children with MLD did not develop more slowly.

Keywords: mathematical learning difficulties; working memory; development; latent change modeling

Difficulties in mathematics despite unimpaired intellectual abilities are a common phenomenon: Approximately 5% of second and third graders in regular schools in Germany exhibit isolated mathematical learning difficulties (MLD), that is, the children show poor scholastic skills (at least one standard deviation below the mean) in mathematics but neither in reading nor in spelling (Fischbach et al., 2013). Working memory (WM) deficits have been discussed as contributing to MLD (e.g., Schuchardt, Maehler, & Hasselhorn, 2008). In the context of learning difficulties Baddeley's (1986, 2000, 2012) multicomponent WM model is a common theoretical framework. According to this model there are at least three WM components: two subsystems called the phonological loop and the visuospatial sketchpad and one superordinate system called the central executive. Whereas the phonological loop stores verbal information and the visuospatial sketchpad stores static-visual and dynamic-spatial information temporarily (Logie, 1995), the central executive is responsible for focusing, switching, and dividing attention across alternative foci (Baddeley, 1996; also cf. Baddeley & Hitch, 2000).

Previous research on WM in children with MLD revealed that these children show deficits compared to typical learners. However, there has been no consensus as to which components of WM are concerned. Whereas many studies revealed visuospatial deficits in children with MLD (cf. Raghubar, Barnes, & Hecht, 2010), there is a debate about whether or not those children only exhibit phonological as well as central executive deficits if numerical material is used (cf. Peng, Congying, Beilei, & Sha, 2012). Compared to the vast amount of cross-sectional studies on WM deficits in children with MLD (see Raghubar et al., 2010 for a review and Swanson & Jerman, 2006 for a meta-analysis), there is a lack of research comparing WM development in children with and without MLD, especially in longitudinal designs. This lack of longitudinal studies prevents the understanding of the role of WM in the development of MLD. Although it is well known that there is an interrelation between WM and MLD (e.g. Schuchardt, Maehler & Hasselhorn, 2008) the nature of WM deficits in MLD is still less clear. In a current approach it is emphasised that MLD is the result of multiple underlying impairments (Fias, Menon & Szucs, 2013). Longitudinal studies including children with and without MLD could contribute to answer the question whether a weak WM is one of various core deficits of MLD. Particularly interesting would be the longitudinal investigation of working memory development in children who overcome their MLD versus children who persist. If overcoming and persistence would be accompanied by different developmental trajectories (improvement in WM vs. constant deficit) this would be a strong evidence that a deficient WM significantly contributes to MLD.

Working Memory Development in Children

In research on WM development two alternative approaches have been taken: one regarding the structure and another regarding the capacity of WM (Michalczyk & Hasselhorn, 2010). The first approach examines the structural development of WM by comparing the structure of WM in children of different ages (e.g., Alloway, Gathercole, & Pickering, 2006). Using confirmatory factor analysis and structural equation modeling the main objective of this approach is to examine whether the central executive, the phonological loop and the visuospatial sketchpad can be verified as distinct and separate components of WM independently from age. The second approach assumes that the central executive, the phonological loop and the visuospatial sketchpad *are* separate components of WM. Based on this assumption developmental increases or declines of the capacity of the three WM components are investigated (e.g., Alloway & Alloway, 2013). Given the finding that the tripartite structure of WM is comparable between children with and without learning difficulties (e.g., Schuchardt, Roick, Mähler, & Hasselhorn, 2008), the approach focusing on the development of the capacity of the three components of WM (functioning approach) is followed in the present study.

Several studies show that working memory is a significant predictor of mathematical abilities (e.g., Alloway & Alloway, 2010; Gathercole, Brown, & Pickering, 2003). However, the relationship between working memory components and mathematics performance seems to be age dependent. Van de Weijer-Bergsma, Kroesbergen and Van Luit (2015) compared the importance of verbal and visuospatial working memory for mathematics learning during primary school and found opposite developmental trajectories. Whereas the predictive power of visual-spatial working memory for mathematics performance diminished the predictive value of verbal working memory increased. Moreover, a review by Friso-van den Bos, van der Ven, Kroesbergen, and van Luit (2013) showed that WM and mathematical achievement relates stronger in children with MLD than in typical learners, that is, mathematical achievement depended more on WM functioning in children with MLD than in typical learners. Therefore, it seems essential to investigate whether or not developmental trajectories are different in the two groups of children.

Different developmental trajectories in the two groups are conceivable: First, WM in children with MLD and in typical learners might develop in a parallel pattern. Thus, if there is a gap between WM functioning in children with and without MLD, it seems possible that it is stable; if there is no gap in WM functioning between the two groups, it seems possible that no gap will be found over time. Second, WM might develop more slowly in children with MLD than in typical learners. Therefore, a gap between the two groups might increase over time or the WM development in children with MLD might still continue but the WM development in typical learners might already have been completed at the same age. Consequently, it seems possible that the gap in WM functioning between children with MLD and typical learners decreases.

Development of Working Memory Functioning in Typical Learners

The development of WM functioning has been studied with cross-sectional designs in typical learners: In a recent study, Alloway and Alloway (2013) investigated the development of *central executive WM* in 5- to 80-year-olds. In childhood, they observed age-related differences between 5- to 8-year-olds and 9- to 10-year-olds as well as between 5- to 8-year olds and 11- to 12-year-olds in performance on all tasks independent of the material used. Results on age-related differences between 9- to 10-year-olds and 11- to 12-year-olds, however, were less clear: Differences emerged in two complex spans (comparing the shape of red and black letters in several trials and recalling the red letters in the correct sequence; comparing the shape of figures in several trials and recalling the location of the figures in a grid with 16 cells) but not in backward digit spans. Nevertheless, these findings suggest that there is developmental growth in WM functioning in children aged 5 to 12. Similarly, Siegel and Ryan (1989) found that WM functioning developed from 7 to 13 years of age. Various studies provided evidence for substantial growth in *phonological WM* in preschool and primary school children (Henry, 1991; Hitch, Halliday, Dodd, and Littler, 1989). Moreover, findings of three studies on the development of the *visuospatial sketchpad* suggest a substantial increase in children from 5 to 10 or 11 years of age. More specifically, performance on static-visual tasks seems to improve more quickly than performance on dynamic-spatial tasks (Hamilton, Coates, & Heffernan, 2003; Logie, & Pearson, 1997; Pickering, Gathercole, Hall, and Lloyd, 2001).

Development of WM Functioning in Children with MLD

It is well known that WM differs in children with and without MLD (e.g., Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Kroesbergen, & van Dijk, 2015; Passolunghi, & Siegel, 2004). However, there have been only a few studies in which the development of WM functioning in children with MLD is compared to that of children without MLD. In a cross-sectional study, Geary, Hoard, Byrd-Craven, and DeSoto (2004) compared the central executive WM functioning of children with MLD to that of children without MLD in first, third, and fifth grades. They found that children with MLD showed lower levels of central-executive WM and that this deficit persisted constantly over time.

Swanson, Jerman, and Zheng (2008) investigated the growth of WM functioning in children at risk and not at risk for MLD (mathematics: percentage ≤ 25). They used a cohort-sequential design including children from first, second, and third grades over a period of three years. In third grade differences between children at risk for MLD and typical learners were observed in all three WM components, indicating a higher level of WM functioning in typical learners. Whereas there were also differences in growth rates from first to fifth grades in both the central executive and the visuospatial sketchpad, revealing more growth in typical learners, there were no differences in growth rates in the phonological loop between the two groups, indicating parallel growth of phonological WM in both groups.

These previous findings suggest that in children with (or at risk for) MLD from first to fifth grades there is growth in the three components of WM but that the developmental trajectories at least of the visuospatial sketchpad and the central executive might be different compared to typical learners (Swanson et al., 2008). However, studies comparing children with MLD to those without MLD and differentiating all three components of WM especially with longitudinal rather than cross-sectional designs are still scarce. In our longitudinal study we investigated the development of working memory in children with and without MLD from grade three to grade five. Unlike Swanson et al. (2008) we used a stricter criterion for MLD (maths performance below percentile 16 instead of percentile 25) whereas the IQ criterion was less strict (IQ ≥ 70 instead of IQ ≥ 85). In addition, children with reading and/or spelling difficulties comorbid to MLD were excluded from the study.

Research Questions

Given the lack of previous research, the present study addresses the following three research questions: First, do phonological, visuospatial, and central executive WM functioning differ in children with and without MLD in third grade? Second, does the functioning of these three WM components increase with age in children with and without MLD from third to fifth grades? Third, if WM functioning increases with age, are phonological, visuospatial, and central executive developmental trajectories comparable in children with and without MLD?

METHOD

Participants

Participants were recruited from a cross-sectional screening sample on learning difficulties at the end of second grade and at the beginning of third grade in regular schools in Germany. A subsample of 151 children was selected for the present longitudinal study, of which 80 exhibited isolated poor mathematical skills (mathematics $T < 40$ equates to percentile < 16; reading and spelling $T \geq 40$) and 71 served as a control group without learning difficulties (mathematics, reading, and spelling $T \geq 40$). These typical learners were selected from a group of 100 children because their IQ and their reading and spelling performance as well matched that of the children with MLD. The participants' IQ was at least 70 (according to the ICD-10 definition of unimpaired intelligence; World Health Organization, 1993).

In the screening the Culture Fair Intelligence Test (CFT 1; Cattell, Weiß, & Osterland, 1997) was administered to assess nonverbal intelligence and German standardized achievement tests were used to assess reading comprehension (ELFE 1-6; Lenhard & Schneider, 2006), spelling (dictation; WRT 2+; Birkel, 2007), and mathematics (arithmetical, word, and geometry problems; DEMAT 2+; Krajewski, Liehm, & Schneider, 2004). Internal consistencies of these tests ranged from .91 to .97 according to the technical manuals.

Table 1 displays the group characteristics at the first measurement point (start of the study). For all analyses α-level was set at .05. As expected, due to the sampling procedure, both groups did not differ in terms of age, $F(1, 149) = 3.59$, $p > .05$; IQ, $F(1, 149) = 3.29$, $p > .05$; reading skills $F(1, 149) = 3.73$, $p > .05$; or spelling skills, $F(1, 149) = 3.63$, $p > .05$; but they differed in mathematics skills, $F(1, 149) = 606.67$, $p < .001$, $\eta_p^2 = .80$. Sex distribution was balanced within the control group, χ^2 (1) = 0.35, $p = .553$, but not within the MLD group, χ^2 (1) = 31.25, $p < .001$. This is in accord with previous research revealing that girls are overrepresented in populations with MLD (Fischbach et al., 2013).

[Please insert Table 1 here.]

Working Memory Assessment

The Working Memory Test Battery for Children Aged Five to Twelve Years (AGTB 5–12; Hasselhorn et al., 2012), a computer-based German test battery, was administered to assess WM functioning. The structure of phonological, visuospatial, and central executive WM was established by confirmatory factor analyses (Michalczyk, Malstädt, Worgt, Könen, and Hasselhorn, 2013). Internal consistencies measured in 9- to 12-year-old children ranged from .92 to .99 (Hasselhorn et al., 2012). In addition to the AGTB 5–12, a *backward word span* task was administered. All WM subtests comprise adaptive span tasks including 10 trials following an adaptive algorithm: The first two trials were used to estimate the child's individual span level of performance. At the first measurement point the span tasks backward and forward started with two and three items respectively. At the second and third measurement point the start levels were three and four items. If the child recalled the presented trial correctly, the sequence length of the consecutive trial increased by one item. If, however, the child’s recall was incorrect, the sequence length of the next trial decreased by one item. From the third trial on, trials were presented in pairs: If both trials were answered correctly the span length of the next pair increased by one item; if both trials were answered incorrectly, the span length of the next pair decreased by one item; in all other cases the span length remained the same. The maximum span length was at the first measurement point seven items for the backward task and eight items for the forward task. At the measurement points two and three the respective maximum span length was eight and nine items. A correct answer was assigned a score equivalent to the span length, whereas an incorrect answer was assigned one point less. Dependent variables were the means of the last eight trials only.

Phonological Loop. In the *digit span* task sequences of two to nine digits and in *word span monosyllabic* and *tri-syllabic* tasks sequences of two to nine mono- or tri-syllabic words have to be reproduced immediately after presentation. Presentation and recall is both acoustical.

Visuospatial Sketchpad. In the *corsi block span* task nine unsystematically located white squares in which a sequence of two to nine smileys appears, are presented on a grey screen. The child has to reproduce the sequence of the smileys by touching the squares on a touchscreen in the presented order. In the *matrix span* task a pattern of two to eight black fields presented in a white 4 x 4 matrix has to be reproduced in a white 4 x 4 matrix by touching the respective fields on the screen.

Central Executive. Similar to forward digit and word span tasks, in the *backward digit* task and *backward word span* task a sequence of two to eight digits or monosyllabic words has to be reproduced in the reverse order. In the *counting span* task squares and one to nine circles are randomly presented on the screen. The circles have to be counted. A sequence of two to eight of these pictures is presented and at the end the number of circles has to be reproduced verbally in the presented order. In an *object span* task a sequence of two to eight objects is presented on a white screen and the child has to say whether or not each object is edible. After a sequence the child has to reproduce the objects verbally in the presented order.

Testing Procedure

WM assessment was realized in the middle of third, fourth, and fifth grades and took place in schools or in university laboratories. The AGTB 5–12 was conducted by trained instructors in two individual sessions lasting 45 min each in third and fourth grades and in one individual session lasting 90 min in fifth grade. Consent of the parents and schools was obtained prior to testing.

[Please insert Figure 1 here.]

Statistical Procedure

Data was analysed with latent modeling in Mplus 7.11 (Muthén & Muthén, 1998-2013) with full information maximum likelihood (FIML) estimation. Latent change modeling (LCM; Reuter et al., 2010) was used to investigate growth of each WM component from third to fifth grades as shown in Figure 1. Model fit indices used were the χ^2 test, the comparative fit index (CFI), and the root mean square error of approximation (RMSEA) as recommended by Hu and Bentler (1998, 1999). A *p*-value of the χ^2 test ≥ .05, a CFI ≥ .97, and a RMSEA ≤ .05 indicates a good fit, whereas a *p*-value of the χ^2-test ≥ .01, a CFI ≥ .95, and a RMSEA ≤ .08 indicates an acceptable fit (Schermelleh-Engel, Moosbrugger, & Müller, 2003). Because the degrees of freedom affect the χ^2 test (e.g., Ullman, 2001; Wang & Wang, 2012), the ratio χ^2/df is additionally used for evaluating the model fit: A ratio < 2 indicates an acceptable fit (Ullman, 2001).

First, each unrestricted model was tested. Second, these models were compared to the maximum restricted models which included equalized parameters across groups as well as across points in time. Except for the visuospatial sketchpad (see below), the maximum restricted models included fixed parameters of both change variables and across both groups. Therefore, the unrestricted and the maximum restricted models were nested and it was possible to compare the goodness of fit of these models using the χ^2 difference test, which tests the null hypothesis that both models fit equally. Hence, a significant result indicates that the restricted model fits the data significantly worse than the unrestricted model and the assumption of equal WM development has to be rejected (Schermelleh-Engel et al., 2003).

[Please insert Table 2 here.]

RESULTS

Manifest means (and *SD*s) for each WM subtest and each point in time are presented as a function of MLD in Table 2. First, we established the measurement models of each WM component. In longitudinal factor analyses, factorial invariance is an important issue with respect to data interpretation: To ensure that the latent factors measure the same underlying construct across groups and time, the measurement model should at least express *strong invariance*. That is, both the factor loadings as well as the manifest intercepts should be set equal across groups and testing waves (Byrne, 2012). Although not necessarily required, *strict invariance* (i.e., additional invariance of the residuals) is of further interest in order to produce most parsimonious models. Nevertheless, if strict invariance does not hold, interpretation of latent chance modeling is not affected (Geiser, 2012). Against this backdrop, we started with measurement models that expressed strict invariance. However, if the model was of only poor fit, invariance constraints of the residuals were released and a strong invariant model was estimated instead. In addition, autocorrelated residuals (i.e., common variance between one and the same WM task across the three testing waves) were included in order to model indicator-specific effects across time (Cole & Maxwell, 2003). The measurement model of each WM component is shown in Figures 2 to 4. Their goodness of fit is the same as the goodness of fit of the unrestricted latent change models, and is therefore described in detail only below. For both the phonological loop and the visuospatial sketchpad, we were able to establish a longitudinal model with strict invariance. For the central executive, however, the strict invariant model showed only poor fit to the data; χ^2 (128) = 190.88, $p < .001$; RMSEA = .08 [90% CI: .06, .10]; CFI = .84. Therefore, we released the constraints of the error variances and estimated a strong invariant model instead. Although this led to a significant improvement in overall model fit (ΔCFI > .01), results were still of poor fit. We therefore consulted modification indices, which showed that the residuals between the object span task and the counting span task co-varied highly in both groups. This covariation might be due to method effects, as both measures are considered complex span tasks in which simultaneous storage and processing is taking place during encoding. By this means, those complex spans are differentiated from backward spans in which simultaneous storage and processing is taking place during retrieval rather than during encoding. We thus included those additional paths in the model to account for potential method effects. This respecified model led to a significant improvement (ΔCFI > .01), and showed a reasonable good fit to the data (see below).

[Please insert Figures 2 to 4 here.]

Does WM functioning differ in children with and without MLD in third grade?

To compare the phonological, visuospatial, and central executive WM functioning in children with MLD to that in children without MLD in third grade, the latent means of the baseline level, which are provided in Table 3, were fixed equally between both groups for each WM component. These restricted models were compared statistically to the unrestricted models.

Concerning the phonological loop, the data were represented well by the unrestricted model, χ^2 (65) = 80.85, p = .089, χ^2/df < 2; RMSEA = .06 [90% CI: .00, .09]; CFI = .97; whereas the restricted model revealed a worse fit to the data, χ^2 (66) = 91.30, p = .021; RMSEA = .07 [90% CI: .03 -.11]; CFI = .95. Accordingly, the χ^2 difference test between the unrestricted model and the restricted model was statistically significant, indicating that the restricted model revealed a worse fit to the data than the unrestricted model, $\Delta\chi^2$ (1) = 10.45, *p* = .001. Hence, these results indicate that typical learners showed a higher level of phonological WM functioning than children with MLD in third grade.

For the visuospatial sketchpad, the unrestricted model fit the data excellently, χ^2 (10) = 7.38, *p* = .689, χ^2/df < 2; RMSEA = .00 [90% CI: .00 - .10]; CFI = 1.00. Again, the restricted model fit the data worse than the unrestricted model, χ^2 (11) = 24.24, *p* = .012; RMSEA = .13 [90% CI: .06 - .20]; CFI = .92 (χ^2 difference test: $\Delta\chi^2$ (1) = 16.86, *p* < .001). These findings indicate that typical learners outperformed children with MLD in visuospatial WM functioning in third grade.

Regarding the central executive, the model fit indices of the unrestricted model also revealed a reasonable to good fit to the data, χ^2 (102) = 132.75, *p* = .022, χ^2/df < 2; RMSEA = .06 [90% CI: .03 - .09]; CFI = .92; whereas the restricted model demonstrated a worse fit to the data, χ^2 (103) = 146.69, *p* = .003, χ^2/df < 2; RMSEA = .08 [90% CI: .05 - .10]; CFI = .89 (χ^2 difference test, $\Delta\chi^2$ (1) = 13.94; *p* < .001). These results indicate that typical learners exhibited higher levels of central executive WM functioning than children with MLD in third grade.

[Please insert Table 3 here.]

Does WM functioning increase with age in children with and without MLD from third to fifth grades?

Table 3 illustrates the latent means of baseline and change factors as a function of MLD. All means except one were significantly different from zero, indicating that there was growth from third to fifth grades in all WM components in children with and without MLD except in visuospatial WM from fourth to fifth grades in typical learners. Given that WM developed in children with and without MLD, in further analyses the developmental trajectories in both groups were compared.

Are the developmental trajectories in children with and without MLD comparable?

For the phonological loop, as reported before, the unrestricted model revealed a good fit to the data. The maximum restricted model was tested and fit the data just as well, χ^2 (68) = 83.02, *p* = .104; RMSEA = .05 [90% CI: .00 - .09]; CFI = .97. Furthermore, the χ^2 difference test between the unrestricted model and the maximum restricted model was not statistically significant, revealing that the restricted model did not fit the data worse than the unrestricted model, $\Delta\chi^2$ (3) = 2.17, *p* = .538. These results reveal linear growth of phonological WM across both points in time and parallel growth across both groups.

Data on the visuospatial sketchpad, as reported before, were represented excellently by the unrestricted model. The mean of the second change factor of the control group was not statistically significant, indicating that there was no WM growth from fourth to fifth grades. Thus, the maximum restricted model tested was the model in which all change factors except the second change factor in the control group were fixed equally. In other words, the change factor between t1 and t2 of both groups and the change factor between t2 and t3 of the MLD group were fixed equally. This model did not fit the data worse than the unrestricted model, χ^2 (12) = 11.06, *p* = .524; RMSEA = .00 [90% CI: .00 - .11]; CFI = 1.00 (χ^2 difference test: $\Delta\chi^2$ (2) = 3.68; *p* = .159). These findings reveal linear growth of WM across both points in time in children with MLD and parallel growth from t1 to t2 in children with and without MLD as well as no growth from t2 to t3 in typical learners for the visuospatial sketchpad.

In addition, the visuospatial WM functioning in children with and in children without MLD in fifth grade was compared by fixing the latent means of both groups in fifth grade in the measurement model. The χ^2 difference test of the unrestricted and the restricted measurement model was not statistically significant, revealing that the restricted model did not fit the data worse than the unrestricted model, $\Delta\chi^2$ (1) = 2.07, *p* = .150. This result suggests that both groups did not differ in visuospatial WM capacity in fifth grade, indicating that the children with MLD reached a WM level comparable to that of the typical learners.

Concerning the central executive, as reported above, the model fit indices of the unrestricted model demonstrated a good fit to the data. In addition, the maximum restricted model did not fit the data worse than the unrestricted model, χ^2 (105) = 133.82, $p = .030$; RMSEA = .06 [90% CI: .02 - .09]; CFI = .93 (χ^2 difference test, $\Delta\chi^2$ (3) = 1.07; $p = .783$). These results reveal linear growth of central executive WM across both points in time and parallel growth across both groups.

DISCUSSION

Many cross-sectional studies have revealed that children with MLD exhibit WM deficits compared to typical learners (e.g., Raghubar et al., 2010); however, longitudinal studies of the development of WM in children with MLD and in those without MLD are scarce. Therefore, in the present study the developmental trajectories of WM functioning in both groups of children were compared.

Does WM functioning differ in children with and without MLD in third grade?

Our findings indicate that there are differences in phonological, visuospatial, and central executive WM functioning in third graders with and without MLD: The children with MLD were outperformed by typical learners in each of the three WM components. This result is in line with cross-sectional research revealing that children with MLD had deficits in WM compared to typical learners (e.g., Raghubar et al. 2010; Swanson & Jerman, 2006). However, whether or not the WM deficits in children with MLD comprise all three components of WM is still debated (e.g., De Weerdt, Desoete, & Roeyers, 2013). Our findings suggest that children with MLD exhibit deficits in phonological, visuospatial as well as central executive WM although they have isolated difficulties in mathematics and no difficulties in reading and/or spelling. Given these deficits, it is of interest whether or not the developmental trajectories of WM in children with MLD also differ from those of typical learners.

Does WM functioning increase with age in children with and without MLD from third to fifth grades?

Our analyses revealed that phonological and central executive WM functioning developed in children with and without MLD from third to fifth grades. In contrast, visuospatial WM improved in children with MLD from third to fifth grades whereas in typical learners WM growth was observed from third to fourth grades only. These results suggest a continuous development of WM in children with MLD from third to fifth grades whereas typical learners' visuospatial development was disrupted from fourth to fifth grades. This finding suggests that the developmental growth rates in the visuospatial WM are different between typical learners and children with MLD.

With the exception of visuospatial WM, the present findings are in line with those of Swanson et al. (2008), who observed development of phonological, visuospatial, and central executive WM functioning in children at risk for MLD and in typical learners. The visuospatial measures employed by Swanson et al. (2008) put a greater load on the central executive than the tasks used in this study because they included both a storage component and a processing component. This might be a reason we did not observe visuospatial development in typical learners over all testing waves but they did. Correspondingly, their results on visuospatial development were not in line with ours but they were in line with our results on central-executive development.

Are the developmental trajectories in children with and without MLD comparable?

We compared the developmental trajectories of WM in children with and without MLD by modeling the change in WM from third to fourth grades as well as from fourth to fifth grades in separate latent change models for phonological, visuospatial, and central executive WM.

Developmental trajectories of phonological and central-executive functioning in children with and without MLD were comparable. The result concerning central executive WM functioning is in line with that of Geary et al. (2004) but not with the finding of Swanson et al. (2008), who observed a less growth in children at risk for MLD. Swanson et al. (2008) defined their sample on the basis of problem solving and number naming, whereas in Geary et al. (2004) and the present study greater emphasis was placed on arithmetical skills. Therefore, the different findings may be due to the fact that the children do have difficulties in different mathematical domains which lead to the suggestion that difficulties in problem solving and number naming might be related to a smaller growth of central executive WM whereas arithmetical difficulties may not.

Whereas Geary et al. (2004) did not measure phonological WM, Swanson et al. (2008) as well as the present study did and they did not observe differences in the developmental trajectories between children with and without (or at risk for) MLD. These results indicate that although children with MLD exhibited phonological WM deficits they showed growth in phonological WM comparable to that in typical learners.

Concerning the visuospatial sketchpad, results of the present study suggest that typical learners' development comes to a halt from fourth to fifth grades whereas children with MLD are developing further and reach a comparable level of WM in fifth grade. This finding illustrates that it is possible that children with MLD overcome their WM deficits by reaching a developmental level in WM later than typical learners. However, since our longitudinal study included children only up to grade five it is unclear whether the absent increase in typically developing children reflects a developmental plateau of the VSSP or whether the halt is preliminary and the development continues when the children are growing older. Thus, it would be interesting for future research to conduct longitudinal studies on working memory development with children and adolescents older than our sample.

As stated above, Logie and Pearson (1997), Pickering et al. (2001), and Hamilton et al. (2003) observed that performance on static-visual tasks developed faster than performance on dynamic-spatial tasks in typical learners. There is evidence that children with MLD exhibit deficits especially in dynamic-spatial WM (McLean & Hitch, 1999; Passolunghi & Mammarella, 2012; van der Sluis, van der Leij, & de Jong, 2005). Therefore, it would be interesting to analyse separately the development of static-visual and dynamic-spatial visuospatial WM. However, since the two visuospatial tasks were spatial in nature in the current study such a contrast was beyond the possibilities for our analyses.

Developmental trajectories of phonological and central-executive functioning of WM were comparable across time points. That is, linear development of WM functioning was observed in children with and without MLD, resulting in a constant deficit in phonological and central executive WM over time in children with MLD. This finding of phonological functioning is in line with that of Swanson et al. (2008) whereas the finding of central-executive functioning is in line with that of Geary et al. (2004). Neither the typical learners nor the children with MLD showed signs of a developmental stagnation in phonological or central executive WM in fifth grade. Hence, it is important to analyse these WM components in older children and young adults to determine further developmental trajectories.

These results lead to the important conclusion that the WM functioning does not develop more slowly in children with MLD than it does in typical learners although development of WM in children with MLD starts at a lower level. At least in visuospatial WM children with MLD caught up to typical learners after the latter had stagnated in their development. Therefore, both groups reached a comparable level of WM in fifth grade. It is still an open question, which might be addressed in future research, as to whether or not it is also possible for children with MLD to overcome their WM deficits in the phonological loop and the central executive during development.

Limitations and Implications

In terms of the external validity of our results there are limitations to be considered. First, there is no uniform definition of MLD. Our sample included children scoring lower than the 16th percentile on a standardized mathematical achievement measurement including arithmetical, word, and geometry problems. The cut-off criterion for defining learning disabilities is currently being discussed in general (e.g., Büttner & Hasselhorn, 2011) and in the context of WM in children with MLD in particular (Murphy, Mazzocco, Hanich, & Early, 2007; Passolunghi & Mammarella, 2012).

Second, we did not differentiate the sub-processes of WM components (e.g., rehearsal, articulatory suppression) which are related to different functions (Baddeley, 2012). Therefore, it might be interesting to examine in future research whether or not there is WM growth in all sub-processes. In addition, we used only CE tasks that required a verbal response. Although visuospatial processes might also be involved in some CE tasks (e.g., backwards tasks, object span task) the main encoding was verbal in our study. It might be of interest for future research to make a stronger distinction between processing of verbal vs. visuospatial information in CE tasks.

Third, we investigated a subgroup of children with MLD, excluding children with additional reading and spelling difficulties. Based on the findings that children with isolated MLD and children with additional reading and spelling difficulties exhibit different WM deficits (e.g., Peng & Fuchs, 2016), it might be interesting to examine in future research whether or not there are differences in the development of WM functioning between the two groups.

We were interested in the intraindividual change in WM functioning because the design of previous research was often cross-sectional rather than longitudinal. Age has been discussed as one cause of heterogeneous results in cross-sectional research on WM deficits in children with MLD (e.g., Raghubar et al., 2010). Our findings suggest that age does not have a critical role in accounting for the differences between the groups in the development of phonological and central executive WM from third to fifth grades because developmental trajectories for both groups were linear and comparable. It is different in the case of visuospatial WM: Whereas WM functioning in both groups was not comparable in third grade, it was in fifth grade. Therefore, age might be an important aspect to consider when analysing differences in visuospatial WM functioning in children with MLD and in typical learners.

Given our finding that the development in phonological and central executive WM is comparable in children with and without MLD, intraindividual change in these WM components might be explored in future research. For instance, the question arises as to whether or not there are differences in the developmental trajectories as a function of WM baseline level. So far, intraindividual growth of WM functioning in children with MLD has been investigated as a predictor, for example, of arithmetical strategy use (Geary et al., 2004) or problem solving (Swanson et al., 2008). Overall, according to these findings and those from the present study it seems to be important to focus on intraindividual change in future research.

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Table 1

Descriptive statistics (t1) and ANOVAs for the mathematical learning difficulties group (MLD) versus control group (CG)

	MLD (*n* = 80)	**CG** (*n* = 71)
	M (*SD*)	*M* (*SD*)
Age (in month)	111.56 (6.83)	109.61 (5.73)
Nonverbal IQ	99.60 (14.56)	103.63 (12.53)
Mathematics[a]	34.06 (3.52)	52.59 (5.60)
Reading[a]	47.98 (5.64)	49.48 (3.57)
Spelling[a]	47.29 (5.84)	48.97 (4.91)
Sex (male/female)	15/65	38/33

Note. t1 = first measurement point in time. [a] *T*-score: *M* = 50, *SD* = 10.

Table 2

Manifest means (and SDs) of the AGTB-measurement for the mathematical learning difficulties group (MLD) and control group (CG)

		3rd grade	**4th grade**[b]	**5th grade**[f]
		M (*SD*)	*M* (*SD*)	*M* (*SD*)
Phonological Loop				
1-syllabic word span	MLD	3.60 (0.57)	3.88 (0.57)	3.97 (0.58)
	CG	3.82 (0.69)	4.10 (0.74)	4.19 (0.83)[g]
3-syllabic word span	MLD	2.86 (0.40)[a]	2.99 (0.48)[c]	3.16 (0.48)
	CG	3.05 (0.42)	3.16 (0.54)	3.37 (0.49)[g]
Digit span	MLD	4.09 (0.56)	4.47 (0.57)	4.74 (0.59)
	CG	4.45 (0.68)	4.73 (0.66)	5.05 (0.64)
Visuospatial Sketchpad				
Corsi block span	MLD	3.82 (0.74)	4.31 (0.77)	4.54 (0.65)
	CG	4.13 (0.65)	4.64 (0.82)	4.77 (0.72)
Matrix span	MLD	4.00 (1.23)	5.01 (1.41)	5.74 (1.29)
	CG	4.77 (1.16)	5.46 (1.53)	5.97 (1.15)
Central Executive				
Counting span	MLD	2.78 (0.74)	3.18 (0.85)[c]	3.38 (0.73)
	CG	3.21 (0.81)	3.59 (0.78)[d]	3.77 (0.91)[g]
Backward digit span	MLD	2.98 (0.49)	3.22 (0.63)	3.66 (0.55)
	CG	3.26 (0.70)	3.45 (0.76)	3.92 (0.70)
Backward word span	MLD	2.79 (0.37)	2.95 (0.57)[c]	3.29 (0.59)
	CG	3.08 (0.60)	3.25 (0.75)	3.45 (0.77)[g]
Object span	MLD	2.88 (0.62)	3.14 (0.84)[e]	3.30 (0.76)
	CG	2.98 (0.78)	3.43 (0.74)	3.41 (0.77)[g]

[a]Data of two participants are missing. [b]Data of twelve participants are missing in each group. [c]Data of 14 participants are missing. [d]Data of 13 participants are missing. [e]Data of 15 participants are missing. [f]Data of 48 participants are missing in MLD and data of 29 participants are missing in CG. [g] Data of 30 participants are missing in CG.

Table 3

Latent means of baseline and change factors as a function of MLD

	MLD	**CG**
PL		
baseline factor	3.54*	3.84*
change factor t2-t1	0.30*	0.33*
change factor t3-t2	0.20*	0.24*
VSSP		
baseline factor	4.01*	4.74*
change factor t2-t1	1.06*	0.87*
change factor t3-t2	0.54*	0.31
CE		
baseline factor	2.92*	3.20*
change factor t2-t1	0.24*	0.31*
change factor t3-t2	0.30*	0.23*

Note. MLD = mathematical learning difficulties group; CG = control group; PL = phonological loop; VSSP = visuospatial sketchpad; CE = central executive; t2 – t1 = difference between second and first measurement point in time; t3 – t2 = difference between third and second measurement point in time.
* $p < .05$.

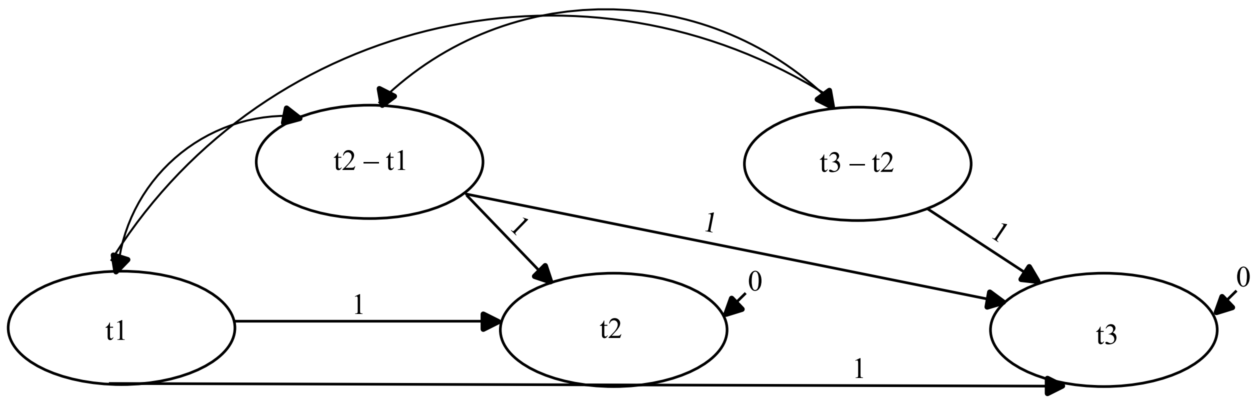

Figure 1. Latent change model for WM. t1 = first measurement point in time; t2 = second measurement point in time; t3 = third measurement point in time; t2 – t1 = difference between second and first measurement point in time; t3 – t2 = difference between third and second measurement point in time.

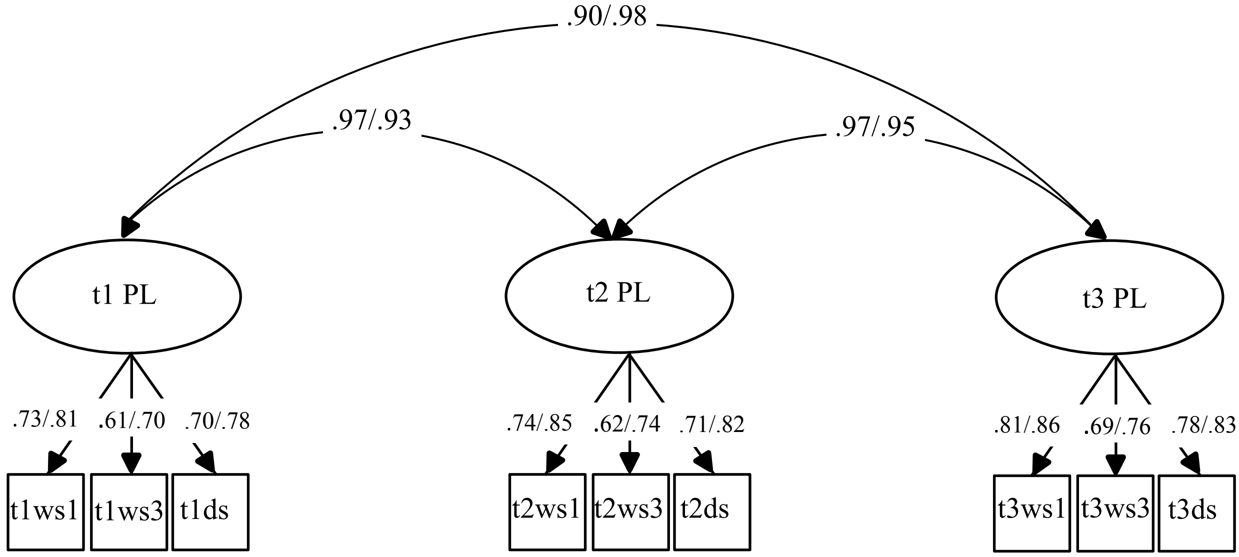

Figure 2. Measurement model of the phonological loop for children with MLD (left standardized parameters) versus typical learners (right standardized parameters). For better clarity, residual variances and autocorrelated residuals are not shown. t1 = first measurement point in time; t2 = second measurement point in time; t3 = third measurement point in time. PL = phonological loop; ws1 = word span monosyllabic; ws3 = word span tri-syllabic; ds = digit span. All parameters were significant ($p < .05$).

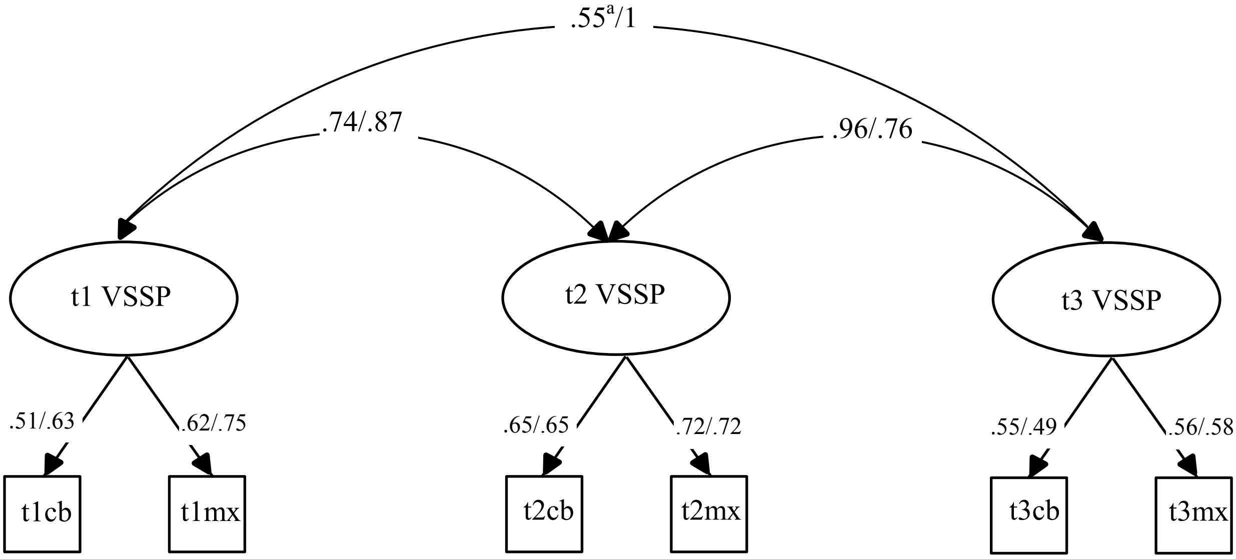

Figure 3. Measurement model of the visuospatial sketchpad for children with MLD (left standardized parameters) versus typical learners (right standardized parameters). For better clarity, residual variances and autocorrelated residuals are not shown. t1 = first measurement point in time; t2 = second measurement point in time; t3 = third measurement point in time. VSSP = visuospatial sketchpad; cb = corsi block span; mx = matrix span. All parameters were significant ($p < .05$). [a] Parameter was not significant (p > .05)

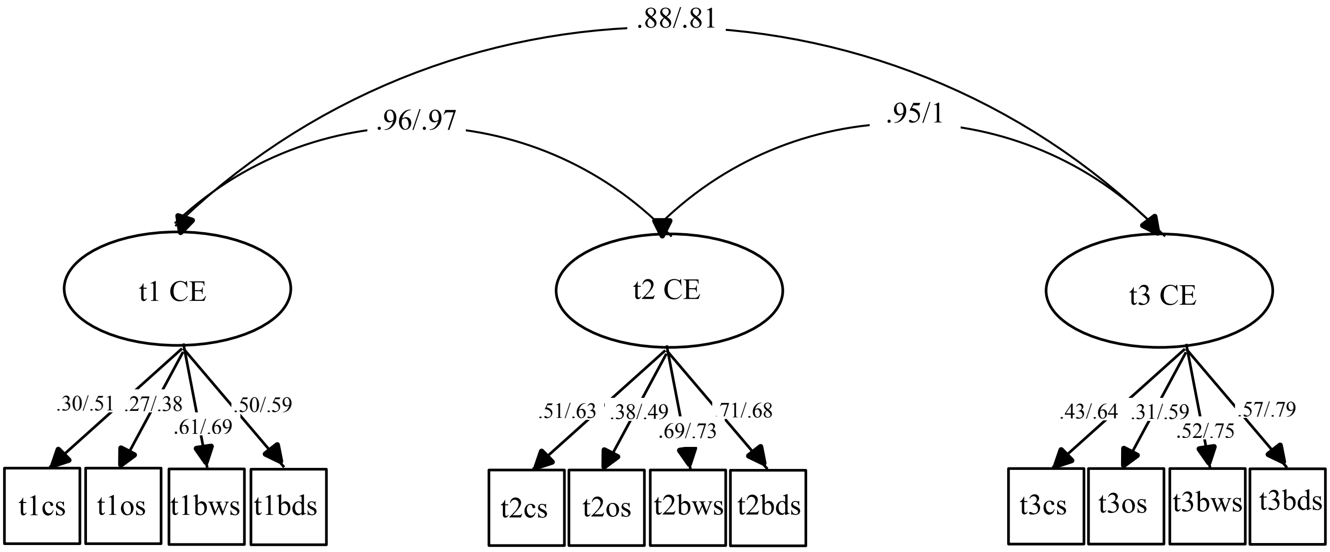

Figure 4. Measurement model of the central executive for children with MLD (left standardized parameters) versus typical learners (right standardized parameters). For better clarity, residual variances and autocorrelated residuals are not shown. t1 = first measurement point in time; t2 = second measurement point in time; t3 = third measurement point in time. CE = central executive; cs = counting span; os = object span; bws = backward word span; bds = backward digit span. All parameters were significant ($p < .05$).