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What is not working in working memory of children with literacy disorders?

Evidence from a three-year-longitudinal study

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Abstract

The goals of this study were to explore the deficits in working memory associated with literacy disorders (i.e. developmental disorders of reading and/or spelling) and the developmental trajectories of these working memory deficits. The performance of 28 children with literacy disorders was compared to a non-disabled control group with the same group size at five bi-annual times of measurement in a three-year-longitudinal study beginning at the end of primary school (9.5 years of age). Storage capacity and central-executive working memory were assessed in phonological and visual-spatial modalities, the latter under static and dynamic conditions. Overall, children with literacy disorders were outperformed by their typical developing peers in all phonological and in dynamic visual-spatial storage and central-executive tasks except for the static visual-spatial storage task. Results at single times of measurement revealed that the most consistent deficit was found in the storage capacity of the phonological loop. An additional central-executive impairment is supported by low backward spans. The causes for output deficits in dynamic visual-spatial tasks and good performance under static visual-spatial condition are discussed.

Keywords

Working memory; dyslexia; spelling disorder; visual-spatial; serial information processing

About 3.6 to 7.3% of all children at school suffer from literacy disorders (Hasselhorn & Schuchardt, 2006). These severe difficulties in reading and/or spelling occur in spite of unimpaired intellectual ability and adequate education. Boys are 1.4 to 3 times more likely to be affected than girls (Rutter et al., 2004). At least in transparent orthographies, spelling disorders are slightly more prevalent than reading disorders (Wimmer, Mayringer, & Landerl, 1998; Gebauer et al., 2012). Nevertheless, reading and spelling deficits do co-occur more frequently than simply by random chance, resulting from common aetiological factors (Landerl & Moll, 2010). Although a lot of effort has been invested in striving to understand the cognitive causes underlying reading and spelling disorders, a number of controversial issues remain. Although research consistently indicates that a core deficit in information processing is an underlying reason for literacy disorders, there are controversial positions and heterogeneous findings with regard to which aspect of information processing is most relevant. Besides the widely held belief that phonological processing impairments are essential, there are also findings on visual processing deficits and regulatory executive deficits (for an overview see Heim et al., 2008; Menghini, Finzi, Carlesimo, & Vicari, 2011; Vellutino, Fletcher, Snowling, & Scanlon, 2004). However, irrespective of the controversial debate of which function is defective, little is known about the developmental trajectories of these deficits in information processing.

Working memory model

A model that is often used to examine different cognitive aspects of information processing is the working memory model by Baddeley and Hitch (1974) that combines phonological, visual-spatial, and executive information processing mechanisms. More specifically, working memory stores speech-based and graphic information for a brief period of time to be able to process and understand written information. This activated and processed information can also be transferred into long-term memory, which enables learning (Baddeley, 1986, 2007, 2012). Two modality-specific, capacity- and time-limited storages exist for holding information: The *Phonological Loop* stores speech-based information with the help of a temporary *Phonetic Storage* of 1.5 to 2 seconds' length (Baddeley, Thomas, & Buchanan, 1975; Schweickert & Boruff, 1986) and an inner rehearsal process that mentally repeats the information to hold more information for a longer period of time (*Subvocal Rehearsal*).

The *Visual-Spatial Sketchpad* is the counterpart of the Phonological Loop and holds visual (e.g. color, shape) and spatial (e.g. physical arrangement, movement) information in the *Visual Cache* by imaging the information in mind (Logie, 1995). A distinction is made between memory of static information that does not move and dynamic information. The *Inner Scribe* helps to refresh the memory contents by retracing them (Logie, 1995).

Besides storing there is the need for an executing working component to describe information processing. In the model, the Central Executive, a modality-unspecific, regulative, and attentionally limited controlling system, implements this. Executive functions include e.g. selecting, processing, and combining the stored information of the subsystems. Therefore, various cognitive functions like attention focusing and strategy use are necessary.

Although working memory comprises very basic information processes, its development is not completed in early childhood and it continues to develop into early adulthood (e.g. Keage et al., 2008). The phonological storage gains in capacity during kindergarten and elementary school years (Brunswick, Martin, & Rippon, 2012) as well as spatial working memory simultaneously gains in accuracy and processing speed (Tsujii, Yamamoto, Masuda, & Watanabe, 2009). Storage capacities in both domains have been found to increase further from the age of 6 to 12 years (Chuah & Maybery, 1999) and an increase of all working memory components between 4 and 15 years is documented, too (Gathercole, Pickering, Ambridge, & Wearing, 2004).

Working memory in reading and spelling

Working memory in the sense of simultaneously holding and processing temporarily activated information is important for successful reading and spelling processes (Baddeley, 1986; Gathercole & Baddeley, 1993; Brunswick et al., 2012): Children who are learning to read and spell make use of working memory capacities during word reading and spelling by decoding graphemes, encoding phonemes, and retaining them simultaneously until the word is detected or written. Advanced readers and spellers still need working memory capacities for higher skill levels of reading comprehension and text writing. In addition, working memory activities support the acquisition of reading and spelling skills by forming word representations and building letter knowledge in long-term memory (Alloway, Gathercole, Adams, Willis, Eaglen, & Lamont, 2005; Gathercole & Baddeley, 1993; Siegel & Ryan, 1989; Wagner & Torgesen, 1987; see Savage, Lavers, & Pillary, 2007 for review).

Working memory and literacy disorders

Due to its relevance, working memory is among the potential causal factors of literacy disorders addressed in recent years. Most studies report limitations in phonological storage (e.g. Bayliss, Jarrold, Baddeley, & Leigh, 2005; Kibby, Marks, Morgan, & Long, 2004; Schuchardt, Maehler, & Hasselhorn, 2008; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003; Smith-Spark & Fisk 2007; Steinbrink & Klatte, 2007) and in phonological central-executive working memory (e.g. Beneventi, Tonnessen, Ersland, & Hugdahl, 2010; Gathercole, Alloway, Willis, & Adams, 2005; Jeffries & Everatt, 2004; Palmer, 2000; Schuchardt et al., 2008; Siegel & Ryan, 1989; Smith-Spark & Fisk, 2007; Swanson, 1999; Swanson, Zheng, & Jerman, 2009; Tiffin-Richards, Hasselhorn, Woerner, & Rothenberger, 2007; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005; Wolf, Sambataro, Lohr, Steinbrink, Martin, & Vasic, 2010). Findings regarding central-executive deficits are more heterogeneous: Besides the claim of a central executive deficit in addition to phonological storage impairment (e.g. Swanson, 2006; Swanson & Ashbaker, 2000; Swanson, Ashbaker, &

Lee, 1996), it has also been hypothesized that observable lower central-executive functioning can fully be explained by phonological storage impairment (Kibby et al., 2004; Schuchardt et al., 2008).

In the visual-spatial domain, storage capacity is mostly found to be not impaired in children with a literacy disorder (e.g. Jeffries & Everatt, 2004; Schuchardt et al., 2008; Kibby et al., 2004; Landerl, Fussenegger, Moll, & Willburger, 2009; Smith-Spark & Fisk, 2007). Visual-spatial central-executive abilities have rarely been investigated and respective results are heterogeneous. Some findings indicate that central-executive deficits do not occur when visual-spatial information is being processed (Kibby et al., 2004; Marzocchi et al., 2008; Willcutt et al., 2005). However, a few studies report the opposite and found both visual-spatial storage impairments (Bayliss et al., 2005; Gathercole et al., 2005; Menghini et al., 2011) as well as visual-spatial central-executive deficits (Smith-Spark & Fisk, 2007; Swanson, 1999; Swanson et al., 1996). Thus, findings on sketchpad and visual-spatial central-executive functioning are less consistent than in the phonological domain. Consequently, it has not been fully clarified whether the storage limitations and central-executive deficits are domain-specific to phonological processing or rather domain-general occurring also when visual-spatial information is being processed.

Irrespective of these issues, only little is known about the developmental trajectories of working memory functioning in children with literacy disorders and related learning difficulties. To our knowledge, there is just one study by Siegel and Ryan (1989) who analyzed not only group differences in two phonological central-executive tasks but also age differences of children with and without reading disorders at three age categories (age between 7 and 8 years, 9 and 10 years, and 11 and 13 years). Besides the general lower performance as compared to unaffected peers, Siegel and Ryan (1989) reported a developmental retardation among children with reading disorders. However, the design of this study was not longitudinal and it did not consider all working memory components.

The current study

The present study attempts to narrow the research gap caused by missing longitudinal studies focusing on working memory development in children with literacy disorders including phonological, visual-spatial, and central-executive working memory components. Thus, we set the following objectives: First, we wanted to recruit children from one cohort with a similar age and to follow them longitudinally. Second, we wanted to assess the storage components as well as central-executive functions with regard to phonological as well as visual-spatial information processing. Hence, these objectives offered the opportunity to examine not only specific working memory deficits in children with literacy disorders but also the developmental trajectories of these deficits over a distinct period of time. More specifically, our study was planned to answer the following research questions:

1. Which working memory functions are deficient in children with literacy disorders?

According to the results of former research, we expected to find storage and central-executive impairments in the phonological domain. As findings on visual-spatial storage and central-executive abilities are more ambiguous, it was more difficult to formulate specific assumptions in this domain. Nevertheless, we attempted to replicate findings by Schuchardt et al. (2008). Thus, we hypothesized to find phonological storage limitations and as a consequence phonological central-executive deficits but no visual-spatial working memory impairments in children with literacy disorders.

2. How do working memory functions develop in children with literacy disorders at the end of primary school and beyond?

Given the lack of longitudinal studies focusing working memory functioning in children with literacy disorders, it remains an open question whether the working memory deficits in children with literacy disorders are developmentally invariant in the sense that they exist from the onset of disorder or even before, or change with age in the sense that they emerge at one time and disappear later on in a particular phase of a disorder. However, since cross-sectional findings on phonological working memory deficits are consistent across many studies, we supposed to find stable phonological working memory deficits in children with literacy disorders. Again it was more difficult to provide hypotheses in the visual-spatial domain. We expected, as it was cross-sectionally found in the study of Schuchardt et al. (2008), that there were no visual-spatial working memory impairments in the long run.

Methods

Sample

The sample consisted of 28 children with diagnosed literacy disorders (18 children had combined reading and spelling impairments, 8 children had isolated spelling, and 2 children had isolated reading impairments) and 28 children without learning difficulties (control group). We recruited the participants in two ways: First, we realized a large-scale screening of 1,660 third graders in 28 regular primary schools in an urban area in Germany in 2008. Trained psychology students conducted a nonverbal intelligence test (German version of the Columbia Mental Maturity Scale, CMM 1–3, see Schuck, Eggert, & Raatz, 1975), and standardized German school achievement tests (reading: WLLP, see Küspert & Schneider, 1998; spelling: DERET 1–2+, see Stock & Schneider, 2008a; math: DEMAT 2+, see Krajewski, Liehm, & Schneider, 2004). Children who met the criteria for literacy disorders or the control group were invited to take part. This way, 17 children with literacy disorders and the 28 control group children were recruited. Second, the remaining nine children with literacy disorders were recruited through licensed learning institutes and were diagnosed by professionals applying standardized IQ-, reading and spelling tests. For the longitudinal sample, the diagnostics were repeated at the end of grade four or at the beginning of grade five, respectively (applied tests were a nonverbal IQ-test: CFT 20-R, see Weiß, 2008; reading: ELFE 1–6, see Lenhard & Schneider, 2008; spelling: DERET 3–4+, see Stock & Schneider, 2008b; math: DEMAT 4, see Gölitz, Roick, & Hasselhorn, 2006).

Criteria for diagnosing literacy disorder were an unimpaired nonverbal intelligence (IQ ≥ 85) and reading and/or spelling test scores that were compared to same-aged peers 1.0 standard deviation (*SD*) below average (*T* scores < 40) as well as 1.2 *SD* below the individual IQ-value in at least one of two diagnostic assessments. Children in the control group also had an average nonverbal intelligence (IQ ≥ 85), but at least average results in the reading and spelling tests (*T* scores ≥ 43). The general criteria for exclusion in both groups were the attendance of a special educational school, deficient knowledge of German, and dyscalculia (excluded by professionals respectively a math test score of *T* scores ≥ 43). Control group children outperformed those with literacy disorder with regard to reading and/or spelling, but were matched by age and IQ (see Table 1).

At the beginning of longitudinal assessments, 24 children with literacy disorders were attending the fourth grade, 2 children the third grade, and 2 children the fifth grade. Of the control group, 25 children were attending the fourth grade and 3 children the fifth grade. Scholastic test norms were adjusted to grade, IQ test norms to age. As expected, children with literacy disorders scored significantly lower in reading, $t(47) = 8.05$, $p < .01$, $d = 2.31$, and spelling, $t(47) = 8.05$, $p < .01$, $d = 2.60$, and this underperformance remained stable at second diagnostics (reading: $t(41) = 7.42$, $p < .01$, $d = 2.26$; spelling: $t(39) = 8.39$, $p < .01$, $d = 2.63$). In addition, at first diagnostics both groups differed unexpectedly in math, too, $t(42) = 2.24$, $p < .05$, $d = 0.70$, although the means of math achievement were in the normal range. There were a few more girls than boys in the control group (girls: 16, boys: 12), while there were three times more boys than girls in the group with literacy disorders (girls: 7, boys: 21), $\chi^2(1) = 5.98$, $p < .05$, $\omega = 0.33$.

(Please insert Table 1 here)

Working memory

To measure working memory functioning, we selected up to seven subtests of the German computer-based *Working Memory Test Battery for Children Aged Five to Twelve Years* (AGTB 5–12; Hasselhorn et al., 2012). Besides five official subtests, two additional subtests were used which are included in a pre-version of this test battery (marked with * below). The AGTB program presents acoustically standardized instructions for each task and offers practice trials to ensure that instructions are understood. The child works on the automatically presented tasks in the presence of an experimenter in an individual testing situation.

Most of the working memory subtests were span tasks (marked with # below) of an adaptive format and consisting of two calibration and eight test trials. During calibration trials, task difficulty adapted immediately after every response while during test trials, task difficulty adapted after every two responses. Hence, task difficulty augmented by an increase of one item in the presented span if the child gave two correct responses. If the child gave one correct and one incorrect response, task difficulty remained stable, and it was reduced by one item after two incorrect responses. The first of ten series started with a sequence of three items under forward recall condition and with a sequence of two items under backward recall condition. The length of a series increases adaptively to a maximum of seven or eight items per sequence depending on recall condition. Every correctly answered test trial was rated on the basis of its sequence length (e.g. five if the sequence consisted of five items) while incorrectly answered trials were rated by its sequence length minus one (e.g. four if the sequence consisted of five items). The span score was the mean performance of the eight test trials.

Phonological Loop. *Digit Span Forward*# was used as an indicator for the storage capacity of the phonological loop. A sequence of single digits (1 to 9) was presented acoustically at a rate of one digit per second. Afterwards the child had to repeat the digits immediately in the presented order. Each digit occurred only once within a sequence.

Nonword Repetition indicated the quality and length of the phonetic storage within the phonological loop. A four-, five-, or six-syllable nonword was solely presented acoustically and the child had to repeat it immediately after presentation. The task consisted of 24 German-like nonwords in total and eight nonwords of each length. The experimenter decided online on the correctness of the nonword repetition, which was given if the child pronounced every phoneme clearly and in the right order.

*Articulation Rate** was used as an indicator for the speed of the subvocal rehearsal. A word triplet was presented and the task was to repeat these three monosyllabic words continuously as fast as possible. The experimenter pressed the space bar every time the child finished pronouncing the last word of a complete triplet. Thereby the duration times for ten triplets were measured in milliseconds. Instead of calculating the mean time of all time measurements, we cleaned the data: As key pressing was often imprecise for the starting and ending measurements, these times were not considered. To correct the remaining eight times for further errors and corrective actions by the child during task procedure, we calculated a mean solely on the basis of the four shortest of eight times. Subsequently, we computed the number of single words of syllables that a child spoke per second by the following equation: (3 words x 1,000 ms) / mean of the four shortest times in ms.

Visual-Spatial Sketchpad. *Matrix*# was to indicate the visual cache of the visual-spatial sketchpad, i.e. working memory capacity for static information. A matrix with 4x4 white and black fields was presented on a touchscreen. The duration of presentation depended on the number of black fields (1,200 ms per black field). Immediately after presentation a blank matrix appeared and the child was asked to touch the fields, which had been black before.

Corsi Block Forward[#] is taping the inner scribe of the visual-spatial sketchpad, in terms of working memory capacity for dynamic information. A grey surface with nine empty unsystematically ordered quadrats (“blocks”) was constantly presented on a touchscreen. A yellow smiley appeared serially for 950 ms and with an interstimulus interval of 50 ms in different blocks. Afterwards the child was asked to touch the empty blocks on the touchscreen in the same serial order of where the smiley had appeared previously.

Central Executive. *Digit Span Backward*[#] indicated a relevant function of the central-executive working memory, more precisely the capacity to hold and manipulate phonological information. As in the Digit Span Forward, a sequence of acoustically presented digits were presented, but this time the child was required to recall them in reverse order immediately after presentation.

Corsi Block Backward[*#] was an estimator of the capacity to hold and manipulate visual-spatial information. On the lines of Corsi Block Forward, a smiley occurred serially in blocks, and the child was asked to tap the blocks in reverse order immediately after presentation. While Digit Span Backward is a frequently used measure, Corsi Block Backward is rarely conducted (like all other visual-spatial central-executive tasks). Vandierendonck, Kemps, Fastame, and Szmalec (2004) demonstrated the content validity of this backward span task and showed that central-executive as well as visual-spatial processing is needed during task procedure.

Procedures

Since autumn 2009, the children were invited into our labs to take part in five bi-annual working memory assessments, which were completed in spring 2012. Trained psychology students conducted the assessments. Data were collected when most of the children (49 of 56) attended the beginning and the end of fourth grade (time 1 and 2), the beginning and the end of fifth grade (time 3 and 4), and the beginning of sixth grade (time 5). Seven children attended one class above or below these grades. The assessments were administered individually. At time 1 we conducted four basic working memory subtests (Digit Span Forward, Matrix, Corsi Block Forward, and Digit Span Backward). Nonword Repetition and Corsi Block Backward were realized from time 2 on, and Articulation Rate assessment started at time 3.

Data analyses

Caused by late recruitment (i.e. late entry into the study) and drop out (i.e. early abandonment of participation), there were fewer than 28 children per group at every time of measurement. The exact group sizes are listed in Table 1 in the rows for age at times 1 to 5. There was 21% missing data in the control group's data set ($N_{T1\text{-}T5} = 111$) and 26% missing data in the literacy disorder group's data set ($N_{T1\text{-}T5} = 103$). These circumstances led us to apply statistical methods that analyze the data without loss of information. Thus, manifest multi-group models and full information maximum likelihood (FIML) estimation were used to analyze working memory functioning. The raw data were analyzed using Mplus 6.1 (Muthén & Muthén, 1998-2010). The stability of subtests is satisfactory in the majority of cases, but lower in the visual tasks (correlations for adjacent times of measurement: Digit Span Forward: $r = .58$ to .80; Nonword Repetition: $r = .48$ to .60; Articulation Rate: $r = .50$ to .59; Matrix: $r = .09$ to .52; Corsi Block Forward: $r = .22$ to .49; Digit Span Backward: $r = .42$ to .69; Corsi Block Backward: $r = .31$ to .53).

To examine differences between children with and without literacy disorders in working memory function, we used a manifest multigroup model for each subtest based on the mean raw scores of all times of measurement with conducted subtest assessments.

Reliability of the data increased by taking the mean raw scores. Furthermore, we applied manifest multigroup models per subtest and time of measurement for detecting change in group differences. The correlations between subtests are presented in Table 2. Subtests of one working memory component correlated in theoretical conformity. In addition and as expected, central-executive backward tasks correlated with forward tasks.

(Please insert Table 2 here)

Results

Table 3 displays the time averaged group mean differences per subtest. The group of literacy disordered children performed worse than the control group in all phonological and central-executive measures, as well as in the dynamic component of visual-spatial working memory (Corsi Block Forward) but not in the static visual-spatial component (Matrix).

(Please insert Table 3 here)

A closer look at the manifest group differences at single times of measurement revealed more about the development of functional strengths and deficits in working memory of children with literacy disorders (see Table 4). Since we measured working memory components up to five times, we were confronted with repeated measures and a cumulated alpha error. Therefore, we used the Bonferroni-Holm-method (Holm 1979) to correct the alpha error per subtest by reducing the global alpha level ($\alpha = .05$) proportionately to the number of retests per subtest.

The storage capacity of the phonological loop (Digit Span Forward) was reduced from the beginning to the end of assessments. There were trends for a reduced phonetic store measured by Nonword Repetition well into grade five (time 3), but the phonetic store progressed to develop so that the trend for this impairment disappeared. In contrast, Articulation Rate was not slowed at time 3, but the difference became statistically significant at times 4 and 5.

As already mentioned in the overall results presented in Table 3, children with literacy disorders did not show any deficits in static visual-spatial working memory (Matrix). Moreover, they even outperformed the control group at times 3 and 4 and their performance was superior by trend while the control group caught up at time 5. Unexpectedly, at the beginning of assessments (times 1 and 2), children with literacy disorders performed poorer on the dynamic visual-spatial task (Corsi Block Forward). This difference re-emerged strongly at the end of assessments (time 5).

The ability to manipulate phonological information (Digit Span Backward) was less developed in children with literacy disorders. The group difference reached significance at times 2 and 5, as well as at time 3 by trend. Under a dynamic visual-spatial condition (Corsi Block Backward), children with literacy disorders performed noticeably but non-significantly below the control group's level. This group difference increased over time and became statistically significant at time 5.

(Please insert Table 4 here)

Discussion

In the current study, the developmental trajectories of working memory subcomponents were investigated in children with literacy disorders compared to those without learning difficulties at the end of primary school and beyond. Storage and central-executive capacities were assessed regarding phonological and visual-spatial processing requirements at five bi-annual times of measurement in a three-year-longitudinal study.

The first aim was to determine which working memory functions are generally deficient in children with literacy disorders. To this end, we made group comparisons for each working memory task on the basis of time averaged mean raw scores. Control group children were shown to outperform those with literacy disorders in all subtests except the static visual-spatial storage task. Although we expected to find phonological storage and consequently central-executive impairments, the results went far beyond this: In addition to what we had expected, children with literacy disorders had problems of storing and manipulating dynamic visual-spatial information, too. On the other hand, there was not even a trend for static visual-spatial storage impairments. This visual working memory component was the only unimpaired working memory functioning aspect in time-averaged measures. At first sight the results seem to be in contrast to the findings by Schuchardt et al. (2008), who used similar tasks with reading disabled children. Even so, a closer look reveals commonalities: In both studies, phonological storage and also central-executive impairments, which might directly result from the reduced storage capacity, are reported. This is in line with the majority of studies in the field (e.g. Schuchardt et al., 2008; Smith-Spark & Fisk, 2007). However, whilst the current study reveals additional dynamic visual-spatial storage and central-executive impairments, the study by Schuchardt et al. (2008) does not. This is possibly due to different statistical methods: Schuchardt et al. (2008) used multiple analyses of variance (MANOVAs) and built one factor for the sketchpad, consisting of both tasks, Matrix and Corsi Block Forward, while we analyzed both tasks separately. Furthermore, a visual-spatial central-executive task was not used in the study of Schuchardt et al. (2008). Other studies that used visual-spatial storage and central-executive tasks have led to inconsistent findings. Our results are in line with studies that report phonological deficits in addition to visual-spatial storage limitations (Bayliss et al., 2005; Gathercole et al., 2005; Menghini et al., 2011) and central-executive impairments (Smith-Spark & Fisk, 2007; Swanson, 1999; Swanson et al., 1996). Especially the study of Menghini et al. (2011) depicted the difficulty children with reading disorder had with remembering moving visual-spatial information. However, the authors did not apply a static task to prove whether the disabled children's underperformance referred to a general visual-spatial working memory deficit or rather to one, which is specific for dynamic information.

The second main aim of the present study was to examine how these working memory deficits develop over time beginning at an age and grade when diagnostics have reached high levels of reliability. The findings indicated that the functioning of the phonological loop is impaired consistently between the ages of 9 and 12 years. This is in accordance with most cross-sectional findings of phonological storage impairments (e.g. Bayliss et al., 2005; Kibby et al., 2004; Schuchardt et al., 2008). However, the particular processes within the phonological loop that are deficient seem to change with age: At an earlier stage, the quality and length of the phonetic storage was reduced by trend, while the speed of the subvocal rehearsal process was slowed at later times of measurement.

Taking a look at the static visual-spatial storage capacity at single times of measurement, it became apparent that the performance of children with literacy disorders does not only remain intact, but there are also hints for strengths halfway through assessments or at the age of 11 years, respectively. This corresponds to some research speculating about compensational effects in the sense that the deficits in phonological information processing are balanced by strengths in the visual-spatial domain (e.g. Winner, French, Seliger, Ross, & Weber, 2001). This approach is based on the assumption that left-hemispheric deficits, leading to phonological impairments, accompany right-hemispheric strengths that are responsible for visual-spatial processes (see von Kàrolyi, Winner, Gray, & Sherman, 2003). However, most of the studies carried out to show a visual-spatial talent in children with literacy disorders failed and rather discovered inconspicuous levels of performance in disordered children (Brunswick, Martin, & Marzano, 2010) or even additional deficits in the visual-spatial domain (e.g. in mental rotation; Winner et al., 2001). To our knowledge, there are only two studies by von Kàrolyi (2001) and von Kàrolyi et al. (2003) documenting a specific kind of visual-spatial strength in the global visual-spatial task *Impossible Figures* in that children with reading disorders were faster than a control group and comparably accurate in the differentiation of possible from impossible three-dimensional figures. The *Impossible Figures* task requires children to inspect a figure globally, which is – perhaps in a less complex way – also the case in the Matrix task, used in the present study. Thus, the assumption by von Kàrolyi et al. (2003) of a specific strength in global inspection supports our findings that children with literacy disorders are not impaired and even talented in the recall of static visual-spatial information.

By contrast, the ability to store dynamic information is recurrently reduced from the beginning of assessments (except for times 3 and 4). Although this was not expected by our hypothesis, the results of the present study are somehow in line with the cross-sectional findings by Menghini et al. (2011) showing deficits of children with reading disorder in phonological as well as dynamic visual-spatial tasks. The authors suggested that the underlying cause of the overall deficit in children with dyslexia is a serial information processing deficit. Menghini et al. (2011) were not able to validate their assumption because of the lack of a static or global working memory task. Thus, if we use the results found here, the assumption of a serial information processing deficit can be supported: The children with literacy disorders had difficulties to store and manipulate phonological as well as dynamic visual-spatial information and therefor serial information, but they had no deficits in reproducing static visual-spatial and therefore global material.

Another explanation for the output deficits under dynamic visual-spatial condition is that central-executive capacities are probably involved in the rehearsal process of dynamic information during simple storage tasks (see Klauer & Stegmaier, 1997). In consequence, an impaired central executive working memory could also have led to a reduced dynamic visual-spatial storage capacity.

Looking at the development of central-executive functions, we expected to find a continuous central-executive disadvantage in phonologically based tasks. We know only one study that examined phonological central-executive impairments in children with reading disorder in different age groups, which showed that the impairments were stable (Siegel & Ryan, 1989). Our findings are in line with this and confirm our hypothesis: Manipulation of phonological material was impaired from the beginning until the end of assessments, although group differences missed to reach significance at three of five times probably as a consequence of insufficient statistical power.

On the contrary, in the visual-spatial domain we did not expect any storage impairment and consequently no central-executive impairments. Since we found an unexpected dynamic storage impairment, it seemed obvious that there was a limited dynamic central-executive performance, too. This was the case although the disadvantage in manipulating dynamic visual-spatial material increased with age until it was supported by a statistical significant result at the last time of measurement, when the children were nearly twelve years old. In sum, the central-executive disadvantage increased over time and comprised both modalities in the end.

Our results need to be treated with caution with regard to some limitations of our study in terms of design and procedure. First, longitudinal studies are confounded with an accumulated amount of practice as a consequence of repeated measurements. Thus, the increase of working memory capacity over time may be interpreted as a training effect rather than development. However, working memory is a very stable construct that is hardly influenced by training (see meta-analysis of Melby-Lervåg & Hulme, 2012). Second, we were confronted with small group sizes that consisted of diverse individuals at different times of measurement because of late recruitment and early drop-out. Moreover, our results refer to a mixed group of literacy disorders consisting of children with either a specific reading disorder, a specific spelling disorder, or a combined reading and spelling disorder. Although there are common aetiological factors underlying both reading and spelling disorders (Landerl & Moll, 2010), there are also hints that reading and spelling might require different working memory processes and that reading and spelling disorders come along with different impairments in working memory (Moll & Lander, 2009; Savage et al., 2007, p. 202). Based on these considerations, future studies on working memory functioning in children with literacy disorders might rather examine the subgroups separately.

Nevertheless, we can draw conclusions on the working memory functioning and its developmental trajectories in children with mixed literacy disorders and the results help to understand the underlying cognitive causes. Taken together, we found that the most consistent deficits in working memory of children with literacy disorders are related to the overall storage capacity of the phonological loop, whereas the basic impaired mechanisms, storage length and accuracy as well as rehearsal speed, seem to change over time. In addition, these phonological deficits also occurred under central-executive demands, and children with literacy disorders had a reduced dynamic visual-spatial storage and central-executive capacity. Thus, literacy disorders seem not only to be a matter of phonological information processing. As impairments concerned both modalities, widely accepted theories that emphasize phonological deficits solely (e.g. *phonological core deficit hypothesis;* Snowling, 1998; Stanovich, 1986; Stanovich & Siegel, 1994) cannot be supported by our findings. Instead, taken together the deficits indicate that children with literacy disorders suffer from additional central-executive impairments. These impairments might have led to difficulties in sustaining dynamic information. Furthermore, our results fit to the assumption of a serial information processing deficit (Menghini et al., 2011): Children with literacy disorders underperformed in all serial tasks, so that there might be a deficient basic, modality-unspecific process in working memory which might be responsible for the processing of serial information.

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Tables

Table 1

Means (*M*), standard deviations (*SD*) and subsample sizes (*n*) for the *T*-values of IQ-test, reading, spelling, and math achievement at first (A) and second (B) time of diagnostics as well as mean age in years at the five times of measurement (labeled T1 to T5) as a function of group (CG: control group; LD: group with literacy disorders)

	CG			LD		
	M	*SD*	*n*	*M*	*SD*	*n*
IQ A	56.48	8.94	27	55.70	7.42	27
Reading A	60.68	9.75	25	40.50**	7.62	24
Spelling A	57.81	10.25	26	36.00**	5.94	27
Math A	57.00	9.57	25	51.32*	6.29	19
IQ B	54.05	7.64	22	54.14	6.67	22
Reading B	56.50	8.53	22	38.00**	7.79	21
Spelling B	55.10	8.93	21	35.00**	6.07	20
Math B	49.30	9.70	23	48.19	8.05	21
Age T1	9.47	0.45	17	9.60	0.42	25
Age T2	10.18	0.45	18	10.28	0.42	26
Age T3	10.68	0.42	25	10.76	0.46	25
Age T4	11.26	0.43	22	11.18	0.31	20
Age T5	11.72	0.46	21	11.71	0.32	15

Note. Significant group differences:
* LD < CG; $p < .05$
** LD < CG; $p < .01$

Table 2

Intercorrelations of working memory subtests across all times of measurement

	1. DGF	2. NR	3. AR	4. MX	5. CBF	6. DSB	7. CBB
1. Digit Span Forward	1						
2. Nonword Repetition	.60**	1					
3. Articulation Rate	.29*	.17	1				
4. Matrix	.01	.07	0	1			
5. Corsi Block Forward	.19	.22	.06	.35**	1		
6. Digit Span Backward	.54**	.35**	0	.17	.16	1	
7. Corsi Block Backward	.13	.17	-.09	.34**	.56**	.39**	1

Note. Correlations are based on mean raw scores of all times (T) of measurement with conducted subtest assessments (DGF, MX, CBF, and DSB: T1-T5, NR and CBB: T2-T5, AR: T3-T5).

* Significant correlation ($p < .05$).
** Significant correlation ($p < .01$).