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small number system. Likewise, holding information in mind and manipulating that information, may on its own or combined with visual-spatial deficits also be at the root of the ability to solve number sense tasks (Dehaene, 2011; Geary et al., 2009). We speculate therefore that in these specific cases number sense may not normalize until their visual-spatial skills and working memory catch up. It may have consequences for treatment whether or not at the root of delays are visual-spatial and/or working memory deficits. Hence, more important than the putative category ‘dyscalculia’ is to specify underlying impairments.

**Future Directions**

The finding that the twins seem to manifest no processing difference in comparing magnitudes with different numerical distance, might point to a weakened parietal representation of non-symbolic magnitudes (Price et al., 2007). According to, for instance Wilson and Dehaene (2007) and Price et al. (2007), at least some children with serious math problems typically show less activation of the parietal cortex while comparing numbers. Likewise, the fMRI studies of Isaacs et al. (2001) and Clark and Woodward (2010) revealed that in children born preterm (in case of the twins at Gestational Age 27) and with calculation problems, grey matter may be reduced in the left intraparietal sulcus (IPS). The IPS is detectable in fetuses around GA (pregnancy week) 26-28. As the twins were born at GA 27, this may have affected prenatal brain development and the IPS in particular. There is also evidence from fMRI studies that during non-symbolic magnitude comparison, nonverbal visual-spatial cerebral networks are activated (Dehaene et al., 1999). As visual-spatial skills are undeveloped, atypical activation of nonverbal visual-spatial cerebral networks could be present in the twins (Clark and Woodward, 2010).

It is also possible that impaired neuronal networks might account for the twins’ severe number sense deficit (Kucian et al., 2006) as task performance is mostly dependent on the cooperation of diverse brain areas (Micheloyannis, Sakkalis, Vourkas, Stam, & Simos, 2005). A consolidated neuronal network is necessary when diverse brain areas are involved in task performance. Weaker activation of a network could be the result of non-reinforced synaptic connections due to lack of experience (Kucian et al., 2006), which is not very plausible here. Next to weak connections between brain areas, intraparietal disconnection after damage to a focal region of subcortical white matter might cause math problems (Rusconi et al., 2009; Sansavini et al., 2011). As a next step in analyzing the twins’ math problems it might make sense to test structural connectivity between brain areas.
The current study extended research on a set of interrelated cognitive processes that play a vital role in organizing and regulating information thereby affecting children's ability to take advantage of natural learning experiences and the school curriculum. Working memory, attention shifting, and inhibitory control problems – hereafter indicated as executive functions (EF) - may all underlie the organization and regulation of information in novel or challenging situations. The following four research questions were targeted in the current thesis:

1. Do EF skills interfere with benefiting from informal experiences that are known to stimulate early literacy development?
2. Do EF skills, beyond other basic learning skills such as visual-spatial development and speed of processing, explain why early literacy and early numeracy co-vary substantially?
3. Are EF skills causally related to early developing academic skills in the age range from preschool through first grade?
4. Can delays in EF skills play an important role in the development of severe delays in math development?

**Effects of EF on Academic Development**

A main conclusion of the current thesis is that effects of EF on academic skills in preschool and kindergarten are rather small; the studies revealed low to moderate correlations among attention control, inhibition, and short-term memory on the one hand and early numeracy and literacy skills on the other hand. In study 1 (chapter 2) correlations for instance ranged from \( r = .19 \) (inhibition and letter knowledge) to \( r = .43 \) (short-term memory and vocabulary). However, after controlling for parent print exposure, book reading frequency, book-cover recognition, and intelligence, only short-term memory remained a significant predictor of vocabulary. In the second study (chapter 3) neither attention control nor short-term memory explained overlap among early literacy and early numeracy skills, after taking into account effects of other learning skills (visual-spatial skills, speed of processing, shared storybook reading and vocabulary). EF skills thus seem less important for early academic development than is commonly claimed (Bodrova & Leong, 2006; Diamond & Lee, 2011; Duncan et al., 2007; McClelland et al., 2007; NICHD, 2003; Valiente et al., 2010; Welsh et al., 2010), and effects of EF skills on early academic skills decrease when other skills that may affect learning are controlled (Raghubar et al., 2010).

Another main conclusion is that short-term memory in preschool, as precursor of working memory in older children (Bull et al., 2008), was the strongest EF correlate of early academic skills. In the first study (chapter 2), only short-term memory predicted vocabulary over and above shared book reading and intelligence. When controlled for shared book reading and intelligence none of the EF skills predicted letter knowledge. Likewise, in the second study (chapter 3), short-term memory explained co-variance among early literacy and numeracy when we controlled for significant effects of visual-spatial skills, vocabulary, and phonological awareness. Effects of attention control became non-significant after the other covariates were taken into account. In the third study (chapter 4), changes in short-term memory predicted changes in math, reading, and writing development, whereas changes in inhibition were solely related to changes in literacy development. The twin study also revealed evidence for working memory as a cause of their number sense impairment: The twins performed poorly on two working memory tasks (digit span backwards and word span). Especially in the subitizing task, poor working memory may have influenced task performance, because objects were covered, added or removed (Dehaene, 2011). Even though in other number sense tasks (number line and magnitude comparison) stimuli remained present, these tasks also made an appeal to working memory skills because information had to be stored and manipulated (Geary et al., 2009). Apparently, holding information in mind is more important for developing early academic skills than attention and inhibitory control. One of the explanations could be that before and during preschool a child's attention is controlled by caregivers and teachers, whereas from Grade 1 and up children often do tasks independently (i.e., they listen to instructions and make a working plan without assistance). Tasks may then make a strong appeal to attention and inhibitory control.

In line with this reasoning, the first study for instance clearly demonstrated that preschool EF skills do not moderate effects of shared book reading on vocabulary and letter knowledge; notwithstanding children's EF skills, shared book reading was beneficial for early literacy development. Shared book reading might be an activity with lower demands on EF, because it is highly structured. During whole group instructions much more distracters are present, thereby making a stronger appeal to EF skills.

Contrary to previous studies suggesting that EF is stronger related to early numeracy than to early literacy (Blair & Razza, 2007; Duncan et al., 2007;...
McClelland et al., 2007), no differences in the strength of the effects of EF on numeracy and literacy development from preschool through first grade were found in the current thesis. Differences in measures may account for this apparent contradiction. In the meta-analysis of Duncan et al. (2007), for instance, questionnaires like the Child Behavior Checklist were used as indicator of attention control. Contrary to EF tests, questionnaires measure EF skills in real life situations which may reveal results that differ from clinical assessments of EF (Isquith, Crawford, Espy, & Gioia, 2005). More importantly, the age of the children in the meta-analysis was 5 or higher (Duncan et al., 2007), whereas in our studies the focus was on a younger age-range. Especially for more advanced math skills, EF skills such as attention and inhibition may be required (Assel, Landry, Swank, Smith, & Steelman, 2003).

Not EF Skills but Visual-Spatial Skills were the strongest Correlates of Academic Skills

Surprisingly not EF skills but visual-spatial skills were the strongest correlates of both early numeracy and early literacy in the second study (chapter 3). Likewise, the twin case study (chapter 5) highlighted the importance of visual-spatial skills for numeracy development, next to effects of working memory (Dehaene, 2011; Geary et al., 2009). The twins’ severe number sense impairment may be explained by an impairment in visual-spatial and working memory skills. Moreover, their irresponsiveness to a training in comparing amounts could be due to severely impaired visual-spatial skills and working memory, since comparing amounts strongly appeals to these skills (Dehaene et al., 1999; Gebuis & Reynvoet, 2012). In similar cases, it might therefore be useful to find out whether training of visual-spatial and memory skills may result in improvements in elementary numerical processing.

Why are visual-spatial skills so important for academic development? In the early years of life, visual-spatial abilities enable identifying and/or discriminating objects by their shape (i.e., a square versus a circle) (Ruff & Rothbart, 2001). As long as children cannot name letters and numbers, they are able to distinguish them by shape (Bull, Espy, & Wiebe, 2008; Dehaene, 2011). Also later on in numeracy and literacy development, visual-spatial abilities remain important. When linking numbers to quantities, visual-spatial skills enable visualizing amounts (Krajewski & Schneider, 2009). In the same vein, visual cues enable young children to familiarize with letter forms (Levy, Gong, Hessels, Evans, & Jared, 2006) which is a precursor for learning letters (Both-de Vries & Bus, 2014).

As the current thesis highlighted the importance of visual-spatial skills for academic development, it may be useful to investigate whether visual-spatial skills are underdeveloped when delays in early numeracy or literacy development are present.

Are EF Skills Causally Related to Academic Skills?

In this research, no effects of preschool EF on academic outcomes in Grade 1 were found (with the exception of the significant effect of preschool inhibition on Grade 1 reading). At an early age, EF skills may be rather variable and only into adulthood skills may become more stable (Davidson et al., 2006; Diamond, 2002). Children with early delays in EF may catch up during preschool and, consequently, may not experience any difficulties with learning to read and write as a result of delays in preschool EF skills. In other words, changes in EF skills may be better predictors of academic skills in Grade 1 than are one-time assessments.

Interestingly, the longitudinal study containing repeated measures for EF and academic skills (chapter 4), revealed that changes in EF from preschool to end of first grade (memory and inhibition) were significantly related to changes in academic skills over the same period (with the exception that changes in inhibition were not related to changes in math development). Relations were positive, indicating that growth in EF from preschool to first grade is causally related to growth in academic skills. The advantage of a Fixed Effect Analysis is that the analysis focuses on changes over time; effects of unmeasured time invariant covariates are thus taken into account, thereby strengthening inferences about causality. In simple regression analysis, it is impossible to control for all possible confounder variables, because many covariates that may cause spurious outcomes are unknown. It thus can be concluded that growth in the ability of maintaining and manipulating information in memory, and growth in the ability of ignoring distracters are causally related to growth in academic development (Diamond & Lee, 2011). In other words, it seems not possible to predict reading and math outcomes in Grade 1 from preschool EF skills, but growth in EF skills can predict academic development.

Maturation of the prefrontal cortex from preschool to Grade 1 might be one of the reasons why EF development is a more reliable predictor of academic
Chapter 6

General discussion

outcomes than are single measurements (Diamond, 2002). Another plausible hypothesis is that EF skills are implicitly trained when children practice numeracy and literacy skills at home or at school (Bodrova & Leong, 2007; Morgan-Borkowsky, 2012). Bodrova and Leong (2007), for instance, show how shared storybook reading can promote EF skills when caregivers set strict behavioral constraints: Children are for instance instructed to listen without interrupting the reader. By setting rules children practice how to suppress impulsive reactions.

Implications for the School Curriculum and Early Intervention Programs

Study 3 revealed that children's EF skills rapidly change during preschool and kindergarten (Davidson et al., 2006). Moreover, these changes may result in improvement in academic development. Whatever the explanation may be for these changes in EF, it seems questionable that early EF interventions are needed, because children often catch up as a result of maturation or activities in school and at home. Moreover, the effect sizes of preschool EF skills on early academic skills were rather small. This outcome thus challenges the need of explicit training of EF skills. Only if delays in EF persist, training might be useful and effective (Diamond & Lee, 2011).

Training working memory skills seems most useful, as working memory was in general the strongest correlate of early numeracy and literacy skills. In the long run, working memory was causally related to math, reading, and writing development, whereas inhibition was solely related to the literacy outcomes. Compared to inhibition, working memory thus seems to have a broader effect on academic development. There is some evidence that working memory can be enhanced at preschool-age by means of training (Thorrell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). There is however no consensus about positive transfer effects on for instance early academic skills. From a review of working memory training studies, Klingberg (2010) concludes that especially when delays in academic skills are present, training of working memory may be an effective remediation tool. Melby-Lervåg and Hulme (2013), by contrast, conclude in their recently published meta-analysis that effects of working memory training are only present over a short period of time. They found no transfer effects on early academic skills such as math and word decoding. These contradicting outcomes may be due to methodological differences: Outcomes of Melby-Lervåg and Hulme (2013) are based on a quantitative meta-analysis approach, whereas Klingberg (2010) only reviewed several experimental studies on working memory training, without applying statistical analyses. However, as most of the existing training studies are done with children older than 9 or with adults (Melby-Lervåg & Hulme, 2013), there is a clear need of experimental studies testing in primary school-age whether training of working memory can enhance performance in early academic skills.

Interestingly, early literacy and numeracy skills remained moderate to strong predictors of academic development when controlled for background variables, EF skills and other cognitive skills. Early intervention programs that aim to improve early numeracy (e.g., Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009; Siegler & Ramani, 2009) or early literacy skills (e.g., Van der Kooy-Hofland, Bus, & Roskos, 2011) are therefore indispensable for the prevention of learning impairments in Grade 1 and beyond. In the same vein, it is important that already early in the school curriculum teachers should pay attention to emerging literacy as well as to emerging numeracy skills, which is not commonly done: Compared to early literacy, less attention is paid to early numeracy skills in preschool and kindergarten (Ginsburg, Lee, & Boyd, 2008). The results of study 2 confirm that numeracy and literacy skills co-vary, which may imply that training of early literacy skills may promote early numeracy skills, and, vice versa, training of early numeracy may promote early literacy. This result also implies that it is important to monitor numeracy development when delays in literacy are apparent, and literacy development should be monitored when delays in numeracy are present.

Conclusions

The current thesis revealed that EF skills in preschool-age were not related to academic outcomes in Grade 1, and they only moderately predicted emerging academic skills in preschool. However, the finding that changes in EF skills relate to changes in academic skills supports the hypothesis that EF is causally related to academic development. These findings thus imply that children's improvement in academic skills partly depends on improvement in executive functions. It is however still unknown whether executive functions develop independently of academic skills or as intrinsic elements of literacy and numeracy development. We hypothesize that children with delays in EF are able to catch up due to maturation, home, and school influences.
Secondly, effects of early EF on early academic skills were not only small, but also differential; effects of short-term memory, attention, and inhibitory control on early academic skills differed. Short-term memory appeared to be the strongest EF predictor for both literacy and numeracy.

Overall, the findings of this series of studies show that EF is at best one of many factors that explain academic development. Early academic skills were much stronger predictors of academic development than were EF skills. After controlling for early EF and other background variables, early academic skills remained moderately strong predictors of academic outcomes in Grade 1. Compared to other basic cognitive skills, EF skills were rather weak predictors of academic development. In particular visual-spatial skills appeared to be much better predictors of early literacy and numeracy development compared to the effects of EF skills.

The current thesis thus challenges the general assumption that delays in early academic skills can be explained by early EF skills (Espy et al., 2004; McClelland et al., 2007; Welsh et al., 2010). In fact, EF skills may be less vital for explaining delays in early academic skills than is commonly assumed. However, the fact that growth in EF is related to growth in academic skills makes plausible that EF in addition to numerous other variables is a causal factor.

**Future Directions**

The EF measures applied in the current study all target specific EF skills, referred to as *situationally constrained processes* (Isquith et al., 2005). These tests assess executive functions in a more clinical setting and do not assess executive behaviour in real-life situations such as executing tasks in the classroom. Assessments such as the BRIEF (Behavior Rating Inventory of Executive Function) may give more specific information about a child’s self-regulatory behaviour at home or in school (Isquith et al., 2005). Using both types of instruments may give a more valid indicator of regulatory behaviour in all kinds of situations.

Secondly, there is a need of more experimental research in the domain of academic development. One of the results was that early numeracy and early literacy skills co-vary substantially. In line with this outcome, intervention studies could test whether training of literacy skills may also lead to improvements in numeracy skills, and, vice versa, whether training of numeracy may lead to improvement in literacy.

Effect studies should also test whether training of early academic skills positively affects EF development, and, vice versa, whether training of EF is beneficial for academic development. It should be taken into account that transfer effects may be small and specific, especially because the strength of the relation among EF and academic skills differed by the sub-skills measured. In other words, training specific early numeracy or literacy skills may only lead to small improvements in certain sub-EF skills.

Finally, the importance of visual-spatial skills for academic development should be further explored. Visual-spatial skills can be trained (Mathewson, 1999), but it is unclear whether training of visual-spatial skills also leads to improvements in numeracy and literacy.