Research Reports

How Do Different Aspects of Spatial Skills Relate to Early Arithmetic and Number Line Estimation?

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Abstract

The present study investigated the predictive role of spatial skills for arithmetic and number line estimation in kindergarten children (N = 125). Spatial skills are known to be related to mathematical development, but due to the construct's non-unitary nature, different aspects of spatial skills need to be differentiated. In the present study, a spatial orientation task, a spatial visualization task and visuo-motor integration task were administered to assess three different aspects of spatial skills. Furthermore, we assessed counting abilities, knowledge of Arabic numerals, quantitative knowledge, as well as verbal working memory and verbal intelligence in kindergarten. Four months later, the same children performed an arithmetic and a number line estimation task to evaluate how the abilities measured at Time 1 predicted early mathematics outcomes. Hierarchical regression analysis revealed that children's performance in arithmetic was predicted by their performance on the spatial orientation and visuo-motor integration task, as well as their knowledge of the Arabic numerals. Performance in number line estimation was significantly predicted by the children's spatial orientation performance. Our findings emphasize the role of spatial skills, notably spatial orientation, in mathematical development. The relation between spatial orientation and arithmetic was partially mediated by the number line estimation task. Our results further show that some aspects of spatial skills might be more predictive of mathematical development than others, underlining the importance to differentiate within the construct of spatial skills when it comes to understanding numerical development.

Keywords: spatial skills, early mathematics development, kindergarten, arithmetic, number line estimation

The acquisition of early numerical abilities in kindergarten is important for later mathematical learning, school achievement and more general life outcomes such as adult socioeconomic status (Ritchie & Bates, 2013). School entry mathematical skills are strongly predictive of later academic achievement, resulting in a need to gain a more profound understanding of the processes and cognitive abilities underlying early mathematical development. This need is further underlined by the fact that children who lag behind their peers in school entry mathematical skills, are at high risk to do so throughout schooling (e.g. Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Kolkman, Kroesbergen, & Leseman, 2013; Krajewski & Schneider, 2009; Ramani & Siegler, 2014). A profound knowledge and understanding of the

cognitive precursors for later mathematical learning is crucial for developing effective intervention programs. The development of evidence-based early interventions should allow fostering these precursor skills before children enter formal schooling, and thus provide them with a sound foundation for later mathematical learning.

Domain-Specific and Domain-General Abilities

In the context of numerical development, domain-specific and domain-general abilities can be distinguished.

Basic numerical abilities such as quantitative knowledge, counting abilities and numeral knowledge are considered as domain-specific precursors of mathematical abilities. The pivotal role of these number-specific abilities has been shown across different studies (e.g. Geary, Hoard, & Hamson, 1999; Hannula-Sormunen, Lehtinen, & Räsänen, 2015; Hornung et al., 2014; Passolunghi & Lanfranchi, 2012). Their importance is further reflected in the assumption, that mathematical skills develop along a learning trajectory, with later mathematics skills building up on skills acquired earlier (Clements & Sarama, 2010). This explains the persistence of difficulties in mathematics and importance to gain a profound understanding of early mathematical development in order to tackle early deficits in mathematics to counteract their eventual persistence (Simon & Tzur, 2004).

Development of numerical cognition occurs, according to Von Aster and Shalev (2007), in a quasi-hierarchical manner. They suggest a four-step developmental model of numerical cognition integrating four basic numerical competencies. The first step are non-symbolic and quantitative core systems of magnitude that are already present in infants (see also F. Xu, Spelke, & Goddard, 2005). Two core systems of numbers can be distinguished: one system allows for the approximate discrimination of large quantities, whereas the other system allows for the exact discrimination of small numerosities up to 4 (Feigenson, Dehaene, & Spelke, 2004). Both core systems are commonly assumed to serve as a foundation for more sophisticated numerical representations (Feigenson et al., 2004). The second developmental step is the knowledge about the verbal number system, which is specifically related to the development of counting abilities (see also Fuson, 1988). The third developmental step encompasses the knowledge of the Arabic number system (also see Knudsen et al., 2015 for recent research on the development of Arabic digit knowledge in the early years). The development of the mental number line is the fourth developmental step. This fourth step includes the representation of the ordinal position of numbers. Number-specific abilities encompass thus the development of non-symbolic (Step 1) and symbolic number knowledge (Steps 2 to 4).

Domain-general abilities are non-mathematical factors contributing to mathematical development. Prior research emphasizes the role of language (e.g. Alloway & Passolunghi, 2011; Kleemans, Segers, & Verhoeven, 2011; Krajewski & Schneider, 2009; LeFevre et al., 2010; Noël, 2009; Passolunghi, Vercelloni, & Schadee, 2007; Purpura & Ganley, 2014; Purpura & Reid, 2016; Zuber, Pixner, Moeller, & Nuerk, 2009), general intelligence (Deary, Strand, Smith, & Fernandes, 2007), verbal and visuo-spatial working memory (Holmes, Adams, & Hamilton, 2008; Hornung et al., 2014; Nath & Szücs, 2014; Szücs, Devine, Soltesz, Nobes, & Gabriel, 2013), and executive functions (Bull, Johnston, & Roy, 1999; Cameron et al., 2012; Clements & Sarama, 2015; Cragg & Gilmore, 2014; Szücs, Devine, Soltesz, Nobes, & Gabriel, 2014; Van de Weijer-Bergsma, Kroesbergen, & Van Luit, 2015) for mathematical development.

Besides the afore-mentioned factors, the literature suggests that *spatial skills* is another construct that should be considered when investigating numerical development.

Spatial Skills

Spatial skills play a special role in mathematical development and a clear classification, as either domain-general or domain-specific abilities, is not straightforward. As spatial skills do not a have a numerical component per se, they could be considered as domain-general abilities. On the other hand, the relation between spatial skills and mathematics has been shown to hold throughout development (for a review see Mix & Cheng, 2012). Therefore, Mix and Cheng (2012) argue that spatial skills are more specifically related to mathematics than other domain-general skills such as language or working memory. Similarly, Verdine, Golinkoff, Hirsh-Pasek, Newcombe, et al. (2014) state that "visual-spatial skills and mathematics, traditionally taught separately, regularly call on a shared set of foundational skills and may have a significant amount of overlap" (p. 1064).

Definition and Terminology

Providing a concise definition of spatial skills is particularly challenging as it is not a unified construct and rarely a precise definition is provided. Studies investigating the same underlying construct of spatial skills differ with regard to the term they use, even when using the same assessment tasks. Terms such as "visuo-spatial abilities", "visual perception" and "spatial skills" are often used interchangeably (e.g. Carroll, 1993; Casey et al., 2015; Chabani & Hommel, 2014; Gunderson, Ramirez, Beilock, & Levine, 2012; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014; Zhang et al., 2014). As the more recent literature tends to use "spatial skills", we will use this term throughout the present paper.

On a general level, Linn and Petersen (1985, p. 1482) define spatial skills as "skills in representing, transforming, generating, and recalling symbolic, non-linguistic information". To add precision to this general definition, Linn and Petersen (1985) classified spatial skills into three broad categories: a) spatial perception, b) mental rotation and c) spatial visualization. Spatial perception is the ability to perceive spatial relationships with respect to the orientation of one's own body in the presence of distracting information. Mental rotation refers to an individual's ability, to rotate two- or three-dimensional figures internally (i.e. *mentally*). Spatial visualization refers to spatial tasks requiring more complicated and multistep manipulations of the presented information. These tasks can integrate aspects of the two first categories, with the main difference being the potential multiple solution strategies. While other classifications of spatial skills have been suggested (Carroll, 1993; Newcombe & Shipley, 2015; Uttal et al., 2013), the classification suggested by Linn and Petersen (1985) has remained very influential and is used as a framework in studies similar to the present study (Zhang et al., 2014; Zhang & Lin, 2015).

Considering the development of spatial skills in early childhood, the importance of a related ability arises: visuo-motor integration (VMI). The main distinction between VMI and the three spatial categories defined by Linn and Petersen (1985) is the motor component. Classically, tasks of spatial perception, mental rotation and spatial visualization, require the treatment of visual information, while tasks of VMI involve the coordination between the treatment of visual input and motor output (Cameron et al., 2015). Empirical research on the relation between mathematics and spatial skills suggests considering VMI when studying this relationship in young children (Carlson, Rowe, & Curby, 2013; Pieters, Desoete, Roeyers, Vanderswalmen, & Van Waelvelde, 2012; Pitchford, Papini, Outhwaite, & Gulliford, 2016; Sortor & Kulp, 2003). In the following, VMI will be considered as an aspect of spatial skills (in line with Frostig, Lefever, & Whittlesey, 1961).

Link Between Spatial Skills and Early Mathematics

The relation between spatial skills and mathematics is generally considerd as "(…) one of the most robust and well-established findings in cognitive psychology" (Mix & Cheng, 2012, p. 198).

An influential research strand, studying the link between spatial skills and mathematics, focuses on the systematic interaction between space encoding and numbers in adults. This interaction is commonly explained through the spatial organization of numerical magnitude on a mental number line (Dehaene, Bossini, & Giraux, 1993). A strong interaction between space encoding and number processing is suggested by brain imaging studies (Cutini, Scarpa, Scatturin, Dell'Acqua, & Zorzi, 2014; Göbel, Calabria, Farnè, & Rossetti, 2006; Goffaux, Martin, Dormal, Goebel, & Schiltz, 2012; Ranzini, Dehaene, Piazza, & Hubbard, 2009) and behavioural studies (Dehaene et al., 1993; Hoffmann, Mussolin, Martin, & Schiltz, 2014; Nuerk, Wood, & Willmes, 2005). In recent years, this interaction has also been investigated in young children, prior formal schooling (de Hevia & Spelke, 2009; Hoffmann, Hornung, Martin, & Schiltz, 2013; Patro, Fischer, Nuerk, & Cress, 2016; Patro & Haman, 2012; Patro, Nuerk, Cress, & Haman, 2014).

Another strand of research, within the broad research area investigating the relation between spatial skills and mathematics, is focusing on "pure" spatial skills: spatial skills without a numerical component (e.g. mental rotation abilities, mental paper folding etc.) (see Linn & Petersen, 1985). It is commonly assumed, that pure spatial skills in young children provide a foundation for later mathematical learning (Ansari et al., 2003; Assel, Landry, Swank, Smith, & Steelman, 2003; Casey et al., 2015; Casey, Dearing, Dulaney, Heyman, & Springer, 2014; Kurdek & Sinclair, 2001; Lachance & Mazzocco, 2006; Verdine, Golinkoff, et al., 2014; Verdine, Irwin, et al., 2014; Zhang et al., 2014; Zhang & Lin, 2015). A closer look at these studies reveals an important issue: even though the researchers conclude that spatial skills are predictive of mathematical achievement, respective studies largely differ with regard to the measure of spatial skills they used. This could potentially be ascribed to the multifaceted nature of the concept of spatial skills.

One approach to assess children's spatial skills is by using assembly and pattern construction tasks. Ansari et al. (2003) used a pattern construction task to assess spatial skills and found a relation to children's understanding of cardinality. Verdine et al. (Verdine, Golinkoff, et al., 2014; Verdine, Irwin, et al., 2014) used a specifically designed spatial assembly task with three year olds. Performance on this task predicted performance on a preschool math achievement task administered concurrently (Verdine, Golinkoff, et al., 2014) and one year later (Verdine, Irwin, et al., 2014). As spatial assembly and pattern construction tasks require multistep solution strategies, they can be categorized as tasks of *spatial visualization* (as suggested by Linn & Petersen, 1985). A relation between *spatial visualization* and arithmetic through first and third grade could also be established using mental transformation tasks (Gunderson et al., 2012; Zhang et al., 2014). Other studies highlighted the predictive role of *spatial perception* for early arithmetic (Zhang & Lin, 2015) and early number competence (Zhang, 2016). And yet another set of experiments focused majorly on *mental rotation*. In that vein, Skagerlund and Träff (2016) found that school-aged children's mental rotation ability predicted overall math ability, and performance on arithmetic equations specifically. Moreover, the influence of early VMI for later academic achievement has been empirically supported (Becker, Miao, Duncan, & McClelland, 2014; Cameron et al., 2012, 2015; Carlson, Rowe, & Curby, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). Studies considering VMI and non-motor spatial skills concurrently report that both constructs are associated with and/or are predictive of better performance in mathematics (Carlson et al., 2013; Pieters et al., 2012; Pitchford et al., 2016; Sortor & Kulp, 2003).

Taking these findings together, spatial skills and VMI should both be considered when investigating the predictive value of spatial skills for mathematical learning (see also LeFevre et al., 2013). In sum, an important role can be ascribed to children's spatial skills for early mathematics, but findings on the differential relations between different aspects of spatial skills and different facets of early mathematics prior formal schooling are still scarce.

Nature of the Link Between Spatial Skills and Mathematics in Children

One explanation *why* spatial skills and mathematics are interlinked in children is the assumption that mental number models are based on spatial representations, the so-called mental number line. Children who develop a better spatial representation of number should be able to build on this knowledge when learning further numerical concepts (Booth & Siegler, 2008). In this vein, Gunderson, Ramirez, Beilock, and Levine (2012) found that children's spatial skills at the beginning of 1st and 2nd grade are predictive of their improvement in number line knowledge over the school year. Children's mental transformation skills at age five predicted their performance on an approximate calculation task at age eight. Moreover, they found that children's linear number line knowledge at age six mediated this relation. Zhang et al. (2014) observed that the associations between spatial visualization, assessed with a mental transformation task, and arithmetic were mediated by children's backward counting abilities (but not forward counting). The authors explain this finding by the mental number line. Forward counting should rely mostly on linguistic information that can be recalled from verbal memory, whereas backward counting requires the manipulation of the number sequence. To successfully manipulate the number sequence, visualization of the number line should be required.

A further tentative explanation why spatial skills and mathematics are related, is based on the findings that mental rotation positively influences children's performance on equations or missing term problems (Cheng & Mix, 2014; Skagerlund & Träff, 2016). Here, it is assumed that children with better spatial skills can use these skills to visualize the mathematical problem and move the operands of the problem mentally (e.g. transforming "3 + x = 5" into "5 – 3 = x"). Such a mental representation of the mathematical problem should facilitate the problem solution. Zhang and Lin (2015) support this hypothesis by reporting a positive influence of kindergarteners spatial perception, assessed by a spatial orientation task, on performance in arithmetic one year later, which they explain by a positive relation between children's spatial perception and their ability to mentally represent mathematical problems. According to these three research groups (Cheng & Mix, 2014; Skagerlund & Träff, 2016; Zhang & Lin, 2015), better spatial skills allow for a better visualization of the respective mathematical problems, which should facilitate problem solving and increase performance.

Whereas all of the studies cited up to now are correlational in nature, first attempts have been made to determine whether training spatial skills has a direct impact on mathematics. If spatial training would prove to transfer to mathematics, this would support the assumption that spatial skills have a causal role in mathematical development. Up to now, data on this topic remains inconclusive. Cheng and Mix (2014) trained children on a mental rotation task. They observed direct transfer to an arithmetic task, namely missing term problems. Other researchers who trained children on mental rotation (Hawes, Moss, Caswell, & Poliszczuk, 2015) or spatial transformation (C. Xu & LeFevre, 2016) however failed to replicate these findings. The latter studies did not observe any transfer from spatial training to performance in mathematics, even though near transfer on the trained spatial task was observed in both studies.

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When studying the role of different aspects of spatial skills for mathematical learning, it is important to keep in mind that spatial skills and mathematics are both multifaceted. In view of the componential nature of mathematics, different spatial skills might only relate to specific aspects of mathematics and not to other aspects (Cragg & Gilmore, 2014).

To investigate the relation between spatial skills and mathematics, it is not sufficient to identify the relevant spatial predictors of mathematics. The choice of measures of mathematical knowledge with regard to its componential nature, also needs to be critically reflected. Due to the componential nature of spatial skills and mathematics, certain spatial skills might relate differentially to certain components of mathematics. A profound understanding of the aspects of spatial skills that are primarily related to mathematical development would provide vital information for early education. This knowledge will provide researchers, teachers and educators with valuable information for the development and implementation of early interventions.

The Present Study

There is currently a shortcoming of empirical data on the differential relation between distinct aspects of spatial skills and early mathematics. Our aim was to investigate the relation between three different spatial tasks and two measures of early mathematics when taking number-specific and domain-general abilities into account. The predictive power of a specific aspect of spatial perception (namely *spatial orientation*), spatial visualization (assessed with a mental transformation task) and VMI (assessed with a design-copy task) for performance in early arithmetic and number line estimation four months later was investigated. The concurrent consideration of different spatial tasks should allow us to gain further insights into the importance of spatial skills for early mathematical development. In addition, the influence of basic number-specific abilities such as quantitative knowledge, counting and Arabic numeral knowledge was considered concurrently. This should allow us to understand if and how performance on different spatial tasks can predict early mathematics over and above number-specific abilities. Different measures of spatial skills and early mathematics were administered. Spatial measures were labelled according to the aspect of spatial skills they are most likely to tap into. As such our measures do not reflect whole spatial categories and it is important to bear in mind that this use of single measures impacts construct validity. To fully establish construct validity, at least two measures per construct are required to compute correlations between measures as an indicator. The present study is a first attempt to explore the role of different aspects of spatial and number-specific skills for mathematical development and our results thus provide first indications about potentially important aspects. To assess early mathematical abilities, we chose arithmetic and number line estimation. *Arithmetic* performance requires the mastering of different aspects of early mathematical development (Butterworth, 2005). For instance, Stock, Desoete, and Roeyers (2009b) consider procedural and conceptual counting knowledge in kindergarten as "preparatory arithmetic abilities" for arithmetic abilities in first and second grade. The *number line estimation* task is a classical measure of a more advanced number knowledge (e.g. Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; LeFevre et al., 2013; Siegler & Booth, 2004; Simms, Clayton, Cragg, Gilmore, & Johnson, 2016; C. Xu & LeFevre, 2016). It is currently debated whether number line estimation tasks tap into children's internal number representation (the mental number line), or whether it reflects proportion judgement strategies (see Dackermann, Huber, Bahnmueller, Nuerk, & Moeller, 2015 for a review on this topic). Nevertheless, performance on the number line estimation task has been consistently related to later mathematical achievement making it a relevant measure of mathematical development (Ashcraft & Moore, 2012; Booth & Siegler, 2008; Friso-van den Bos et al., 2015; LeFevre et al., 2013; Siegler & Opfer, 2003; Simms et al., 2016).

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To evaluate the specific relation between spatial skills and early mathematic knowledge, we included further variables that are potentially predictive of early mathematics. Adding measures of verbal short-term memory and verbal intelligence, should allow us to disentangle the relation between different aspects of spatial skills and different aspects of early mathematics while controlling for the influence of other domain-general abilities. Parent's occupational status, school affiliation, children's age in months and gender were considered as control variables (see also Jordan et al., 2009; Zhang & Lin, 2015).

Considering the heterogeneity regarding the operationalization of spatial skills throughout different studies, the present study was mainly exploratory concerning the relation between different spatial tasks and different aspects of early mathematics.

First, we attempted to determine the predictive power of three spatial tasks respectively, namely spatial orientation, spatial visualization and VMI, for early mathematics when being considered concurrently. The current state of research does not allow us to formulate any precise hypotheses, about the importance of one specific spatial aspect over the other, as most studies considered these aspects isolated from each other. Nevertheless, considering recent literature on the importance of spatial skills for early mathematics in the preschool years, we hypothesized, according to Zhang and Lin (2015), that spatial orientation, rather than spatial visualization, should predict arithmetic and number line estimation. We were particularly interested in studying the role of spatial skills for early mathematics when being considered concurrently with number-specific abilities. The concurrent consideration of different aspects of spatial skills and different aspects of early mathematics should expand our understanding of the role of spatial skills in numerical development. We hypothesized that spatial skills should predict arithmetic and number line estimation, over and above domain-general and number-specific abilities.

In a second step we attempted to elucidate the nature of the relation between spatial skills and early mathematics more thoroughly. One explanation for the relationship between spatial skills and mathematics in children is that better spatial skills lead to a more refined representation of the mental number line, which in turn should lead to better performance in mathematics (Booth & Siegler, 2008; Gunderson et al., 2012). On the other hand, researchers report a beneficial influence of good spatial skills on arithmetic, which can be explained through a better visualization of the mathematical problem (Cheng & Mix, 2014; Skagerlund & Träff, 2016; Zhang & Lin, 2015). To gain further knowledge on this topic we performed a mediation analysis analysing if number line estimation mediates the relation between spatial skills and arithmetic. This mediation analysis was run for the spatial tasks predicting both outcome measures. If the relation between spatial skills and arithmetic were mediated by number line estimation, this would account for the assumption that better spatial skills go along with a better spatial representation of the mental number line.

Method

Participants

Data were collected in two public kindergartens in Luxembourg. Children from ten different classrooms participated in the present study. In Luxembourg, children visit kindergarten for two years, when they are between four and six years old. Formal structured mathematics instruction in the Luxembourgish schooling system starts after kindergarten, when children enter first grade. A total sample of *N* = 125 children (61 girls)

with a mean age of 5.49 years (*SD*age = .63) was recruited. Children were from diverse language backgrounds, 53.8% were native Luxembourgish speakers, and the other 46.2% had different first languages (mainly Portuguese and French). Fifty-nine children were in the first year of kindergarten; the other 66 children were in the second year of kindergarten. All children were fluent in the language of instruction.

Children's socio-economic and cultural background was measured by a parental questionnaire adapted from Martin, Ugen, and Fischbach (2013). Parents' occupational level was operationalized through the International Standard Classification of Occupation (ISCO, Ganzeboom & Treiman, 1996) and the corresponding International Socio-Economic Index of Occupational Status (ISEI). The exact ISEI values were based on the data from the Luxembourgish PISA study (EMACS, 2012). Data were collected from the mother and the father respectively, but for further analyses a family index was computed by considering the highest value out of the two. For more detailed information on the occupational level please refer to Appendix A.

Materials and Procedure

Children were tested in a quiet place in their school building during regular school hours. Assessment took place at two measurement time points, in the middle of the school year (t1) and four months later, at the end of the school year (t2). Tasks were administered in two separate testing sessions of approximately 20 minutes. Task administration, within a testing session, occurred in fixed order. All the tests were administered in Luxembourgish, the language of instruction. Data collection was carried out in the context of a larger research project, in which additional measures have been administered during both sessions at both measurement time points. For the purpose of the present study, only a part of the tasks administered at the two measurement time points will be considered. The relevant measures of the present study are described in the following section.

Parents or caregivers gave their informed written consent and children gave their verbal assent for their participation in the present study. The study was authorized by the Ethics Review Panel of the University of Luxembourg.

Measures Administered at t1

Three different measures of spatial skills and number-specific abilities, respectively, were administered. Further, brief measures of verbal short-term storage and intelligence were included. No feedback was provided on any of the test items.

Measures of Spatial Skills

Spatial orientation — The measure of spatial orientation was adapted from the subtest "position in space" of the developmental test of visual perception (Frostig, 1973). It is a motor-free assessment of spatial orientation. The tasks did not require any mental transformations or manipulations. This measure can thus be classified, according to the classification of spatial skills by Linn and Petersen (1985) and Newcombe and Shipley (2015), as a test of spatial perception. A similar task has been used by Zhang and Lin (2015)[i]. The test consisted of eight items in total. The first part of this measure (Items 1 to 4) is an "odd one out" task requiring children to detect one picture out of five pictures that is different (a rotated version of the other four pictures). The second part (Item 5 to 8) is a "matching" task requiring children to find the picture out of four similar, but mirror reversed or rotated, pictures that matches the target picture. A sample item for each part is provided in Figure 1a and

Figure 1b. No discontinuation criterion was applied. Scoring was 1 point for a correct answer, and 0 for a wrong answer. The maximum score was 8. Cronbach's alpha was α = .68.

Spatial visualization — Spatial visualization was assessed by a mental transformation task. A shortened 12-item version of the Children's Mental Transformation Task (CMTT; Levine, Huttenlocher, Taylor, & Langrock, 1999) was used. Tasks of mental transformation fit into the category of spatial visualization (Linn & Petersen, 1985; Newcombe & Shipley, 2015). Mental transformations were all in picture-plane. Two separate pieces of a shape and four complete shapes were presented. Children were asked what shape they would get when putting the two pieces together. They gave their response by pointing at one out of the four shapes. A sample item is provided in Figure 1c. Half of the items required mental rotation, the other half required mental translation of the pieces. Each correctly solved item yielded 1 point for a maximum score of 12. Cronbach's alpha for this shortened version was α = .69.

Visuo-motor integration — The measure of VMI was adapted from the "spatial relations" subtest of the developmental test of visual perception (Frostig, 1973). This measure is a design copy task consisting of seven items. For every item, a line combination is presented in a dotted grid on the left side of a Din A4 sheet. For Items 1 to 6, two items per sheet were presented. Item 7 was presented on a separate sheet. Children were instructed to copy the drawing presented on the left side into an empty dotted grid on the right side of the sheet. The difficulty level increased throughout the task with the grid size and the number of lines increasing. A sample item is provided in Figure 1d. Scoring was 1 point per item that has been copied correctly, and 0 for a wrong answer. Testing was discontinued after two consecutive wrong reproductions and the remaining items were scored with 0. The maximum score that could be obtained on this task was 7. Cronbach's alpha was α = .85.
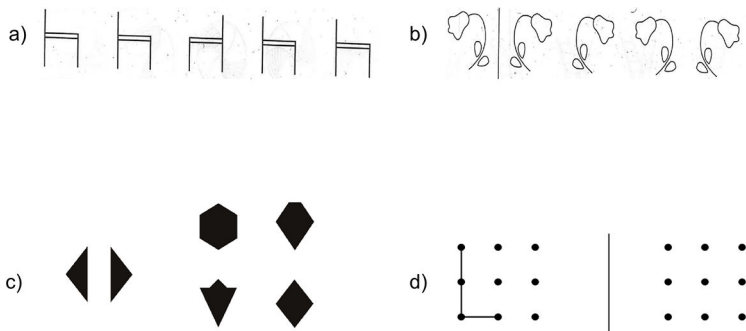
Figure 1. Sample Items of the a) First and the b) Second Part of the Spatial Orientation Task, c) the Spatial Visualization Task and the d) Task of Visuo-Motor Integration. (Figure 1a and 1b reprinted from "Test de développement de la perception visuelle", by M. Frostig, 1973. Copyright 1973 by Les Editions du Centre de Psychologie Appliquée).

Quantitative Knowledge

To assess children's quantitative knowledge, the first step in the developmental model of Von Aster and Shalev (2007), we used the non-symbolic dot comparison task of the Panamath software (Halberda, Mazzocco, & Feigenson, 2008). The task is a classical computer-based dot-comparison task. Children's performance was measured by the Weber fraction (*w*). A detailed description of the test administration can be retrieved from Appendix B.

Counting Abilities

Children's counting abilities were assessed through five brief counting and cardinality tasks: a free counting task, a "how many" task, a "give a number" task, a backward counting task and a forward counting task. In the free counting task, children were instructed to count as high as possible, starting at 1, thus reflecting children's knowledge of the verbal number chain. Each child had two attempts, the best out of these two attempts was considered for analysis. Children were stopped when they could count up to 30. When children could not count up to 10, the scoring for this task was 0, for counting up to a number between 10 and 14 they were awarded 1 point, for counting up to 15 – 19 they were awarded 2 points, between 20 – 29 they were awarded 3 points and counting up to 30 was scored as 4 points on this task. In the "how many task", the experimenter laid out a given number of marbles in front of the child and the child was asked to tell the experimenter how many marbles there were in total. The number of marbles for these trials were: 4, 5 and 7 respectively. Correct answers were coded as 1, wrong answers as 0. Answers were considered correct if children counted out the marbles correctly or gave the cardinal answer correctly. In the "give a number" task, children were instructed to hand the verbally requested number of marbles to the experimenter. Children were given 12 marbles in total. They were instructed to give the requested number of marbles to the experimenter. The numbers requested in these trials were 3, 5 and 10 respectively. Correct answers were coded as 1, wrong answers as 0. In the backward counting task children were given three test trials with starting points at 4, 6 and 10 and they were instructed to count back to 1. In the forward counting task children were asked to count forward from a given number. This task consisted of two trials with starting points at 3 and 5. Children were stopped when they counted correctly for subsequent numbers. For each task, correct answers were coded as 1, wrong answers as 0. A total score was calculated. The maximum score that could be reached on this scale was 15. Cronbach's alpha was α = .82.

Knowledge of Arabic Numerals

Children's symbolic knowledge of Arabic numerals was assessed through a number comparison task and a number naming task. The *number comparison task* was adapted from the TEDI-Math test battery (van Nieuwenhoven, Grégoire, & Noël, 2001). Four additional items were added to the adapted version, two items of single-digit comparisons and two items of two-digit number comparisons making a total of ten test trials. Children were presented with two numbers printed on a DIN A4 sheet. They had to judge which out of the two numbers is larger in numerosity. The response was given by pointing to the numeral children considered as the larger one. One practice item preceded the test items. Each correct answer was coded as 1, wrong answers as 0. In the *number naming task* children were presented with Arabic numerals from 1 to 10 ordered quasi-randomly on a DIN A4 sheet. They were instructed to name the numerals. Each correctly named numeral was coded as 1, wrong answers as 0. The maximum score that could be reached on the scale "knowledge of Arabic numerals" was 20. Cronbach's alpha for this scale was α = .86.

Verbal Short-Term Memory (STM)

In addition to measures of spatial skills and early mathematics, the ordered digit span task ("*Hamburg-Wechsler-Intelligenztest für Kinder III*"; Tewes, Rossmann, & Schallberger, 1999) was administered to assess children's capacity of verbal STM. In the digit span task, children have to recall a list of single digits presented at a 1 second interval in the same order immediately after presentation by the experimenter. The task starts with two trials of two digits. Two sequences were presented per span. The task was stopped when children

failed to recall the two sequences of one span. Reliability for this subtest is reported by the authors of the test as ranging between .75 and .86.

Verbal Intelligence

To assess children's verbal intelligence, we administered the information subtest from the French version of the *Wechsler Preschool and Primary Scale of Intelligence – III* ("*Echelle d'intelligence de Wechsler pour la période pré-scolaire et primaire – troisième edition";* Wechsler, 2004). In this task, questions that target a broad range of general knowledge topics are presented verbally to the children (e.g. "How many ears do you have?"). In order to use it in the Luxembourgish kindergarten setting we translated the items to Luxembourgish. The items 11 to 34 from the original test were used. Testing was discontinued after five consecutive wrong answers and the remaining items were scored with 0. Every correct answer was coded as 1 a wrong answer was coded as 0. Z-Scores were computed for each age group separately. Cronbach's alpha was α = .89.

Measures Administered at t2

Number Line Estimation

The number line estimation task was adapted from Berteletti et al. (2010). It was a number-to-position task in which children were presented with 25 cm lines printed in the centre of an A4 sheet. The interval used was 0 – 20; the left end of the line was marked with 0 whereas the right end was marked with 20. The target numbers that had to be positioned on the line were presented in the upper left corner of each testing sheet. An illustration item, with 10 as target number that had to be positioned on the line, preceded the eight test trials (test items were 2, 4, 6, 7, 13, 15, 16, 18; order of presentation was pseudo-randomized across children). Instructions were adapted from Berteletti et al. (2010) and translated into Luxembourgish. Children's estimation accuracy was assessed through the percentage of absolute error (PAE). This metric seems to be a better predictor of children's mathematics achievement and less skewed than curve estimation (see discussion by Simms et al., 2016) and has been the metric of choice in a very similar study (Hornung et al., 2014). PAE was computed for every item according to the formula of Siegler and Booth (2004): PAE = abs([estimate – target number]/scale of estimate) * 100. A total PAE was calculated by considering the PAE averaged accross all the items. Cronbach's alpha was α = .82.

Arithmetic

To assess children's early arithmetic skills we adapted the first part of the arithmetic subtest from the TEDI-Math test battery (van Nieuwenhoven et al., 2001). The same task has also been used by other researchers to assess arithmetic skills in kindergartners (Praet & Desoete, 2014; Praet, Titeca, Ceulemans, & Desoete, 2013). Children were presented with six arithmetic operations (three additions and three subtractions) on images (e.g. "On this picture you see two red balloons and three blue balloons, how many balloons are there in total?"). The arithmetic problem was visually available throughout the task. Items 1 to 3 required addition, whereas the items 4 to 6 required subtraction. Each correct answer was coded as 1, wrong answers as 0. Cronbach's alpha was α = .72.

Data Analysis

To investigate the predictive value of spatial skills, number-specific abilities, verbal STM, and verbal intelligence for children's performance in early arithmetic and acuity in number line estimation, hierarchical regression analyses were performed. Due to the longitudinal nature of the data collection, the criterion of time precedence

was met, allowing us to specify the directionality of the presumed effects (as formulated by Kline, 2005). The influence of age, gender, school and socio-economic status (i.e. occupational level) was controlled for by including these variables as control variables.

To assess the relation between every independent variable and the two dependent variables, arithmetic and number line estimation skills, hierarchical multiple regressions were computed for every dependent variable respectively. To evaluate the predictive value of different abilities and control variables, hierarchical multiple regressions were run in four steps. In a first step the control variables gender, age, school affiliation and occupational level were entered in the model. In a second step the domain-general variables verbal STM and verbal intelligence were entered in the model. In a third step the number-specific predictor variables, namely quantitative knowledge, counting abilities and Arabic numeral knowledge, were entered. In a fourth step, the three spatial measures, namely spatial orientation, spatial visualization and VMI were entered. The focus of the present study is the estimation of the predictive value of the single independent variables and the amount of variance the respective models can explain (R^2).

If one or more aspects were significantly predictive of arithmetic and number line estimation, a mediation analysis with number line estimation as a potential mediator of the relation between spatial skills and arithmetic was performed (in analogy to Gunderson et al., 2012).

Multiple regression and mediation analysis were performed using *MPlus* (Muthén & Muthén, 1998-2013). As described above, 12 independent variables and two dependent variables were entered in the regression analyses. All the variables entered into the regression and mediation analyses were observed variables. No latent variables were included. Parameters were estimated using Full Information Maximum Likelihood (FIML) estimation with non-normality robust standard errors (MLR option in Mplus).

Results

Descriptive Statistics an Bivariate Correlations

Descriptive statistics and correlations between the variables of interest are reported in Table 1. Skewness was less than three and Kurtosis was less than four indicating no severe skew or kurtosis (see Kline, 2016, pp. 62-63). An exception was the quantitative knowledge operationalized through the Weber fraction (*w*) with a value of the kurtosis reflecting a leptokurtic data distribution for that specific variable.

Table 1 yields medium to strong correlations among children's arithmetic performance and performance on the number line estimation task and between all the variables of interest, except for school and gender.

Table 1

Correlations and Descriptive Statistics for Study Variables

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. School[a]	-													
2. Age (months)	-.09	-												
3. Gender[b]	-.00	.07	-											
4. Occupational level	.22*	.03	-.15	-										
Administered at t1														
5. Spatial orientation	.06	.50**	.09	.27**	-									
6. Spatial visualization	-.17	.33**	.03	.36**	.51**	-								
7. Visuo-motor integration	.05	.52**	.09	.27**	.56**	.36**	-							
8. Quantitative knowledge (w)	.11	-.36**	.03	-.19*	-.43**	-.28**	-.32**	-						
9. Counting abilities	-.09	.55**	-.01	.32**	.57**	.47**	.53**	-.38**	-					
10. Knowledge of Arabic numerals	.12	.49**	.02	.31**	.63**	.42**	.49**	-.28**	.75**	-				
11. Digit span	-.09	.16	.06	.23*	.21*	.26**	.25**	-.32**	.47**	.38**	-			
12. Verbal intelligence	.06	.02	.03	.40**	.38**	.30**	.26**	-.09	.55**	.51**	.31**	-		
Administered at t2														
13. Arithmetic	.03	.38**	-.03	.30**	.64**	.38**	.59**	-.32**	.62**	.67**	.26**	.44**	-	
14. Number line estimation	-.13	-.47**	.04	-.27**	-.60**	-.34**	-.44**	.34**	-.59**	-.65**	-.34**	-.32**	-.58**	-
M	37.6%[c]	65.89	48.8[d]	50.42	5.30	5.54	4.22	.35	9.67	15.75	4.5	.01[e]	4.06	17.51
SD		7.60		15.73	2.00	2.69	2.25	.35	3.81	4.15	1.88	.99	1.79	11.19
Number of items	-	-	-	-	8	12	7	-	15	20	16	24	6	8
Mean percentage correct (%)	-	-	-	-	66.25	46.17	60.29		64.47	78.75	28	-	67.67	-
Min.-Max.	-	-	-	-	0-8	1-12	0-7	.02-2	0-15	4-20	0-8	-2.32-2.29	0-6	3.19-53.25
Skewness		.23		-.18	-.55	.34	-.55	3.10	-.49	-.98	-.28	-.01	-.79	1.23
Kurtosis		.34		-1.25	-.38	-.79	-.92	11.99	-.56	.33	-.19	-.69	-.33	1.13

[a]Dummy coded: 1 = Kindergarten A, 0 = Kindergarten B. [b]Dummy coded: 1 = female, 0 = male. [c]% of children affiliated to kindergarten B. [d]% of children who are female. [e]Please note that the values of the verbal intelligence score are z-values that have been calculated per age group.

*p < .05. **p < .001.

Several correlations are worth noting. The eight variables measured at t1 were significantly correlated. Quantitative knowledge was related to spatial skills, Arabic number knowledge, counting abilities and verbal STM but not to verbal intelligence. Measures of spatial skills were all interrelated with correlation coefficients ranging from $r = .36$ to $r = .57$. The strongest correlation was found between counting abilities and Arabic numeral knowledge ($r = .75$). Moreover, the predictor variables were all significantly correlated to the early mathematics outcome variables, arithmetic and number line estimation, assessed four months later. Arithmetic was strongly related to Arabic numeral knowledge ($r = .67$), counting abilities ($r = .62$), spatial orientation ($r = .64$) and visuo-motor integration ($r = .59$). Similarly, number line estimation was most strongly correlated with Arabic numeral knowledge ($r = -.65$), spatial orientation ($r = -.60$) and counting abilities ($r = -.59$). Quantitative knowledge, verbal STM and verbal intelligence correlated moderately with both early mathematics outcomes (range of correlation coefficients between $|.27|$ and $|.44|$). Complementary analyses on the association between the number-specific predictor variables and spatial measures can be retrieved from Appendix C.

Prediction of Early Mathematics

The effects of different predictor combinations (described earlier in the methods section) on arithmetic and number line estimation were studied by four different multiple regression models.

Prediction of Arithmetic

The standardized parameter estimates are summarized in Table 2. In Model 1, age (estimate = -.37, $p < .01$) and occupational level (estimate = .29, $p < .01$) predict arithmetic. Model 1 accounts for 23% of the variance in arithmetic. In Model 2, verbal STM and verbal intelligence were added to the model. Model 2 accounts for 35% of the variance in arithmetic. Age (estimate = .36, $p < .01$) and verbal intelligence (estimate = .35, $p < .01$) predict arithmetic. In Model 3, Arabic numeral knowledge significantly predicts arithmetic (estimate = .47, $p < .01$). Model 3 accounts for 50% of the variance in arithmetic. In Model 4, Arabic numeral knowledge (estimate = .36, $p < .01$), spatial orientation (estimate = .26, $p < .01$) and VMI (estimate = .29, $p < .01$) significantly predict arithmetic. Model 4 accounts for 61% of the variance in arithmetic. The results of a complementary analysis, where spatial predictors are entered before the number-specific predictors into the model, can be retrieved from Appendix D.1.

Prediction of Number Line Estimation

The standardized parameter estimates are summarized in Table 3. In Model 1, age (estimate = -.48, $p <.01$) and occupational level (estimate = -.22, $p < .01$) predict number line estimation. Model 1 accounts for 30% of the variance. In model 2, age (estimate = -.45, $p < .01$), school affiliation (estimate = -.16, $p = .02$), verbal STM (estimate = -.20, $p = .01$) and verbal intelligence (estimate = -.22, $p = .01$) predict number line estimation. Model 2 accounts for 39% of the variance. In model 3, age (estimate = -.18, $p = .03$) and Arabic numeral knowledge (estimate = -.37, $p = .01$) predict number line estimation. Model 3 accounts for 49% of the variance. In model 4, only spatial orientation (estimate = -.29, $p = .01$) significantly predicts number line estimation. Model 4 accounts for 53% of the variance. The results of a complementary analysis, where spatial predictors are entered before the number-specific predictors into the model, can be retrieved from Appendix D.2.

Table 2

Standardized Parameter Estimates of the Different Models Predicting Performance in Arithmetic

Model	Estimate	SE	p
Model 1			
Intercept	-1.89	.87	.04
Gender[a]	.01	.08	.91
Age	.37	.09	<.01
School[b]	-.01	.08	.91
Occupational level	.29	.07	<.01
R^2	**.23**	.07	<.01
Model 2			
Intercept	-1.62	.78	.04
Gender	-.05	.07	.52
Age	.36	.07	<.01
School	.01	.07	.85
Occupational level	.13	.08	.10
Verbal STM	.07	.07	.34
Verbal Intelligence	.35	.08	<.01
R^2	**.35**	.07	<.01
Model 3			
Intercept	-.05	.75	.95
Gender	-.03	.07	.96
Age	.03	.09	.71
School	-.03	.07	.61
Occupational level	.09	.07	.19
Verbal STM	-.08	.07	.22
Verbal Intelligence	.10	.09	.28
Quantitative knowledge (*w*)	-.11	.07	.11
Counting abilities	.16	.13	.25
Arabic numeral knowledge	.47	.11	<.01
R^2	**.50**	.07	<.01
Model 4			
Intercept	.57	.74	.44
Gender	-.05	.06	.41
Age	-.12	.09	.18
School	-.08	.07	.25
Occupational level	.05	.07	.42
Verbal STM	-.05	.06	.41
Verbal Intelligence	.03	.08	.66
Quantitative knowledge (*w*)	-.02	.08	.83
Counting abilities	.10	.12	.36
Arabic numeral knowledge	.36	.12	<.01
Spatial orientation	.26	.09	<.01
Spatial visualization	-.04	.07	.52
VMI	.29	.08	<.01
R^2	**.61**	.06	<.01

[a]Dummy coded: 1 = female, 0 = male. [b]Dummy coded: 1 = Kindergarten A, 0 = Kindergarten B.

Table 3

Standardized Parameter Estimates of the Different Models Predicting Performance in Number Line Estimation

Model	Estimate	SE	p
Model 1			
Intercept	6.97	.61	<.01
Gender[a]	.04	.08	.62
Age	-.48	.06	<.01
School[b]	-.12	.08	.11
Occupational level	-.22	.07	<.01
R^2	**.30**	.07	<.01
Model 2			
Intercept	6.98	.53	<.01
Gender	.08	.07	.30
Age	-.45	.06	<.01
School	-.16	.07	.02
Occupational level	-.07	.08	.33
Verbal STM	-.20	.08	.01
Verbal Intelligence	-.22	.08	.01
R^2	**.39**	.06	<.01
Model 3			
Intercept	5.62	.64	<.01
Gender	.04	.07	.53
Age	-.18	.08	.03
School	-.12	.07	.07
Occupational level	-.04	.07	.61
Verbal STM	-.08	.07	.27
Verbal Intelligence	-.01	.10	.92
Quantitative knowledge (*w*)	.09	.08	.22
Counting abilities	-.14	.16	.40
Arabic numeral knowledge	-.37	.14	.01
R^2	**.49**	.06	<.01
Model 4			
Intercept	5.62	.70	.00
Gender	.07	.07	.30
Age	-.12	.10	.20
School	-.11	.07	.11
Occupational level	-.03	.08	.68
Verbal STM	-.12	.07	.09
Verbal Intelligence	.04	.10	.71
Quantitative knowledge (*w*)	.02	.08	.80
Counting abilities	-.13	.17	.42
Arabic numeral knowledge	-.27	.14	.06
Spatial orientation	-.29	.10	.01
Spatial visualization	.04	.07	.60
VMI	.00	.09	.98
R^2	**.53**	.05	<.01

[a]Dummy coded: 1 = female, 0 = male. [b]Dummy coded: 1 = Kindergarten A, 0 = Kindergarten B.

Additional Analyses – Role of Different Aspects of Spatial Skills

To further study the respective role of the spatial measures, hierarchical regression including the three measures of spatial skills in three different steps was performed. The regression analysis was run for arithmetic and number line estimation separately. In a first step, spatial visualization was entered, in a second step the VMI was entered and in a third step spatial orientation was entered as a predictor. The order of predictors was based on the correlation coefficients between the predictors and the dependent variables. Spatial visualization showed the lowest correlation with the dependent variables, VMI showed higher correlation with the dependent variables than spatial visualization and spatial orientation exhibited the highest correlation with the dependent variables.

Spatial visualization is a significant predictor of *arithmetic* (standardized estimate of .38; $p < .01$) when it is entered in a first step into the regression model. In a second step, VMI is entered as a predictor and both predictors are significant with a standardized estimate for spatial visualization of .20 ($p < .01$) and for VMI of .52 ($p < .01$). In a third step, spatial orientation is added to the model. Spatial orientation with a standardized estimate of .42 ($p < .01$) and VMI with a standardized estimate of .34 ($p < .01$) are significant predictors, whereas spatial visualization is not significant anymore with a standardized estimate of .05 ($p = .47$).

Spatial visualization is a significant predictor of *number line estimation* (standardized estimate of -.34; $p < .01$) when it is entered in a first step into the regression model. In a second step, VMI is added to the model and both predictors are significant with a standardized estimate for spatial visualization of -.21 ($p = .01$) and for VMI of -.37 ($p < .01$). In a third step, spatial orientation is added to the model. Spatial orientation with a standardized estimate of -.50 ($p < .01$) and VMI with a standardized estimate of -.16 ($p = .05$) are significant predictors, whereas spatial visualization is not significant anymore with a standardized estimate of -.04 ($p = .66$).

Number Line Estimation as a Mediator of the Relationship Between Spatial Skills and Arithmetic

Mediation analysis was performed by computing total, direct and indirect effects of the model depicted in Figure 2 using Mplus (Muthén & Muthén, 2013). In this model, spatial orientation figures as independent variable (x), number line estimation as a mediator (m) and arithmetic as the dependent variable (y) (note that spatial orientation was predictive of arithmetic and number line estimation, see Table 2 and Table 3).
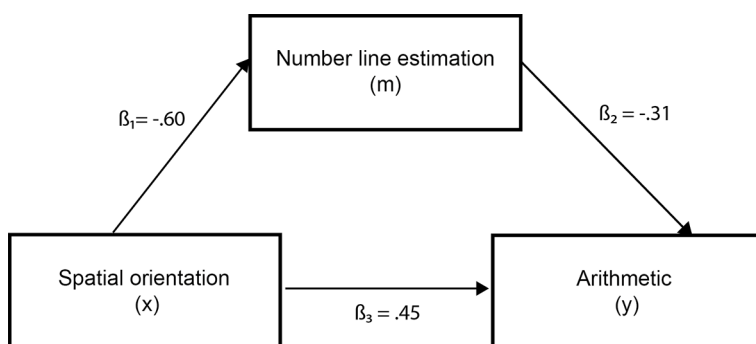

Figure 2. Mediation Model with Spatial Orientation as Independent Variable (x), Number Line Estimation as Mediator (m) and Arithmetic as Dependent Variable (y).

Results of the analysis reveal a partial mediation of the relation between spatial orientation and arithmetic through number line estimation. The standardized total effect from spatial orientation to arithmetic is 0.64 (*SE* = .05, *p* < .01) and the standardized indirect effect from spatial orientation to arithmetic ($\beta_1 \times \beta_2$) is 0.19 (*SE* = .05, *p* < .01). The standardized direct effect between spatial orientation and arithmetic is .45 (*SE* = .08, *p* < .01).

Discussion

The purpose of the present study was to study the predictive power of spatial skills on mathematical learning in young children prior formal schooling. Regression models, including indicators of number-specific and domain-general abilities for mathematical learning, highlight the importance of different spatial measures for children's arithmetic performance and number line estimation.

Role of Different Spatial Measures for Early Mathematics

Performance on the arithmetic task was predicted by spatial orientation, VMI and Arabic numeral knowledge in the final model. Performance on the number line estimation task was predicted by spatial orientation only in the final model. These findings highlight the predictive power of spatial skills for early mathematics in children prior formal schooling. Furthermore, our results show, that different measures of spatial skills are not equally important for the prediction of early mathematics. One spatial measure, spatial visualization, did not significantly predict any of the outcome measures when controlling for other aspects. In contrast, spatial orientation predicted arithmetic and number line estimation. In addition to spatial orientation, VMI predicted arithmetic when being considered with number-specific and control variables concurrently.

To interpret these findings, a closer look at the spatial tasks is necessary. The spatial orientation task requires orientation discrimination of the same object. The target item and distractor items are mirrored or rotated versions of the same object. In contrast, the spatial visualization task used in the present study is more object-based and it requires mental transformation. Children have to identify the target shape out of four different shapes that they get when two separate pieces are put together. As the four shapes (one target shape and three distractor shapes) presented to the child differ as objects, focusing on one aspect of the target shape might be sufficient to solve this task. The key aspect of the spatial orientation task might thus be orientation discrimination (e.g. left-right orientation) of specific features within series of shapes that are otherwise identical (see e.g. Fisher & Braine, 1981; Huttenlocher, 1967; for research on left-right discrimination in children). Especially the mirror-reversed items (such as the items presented in Figure 1) require a consistent left-to-right or right-to-left visual scanning of information. Moreover, the number line estimation task also requires accurate left-right discrimination to assure a consistent response pattern on this task. Children's left-right discrimination could thus be the key aspect explaining why the abilities assessed in the spatial orientation task relate to children's performance in arithmetic and number line estimation. Furthermore, left-right discrimination is also required in the VMI task to ensure a correct copy of the line drawings. Insufficient left-right discrimination likely results in increased errors on this task (e.g. mirror-reversed lines). Some further explanations, going beyond the importance of left-right discrimination, are worth to be discussed. The finding that spatial orientation predicts arithmetic and number line estimation in kindergarten children, corroborates previous research findings (e.g. Zhang & Lin, 2015). Zhang and Lin (2015) discuss that for solving this specific spatial task, children need to

maintain the information while processing it in order to perform the comparison between the different objects. This gives raise to the assumption, that working memory might be involved. The present study included a measure of verbal STM, which acts as a proxy for working memory in young children (Hornung, Brunner, Reuter, & Martin, 2011). The relation between spatial orientation and arithmetic remained, even when verbal STM was considered. For future studies, we would recommend to add a measure of *visuo-spatial* short-term memory to assess the respective roles of working memory depending on the nature of the processed information. Zhang and Lin (2015) explain the observed relationship between spatial skills and arithmetic through the spatial representations of numbers, along a mental number line. This assumption fits with the present finding that performance on the spatial orientation task also predicts number line estimation. The predictive value of spatial orientation (assessed with the "position in space" task) for performance on the number line estimation task can be explained through the spatial requirements of the latter task. In the number line estimation task children have to "align the numbers according to their place value within to predetermined endpoints of a continuum", as formulated by LeFevre et al. (2013, p. 8). Or, to put it differently, children have to *position* a number *in space*, making the link between the two tasks obvious.

The administered task of VMI taps into children's ability to coordinate spatial processing and fine-motor control. VMI significantly predicted performance in arithmetic, but not in number line estimation, when considered concurrently with other measures. The latter seems to be in conflict with the assumption of Simms et al. (2016) arguing that VMI can be especially useful for the number line estimation task as both tasks require the translation of visuo-spatial information into a physical space through a motor response. It is worth noting, that children in the study by Simms et al. (2016) were about 4 years older than children in the present study. The results of the additional analyses investigating the predictive value of the spatial measures showed that VMI predicts number line estimation, when only the three spatial skills are added as independent variables to the regression model. In the main analyses, number-specific and domain-general abilities were considered concurrently. Here, VMI does not significantly predict number line estimation anymore. The predictive power of VMI for early arithmetic confirms the findings by Cameron et al. (2012) who report that VMI relates to mathematics in kindergarten children (and in older children, see Sortor & Kulp, 2003). We might even suggest that this finding fits with the literature documenting a link between children's finger representation and early mathematics (Fayol, Barrouillet, & Marinthe, 1998; Reeve & Humberstone, 2011). The latter authors assume that tasks involving tactile perception and psychomotor abilities are important for quantification. Reeve and Humberstone (2011) hold the view that finger representation mediates the spatial representation supporting numerical development. However, the suggestion of linking our data to empirical data on finger representation and early mathematical development remains speculative, because children's finger representation or finger counting abilities were not directly assessed.

In the final regression model, the task of spatial visualization did not predict any of our outcome measures. This is most likely explained by the additional consideration of spatial orientation in our model. Spatial orientation might be the more relevant aspect of spatial skills in the context of mathematical development. This assumption is confirmed by results of the additional regression analysis with arithmetic and number line estimation as dependent variables respectively. Spatial visualization is a significant predictor of arithmetic and number line estimation, until spatial orientation is added to the model. Both measures of spatial skills appear to be overlapping (underpinned by their correlation). When considered isolatedly from other spatial measures, the measure of spatial visualization seems to carry significant information, but the measure of spatial orientation may contain the only relevant information. These findings are in line with Zhang and Lin (2015) who argue in

the introduction of their paper that sophisticated spatial skills such as spatial visualization may not be required for basic number competencies assessed in the preschool years. More basic spatial skills, such as spatial perception, may be especially important for *early* mathematics. Our results fit with that assumption. The concurrent consideration of spatial orientation and spatial visualization might be at the basis of the discrepancy between our findings and the findings by Gunderson et al. (2012) and Zhang et al. (2014) (who did only consider spatial visualization).

Role of Number-Specific Abilities for Early Mathematics

The predictive power of three different number-specific abilities on arithmetic and number line estimation was studied. In the hierarchical regression analyses, number-specific predictors were added in model 3 to more general predictors. Adding number-specific predictors to the regression models, predicting arithmetic and number line estimation respectively, yielded the importance of Arabic numeral knowledge for both dependent variables. Arabic numeral knowledge was the only significant predictor of arithmetic in Model 3; Arabic numeral knowledge and age were both two significant predictors for number line estimation in Model 3.

Quantitative knowledge did not predict any of our two outcome measures. In prior research, findings about the importance of the ANS in mathematical development remained inconclusive (De Smedt, Noël, Gilmore, & Ansari, 2013; Halberda et al., 2008; Kolkman et al., 2013; Libertus, Feigenson, & Halberda, 2011, 2013a, 2013b; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013). Our results corroborate prior findings (Kolkman et al., 2013; Sasanguie et al., 2013) showing that as soon as symbolic skills are mastered, non-symbolic skills lose their predictive value for mathematics.

Counting abilities did not predict arithmetic and number line estimation. This finding is particularly surprising with regard to arithmetic. It contrasts with findings suggesting that arithmetic builds up on counting abilities (Aunola et al., 2004; Hannula-Sormunen et al., 2015; Stock, Desoete, & Roeyers, 2009a; Stock et al., 2009b). This finding could be potentially explained by the task we used to assess children's early arithmetic abilities. Arithmetic problems were presented verbally along with a visual support and children were required to give a verbal response. Considering the verbal nature of the instruction and the response, it seems surprising, that counting abilities do not predict arithmetic performance (even though they are moderately-strong correlated, $r = .62$). Yet, due the visual support provided along with the verbal instruction of the arithmetic task, children might have used visual strategies over verbal strategies to solve the arithmetic problems. This explanation remains only speculative as neither children's strategy-use was assessed, nor was a second arithmetic task without visual support administered, that would have allowed us to control for the potential influence of the visual support.

The finding that Arabic numeral knowledge, but not counting abilities, is predictive of arithmetic performance, could indicate that a more mature understanding of numbers is needed to solve this task. Simple counting strategies might be insufficient. Knowledge of the number symbol and the cardinality, especially the understanding of relations between numerical quantities (as described by Krajewski & Schneider, 2009), are needed to perform arithmetic operations.

Nature of the Relationship Between Spatial Skills and Early Mathematics

Results of the mediation analysis reveal that number line estimation partially mediates the relation between spatial orientation and arithmetic. A complete mediation of the latter relation by number line estimation could have accounted for the assumption that better spatial skills go along with a more refined representation of the mental number line, which in turn leads to better performance in arithmetic (Booth & Siegler, 2008; Gunderson et al., 2012). The observed partial mediation suggests, that better spatial orientation does indeed go along with a better performance on the number line estimation task (see discussion on left-right discrimination above), which in turn mediates *a part* of the relation between spatial orientation and arithmetic. However, this explanation is not sufficient as we do only observe partial mediation. Spatial orientation might thus predict arithmetic over and above the understanding of the mental number line (given the assumption that the number line estimation task really assesses children's mental number line, which is a current topic of debate; Dackermann et al., 2015), as e.g. through allowing a better visualization of the mathematical problem, which in turn should facilitate the solution process of the mathematical problem (Cheng & Mix, 2014; Skagerlund & Träff, 2016; Zhang & Lin, 2015).

In a previous study, Gunderson et al. (2012) found that number line estimation at age six *fully* mediated the relation between spatial visualization at age five and arithmetic performance three years later. Our study differs from the study by Gunderson et al. (2012) in a two ways. Firstly, they used a measure of spatial visualization for the mediation analyses, whereas we used a measure of spatial orientation. A second difference is the time course. We assessed spatial skills four months before number line estimation and arithmetic, whereas Gunderson et al. (2012) measured spatial skills at age five, number line estimation at age six and arithmetic at age eight. These differences between the two studies should be noted when comparing both results.

Spatial Skills – Domain-General or Domain-Specific Abilities?

In the introduction, the non-consensus with regard to the classification of spatial skills as either domain-specific or domain-general abilities for mathematical development was discussed. In our study we considered number-specific abilities (i.e. quantitative knowledge, counting abilities and Arabic numeral knowledge), domain-general abilities (i.e. verbal STM and verbal intelligence) and three measures of spatial skills (i.e. spatial orientation, spatial visualization and VMI) concurrently. The concurrent consideration of these different variables allows us to gain a clearer view of their relation with early mathematics.

Two major findings can be retained. First, we observed that different measures of spatial skills were not equally predictive of early mathematics. Spatial orientation predicted arithmetic and number line estimation, VMI predicted arithmetic only and spatial visualization predicted neither arithmetic nor number line estimation when controlling for other spatial skills. Second, the specific role of spatial orientation is highlighted by its prediction of arithmetic *and* number line estimation, and it is the only significant predictor of number line estimation. In the hierarchical regression model, number-specific predictors were added in a third step and spatial skills in a fourth step to our model. Interestingly, in the third step, age, school affiliation and Arabic numeral knowledge predict performance on the number line estimation task. But as soon as spatial skills are added to our model, all the other variables lose their predictive value and spatial orientation remains the only significant predictor.

Two measures of domain-general abilities that could potentially predict early mathematics were included, but neither verbal intelligence nor verbal STM significantly predicted arithmetic or number line estimation in the final

model. In the model predicting number line estimation, verbal STM and verbal intelligence lose their predictive value as soon as number-specific variables are added. In the model predicting arithmetic, verbal intelligence loses its predictive value when numerical precursor variables are added.

Taking these findings together, we can conclude that in the present study, spatial skills, and notably the spatial orientation task, predict performance on two early math measures. Whereas domain-general abilities, such as verbal STM and verbal intelligence, are not significantly predictive of early mathematics when number-specific variables are considered, spatial measures significantly predict early mathematics even when considered concurrently with domain-general and number-specific abilities. These findings suggest that spatial skills might indeed be domain-specific abilities rather than domain-general abilities. To investigate this further, a follow-up of children's school achievement in mathematics, and another school domain such as reading, should be envisaged to assess whether spatial skills do predict children's achievement in mathematics but not in reading. If the latter were true, this would allow us to conclude that the predictive value of spatial skills is specific to mathematics and does not generalize to other domains.

Outcome Measures

A further point of discussion is the choice of the early mathematics outcome measures. We chose two measures we considered as tapping into children's more mature understanding of mathematics: arithmetic and number line estimation.

When assessing arithmetic performance in children, it is crucially important to choose an age-appropriate task. In kindergarten formal mathematics instruction has not yet begun. Thus, we cannot expect children to be familiar with written arithmetic (e.g. "3 + 5 = _") nor with the verbal presentation of a simple arithmetic problem (e.g. "one plus three makes…?"). The administration of word problems goes along with a comparably high load in verbal working memory and proficiency in the language of test administration is required. We used an arithmetic task with visual support and verbal instruction to address these issues. We do acknowledge that the presence of visual support throughout the arithmetic task could have affected the results. The additional visual presentation of the arithmetic problem could have led some children to use simple counting strategies rather than mental arithmetic operations. If this were the case, it would be possible that the task would rather be a task of basic counting abilities than a task of early arithmetic. Nevertheless, two arguments can be put forward suggesting that the task does indeed assess early mental arithmetic operations. First, our results suggest that the arithmetic task is "more" than a simple counting task: counting abilities do not predict children's performance on the arithmetic task. If the arithmetic task would solely assess children's counting abilities, counting abilities would significantly predict performance on that task. Second, the nature of the visual support for subtraction items does not fit with the assumption that performance on the arithmetic task is assessing children's counting abilities solely. Here a counting strategy would be insufficient to solve the item: if children would only count the visually presented items, their answer would correspond to the first operand, no subtraction operation would be performed.

The second outcome measure was a number line estimation task, more precisely a number-to-position task. We chose a number line between 0 to 20, because this should reflect the number range children are familiar with in kindergarten (see Berteletti et al., 2010). The metric used to measure performance on this task could be a point of discussion. Two different measures are commonly used: linear curve estimation (expressed by the

metric R^2_{lin}) and the percentage of absolute error (PAE). In a recent study, Simms et al. (2016) used both measures to assess performance on the number line estimation task. They concluded, that PAE is less biased than curve estimation and it proves to be a better predictor of mathematical achievement than R^2_{lin}. This conclusion informed our choice to use PAE rather than R^2_{lin} to assess performance on the number line estimation task.

Limitations

One limitation of the present study is that only single measures were used to assess each aspect of spatial skills. Ideally, method triangulation should be used to measure the different spatial aspects more reliably and reduce potential measurement errors (see discussion in Oostermeijer, Boonen, & Jolles, 2014). The present study was a first attempt to differentiate within the construct of spatial skills and to test the differential role of the respective aspects for predicting different aspects of early mathematics. This allowed us to distinguish between three types of tasks that are often summed up under the umbrella term of spatial skills, but relate differentially to distinct aspects of early mathematics in our sample. The use of only one task per spatial category reduces the generalizability of our results. Further studies should include multiple measures of each aspect to increase reliability and generalizability of the different constructs. To be able to assess a large range of different abilities and basic number competencies, the administered tests were all comparably brief. Nevertheless, they all had acceptable to good internal consistency.

A further limitation is the choice of statistical analysis and modelling as we did only consider observed variables. Working with latent variables that are operationalized through at least two different measures, would have allowed to integrate variables that are free of measurement error and it would have provided a more coherent representation of the underlying construct than a single measure (see argumentation of Hornung et al., 2014).

The delay between the two testing waves was comparably short (e.g. Zhang & Lin, 2015, or Hornung et al., 2014, who have a one year delay between the two testing points) and it would be interesting to perform a further assessment wave when children have started formal schooling, to investigate in how far spatial skills in kindergarten are predictive of children's performance on formal mathematics achievement tests.

Even though our model included number-specific abilities, as well as measures of spatial skills, verbal STM, verbal intelligence and children's social and cultural background, we do not claim it to be exhaustive. We consider it especially important to specify that we did not include any specific measures of children's language ability and executive functions. Language skills and executive functions are related to mathematical development, as pointed out in the introduction section. Future research should take into account further aspects of language, executive functions and spatial skills concurrently when studying their role as precursors for mathematical development

Conclusion

The present findings highlight the role of spatial skills for mathematical development prior formal schooling when controlling for number-specific and domain-general abilities. They emphasize the importance of differentiating between different aspects of spatial skills, as they tend to relate to early mathematics differentially. From a more practical point view, they also yield fruitful information for instruction in the

kindergarten classroom as they support initiatives that aim to foster pre-schoolers' spatial skills, most notably spatial orientation and visuo-motor integration, as important prerequisites for optimal learning in mathematics.

Statement of Ethics

The authors confirm that the present empirical work has been carried out in accordance with relevant ethical principles and standards. Ethical approval has been obtained by the Ethics Review Panel (ERP) of the University of Luxembourg.

Notes

i) Mix and Cheng (2012), classify the position in space subtest used by (Lachance & Mazzocco, 2006; Mazzocco & Myers, 2003) as measure of spatial visualization, whereas Zhang and Lin (2015) use a similar task and classify it as task of spatial perception. For the purpose of the present study we agree with the classification by Zhang and Lin (2015) and consider the task as a measure of spatial perception, as the task does not involve spatial transformations or manipulations but it requires the accurate perception of spatial relations of object components.

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Competing Interests

The authors have declared that no competing interests exist.

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Appendices

Appendix A: Information on Parents' Occupational Level

Socio-economic status was assessed by a parental questionnaire. Not all the parents returned the questionnaire fully completed. Information on the occupational level was missing for 10 children. Children were from diverse socioeconomic background: 0.8% of mothers and 0.8% of fathers have never carried out remunerated work, 6.4% of mothers and 8.8% of fathers are company managers or executive employees, 27.2% of mothers and 22.4 of fathers work in a scientific or related profession, 5.6% of mothers and 6.4% of fathers work as technicians, 23.2% of mothers and 10.4% of fathers are office workers, 12% of mothers 6.4% of fathers are employed in the services and sales domain, 14.4% of mothers and 10.4% of fathers are semi-skilled workers, 3.2% of fathers are qualified agricultural workers, 15.2% of fathers are craftsmen and 5.6% of fathers are motorists, machine operators or assembly workers.

Appendix B: Administration of the Non-Symbolic Dot Comparison Task

The test was administered on a 13-inch Apple MacBook Pro. Each trial consisted of red and yellow dots that were presented within two rectangles. A picture of a sesame street character (Big Bird and Elmo) was associated with each rectangle. For each trial, dots appeared simultaneously in each rectangle and children had to judge in which rectangles more dots were presented. The number of dots within each set varied between 5 and 21. The ratio of the sets per trial and the time of presentation were adapted to children's age according to the recommended settings by the authors of the test (Halberda et al., 2008). For four year olds the display time was 2322 ms and the total range of the ratio varied between 1.25 and 3.18. For five year olds the display time was 2128 ms and the total range of the ratio varied between 1.22 and 3.4. For children who were six years old the display time was 1951 ms and the ratio varied between 1.2 and 2.94. In 50% of the trials dot size varied to account for the total surface of dot size. Children received 24 test trials that were preceded by two practice trials. The examiner recorded children's answers by pressing the corresponding key on an external keyboard connected via USB to the laptop. Children's performance was measured by the Weber fraction (w), allowing us to equate performance across the different age groups.

Appendix C: Association Between Number-Specific and Spatial Measures

To further study the association between the number-specific and spatial measures, we conducted a regression analysis with the spatial measures as independent variables and each number-specific measure as dependent variable (DV) respectively. In the table below, the standardized estimates are reported. The measure of spatial orientation is significantly associated with the three number-specific measures. VMI is significantly associated with counting abilities and Arabic numeral knowledge. Spatial visualization is significantly associated with counting abilities. Overall, strong associations between spatial measures and measures of symbolic number knowledge (counting abilities and Arabic numeral knowledge) are observed.

Independent variable	DV: Quantitative knowledge			DV: Counting abilities			DV: Arabic numeral knowledge		
	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p
Spatial orientation	-.34	.11	<.01	.30	.11	<.01	.46	.10	<.01
Spatial visualization	-.06	.09	.45	.22	.09	.01	.12	.08	.15
VMI	-.11	.11	.30	.29	.09	<.01	.20	.09	.02
R^2	.20	.07	<.01	.43	.07	<.01	.43	.07	<.01

Appendix D

Appendix D.1. Prediction of Arithmetic – Entering Spatial Skills Before Number-Specific Measures

Additional 7% of variance in arithmetic are explained by adding number-specific measures to the model.

Model	Estimate	SE	p
Model 1			
Intercept	.32	.75	.67
Gender[a]	-.09	.06	.15
Age	.03	.08	.71
School[b]	-.04	.06	.57
Occupational level	.04	.07	.52
Verbal STM	.04	.06	.53
Verbal Intelligence	.18	.08	.02
Spatial orientation	.37	.09	<.01
Spatial visualization	-.01	.07	.88
VMI	.32	.08	<.01
R^2	**.54**	.06	<.01
Model 2			
Intercept	.58	.74	.43
Gender	-.05	.06	.41
Age	-.11	.08	.18
School	-.08	.07	.25
Occupational level	.05	.07	.42
Verbal STM	-.05	.06	.41
Verbal Intelligence	.03	.08	.66
Spatial orientation	.26	.09	<.01
Spatial visualization	-.04	.07	.52
VMI	.29	.08	<.01
Quantitative knowledge (*w*)	-.02	.08	.83
Counting abilities	.10	.12	.36
Arabic numeral knowledge	.36	.12	<.01
R^2	**.61**	.06	<.01

[a]Dummy coded: 1 = female, 0 = male. [b]Dummy coded: 1 = Kindergarten A, 0 = Kindergarten B.

Appendix D.2. Prediction of Number Line Estimation – Entering Spatial Skills Before Number-Specific Measures

Additional 3% of variance in number line estimation are explained by adding number-specific measures to the model.

Model	Estimate	SE	p
Model 1			
Intercept	5.54	.62	<.01
Gender[a]	.10	.07	.13
Age	-.26	.09	<.01
School[b]	-.13	.06	.03
Occupational level	-.03	.08	.65
Verbal STM	-.20	.07	<. 01
Verbal Intelligence	-.10	.08	.23
Spatial orientation	-.38	.10	<.01
Spatial visualization	.01	.07	.90
VMI	-.02	.09	.81
R^2	**.48**	.06	<.01
Model 2			
Intercept	5.12	.66	<.01
Gender	.07	.07	.30
Age	-.12	.10	.21
School	-.11	.07	.10
Occupational level	-.03	.08	.67
Verbal STM	-.12	.07	.09
Verbal Intelligence	.04	.10	.70
Spatial orientation	-.29	.10	<.01
Spatial visualization	.04	.07	.60
VMI	.00	.09	.98
Quantitative knowledge (*w*)	.02	.08	.83
Counting abilities	-.14	.17	.40
Arabic numeral knowledge	-.26	.15	.07
R^2	**.53**	.05	<.01

[a]Dummy coded: 1 = female, 0 = male. [b]Dummy coded: 1 = Kindergarten A, 0 = Kindergarten B.