Cognitive Influences on an Emerging Mathematical Skill in Children

by

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Abstract

Fifty-eight children of varying math abilities, ranging in age from 7 to 8 years, were tested to investigate the influence of certain low-level cognitive abilities on their use of spatial representations of number magnitude (i.e., the so-called mental number line). A number-line estimation task and a number comparison task were administered to measure their use of the mental number line. A combined spatial-cueing and flanker task was used to assess three attention networks: executive functioning, alerting, and visual attention orienting. Visuospatial working memory was assessed with a mental rotation task, and intelligence was measured with a short-form IQ test. Regression results showed that visuospatial working memory ability was related to performance on the mental number line tasks. Hence, children with stronger visuospatial working memory ability are able to more efficiently manipulate the mental number line, and thus perform better on tasks involving understanding of number magnitude.

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Dedication

I would like to dedicate this work to the superintendents, principals, teachers, parents, and especially the children who participated in my research. Without their enthusiasm, researchers would not be able to investigate important educational and psychological questions.

Table of Contents

Abstract 2

Acknowledgements 3

Dedication 4

List of Tables 7

List of Figures 8

  Background: The Importance of Magnitude Processing 9

  Development of Mental Representations of Magnitude 10

  Importance of Studying Children's Magnitude Representations 14

  Attention and Magnitude Processing 16

  Children, Attention, and Magnitude Processing 20

  Current Study 23

Method 24

  Participants 24

  Apparatus 25

  Materials 25

    Magnitude processing outcomes. 26

    Visual attention predictors. 29

    Control factors. 34

  Procedure 36

Results 38

  Descriptive Statistics 38

    Inferential Statistics 39

Discussion 42

    Attention Network Findings 42

    Visuospatial Working Memory Findings 47

Limitations and Future Directions 51

General Conclusion 53

References 55

List of Tables

Table 1 73

Table 2 75

Table 3 77

Table 4 78

Table 5 80

Table 6 81

List of Figures

Figure 1 82

Figure 2 83

APPENDIX A – Instructions for ANT Task (Child Version) 84

APPENDIX B - Instructions for Mental Rotation Task 86

Cognitive Influences on an Emerging Mathematical Skill in Children

Acquiring basic math skills is important for many important aspects of life, including occupational tasks (interpreting a statistic, making change, measuring ingredients), home-based activities of daily living (balancing checkbooks, paying bills), and tasks related to community involvement (calculating discounts, comprehending health records and medical prescriptions) (see McCloskey, 2007 for a review). Unfortunately, many children and youth struggle with mathematics and leave school unprepared to use math functionally (Berch & Mazzocco, 2007; Coyne, Kame'enui, & Carnine, 2011). Thus, in order to understand these students' needs and to ameliorate their limitations on functional math skills, we need to improve our knowledge about the underlying factors that contribute to children's math difficulties, including cognitive abilities that influence mathematical learning. Number processing deficits and domain-general cognitive abilities have already received a great deal of attention (e.g., Feigenson, Dehaene, & Spelke, 2004; Butterworth, 2005; Wilson and Dehaene, 2007; Mazzocco, Feigenson, & Halberda, 2011; Skagerlund & Traff, 2014). I aim to expand on current knowledge by exploring the role that certain cognitive functions play in an integral skill in mathematical learning: magnitude processing.

Background: The Importance of Magnitude Processing

A fundamental competency for mathematical learning is understanding magnitude. Number magnitude refers to cardinality (the quantity or "manyness" that a number represents). For example, a set of nine apples is more than a set of five apples and less than, but "close to," a set of ten apples (see Fuson, 1992). Children's abilities to process number magnitude is related to other emerging mathematical skills such as their estimation ability (Booth & Siegler, 2006; Thompson & Siegler, 2010) and their arithmetic proficiency (Griffin, Case, & Siegler, 1994; Jordan, Hanich & Kaplan, 2003). It is also related to their general math achievement (Desoete, Ceulemans, De Weerdt, & Pieters, 2010; De Smedt, Verschaffel, & Ghesquie're, 2009; Duncan, Dowsett, Claessens, Magnuson, Huston, Klebanov, et al., 2007; Gersten, Jordan, & Flojo, 2005; Case & Okamoto, 1996). Thus, understanding numerical magnitude is integral to number sense development, and developing this understanding is a primary goal of mathematics instruction (Dowker, 1992, 2003; Dowker, Flood, Griffiths, Harriss, Hook, 1996; Kilpatrick, Swafford, & Findell, 2001; National Council of Teachers of Mathematics (NCTM), 2013; Noël, Rousselle, & Mussolin, 2005).

Recent studies of mathematical learning disability focus on basic numerical processing, and have identified difficulties in children with mathematical learning disability in several tasks that require magnitude understanding, such as size congruity (Rubinsten & Henik, 2005, 2006), comparison of number magnitudes (Ashkenazi, Mark-Zigdon, & Henik, 2009; Geary, Hamson, & Hoard, 2000) and subitizing (Koontz & Berch, 1996). Hence, helping children comprehend number magnitude may lead to improved performance on many functional and academic mathematical tasks. The next section will focus on the development of how children mentally store and use symbolic numerical magnitude.

Development of Mental Representations of Magnitude

There is a strong link between the way humans process numbers and space. The Spatial Numerical Association of Response Code (SNARC) task was developed by Dehaene and colleagues in 1993, to demonstrate that larger numbers are responded to more quickly with a right response key (on a response box or computer keyboard) while smaller numbers are responded to more quickly with a left response key. This finding was since replicated in other labs (e.g., Fischer, Castel, Dodd, & Pratt, 2003; Ristic, Wright, & Kingstone, 2006). The relation between number magnitude and horizontal spatial orientation occurs even when the SNARC task itself has nothing to do with understanding number magnitude. Even when participants are asked whether a digit is odd or even (Dehaene et al., 1993), or about phonemic content of number words (Fias, Brysbaert, Geypens, & D'ydewalle, 1996), larger numbers are still associated with the right side of space and smaller numbers with the left.

Behavioural and neuroscience research has shown that the way children mentally represent the horizontal spatial continuum of numbers changes with age and experience. Children in Western countries gradually move from relying on logarithmic mental representation of magnitude to relying on linear representations (Booth & Siegler, 2006; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Opfer, Thompson, & DeVries, 2007; Siegler & Booth, 2004; Siegler & Opfer, 2003). A logarithmic representation is demonstrated when children exaggerate differences in the magnitudes of smaller numbers and compress differences in the magnitudes of larger ones. It is believed that with increasing experience with the symbolic number system, children learn to compensate for the logarithmic representation of magnitude. In other words, the innate magnitude representation is honed through the acquisition of the exact symbolic number system (Feigenson et al., 2004; Halberda and Feigenson, 2008; Mundy and Gilmore, 2009; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). By the age of seven years, linear representation emerges; children tend to neither exaggerate nor compress differences among numbers throughout a scale (Siegler & Booth, 2004), and this linear form is a more accurate representation of number magnitude. In the literature, a helpful and often referred-to metaphor for this internal representation of magnitude is "the mental number line." On the mental number line, the smallest numbers are placed towards the left, and larger numbers towards the right (Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005, 2009), similar to how magnitude can be depicted physically in spatial form, such as on a ruler (Göbel, Calabria, Farné, & Rossetti, 2006; Longo & Lourenco, 2007; Zorzi, Priftis, & Umiltà, 2002). Two ways to assess children's use of internal magnitude representations are number line estimation and number comparison tasks.

Number line estimation. Number line estimation is a magnitude estimation task that requires children to identify the positions of target numbers on a displayed number line, with endpoints such as 0 and 100 and no marks or numbers in between. When position estimates are plotted as y values with target numbers plotted on the x-axis of a graph, perfectly accurate performance would fall on the line $y = x$. Deviations from this line are indicative of estimation error. Although the shift from relying on logarithmic to linear representations of magnitude is gradual, studies have shown that by about the second grade, children begin to produce a more linear pattern of estimates for 0 -100 number lines, and between second and fourth grades for 0-1000 number lines (Booth & Siegler, 2006; Geary et al., 2007; Laski & Siegler, 2007; Siegler & Booth, 2004). Slusser et al (2011) argue that the categorization of magnitude estimation data as either logarithmic or linear is flawed, even though most studies consider only these two possibilities, and in their research found no support for the logarithmic-to-linear developmental shift of magnitude representation. These researchers theorize that increased accuracy on number line estimation tasks are related to the number of reference points utilized by the participant. For example, a participant who visualizes both the lower and upper endpoint values on the line, as well as a mid-point value on the line, will perform more accurately than a participant who attends only to the lower endpoint. Regardless of how an inaccurate, internal representation of magnitude may look for a child, there is solid evidence that children internally represent the abstract concept of magnitude in a spatial format (Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005, 2009) and that, if graphed, more accurate estimates would be linearly related to the presented values.

A variety of number position estimation strategies can be employed by children to complete this task. For example, children may use proportional reference points, such as the midpoint or quarter points, or they may estimate based on distance to or from an endpoint, to facilitate estimates (Siegler & Opfer, 2003; Barth & Paladino, 2011; Slusser et al., 2011). Perfectly accurate performance on the number line estimate task signifies an understanding of the equal spacing between comparable magnitudes, such as the difference between 6 and 10 being the same as the difference between 76 and 80, and use of a more mature (higher quality, more accurate) representation of magnitude. Thus, increasingly linear patterns of estimates are indicative of a more advanced understanding of numerical magnitude. It is important to understand the underlying cognitive processes that may influence development of accurate magnitude representation.

Number comparison. Number comparison tasks have also been used to assess children's processing of number magnitudes, and have been consistently tied to mathematical learning disability and general math achievement (e.g., Rousselle and Noël, 2007; Landerl and Kölle, 2009; Andersson and Östergren, 2012). These tasks involve questions such as "Which is more, 26 or 64," or "Which is less, 35 or 74." Similar to the results of studies involving number line estimation, results from studies involving number comparison tasks demonstrate that children vary in their ability to accurately and internally represent number magnitude and that they develop from immature performance involving over-reliance on logarithmic or other inaccurate representations to mature performance involving reliance on linear representations (Berch, Foley, Hill, & Ryan, 1999; Case & Odamoto, 1996; Sekuler & Mierkiewicz, 1977; Siegler & Robinson, 1982). Children with mathematical learning disability perform poorly on this task compared to typically developing peers, in that they require significantly more time than typically developing children in completing this task (Landerl, Bevan, & Butterworth, 2004; Gersten et al., 2005; Anderson & Ostergren, 2012). A solid and accurate understanding of numerical magnitude is associated with more "automatic processing" (and faster response times) on a task like number comparison. In summary, a more mature, developed representation of magnitude is less prone to error on a number line estimation task, and requires less "processing time" on a number comparison task. Children with less-developed internal representation of magnitude may make more errors on a number line estimation task, and may require more time in judging the difference between two quantities.

Importance of Studying Children's Magnitude Representations

It has been established that the abstract idea of magnitude is internally and spatially represented, and the mental number line is a useful metaphor to capture this idea. Children's performance on tasks that access magnitude representations, such as number line accuracy and number comparison is linked to performance on standardized math tests and other measures of mathematical ability (Booth & Siegler, 2008; Ramani & Siegler, 2008; Siegler & Booth, 2004; Siegler & Ramani, 2009). Children's processing of magnitude serves as a building block to more complex mathematical procedures. Booth and Siegler (2008) found a relation between number line estimation accuracy and children's ability to answer novel addition problems correctly. In addition, within-grade correlations exist between children's number line estimation accuracy and their math achievement test scores (Booth & Siegler, 2006). Bachot et al (2005) found that a group of children who, unlike same-aged controls, did not display a typical SNARC effect on a number comparison task, also performed more poorly on a complex mathematical task. Andersson and Ostergren (2012) found that children with mathematical learning disability performed poorly on number line and number comparison tasks compared to age-matched controls, and attributed this to "less precise or fuzzy" magnitude representations. Furthermore, researchers have created interventions that aim to improve children's representations of number, and have found parallel improvements in magnitude processing tasks such as number comparison and number line estimation (Wilson, Dehaene, Dubois, & Fayol, 2009; Ramani & Siegler, 2008; Siegler & Ramani, 2009). One example of these interventions is a game that involves a child playing the character of a dolphin, and the task is to choose the larger of two numbers before a competitor (the crab) arrives at the key and steals the larger quantity. This game can become increasingly complex, where addition and subtraction are required to make a correct comparison (Wilson, Dehaene, Pinel, Revkin, Cohen, & Cohen, 2006).

In sum, helping children to process number magnitude may lead to improved performance on many functional and academic mathematical tasks. Measures that involve accessing spatial representations of number magnitude are correlated with math performance. Children with mathematical learning disability perform poorly on tasks involving access to magnitude representation, and interventions involving the improvement of number representations are low-cost and effective remediations of poor number sense. In order to better understand children’s mathematical difficulties and the mechanisms that link spatial representation to math performance, research must investigate the cognitive factors that influence performance on tasks that require access to the mental number line task. One such factor is attention.

Attention and Magnitude Processing

Although it has been established that children’s speed and accuracy vary widely on tasks involving magnitude representations, such as number line estimation and number comparison, less is known about the cognitive abilities that influence children’s performance on these tasks. The research on cognitive abilities and general mathematical learning that is pertinent to magnitude understanding is described below.

Cognitive processes and mathematics. Many general cognitive abilities (linked at the biological level to other brain areas) must be working efficiently and in a coordinated manner to permit successful mathematics processing. These cognitive abilities include memory (Bull & Scerift, 2001; Geary, 2004; Geary & Hoard, 2001; Geary et al., 2007; Koontz & Berch, 1996; McLean & Hitch, 1999), executive functions (Askenazi & Henik, 2010; Bull & Scerift, 2001; D’Amico & Passolunghi, 2009), verbal or visuo-spatial working memory (Passolunghi & Mammarella, 2010; Rotzer, Loenneker, Kucian, Martin, Klaver, & von Aster, 2009; Wilson & Swanson, 2001; Andersson & Ostergren, 2012) and finally, attention (Askenazi & Henik, 2010; Lindsay, Tomazic, Levine, & Accardo, 2001; Shalev, Auerbach, & Gross-Tsur, 1995). Askenazi and Henik (2010) have investigated attentional networks and their relation to mathematical performance in adults; however, the nature of the relation between attention and children's mathematical cognition is less understood. Findings from brain imaging studies on attention confirm that a network of neural areas that are separate, yet interrelated, work together to compute cognitive and emotional tasks. These attentional networks are involved in the selection and control of processing sensory information and information in memory (Posner, 2004). The current study aims to investigate a possible link between children's attentional abilities and their performance on a key dimension of mathematical understanding: magnitude processing. Demonstrating that lower-level cognitive skills, like attention, are needed to efficiently process magnitude may help further our understanding of children's mathematical development.

Attention and mathematical learning. Many deficits that characterize mathematical learning disability can be connected to impaired recruiting of attention (Geary, 2004). Koontz and Berch (1996) found that individuals with mathematical learning disability have a smaller subitizing range (i.e., the ability to quickly determine the quantity of small sets of objects). Recently, it was proposed that subitizing is moderated by attention in that limited attention decreases subitizing range (Railo, Koivisto, Revonsuo, & Hannula, 2007). Also, training in visual attention has been shown to increase subitizing range (Green & Bavelier, 2003). Askenazi and Henik (2010) demonstrated that deficits in attentional networks exist in adults with mathematical disability. Namely, those with developmental dyscalculia seem to be deficient in the executive function and alertness networks. They suffer from difficulty in recruiting attention, in addition to the deficits in magnitude processing.

The attentional networks. As previously mentioned, cognitive research has differentiated among several networks of attention: alerting, visual attention orienting, and executive functioning (Fossella, Posner, Fan, Swanson, & Pfaff, 2002; Posner & Peterson, 1990).

The *alerting system* refers to the state of "awakeness." It helps to activate and preserve attention. The role of the *attention-orienting network* is to help an individual move attention from and to specific locations in space. Attention orienting can be stimulus-driven (exogenous, reflexive, or bottom-up) or goal-directed (endogenous, voluntary, or top-down). Covert shifting of attention, as part of attention orienting, refers to shifts of spatial attention during which the eye gaze does not physically move. When participants are cued to attend to some location in space other than the central focus of gaze, they become sensitive to information that occurs at the cued location, and this results in faster processing of stimuli that may subsequently appear there (Posner, 1980). When the cues are predictive, the covert shifts are endogenous, and when they are nonpredictive, the shifts are considered exogenous (Askenazi & Henik, 2010). Finally, the *executive functioning network* of attention is implicated in conflict situations, in which conflicting visual stimuli compete for attentional resources, and in the inhibition of irrelevant information. The Stroop and flanker tasks are most often employed to assess this network. The present study aims to explore the possible role of these three networks in navigating the mental number line.

The Attention Network Test (ANT) was developed to assess the three attentional networks. It is based on the assumption that these systems operate independently (Fan, McCandliss, Sommer, Raz & Posner, 2002). The ANT has also been adapted to study the development of children's attentional networks, and it was found that these three systems are uncorrelated across individuals, confirming the independence of the networks (Rueda, Fan, McCandliss, Halparin, Gruber, Lercari, & Posner, 2004). On the other hand, Callejas, Lupianez and Tudela (2004) reported interactions among the attentional networks. Callejas and colleagues (2004) developed the Attention Networks Test-Interactions ANT-I, to study all three systems separately, as well as their interactions . The ANT uses only a valid/predictive cue whereas the ANT-I uses a nonpredictive cue with valid, invalid, and non-cued conditions (Askenazi & Henik, 2010). The ANT allows both endogenous and exogenous systems to be operating, whereas the ANT-I depends on the degree to which peripheral cues capture attention exogenously. Rueda and colleagues (2004) found no interactions between cue conditions and target flanker condition. This finding is consistent with evidence that the networks depend on generally different brain areas (Fan et al., 2001). Rueda and colleagues did state that even when lack of correlations between the networks is found, it would not be reasonable to consider the networks as totally independent since the brain areas involved clearly communicate with each other and orienting can result from instructions that activate the executive network. Using the child version of the ANT, Rueda et al (2004) found that the alerting system was fully functioning by the age of 10, executive functioning was fully developed by the age of 7, and the orienting network was found to be variable among individuals and not moderated by age.

Children begin to internally represent magnitude more linearly at around age 6 or 7, yet there is variability in their performance on tasks requiring accurate use of the mental number line, which is likely related to their differences in visual attention orienting. Investigating the role of the attentional networks in children's processing of number magnitude would help illuminate how mathematical abilities related to individual variability in magnitude processing develop.

Children, Attention, and Magnitude Processing

Research has pointed to deficits in attention in children with mathematical learning disability (e.g., Lindsay et al., 2001; Shalev et al., 1996); however, the subtleties within the relationship between attention and mathematical learning disability have not been investigated. There are several attentional systems, and they seem to interact with one another. Thus there are various ways to consider relationships between attention and children's magnitude processing. For instance, there may be a relation between the spatial attention orienting network and use of the mental number line, or perhaps a relation between attending to relevant information and suppressing irrelevant information (i.e., executive functioning) and use of the mental number line. We hypothesize that the visual attention orienting network will be predominantly related to performance on tasks involving access to internal representations of magnitude, as opposed to executive functioning or alerting for the following reasons: a neural overlap of brain areas coded for visual attention orienting and processing of magnitude, and an already established causal relationship between using a mental number line and covert shifts of attention.

Brain basis. Research has demonstrated a neural overlap between the region of the brain that processes magnitude (i.e., the intraparietal sulcus or IPS) and the nearby areas involved in processing visuospatial information (Dehaene, Piazza, Pinel, & Cohen, 2003; Hubbard et al., 2005; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009). Thus, it is thought that magnitude may be represented in the brain, at least in part, because neurons that are coded for visually representing spatial arrays are intermixed within the same patches of cortex as the IPS, which, as previously discussed, is an area associated with processing magnitude (Bueti & Walsh, 2009; Dehaene, 2011). Also, there is evidence that the IPS is not entirely exclusive to magnitude processing, but that it is also strongly involved in tasks that involve visual attention orienting (Corbetta & Shulman, 2002; Coull & Frith, 1998; Dehaene et al., 2011; Isaacs et al., 2001; Molko et al., 2003; Pinel et al., 2001; Simon et al., 2002; Wojciliuk & Kanwisher, 1999; Goffaux, Martin, Giulia, Goebel, & Schiltz, 2012). Areas of the brain that are involved in tasks requiring executive functioning are less proximal to the IPS. In fact, the frontal lobe, mostly the midline frontal areas (i.e., the anterior cingulate cortex), and the lateral prefrontal cortex are associated with executive control of attention (Bush, Luu, & Posner, 2000; Macdonald, Cohen, Stenger, & Carter, 2000).

Perhaps the most compelling evidence of the neural overlap between visual attention orienting and processing of number magnitude involves spatial neglect patients. Brain lesion studies show that patients with an acquired bias in orienting attention due to damage in the parietal cortex, also known as spatial neglect, struggle to accurately perform on mental number line tasks, such as answering the question "What is the midpoint between 1 and 20," as they do on similar tasks involving physical lines (Zorzi et al., 2002; Zorzi et al, 2006; Price et al., 2007; Simon, Mangin, Cohen, LeBihan, & Dehaene, 2002). In sum, neuroimaging studies have shown that numerical-spatial interactions arise from common parietal circuits for orienting of attention and processing quantity. Thus, it is very possible that variability in children's performance on tasks of visual attention orienting may be related to their performance on tasks involving internal representations of magnitude, such as the mental number line.

Causal connections and behavioural basis. Merely attending to a number during a magnitude comparison task actually causes covert shifts of attention, depending upon the number's magnitude -- to the left side for small numbers, or right side for large numbers. Thus, in one study, circles in the left visual field were detected faster when preceded by a low number (1 or 2) compared to a high number (8 or 9), and circles in the right visual field were detected faster when preceded by a high number relative to a low number (Fischer et al., 2003). This shows that mere observation of number activates automatic spatial representations associated with processing number magnitude. This phenomenon is consistent with the perspective that the same visuospatial attention mechanisms used in orienting attention between positions in physical space are used to shift attention across the mental number line (Hubbard et al., 2005; Knops et al., 2009a; Knops et al., 2009b; Goffaux et al., 2012). The Fischer et al. (2003) study shows us that covert shifts of attention are used during tasks involving the mental number line. Thus, it is important to demonstrate the effect that performance on this aspect of visual attention orienting may have on children's efficiency in using the mental number line. It has not yet been demonstrated whether or not the effect of poor performance of these visuospatial attention mechanisms, such as visual attention orienting, is related to an anomaly in using the mental number line.

Current Study

Askenazi and Henik (2010) investigated the role of attentional networks in adults' numerical comprehension, and found that participants with mathematical learning disability were more likely to demonstrate deficits in the executive function and the alertness networks, compared to matched controls. Very little is known about the role of children's attentional networks in their emerging numerical comprehension abilities, particularly in children who struggle with learning mathematics. This study aimed to delineate the role of three types of attentional networks (i.e., alerting, visual attention orienting, and executive functioning) in processing magnitude, which is assumed to be represented spatially.

Based on findings showing neural overlap, and the established link between magnitude processing via use of a horizontal representation of number magnitude and covert attention shifting, the visual attention orienting network was expected to account for unique variance in efficiency of using mental number line representations in children. Strong performance on visual attention orienting tasks is expected to be associated with more proficient performance on tasks that involve accessing spatial representations of number magnitude, demonstrating the role visual attention plays in emerging number processing abilities.

It was expected that variability in accuracy on the number line estimation task would be significantly predicted by visual attention orienting ability, after accounting for influences of executive functioning and alerting. Faster response times on the attention orienting portion of the attentional task were expected to be associated with more effective navigating of the mental number line, and better performance on tasks that require access to the mental number line. More specifically, strong attention orienting, as indicated by high accuracy and short response time in the spatial cueing trials of the ANT, compared with central cueing trials, was expected to be associated with better performance on magnitude processing tasks (i.e., fewer errors on the number line estimation task and faster response times on number comparison).

It was expected that certain variables would be correlated with magnitude processing, namely pre-existing math ability and general intelligence. If intercorrelations between these variables and the outcome variable were significant, they were to be included in the regression as control variables. The rationale for the inclusion of additional control variables is outlined, below.

Method

Participants

Participants were 58 children (21 boys and 37 girls; mean age = 7.75 years, *SD* = .32), from grade two classrooms in four public and private elementary schools in Winnipeg. The age was chosen because this is the age at which most children have begun to rely on a more linear representation of magnitude, and because this is the age at which clear mathematical difficulties can be observed. Also, according to the mathematics curriculum used by schools in Manitoba, instruction surrounding the 1-100 number line is received in grade two (Manitoba Education, Citizenship, and Youth, 2008). The four schools involved in the study represent the diversity of educational programming in Winnipeg; two schools involved French immersion programs and were part of the public school system, and the other two were private schools in which English was the language of instruction. Preliminary analyses showed that there were no significant differences in math ability between participants from either the private or public schools, as well as no differences in math ability between participants from French immersion programs and English language programs. Thus, these variables were not entered in later analyses.

Demographic data (age, gender, parental education and income levels, language spoken in the home) were collected to ensure the sample represented local socioeconomic and ethnic diversity. The dominant language used in participants' homes was English; however, other languages spoken in some of their homes included Tagalog, Spanish, Arabic, Bilen, Tigrigna, Amharic, and Bosnian. Household income ranged from less than $30,000 per year to more than $100,000 per year, and parent education levels ranged from junior high school education to graduate degrees. Participation of teachers, parents, and children was voluntary. Teachers received mathematical instructional materials, and children received math activity books and stickers, in order to thank them for their time. The primary investigator was a female Caucasian graduate student. The research assistants were two female Caucasian undergraduate students. More detailed frequency of occurrence within each demographic variable can be viewed in Table 1.

Apparatus

Computer-based tasks were created using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Tasks were presented using a Dell Precision M4800 laptop computer, with an ultra-high resolution (3200 X 1800 ppi) monitor, and a high-precision computer mouse used by participants to enter responses.

Materials

We used a number-line estimation task and a number comparison task to assess children's use of the mental number line. These are commonly used tasks in studying comprehension of number magnitude via use of an internal representation (Booth & Siegler, 2006; Geary et al., 2007; Laski & Siegler, 2007; Siegler & Booth, 2004). We used the Attention Network Test, Child (ANT; Rueda et al., 2004) to assess children's exogenous visual attention orienting, alerting, and executive functioning.

Magnitude processing outcomes.

Number line estimation. As indicated above, number line estimation is a commonly used index in exploring quality of representation of number magnitude (i.e., linear or otherwise). Estimation accuracy on this task can be used as a measure of children's magnitude processing (Barth & Paladino, 2011; Booth & Siegler, 2006; Geary et al., 2007; Laski & Siegler, 2007; Siegler & Booth, 2004; Siegler & Opfer, 2003; Slusser et al., 2011).

For the duration of each trial, a target number between 1 and 99 appeared at the top of a computer screen. Concurrently, a horizontal number line appeared in the middle of the screen, spanning the width of the screen, with the number 0 at the left end and the number 100 at the right end, each appearing below the line. See Figure 1 for an example.

Prior to beginning the experimental trials, the researcher explained to the participants that the number line always ranges from 0 to 100, and that the child was to use the computer mouse to position an on-screen cursor to the position on the line where the target number should be located, and to click the mouse button when the cursor had been placed in position on the line showing where he or she thought the displayed target number should go. There were two practice trials during which children were to mark the locations of the numbers 100 and then 0 on the extreme ends of the number line. If the children did not correctly place the 100 and 0 endpoints, the researcher provided corrective feedback about where the numbers belong. Although the researcher and research assistants followed a pre-set script, experimenters provided additional explanation if required before moving onto test trials. After the practice trials, no feedback was provided to children. The criterion for moving forward to test trials for participants was that they could independently indicate the correct position of the endpoints.

There were four numbers (two odd, two even) from each numeric decade, and eight from the first decade, consistent with past practice (Booth & Siegler, 2008; Laski & Siegler, 2007). The numbers that were presented were chosen by using a random number table, and they were as follows: 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 16, 18, 20, 24, 25, 27, 31, 36, 38, 39, 40, 44, 47, 49, 51, 53, 56, 58, 61, 62, 66, 67, 70, 74, 75, 79, 82, 83, 87, 88 91, 95, 96, and 98. Each child received a different random order of the numbers, and each number appeared only once, giving 44 trials per participant. Pilot testing with seven adults was conducted to ensure that the task instructions were considered understandable. Pilot participants had experience with children, and were deemed to have good judgement of what would be understandable by children.

To analyze the accuracy of number line estimates (also referred to as the degree of linearity), each child's absolute error was computed. For example, if a child was asked to estimate the location of 46 on the number line, and placed the mark at the point that corresponded with 38, the absolute error would be 8, as $|38 - 46| = 8$. Deviations were taken for the trials where y, the vertical deviation from the line, was clicked within +/- 5 units from the target line only. The proportion of trials that were excluded based on this rule was less than 1%. Clicks outside of the specified area are extreme outliers and attributed to motor error or premature clicking due to over-anticipation. The line was 174 mm in length, and thus, the length of a single unit on the number line was 1.74 mm. A click outside of this range was deemed to be anomalous error, possibly due to fine motor "over anticipation". Each child's median score across the 44 trials was the unit of measurement. Because a perfect linear pattern involves a 0 deviation between the child's estimate and the correct location, better accuracy performance is indicated by smaller median absolute error scores. To calculate internal reliability, we entered every second item into a split half reliability analysis, and found there was an acceptable correlation of .87.

Numerical magnitude comparison. In addition to the number line estimation task, number comparison tasks are also valid indicators of magnitude processing. Accuracy on this task was 94% for the entire sample. Hence, median solution time for correct trials only, taken from the onset of stimulus presentation to the point at which response was given, was used as a measure of efficiency of magnitude processing, as a second indicator of magnitude understanding. Because children must access magnitude representations to accurately complete the task, automaticity of magnitude processing, reflected in short solution times, can be considered an indicator of strength of magnitude understanding.

Similar to the design of Laski and Siegler (2007), half of the numbers from the number line estimation task (from each decade) were used, giving one number from each decade, and two for the 1-10 decade. Thus, children were asked to compare the magnitudes of 55 pairs of numbers, instead of all possible pairs. The 55 pairs presented for this task were combinations of the following numbers: 3, 8, 14, 27, 31, 42, 58, 66, 74, 82, and 96. Two blocks of 55 trials were used; one involved answering the question "which is more?" and the other involved answering the question "which is less?" In each trial, a pair of numbers appeared side-by-side, and children answered the question for the given block of trials. Each pair of numbers appeared equally often in each block. Block order was counter-balanced and the order of number-pairs within each block varied randomly across children. Prior to beginning the task, the researcher explained to children that on each trial two target numbers would appear on the screen and that the child would be asked to verbally indicate which number is more (or less). The numbers were displayed until the child responded. The child responded by clicking the left response key for the number on the left and the right response key for the number on the right.

The outcome for this task was median response time across trials. Medians were used in correlation and regression analyses, as opposed to means, because the means were not normally distributed. This is often the case with response time data. To calculate internal reliability, the mean overall response times on correct trials only for the "which is more?" block were correlated with the mean overall response times on correct trials only for the "which is less?" block. There was a significant Pearson correlation of .78 between these two blocks.

Visual attention predictors.

Attention Network Test (ANT). The ANT was used to assess the visual attention orienting, executive functioning, and alerting networks as influences on magnitude processing ability. Since these networks have been defined anatomically in many studies (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Corbetta & Shulman, 2002; Fan et al., 2001; Fan et al., 2003), this feature can make it attractive for investigating attentional development in children. The ANT has been previously used with children aged 6 to 10 years old (Rueda et al., 2004). The Sackler Institute for Developmental Biopsychology makes the ANT task available for download on its website (https://www.sacklerinstitute.org/cornell/assays_and_tools/). The ANT is a combined cueing and flanker task. For adults, target and flanker stimuli typically involve arrows; however, studies of the ANT with children have used animal displays, such as fish (Bednarek, Saldaña, Quintero-Gallego, Garcia, Grabowska, & Gómez, 2004; Rueda et al., 2004). Thus, the targets and flankers of the task in the current study were goldfish. The fish appeared on a blue background, and became animated on correct trials to maintain children's motivation. Sample stimuli and the verbal instructions for the task can be found in Appendix A.

In each trial, the stimuli either appeared above or below an initial central fixation point. Participants were instructed to attend to the target goldfish and respond indicating the direction the goldfish was pointing (leftwards or rightwards). Children pressed a left-side mouse key to indicate left-facing goldfish or a right-side key to indicate right-facing goldfish. Accuracy and response times were recorded. The target goldfish appeared either by itself, or with two goldfish flanking the left and right sides, pointing either in the same direction as the target goldfish or in the opposite direction (see Appendix). In sum, there were 3 types of flanking: no flanker (i.e., neutral condition), congruent flanker, and incongruent flanker.

There were four types of cueing: no cue, central cue, double cue, and spatial orienting cue. In the central cue condition, an asterisk appeared at the location of the initial central fixation cross. In the double cue condition, an asterisk appeared both above and below the central fixation cross. In the spatial cue condition, an asterisk appeared in the location of the upcoming fish display.

Since the cueing and flanker factors were combined with each other, there were 12 types of trials (e.g., no cue, no flanker; no cue, congruent flanker; no cue, incongruent flanker, etc.). There were three blocks, and one practice block involving 24 trials. The number of presentations above or below the fixation cross, as well as target orientation to the left or to the right was the same in each block. In total, there were 48 trials per block (12 types of trials x 2 target locations x 2 target orientations). Response times (defined as the time between the target onset and the subject's response), as well as response accuracy (correct report of fish facing direction), were recorded in each trial. Presentation order of conditions across trials was random. Children were directed to focus on the central fixation cross throughout the task, and to respond as quickly and accurately as possible.

Each trial began with a fixation point presented for a randomly determined duration of between 400 and 1600 ms. Subsequently, the cue (or no-cue fixation-only stimulus) appeared for 150 ms. A fixation-point-only stimulus was then presented for 450 ms, followed by either the onset of the target and flankers together, or by the onset of the target alone. The target stimulus remained on display until the participant responded, but not for longer than 1700 ms. After responding, the participant received auditory and visual feedback from the computer. The target fish became animated and "excited" after correct trials (with an auditory "woohoo" cheer from the computer), or a static display of the target with a low auditory tone sounded after incorrect trials.

Similar to the procedure in the study by Rueda and colleagues (2004), children were told that a hungry fish would appear on the screen and that to feed the fish, the child must press the correct mouse key (i.e., the key that is consistent with the direction the target fish is facing). The participant was told that the hungry fish would either be alone, or swimming with other fish. Hard-copy images of the target fish alone, and the target fish with the remaining two flanking conditions were shown to accompany verbal instructions.

The practice block took about 3 minutes and each test block took approximately 5 minutes. Participants were allowed to take breaks at the end of each test block. A small prize, such as stickers or ear buds, was given to the children at the completion of each block.

Following the recording of the response times and accuracy, the attentional effects of alerting, orienting, and executive functioning were computed. Accuracy on this task was 90%. Attention network scores were determined using response times for correct trials only. To calculate internal reliability, the mean overall response times on correct trials only for the data was divided into odd and even trails and correlated. There was a significant Pearson correlation of .60 between these two blocks.

Alerting attention network measure. The alerting effect for each child was computed by subtracting the mean response time of the double cue condition (averaged across the 3 types of flanker) from the mean reaction time of the no-cue condition (also averaged across the 3 types of flanker), with means calculated using data from accurate trials only. A large positive alerting effect indicates that the appearance of a double cue facilitated faster responding than the appearance of no cue at all. A small alerting effect (shown by negative scores) indicates that the appearance of a double cue was less helpful in facilitating faster responding than the appearance of no cue at all. Obtaining a negative value for an alerting effect means that the appearance of the double cue somehow hindered the ability to respond faster than if there was no cue at all.

Executive functioning attention network measure. The executive functioning network performance was computed by subtracting the mean reaction time of the congruent flanker condition (averaged across the 4 types of cueing) from the mean reaction time of the incongruent flanker condition (also averaged across the 4 types of cueing), for accurate trials only. A large positive executive functioning score indicates that the appearance of congruent flankers facilitated faster response times than the appearance of incongruent flankers. A small executive functioning effect indicates that the appearance of congruent flankers was less helpful in facilitating faster response times than the appearance of incongruent flankers. It is also possible that incongruent flankers resulted in greater response time "costs" and that the mean time difference indicates the "savings" brought on by the facilitation from congruent flanker condition. Obtaining a negative value for an executive functioning network score indicates that the appearance of congruent flankers somehow hindered the ability to respond faster than if there were incongruent flankers.

Attention orienting network measure. Finally, the orienting effect was computed by subtracting the mean reaction time of the spatial orienting condition from the mean reaction time of the central cue condition for accurate trials only. A large positive attention orienting score indicates that the appearance of a spatial cue facilitated faster response times than did the appearance of a central cue. A small attention orienting score indicates that the appearance of a spatial cue was less helpful in facilitating faster response times than the appearance of a central cue. Obtaining a negative value for an attention orienting effect indicates that the appearance of a spatial cue hindered the ability to respond faster than if there was a central cue. It was hypothesized that strong attention orienting ability (indicated by large positive scores) would be related to better performance on the magnitude processing tasks, as shown in regression analyses. It was not expected that the executive functioning or alerting networks would be related to magnitude processing.

Past research with 40 adults has found relatively high immediate test–retest reliability for the scores of each attentional network provided by the ANT test (Fan et al., 2002). These scores typically are not correlated, suggesting that the efficiency of each network can be measured somewhat independently with the ANT. There is only limited evidence on test–retest reliability in children. Rueda and colleagues (2004) conducted the test twice with a set of 28 children who repeated the task 6.5 months later. There were no significant correlations between the original network scores and their repetition 6.5 months later. To get some additional information on this question the researchers divided the first session data into odd and even trials and calculated the split half reliability between them. Overall RT (0.94) and error rate (0.93) were highly correlated in this comparison. The executive functioning (0.59) and alerting (0.37) network scores were significantly correlated but orienting (0.02) scores were not. One reason for the relatively low correlations could be the smaller number of trials available for each half of the data.

Control factors.

Visuospatial working memory. It is clear that both visuospatial working memory and attention are closely intertwined (Awh, Vogel, & Oh, 2006), and thus it is possible that children's visuospatial working memory would be correlated with their performance on the ANT, and thus might also be related to performance on the magnitude processing tasks. Entering visuospatial working memory ability would provide an indication of possible mediation of a relationship between attention orienting ability and magnitude processing.

Participants were shown a series of 100 trials that involved displaying pairs of images of animals (see Figure 2 for examples). One image in the pair depicted either a valid rotated rendition of the model image, or an invalid rotated rendition (a mirror image of the model). Participants were instructed to indicate whether the second rotated image (on the right of the screen) was identical to or different from the first image (on the left of the screen) by pressing a specified mouse button for same and different images. Whether the image on the right side of the screen was a mirror image or facing the same direction as the image on the left, it was rotated 0°, 22.5°, 67.5°, 112.5°, or 157.5° from the image on the left. Instructions for this task were adapted from a similar mental rotation task (Shepard and Metzler, 1988). A script for teaching trials was provided to research assistants for consistency (Appendix B). The teaching trials involved using paper images of animals in order to demonstrate the task that would soon appear on the computer. Researcher assistants were instructed to discontinue the task if the child is not correct on at least 6 of 8 practice trials, and to discontinue if the child was not able to do so.

Response time data from correct trials were recorded for each participant, and participants' median overall response time was used as the measure of visuospatial working memory. Faster response times were assumed to be associated with stronger visuospatial working memory. The stimuli for this task were provided by Sandra Kaltner, and were previously used in a study on mental rotation and motor performance in children with developmental dyslexia (Kaltner & Jansen, 2014). A similar mental rotation task was also used to measure visuo-spatial working memory in a study investigating magnitude processing abilities in children with developmental dyscalculia (Skagerlund & Traff, 2014).

General math ability. It was expected that, given the importance of magnitude processing in math learning, a child's current math ability could covary with his/her magnitude processing skills, and potentially mediate a relationship between attention orienting and magnitude processing. In order to control for this possibility, the WRAT-4 Math Computation subtest (Wilkinson & Robertson, 2006) was used to measure general math ability. Standard scores were used.

Intelligence. The Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-2) was used to provide a brief measure of children's general intelligence. The Vocabulary and Matrix Reasoning subtests were used to obtain an estimate of children's IQ. Standard scores were used, in order to control for possible mediation by intelligence in the relationship between attention orienting and magnitude processing.

Procedure

The two magnitude processing tasks, the ANT, and the mental rotation task were computer-administered, with the researcher providing verbal instructions, and with participants entering responses using the computer mouse. All three examiners (i.e., primary investigator and the two research assistants) were trained for a minimum of two four-hour sessions prior to the testing of participants. The primary investigator exceeded this minimum. There was a team of ten undergraduate honours psychology research volunteers who were each trained in hour-long sessions on how to administer the computer tasks. The primary investigator or research assistants were responsible for administering all paper/pencil tasks (i.e., the WRAT-4 and the WASI-2), and they often administered the computer tasks as well. The research volunteers administered computer tasks, under supervision of either the primary investigator or the research assistants. All testing was carried out during three sessions in a quiet room at the children's schools, and each session required approximately 20 to 30 minutes to complete. In total, each participant was tested for approximately one hour and a half. There was a brief exit interview to check in with the child and make certain he or she returned to the classroom in a positive mood. The child also chose a prize (i.e., stickers, ear buds, or a math activity book) upon exiting each session, to thank them for their time.

Written and informed consent was obtained from parents, and the study was conducted with approval of the Psychology/Sociology Research Ethics Board (REB) at the University of Manitoba, and with permission from involved school divisions, principals, and teachers. Assent was obtained from children by the researcher prior to the testing session. If at any point the child indicated a wish to discontinue, the session was terminated. No participants expressed a desire to cease testing. Consent forms were sent to all second grade students in each school to take home for parents to sign. To maximize generalizability of the results, the only exclusionary criteria were that participants must have reported normal or corrected-to-normal vision. To prevent differential treatment in the classroom, all children from each class involved in the study received stickers and math activity books, regardless of whether or not they participated in the study.

Information collected on the parent consent forms was as follows: child's date of birth, sex of child, child's ethnicity, whether or not the child had normal or corrected-to-normal vision or formal diagnosis of ADHD, language spoken at home, household income range, and highest levels of educational achievement.

These data are summarized in Table 2.

In order to test hypotheses, the original data analysis plan was to test zero order correlations to establish that there were relationships among conceptually related variables, like the magnitude processing tasks and math ability, and no relationships involving certain criterion variables (i.e., between each of the attentional networks and between the attentional networks and other predictor variables such as visuo-spatial working memory, general arithmetic ability, and general intelligence). It was expected that certain criterion (control) variables might be related, such as general arithmetic ability with general intelligence. The next step in data analysis was to use hierarchical regression to establish the extent to which the relationships with the criterion variables (i.e., the two magnitude processing tasks) are unique.

Results

Descriptive Statistics

Information on the demographic variables can be found in the Participants section, and in Table 1. Mean response times and accuracy rates for all computer tasks (number line estimation deviation, number comparison response time (for correct responses only), the three ANT networks (response times for correct responses), and mental rotation (response times for correct responses), and their respective standard deviations are reported in Table 2. Number line estimation statistics are reported in terms of absolute deviations. Preliminary calculations including signed deviations indicated a minimal bias towards the right (*M* = 0.56, *SD* = 4.05). Averages and standard deviations are also reported for the central/double/spatial/no cue trials and the congruent/incongruent/neutral flanker trials on the ANT. As expected, accuracy on all of the tasks using response time as an outcome was high. Accuracy on the number comparison task was 94%. Accuracy on the ANT was 90%. Accuracy on the mental rotation task was 85%. On the mental rotation task, a typical mental rotation pattern was found, in that as angular disparity increased, accuracy decreased and response time increased (see Table 3). Outliers were winsorized, based on a constant of 1.5, as consistent with standard practice (Tukey, 1977). All variables were normally distributed, except for response times on mental rotation and number line deviation scores. In order to avoid violating assumptions of linear regression, the data for these two variables were transformed using the least impactful transformation: square root. After this transformation, these variables were found to be normally distributed, and analysis proceeded as planned. Tables 3

Inferential Statistics

Correlation and regression analyses related attention and cognitive predictor variables to magnitude processing outcome variables (i.e., number line estimation and number comparison) to test hypotheses. Demographic variables (age, gender, parental education and income levels, language spoken in the home) were transformed into categorical variables and correlated with the outcome variables using Spearman's. None of the demographic variables were significantly related to the outcome variables except for one: years of age. Thus, age was included in subsequent analyses.

Correlations. Table 4 depicts the Pearson correlation coefficients for all the variables included in the multiple regression analysis. Although there were many significant correlations, it is notable that there were no significant correlations between attentional network scores and magnitude processing measures. Bivariate correlations did reveal significant and interesting relationships. There was a significant, negative correlation between two of the attentional network measures: alerting and executive functioning. This indicates that high scores on alerting are associated with low scores on executive functioning. This relationship was unexpected, as previous research has shown independence between these attentional networks in children (Rueda et al., 2004).

There was also a significant, positive correlation between the two magnitude processing tasks -- number line estimation deviations and number comparison response time -- consistent with the claim that both measure the same proposed construct. As number line estimation deviations increased, so did response time on number comparison. As expected, there were also significant relationships found between performance on both of the magnitude processing tasks and general arithmetic ability. Deviation scores on the number line task were negatively related to performance on the math computation subscale; large deviations (hence poorer number line performance) were associated with lower WRAT scores. Similarly, good performance on the number comparison task (reflected by small response times), were associated with high scores on the WRAT. This can also be described as performance on the number comparison task being positively related to better performance on the math computation subscale.

Another interesting and unexpected (positive) relationship emerged between performance on the mental rotation task and performance on the number comparison task. Good performance on the mental rotation task (reflected by small response times), was associated with good performance on the number comparison task (also reflected by small response times). There was also a near-significant correlation between performance on the mental rotation task and number line estimation accuracy, the other magnitude processing task. Good performance on the mental rotation task (reflected by small response times), was associated with good performance on the number line estimation task (reflected by small deviations). This relationship is noteworthy for reasons that will be discussed in the next section.

Finally, as expected, there was a significant positive correlation between general intelligence and arithmetic ability.

Further analysis of mental rotation. An analysis of variance revealed that on the mental rotation task, there was no significant difference between response times on trials for which the animals were facing the same direction and on trials for which the animals were mirror images of each other, $F(1, 4786) = 0.75$, $p = .745$. There was, however, an overall gender difference in response time favouring males, $F(1, 56) = 8.37$, $p = .005$. There was also a significant effect of angular disparity on response time for all children, $F(4, 4783) = 35.60$, $p < .001$.

Regression analyses. Despite the absence of expected significant zero-order correlations involving the attentional networks, the original data analysis plan with all predictor and criterion variables was followed. Using the enter method, two significant models emerged- one for each magnitude processing outcome variable (number line estimation deviation, and number comparison response time).

The first model accounted for significant variance on the number line estimation task, $F(7,50) = 350$, $p < .05$. This model explained 23.5% of the variance (Adjusted R^2 = .235) in performance on this task. Table 5 gives information for the predictor and control variables entered into the model. Arithmetic ability, general intelligence, and the attentional networks were not significant predictors, contrary to hypothesized expectations, but age contributed unique variance to performance on the number line estimation task. Also, visuospatial working memory (i.e., performance on mental rotation) contributed unique variance to performance on the number line estimation task, despite showing a near-significant zero-order correlation. Age contributed 10% of unique variance in number line estimation, while mental rotation contributed 6% of unique variance in number line estimation.

The second model accounted for significant variance on the number comparison task: $F(7,50) = 6.113$, $p < .0005$. This model explained 38.6% of the variance (Adjusted $R^2 = .386$) in performance on the task. Table 6 gives information for the predictor and control variables entered into the model. Contrary to hypothesized expectations, general intelligence and the attentional networks were not significant predictors, but arithmetic ability and visuospatial working memory (i.e., performance on mental rotation) did contribute unique variance to performance on the number comparison task. Mental rotation contributed 32% of unique variance in number comparison, and arithmetic ability contributed 7% unique variance in number comparison.

Discussion

Attention Network Findings

The original hypothesis was that attention orienting would be related to magnitude processing over and above alerting, executive functioning, and control factors such as intelligence and current math ability. This hypothesis was based on findings demonstrating neural overlap between areas of the brain involved in orienting of visual attention and magnitude processing (Dehaene et al., 2003), and that humans use visual attention orienting to access mental representations of magnitude (Fischer et al., 2003). It was expected that those who had poor visual attention orienting abilities would be less equipped to make a precise estimate on a physical number line than those with better-developed visual attention orienting abilities. Furthermore, it was expected that variability in response times on the magnitude comparison tasks would be uniquely predicted by visual attention orienting ability, because spatially-based magnitude representations are accessed to facilitate completion of this particular task. Thus, the time it takes to complete this task was expected to depend on the ability to orient visual attention efficiently across a mental number line, over and above alerting, executive functioning, and control factors such as intelligence, current math ability, and visuospatial working memory. Areas of the brain that are involved in tasks requiring executive functioning are distal to the IPS, in comparison to brain areas involved in attention orienting tasks. In fact, the frontal lobe, mostly the midline frontal areas (i.e., the anterior cingulate cortex) and the lateral prefrontal cortex, are associated with executive control of attention (Bush, Luu, & Posner, 2000; Macdonald, Cohen, Stenger, & Carter, 2000). Consistent with expectations, the executive functioning network and alerting networks were not related to magnitude processing. Although previous research has demonstrated that visual attention orienting is used during tasks involving the mental number line (Fischer et al., 2003), the current hypothesis that attention orienting ability would account for unique variance in measures of magnitude processing, which assume the use of a mental number line, was not supported. This outcome might be explained in the context of more recent research on the relationship between mental number line and visual attention.

A recent attempt to replicate the 2003 study by Fischer and colleagues (Zanolie & Pecher, 2014) provides little support for the idea that merely attending to physically presented numbers brings about shifts in visual attention consistent with orienting across a mental number line. This recent study gives some insight on why we failed to find the expected outcomes. Consistent with the Fischer et al. (2003) study, participants were adults, and mathematical ability was not a factor controlled for. Only in one of the two experiments in which participants processed number magnitude did participants in this study respond faster to targets in congruent locations (left for low magnitudes and right for high magnitudes) than in incongruent locations. In the other five experiments number magnitude did not affect spatial attention. This demonstrates, in contrast to Fischer et al.'s (2003) results, that the mental number line is not activated automatically but only when it is contextually relevant. Furthermore, these results suggest that, in general, image schemas like the mental number line may be context-dependent rather than fundamental to mental concepts. They may be called upon when relevant to the task, rather than influence the way we perform on tasks that are not necessarily relevant. Merely attending to numbers does not seem to activate use of a mental number line, but research on the SNARC effect demonstrates that being asked to estimate a number on a line or choose the larger of two numbers does seem to activate this schema. Thus, the argument that covert shifts of attention, which are shifts of attention that do not involve eye movement (attention orienting network), are automatically used during tasks like the number line estimation and number comparison tasks used in the current study has now been challenged. Although access to internal magnitude representations does not seem to be influenced by the attention orienting system, it seems to be influenced by another cognitive variable, which will soon be discussed. On the question of whether or not attention orienting influences magnitude processing, our study's results are consistent with Zanolie et al.'s finding, that the relationship between attention orienting and accessing the mental number line may not be as strong as past research has suggested.

Another potential explanation for why the hypothesized relationships were not found is that the visual attentional networks in children of this age simply are not as well developed as was suggested by previous research (e.g., Rueda et al., 2004). Evidence for this can be found in our preliminary analysis of the attentional networks data. In calculating the score for the attention orienting network, the participant's mean response time in the spatial cue condition was subtracted from his/her mean response time in the central cue condition. Notably, there were often negative values obtained for the attention orienting network, indicating that many participants did better – had shorter response times – in the central cue condition (presumably a more difficult condition that should require longer response times), than they did when the spatial location of the target was cued. In fact, the mean attention orienting network score was actually a negative number ($M = -13.03$) indicating that some participants may have taken longer to respond in the spatial cue condition than in the central cue condition. The mean score of attention orienting was not significantly different from zero, $t(57) = 1.47$, $p = .146$; however, spatial cue facilitation would have been indicated by a mean score significantly different from zero in the positive direction. The mean score of alerting was positive ($M = 43.15$), and significantly different from zero, $t(57) = 6.37$, $p < .005$, indicating that the warning asterisk was more helpful than no warning. The mean score of executive functioning was also positive ($M = 77.90$), and also significantly different from zero, $t(57) = 10.36$, $p <$

.005, indicating that congruent stimuli are more quickly processed than incongruent. Negative values in network calculations likely reflect noise and measurement error.

It should also be noted that no significant zero-order correlations between the network scores were expected; however, there was a significant correlation between alerting network and executive functioning network scores. In communication with Rosario Rueda (personal communication, March, 2015), it was suggested that the attentional networks are simply not as independent or as well-developed in children aged 7 and 8 years old, despite past research findings. As previously mentioned, Callejas and colleagues (2004) used a modified version of the ANT, in order to incorporate a cost-benefit paradigm into the task, allowing for analysis of interactions between the attentional networks. These researchers did find interactions between the networks for adults, and it is possible the networks influence each other for children as well. It also seems likely that the spatial and double cueing effects with valid cueing, and flanker effects, may depend upon physical characteristics of the stimuli of the measure, including overall display size, target visual angle, and stimulus intensity (luminance and duration). The split-half reliability of the ANT for the children involved in this study was only .60, and negative values were obtained in network calculations when theoretically these should not have been found. Thus, the ANT may not have had sufficient reliability or validity for use with this age group of children.

As previously mentioned, there is only limited information on test-retest reliability of the ANT flanker task with children. Rueda and colleagues (2004) conducted the test twice among a set of 28 children who repeated the task 6.5 months later. There were no significant correlations between the original network scores and their repetition

6.5 months later. The adult ANT was found to have reasonable test-retest reliability for the network scores within the same testing session and show relatively high correlations in a subsequent twin study (Fan et al., 2001). Future investigations could be dedicated to exploring test-retest reliability of the attention networks task in different age groups of children, or to studying the development of these networks in children longitudinally, as only cross-sectional developmental data has been reported to date. In conclusion, the results show that it is not reasonable to consider the attentional networks as independent. The brain areas involved clearly communicate with each other, and the effects of congruent flankers and spatial- and double-cueing conditions on magnitude processing may be more pronounced at a later age.

Visuospatial Working Memory Findings

Preliminary analysis demonstrated that there was no significant difference between response time performance on mental rotation trials that involved animals facing the same direction, and response time performance on trials involving mirror image animals (facing opposite directions). Theoretically, the latter condition should be more difficult to process than animals facing the same direction, but this finding may attest to the fact children of this age understand and are generally proficient at this task. There was, however, an overall gender difference in response time favouring males, which is consistent with previous findings (Jansen, Schmelter, Quaiser-Pohl, Neuburger, & Heil, 2013). There was a significant effect of angular disparity on response time for all children, $F(4, 4783) = 35.60, p < .001$, which is also consistent with previous findings (Jansen et al., 2013).

Although unexpected, visuospatial working memory emerged as an important piece of the puzzle about the magnitude processing aspects of mathematical learning in children, accounting for significant variance in both measures of magnitude processing. Since magnitude processing is a large part of mathematical learning, it is important that research investigates the relation between the cognitive predictors and magnitude processing. Children differ in their ability to process magnitude, and they also differ in their visuospatial working memory ability.

Visuospatial working memory and attention are closely related (Awh, Vogel, & Oh, 2006), and thus it was possible that at some point in development (perhaps in adulthood), visuospatial working memory abilities would be correlated with performance on the ANT, and exert a significant influence on magnitude processing task scores. However, in our study with children, the attentional networks were not related to either outcome of magnitude processing, but visuospatial working memory *uniquely predicted* performance on these outcome variables. A role of mediation cannot be ruled out for older individuals for whom attention networks are better developed, and potentially begin to play a role in magnitude processing.

Interpretation of the present results is quite straightforward and not surprising. The link between number- and space-processing, identified in the Spatial Numerical Association of Response Code (SNARC) effect (Dehaene et al., 1993; Fischer, et al., 2003; Ristic et al., 2006), is widely studied and often referred to as "the mental number line." It is believed to influence children's performance on tasks involving comparison of number quantities (Laski & Siegler, 2007). The results from the current study indicate that children with stronger visuospatial working memory ability are able to more efficiently manipulate the mental number line, and thus perform better on tasks involving comparison of number quantities. Magnitude is often visualized (i.e., mentally represented) in a spatial format. Thus, it is sensible to hypothesize that children who more efficiently manipulate this information in visuospatial working memory would perform better on tasks that involve access to and manipulations of magnitude representations as elements of visual memory. A host of research is consistent with this hypothesis (Bachot et al., 2005; Andersson & Ostergren, 2012; Dumontheil & Klingberg, 2012; Simmons,Willis, & Adams, 2012; Skagerlund & Traff, 2014). It is possible that children with poor visual–spatial working memory are prevented from establishing and processing symbolic spatial number representations founded on the innate number system. Finally, the body of research that supports the concept of the mental number line has led to low-cost interventions that can improve math performance in children with mathematical learning disability and in children from lower income backgrounds, by supporting changes in their mental representation of number magnitude (Wilson, Dehaene, Pinel, Revkin, Cohen, & Cohen, 2006; Ramani & Siegler, 2008; Siegler & Ramani, 2009).

Previous research has shown that numerical-spatial interactions arise from common parietal circuits for visual attention orienting and processing of quantity. Thus, it was originally hypothesized that visual attention orienting would uniquely contribute to performance on tasks accessing magnitude representations. This was based on research involving spatial neglect patients, who had lesions to the parietal cortex, and had difficulty bisecting a number line in the way spatial neglect patients have difficulty bisecting physical lines (Zorzi et al., 2002; Zorzi et al, 2006; Price et al., 2007; Simon, Mangin, Cohen, LeBihan, & Dehaene, 2002). This demonstrates the spatial nature of the mental number line and a striking functional similarity between the way humans process the mental number line and physical lines. As previously mentioned, it also demonstrates a possible neural overlap between regions of the brain involved in attention orienting and the region of the brain that processes quantity (the IPS). It is also true, however, that the IPS is implicated in a variety of cognitive processes, including visuospatial working memory (Klingberg, Forssberg, & Westerberg, 2002). Current neurological and behavioural research continues to demonstrate associations among visuospatial working memory and arithmetic abilities (Bull, Epsy, & Wiebe, 2008; De Smedt, Janssen, Bouwens, Verschaffel, Boets, & Ghesquière, 2009; Dumontheil & Klingberg, 2012; Simmons et al., 2012; Metcalfe, Ashkenazi, Rosenberg-Lee, & Menon, 2013). Furthermore, recent studies point to a deficiency in visuospatial working memory in individuals diagnosed with developmental dyscalculia (Rostzer, Loenneker, Kucian, Martin, Klaver, & Von Aster, 2009; Rykhlevskaia, Uddin, Kondos, & Menon, 2009; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). Visuo-spatial working memory likely provides a "mental workspace" for various transformations and manipulations crucial for mathematics. Visuo-spatial strategies, shortcuts, and representational schema can be used in seemingly non-visual tasks; for example, when adding or subtracting numbers, one can visualize the numbers along an imagined number line. The mental number line is a helpful way to conceptualize the manner in which children represent the abstract concept of magnitude in a more tangible, concrete format.

In addition to being implicated in processing quantity and during tasks that require visuo-spatial working memory, the IPS also activates during tasks that involve motion coherence (Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000). Motion coherence is our ability to imagine and process movement. Humans hold onto the image of the mental number line in visuo-spatial working memory, but our use of the mental number line does not stop there. It is possible that in order to process stimuli on this line, we must be able to proficiently imagine movement along this line. Research has begun to investigate the role of deficient motion coherence in children with mathematical learning disability (Sigmundsson, Anholt, & Talcott, 2010). Future studies can further explore whether or not motion coherence plays a role in magnitude processing.

It will be important for future research to investigate the causal relationships between the cognitive predictors of visuospatial working memory, magnitude processing, and general arithmetic ability. For instance, does visuospatial working memory develop first, and play a key role in children's emerging ability to manipulate mental representations of magnitude, in turn improving math performance? Or do children with more proficient math ability do better on tasks involving magnitude processing, and this influences their development of visuospatial working memory? After these relationships are established, it would be beneficial to explore whether or not highly motivating games that involve a heavy visuo-spatial working memory component, such as *Minecraft*, could be beneficial in improving children's early mathematical skills, including their magnitude processing (Peerson, 2011).

Limitations and Future Directions

Despite the careful planning of any psychological research, all studies exhibit some limitations and bias. Acknowledgement of limitations allows the reader to keep the study in perspective, and avoid over-generalization of results.

A limitation of our study exists in the chosen methods. Use of correlational techniques among concurrent measures of perceptual processes and criterion tasks (e.g., magnitude processing) is quite common in the math development literature. As with all correlational research, no causal relationships can be inferred from the findings in this study; however, the findings do make a significant contribution in illuminating the limits of attention network influences and the predominance of visuospatial working memory in accounting for variance in magnitude processing in children, as an important step towards understanding the underlying factors that account for children's magnitude processing. This study served an exploratory purpose to identify cognitive factors that account for significant variance in early mathematical skill of magnitude processing. Understanding of magnitude is fundamental for mathematical development, and thus it is imperative to explore the potential role of core attentional and cognitive factors that influence the way in which magnitude processing is manifested in children learning about mathematics. Future research could investigate potential causal relationships that bring about strong understanding of magnitude in children. Also, because the data were concurrently collected, the direction of effects could not be established. Hence, longitudinal research is needed to provide information about the predictive aspects of visual attention orienting and visual working memory for the development of magnitude processing in children.

Another limitation in the chosen methods relates to the low reliability that was found in the measures of visual attention for the age group of children in this sample. Past research found that the ANT Child can provide reliable and valid measures of children's visual attention orienting, executive functioning, and alerting (Bednarek et al., 2004; Rueda et al., 2004). However, in the current study this task was not found to be valid in describing anatomically separate attentional networks for 7 and 8 year old children, given the correlation found between two of the three attention network outcomes. Future research could explore the potential relationship between other measures of attention that are more valid (and more reliable) for measuring attention in this age group.

A final point to acknowledge is that visuospatial working memory explained only part of the variance in the early mathematical skills studied. The contribution of other cognitive factors must be recognized in addition to working memory. Future research needs to expand existing work on the role of phonological awareness (De Smedt et al., 2009; Fuchs et al., 2005; Simmons et al., 2008), processing speed (Bull & Johnston, 1997), motion coherence (Sigmundsson et al., 2010), and fundamental domain-specific quantitative abilities (Gilmore, McCarthy, & Spelke, 2007; Halberda, Mazzocco, & Feigenson, 2008; LeFevre et al., 2010; Mundy & Gilmore, 2009; Nordman, Bull, Davidson, & Church, 2009) to further consider how they relate to individual mathematical skills in magnitude processing, and the extent to which they explain variance that is not explained by working memory.

General Conclusion

The current study aimed to investigate the relation between certain cognitive/attentional predictors and magnitude processing reflected in use of the mental number line. Our study shows that although children's visual attention orienting was not related to their magnitude processing, their visuospatial working memory was. It is hoped that the results add to the "bigger picture" in children's mathematical education, in that we now know of another potential influence in an emerging mathematical skill: visuospatial working memory magnitude processing. Researchers, policymakers, teachers, and school psychologists should recognize that solid research in mathematics difficulty considers the strengths and limitations of math-related areas of the learner’s abilities, reflected in behavioural and neural processes. Understanding more about the variety of cognitive skills that contribute to emerging magnitude processing skills will illuminate the nature of anomalies in early mathematical development, and help in early identification and intervention.

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Table 1

Frequencies of Demographic Variables.

Variable	Frequency	Percent
Gender		
Boys	21	36
Girls	37	64
Years of Age		
7	37	64
8	21	36
School		
1	13	22
2	11	19
3	14	24
4	20	35
Provincial Status of School		
Private	30	52
Public	28	48
Highest Level of Parental Education		
High School	11	19
College Certificate	10	17
College Diploma	8	14
University Degree	16	28
Graduate Degree	8	14

Range of Household Income		
Less than 30,000/year	6	10
30,000 – 60,000/year	12	21
60,000 – 100,000/year	20	35
Over 100,000/year	13	22
Dominant Language Spoken in Home		
English	43	74
Tagalog	1	12
Spanish	1	2
Arabic	1	2
Other	5	9

Table 2

Descriptive Statistics of All Measures Averaged Across Participants (N = 58)

Variable	Minimum	Maximum	Mean	Std. Deviation
WASI IQ	68	122	100	12
WRAT Math	72	114	95	10
Alerting Network	-62	161	43	52
Attention Orienting Network	-159	123	-13	67
Executive Functioning Network	-32	175	78	57
ANT Central Cue Condition	624	1100	887	105
ANT Double Cue Condition	616	1260	8578	110
ANT Spatial Cue Condition	639	1116	899	98
ANT No Cue Condition	678	1167	901	107
ANT Congruent Flankers Condition	659	1107	870	98
ANT Incongruent Flankers Condition	726	1253	947	110
ANT Neutral Flankers Condition	591	1145	846	109
Mental Rotation	835	2907	1591	463
Number Comparison	865	2293	1403	311
Number Line Estimation	.00	3	1	.61

Note: WASI IQ: Standard score on composite of WASI matrix reasoning and vocabulary subtests; WRAT Math: Standard score on WRAT math computation subscale; Alerting: Visual attention alerting network (ms); Executive Functioning: Visual attention executive functioning network (ms); Attention Orienting: Visual attention orienting network (ms); ANT conditions: response time (ms); Mental Rotation: Mental Rotation response time - visuospatial working memory (ms); Number Comparison: Number Comparison task response time (ms); Number Line Estimation: Number Line task accuracy (absolute error deviation units).

Table 3

Average Accuracy (%) and Response Times (ms) for Each Angle in the Mental Rotation Task

Angle	Degree of Rotation	Accuracy *M (SD)*	Response Time *M (SD)*
1	0	91 (13)	1663 (663)
2	22.5	90 (14)	1757 (609)
3	67.5	88 (16)	1974 (822)
4	112.5	85 (18)	2277 (1132)
5	157.5	73 (19)	2665 (1175)

Table 4

Correlations Among Cognitive/Visual Processing Predictors and Concurrent Math Skills Outcomes

	1	2	3	4	5	6	7	8
1. Number Line Estimation								
2. Number Comparison	.387**							
3. Alerting	.082	-.069						
4. Attention Orienting	-.093	.010	-.164					
5. Executive Functioning	-.161	.113	-.305*	.050				
6. Mental Rotation	.230	.532**	-.063	.081	.008			
7. WRAT Math	-.289*	-.323*	.11	-.078	-.079	.016		
8. WASI IQ	-.252	-.240	.143	-.110	-.043	.057	.369**	
9. Age	.352**	.182	-.054	-.116	-.110	.019	.062	-.169

Note: Number Line Estimation: Square root transformation of the medians of the Number Line task accuracy; Number Comparison: Number Comparison task response time; Alerting: Visual attention alerting network; Attention Orienting: Visual attention orienting network; Executive Functioning: Visual attention executive functioning network; Mental Rotation: Square root transformation of Mental Rotation response time - visuo-spatial working memory; WRAT Math (standard score on WRAT math computation subscale); WASI IQ (estimated from standard scores on WASI matrix reasoning and vocabulary subtests); Age (in years)

*** $p < .001$; ** $p < .01$; * $p < .05$; ~ $p < .10$ all other correlations not significant.

Table 5

The Unstandardized and Standardized Regression Coefficients for the Variables Entered into Model #1: Magnitude Processing Reflected in the Number Line Estimation Task

Variable	B	SE B	β
Alerting Network	.001	.008	.118
Attention Orienting Network	-.001	.002	-.088
Executive Functioning Network	-.001	.001	-.116
Visuospatial Working Memory	.028	.001	.252**
Arithmetic Ability	-.019	.006	-.293*
General Intelligence	-.007	.151	-.136
Age	.407	.939	.326*

*$p = .05$, **$p = .001$

Table 6

The Unstandardized and Standardized Regression Coefficients for the Variables Entered into Model #2: Magnitude Processing Reflected in the Number Comparison Task

Variable	B	SE B	β
Alerting Network	.339	.674	.056
Attention Orienting Network	-.226	.494	-.049
Executive Functioning Network	.642	.597	.118
Visuospatial Working Memory	29.993	5.723	.548**
Arithmetic Ability	-9.000	3.501	-.291*
General Intelligence	-3.458	2.797	-.143
Age	107.518	66.147	.176

*$p = .05$, **$p < .005$.

Figure 1

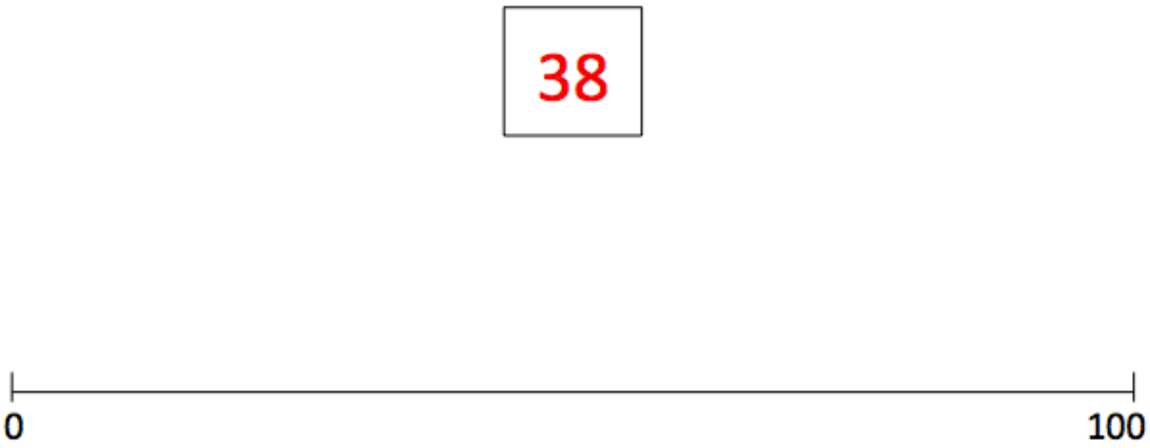


Figure 1. Example of stimulus from the number line estimation task.

Figure 2

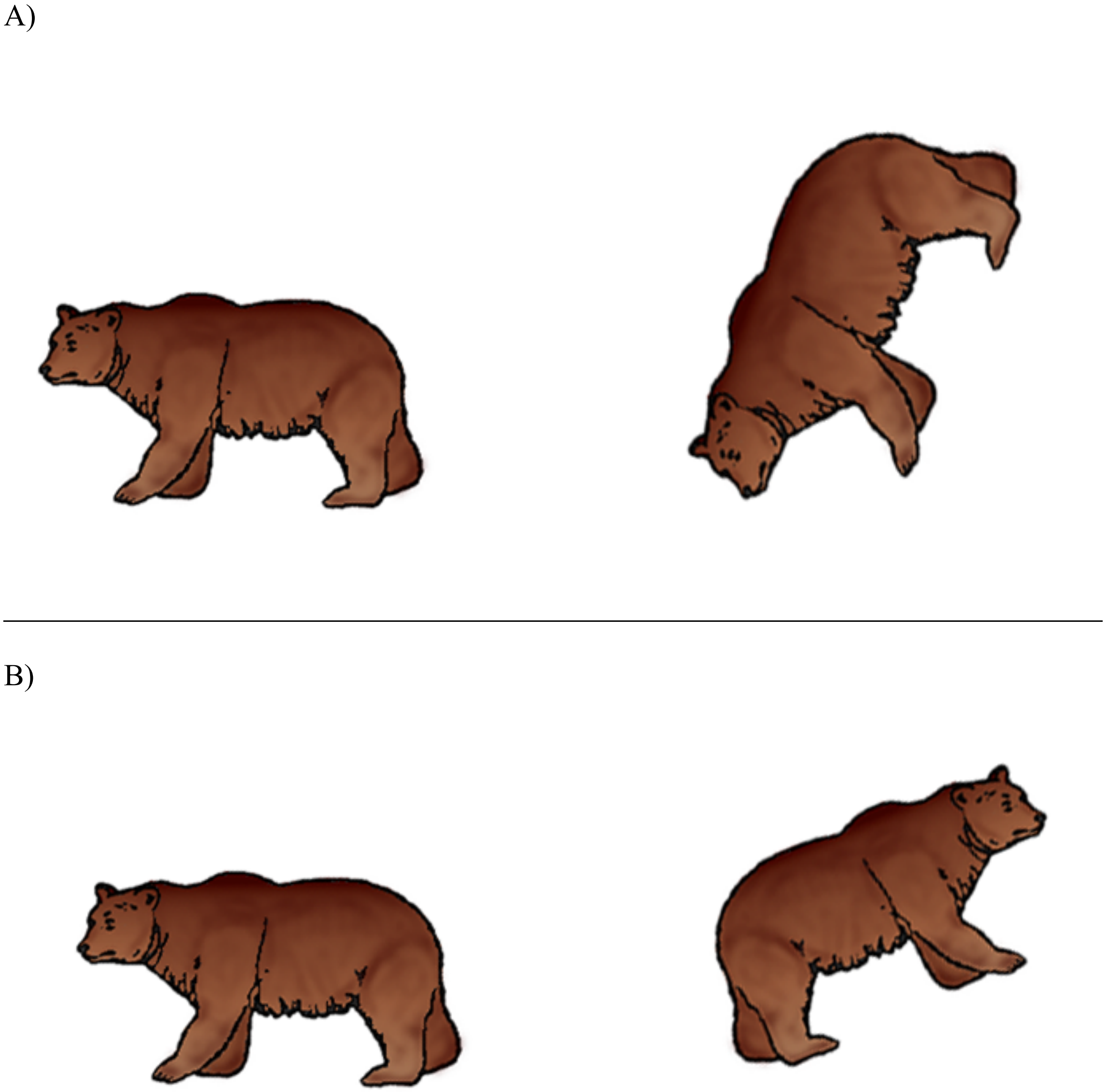


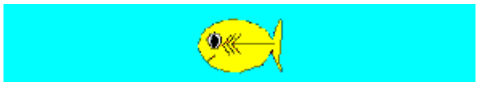
Figure 2. Sample pairs of images for the mental rotation task. The first pair (A) is an example of a pair with a valid rotated rendition of the model image, because they face the SAME way. The second pair (B) is an example of a pair with an invalid rotated rendition of the model image, because it faces a DIFFERENT way.

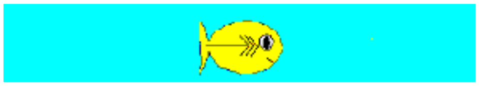
APPENDIX A – Instructions for ANT Task (Child Version)

(From Fan et al.; https://www.sacklerinstitute.org/cornell/assays_and_tools/)

"You're going to play a computer game where your job will be to feed a hungry fish using the mouse. The way that you feed a fish when it appears on the screen is by pressing the button on the mouse that matches which way the fish's mouth is pointing."

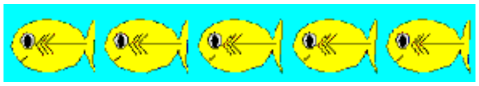
Then show them cue cards of the single-fish stimuli and ask them to each demonstrate which button they would press to feed that fish.

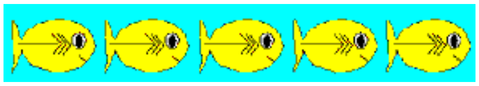


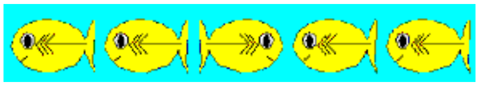


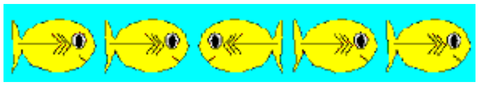
When you are sure each subject understands, continue:
"Sometimes the hungry fish will be alone, the way you just saw, and sometimes the fish will be swimming with some other fish as well. When you see more than one fish, your job is to feed only the fish in the center. So what matters is the where the middle fish's mouth is pointing."

Then show them cue cards of the stimuli with flankers (first congruent, then incongruent) and ask each to demonstrate which button they would press.









When each subject understands, go on to the practice trials. Tell them that they will see a plus-sign in the middle of the screen and that they should keep their eyes on the plus-sign throughout the game. Also tell them that they should try to feed the fish as quickly as they can, but not so fast that they will make many mistakes. Each child's practice trials should be individually supervised (so if there are more subjects than testers they will complete the practice trials one at a time). They get the "woohoo" feedback through headphones, and you can also give them verbal feedback during the practice trials. When they finish the practice trials they complete three test blocks on their own and get stickers at the end of each block. All subjects can begin the test trials at the same time. In between each block the subject can choose to take a short break or continue, but they should not take breaks within the blocks, only between them.

APPENDIX B - Instructions for Mental Rotation Task

(Adapted from Shepard & Metzler, 1988**)**

"We’re going to play a computer game where your job will be to say if one animal is the same as the other animal, using the mouse. The other animal is moved around, but when they are the same the other drawing can be made to look exactly the same as the first drawing if it was moved back, like this” … *(researcher uses the cut out example animals labelled A to demonstrate how if the second one is rotated or “moved back”, it looks the same as the first one)*. “So, are these two the same or different?” *(researcher waits for an answer, and corrects the child if an incorrect answer is given).* “When the drawings are different, there is no way to move them to make one animal look exactly the same as the other, like this” … *(researcher uses cut out examples animals labelled B to demonstrate how if the second one is rotated or “moved back”, it looks the same as the first one)*. “So, are these two animals the same or different?” *(researcher waits for an answer, and corrects the child if an incorrect answer is given).*

“Let’s try some on the computer. The way that you say that the animals are the same is by pressing the button on the mouse on the right side; if the animals are different, then press the mouse button on the left side."

Then show them cue cards of identical animal stimuli (pair of crocodiles) and ask them to say if the drawings are the same or different. If correct, ask them to demonstrate which button they would press to indicate the two drawings are the same.

If the participant cannot indicate sameness, then provide additional instruction, such as: "If you try to imagine moving this one around *(point to the right-side drawing, and indicate a rotating motion with your finger, in the direction that would match the orientation of the left-side drawing)*, then you can see that the drawing is the same as the one on the right side." Repeat again with a "same" item.

When the participant indicates understanding of the task with the "same" items, present a cue card (pair of animals) with "different" items, and ask for the answer. If correct, then ask the participant to indicate the mouse button to be pressed.

Carry out the practice trials on the computer (4 same, and 4 different, randomly ordered). Continue to experimental trials when the participant is correct on at least 6 of 8 practice trials. Otherwise, repeat the practice trials. If the child is not able to obtain at least 6 correct answers out of 8, discontinue the task.

Present the experimental trials. There is a break after the 50th trial, to provide a rest for the participant if needed.