A VISUOMOTOR PERSPECTIVE ON DEVELOPING TEMPORAL AND SPATIAL REPRESENTATIONS OF NUMBER

by

Rebecca Ruth Sheridan

Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds

School of Psychology, Faculty of Medicine and Health

October 2015

When the spirits are low, when the day appears dark, when work becomes monotonous, when hope hardly seems worth having, just mount a bicycle and go out for a spin down the road, without thought on anything but the ride you are taking.

Arthur Conan Doyle, 1896

Number is the within of all things.

Pythagoras of Samos

INTELLECTUAL PROPERTY AND PUBLICATIONS

The candidate confirms that the work submitted is his/her own and that appropriate credit has been given where reference has been made to the work of others.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisors, Amanda Waterman, Mark Mon-Williams, Richard Allen and Charity Brown. I am especially indebted to Amanda for putting up with me so long! Her support and guidance in the thesis and beyond has not gone unnoticed and I am very grateful; it's been a pleasure.

I am thankful to the numerous schools who welcomed me with gates wide open and to all the children who have participated in my research. Thanks also goes to the lovely helpers I have had, notably Ed, Katie and Joyti.

My thanks go to my colleagues and friends in the School of Psychology for a brilliant few years. Special mentions here go to Jess, for being an excellent coffee and gig buddy, to Rachel, for all the fun during circuit training and to Denise and Jac for their invaluable kindness, generosity and friendship. I also wish to thank George, Earle and Oscar for their friendship and help in times of need. Special thanks go to all my fantastic office mates, but especially Emma, Helen, Katy and Callum. From batting piñatas with poster tubes to impressive theme cakes and all that's in between (notably tough mudder, pints of tea and four fish) – it's been a joy! I would also like to thank all of the incredible people who looked after me so well in Madison, notably Andrea, Scott, Hannah, Grace and Rachel.

During my PhD I lived with three amazing people, Radka, Paula and Dave. An eclectic mix of thoughtful (yet random!) conversations, boy band harmonising and the occasional night of trashy TV kept me sane and so I say to you děkuji, danke and xiè-xie. I also have the best friends I could wish for in Sophie, Ashleigh and Karl. I look forward to seeing more of them all post PhD!

Finally, endless love and gratitude of course goes to my wonderful family; my parents Jane and David, my brother's Mark and Philip (and their partners Helen and Jenna) and all my fantastic grandparents. But most of all, this thesis is dedicated to Kevin, whom we love and miss dearly.

ABSTRACT

Despite being an abstract concept, our representation of number appears to be grounded in the physical realities of time and space. However, very little research investigates the relationship between these three concepts in children. Thus, this thesis investigated children's ability to represent number temporally (pertaining to time) using frequency processing tasks, and their ability to represent number spatially using a novel adaption of a number line task. Firstly, two experiments (Chapters 2 & 3) revealed that children are remarkably accurate at recalling the frequency of both everyday events, specifically their intake of fruit smoothies, and of short term events, namely shape repetitions in a computer based task. Secondly, it was observed that Western educated adults have a default preference for representing number spatially with small numbers on the left and large numbers on the right (Chapter 4). Whilst these default preferences were not observed in children (Chapter 5), there was some evidence that cultural background can influence the direction of these preferences (Chapter 6). Nevertheless, irrelevant of directional preferences, children became more accurate at representing number spatially with age; this ability was related to both mathematical achievement and fine motor skills.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Our understanding of number has a rich ontological and evolutionary history (Dehaene, 2011); it appears that both human and non-human animals share a basic understanding of numerosity, that is, the ability to judge and compare small quantities (Dehaene, 2011; Hubbard et al., 2008). For example infants and non-human animals such as rats and monkeys are able to discriminate between numerosities with increasing precision and decreasing ratio differences, and are able to track small quantities (~4 items) (for review see Feigenson, Dehaene, & Spelke, 2004). Further, it appears that children have a non-symbolic numerical system which develops before language skills and is used for the approximate estimation of number (Feigenson et al., 2004; Hyde, 2011; Libertus, Feigenson, & Halberda, 2013; Mazzocco, Feigenson, & Halberda, 2011). However, it is only humans who are able to build on these basic numerosity skills to gain a deeper understanding of number which allows us to, for example, perceive cardinality, use number words and count (Hubbard et al., 2008). These evolutionarily developed skills can be termed early number knowledge, and with practice and formal education are further developed to underscore children's mathematical attainment (Östergren & Träff, 2013). In this sense, mathematics attainment is a broad concept including, for example, our ability to complete complex calculations and our knowledge of shapes and basic algebra (Department of Education, 2013).

As humans, we utilise numerical information every day to manage our time, pay bills and understand shopping discounts. As children, mathematical knowledge is a core part of the school curriculum, but is also utilised in games and activities outside of school, such as counting to 10 in hide and seek.

However, in 2013 20% of British children leaving primary school did not pass their mathematics test at the level expected by the Government and 5% didn't pass at the level a seven year old should be achieving (National Numeracy, 2014). This underperformance in mathematics is also common in the USA (see National Centre for Education Statistics, 2013). This is both a personal and a societal issue given that mathematical problems are cumulative and persist through life (Jordan & Kaplan, 2009), and that appropriate development in mathematics appears to be important for a number of factors in later life, such as job success and earning potential (Crawford & Crib, 2013). This thus suggests that children's mathematical development during the early years is crucial for life success, and that any underperformance may lead to negative life outcomes; it is therefore important to investigate how mathematical knowledge develops and how it can be enhanced.

The literature into how humans represent number has grown steadily since the early 90's with research spanning cognitive, neurological, pedagogical, philosophical and linguistic disciplines (Cohen Kadosh, Lammertyn, & Izard, 2008). Research has investigated topics including the development of children's basic mathematical knowledge, calculation abilities, mathematical reasoning, the relationships between numerical skills and the interrelation between numerical and non-numerical skills. It has also focused on areas where skills appear to have developed atypically such as in developmental dyscalculia (Butterworth & Laurillard, 2010; Kaufmann et al., 2013; Landerl, Bevan, & Butterworth, 2004; Von Aster & Shalev, 2007) and mathematics anxiety (Lyons & Beilock, 2012; Maloney, Ansari, & Fugelsang, 2011; Vukovic, Kieffer, Bailey, & Harari, 2013; Wu, Barth, Amin, Malcarne, & Menon, 2012). For example, we now know that children with developmental dyscalculia have deficiencies in a number of basic numerical skills such as comparing non-symbolic numbers (e.g. sets of dots) and linking non-symbolic numbers to Arabic words (for review see Kaufmann et al., 2013).

One area which has been relatively neglected relates to our representation of number in time and space, especially in children, despite the hypothesis that time, space and number are interconnected (Cohen Kadosh et al., 2008; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Walsh, 2003). The most obvious example of these connections is the use of the number line which links number and space (e.g. Dehaene, Bossini, & Giraux, 1993), and the use of spatial references when discussing time (Casasanto & Boroditsky, 2008; Núñez & Cooperrider, 2013). Evidence for links between these three concepts is present in human infants, trained animals and in people living in remote cultures, such as Amazonian tribes, thus suggesting these associations may be present from birth; we are predisposed to link these concepts (de Hevia et al., 2014). For example, eight to nine month old babies create number-space mappings such that longer lines are related to greater numbers (de Hevia & Spelke, 2010), and to longer temporal durations (Srinivasan & Carey, 2010). It is debated whether an underlying common magnitude system is responsible for these links (see Walsh, 2003), or whether they are represented by separate, but overlapping systems (de Hevia et al., 2014, see Cohen Kadosh et al., 2008 for review). For example, a common view in the spatial-numerical cognition literature is that the systems share overlapping neural circuitry which results in the strong associations seen between space and number (Hubbard, Piazza, Pinel, & Dehaene, 2005).

Thus far, much of the temporal-numerical research focuses mostly on very young children, non-symbolic forms of number and the processing of duration, whilst the spatial-numerical research is in adults. This thesis will build on this existing research by assessing the link between number and time in the form of frequency processing (the number of times an event has occurred), and spatial-numerical associations in the form of a novel use of the standard number line task. In this chapter I will start by discussing the current literature regarding children's ability to make temporal judgements of real contextually experienced events, such as staged events in a classroom. Second, I will discuss children's ability to judge the frequency of short term events, such as the appearance of pictures in a computer based task. I will then move on to consider how we represent number, specifically the links between number and space, how these links develop and how they might influence mathematical achievement.

1.2 The Temporal Representation of Number: Frequency Processing

Frequency processing can be considered as a numerical skill; it involves a judgement of how many events have occurred within a given time period instead of a judgement of how many items are in a constant set at a single time point as is typical in counting. Frequency processing can also be studied in relation to real life events, or a judgement of stimuli in a short computer based task. Both of these types of frequency processing are important skills in life. The former may be important in medical and forensic settings as well as in day to day life such as when monitoring food intake. The latter is involved in new word learning in infants and adaptive functioning from an evolutionary perspective. These themes will be discussed further in the following two sections.

1.2.1 Frequency Processing of Everyday Events

Currently, very little is known about children's ability to judge how many times an event has occurred within a given time period (Orbach & Lamb, 2007; Roberts et al., 2015). However, it has a number of important applications. For example, when visiting the doctor or dentist, they may ask about the frequency of certain behaviours or pains which could provide crucial information for diagnosis and treatment (Conrad, Brown, & Cashman, 1998). A further application is in forensic settings, particularly child abuse investigations, where frequency information can be crucial (Orbach & Lamb, 2007; Sharman, Powell, & Roberts, 2011; Wandrey, Lyon, Quas, & Friedman, 2012). For example, interviewers are expected to obtain event specific information from witnesses, but this may be hindered if a child cannot accurately determine the frequency of the alleged events (Orbach & Lamb, 2007). It also bears direct relevance to the Governments 'Five a Day' scheme which encourages people to consume at least five portions of fruit and vegetables per day in order to reduce the risk of obesity and chronic diseases such as cancer and cerebrovascular disease (NHS, 2011). Consuming the five pieces of fruit and vegetables per day may rely on being able to recall how many portions you have already consumed that day, and whether you have met the target or need to consume more. In other words, you have to estimate, and monitor, the frequency of your daily intake.

Much of the present literature centres on either short, computer based laboratory studies, or forensic settings. The former studies typically involve asking participants to determine how many times items (normally words or pictures) have been presented to them; this is discussed in full in Chapter 1.2.2. However, it is in the forensic literature where most of the research has been conducted due to the importance of frequency information in legal settings (Orbach & Lamb, 2007; Sharman et al., 2011; Wandrey et al., 2012). Notably, one forensic study analysed the transcripts of children who had alleged child abuse for references to temporal information (Orbach & Lamb, 2007). The authors found children were able to give temporal information including the frequency, date and duration of alleged events, however temporal information in general was rare compared to non-temporal information. Of particular relevance, frequency information was most often in non-enumerative form e.g. “it happened lots” and therefore lacked specificity (Orbach & Lamb, 2007). A further study with maltreated children also suggested children struggle with giving enumerative answers. Wandrey, Lyon, Quas and Friedman (2012) asked maltreated children aged six to ten years about their foster care placements and court visits in order to investigate salient life events whilst also being able to measure accuracy. The authors found children’s accuracy when giving an exact answer to an everyday numerosity question (e.g. “how many times have you visited the court?”) was low (13 to 27%), and there was no improvement in the answers of the older children.

In the typical population, research tends to be conducted using tightly controlled events which often occur in the classroom. Sharman et al (2011) asked children aged between four and eight years of age to participate in a staged event either one or six times. The event centred on a number of activities including doing a puzzle and getting a surprise present. Using this methodology, they found that 49% of children who experienced the event multiple times gave numerical estimates when asked how many times a staged event had occurred. However only 9.4% of these children gave the correct answer, 23% of children gave an estimate only one away from the correct answer. Furthermore, younger children were less accurate than older children. Unsurprisingly, when the event had only happened once, 90% of children gave a numerical response, and 96% of those gave the correct frequency estimate; this was not affected by age. Further a number of children were interviewed after five to six days and also after five to six weeks; this had no impact on the accuracy of frequency recall. Finally, in four similar studies reported by Roberts et al (2015), only 23% of children accurately recalled that they had taken part in four staged events. Of the remaining children 22.9% answered either three or five events, 27.5% provided other inaccurate answers and 28.3% said they didn't know. Consistent with Sharman et al (2011), older children (six to eight years) were more accurate than younger children (four to five years) (Roberts et al., 2015).

1.2.2 Frequency Processing of Short Term Events

The ability to judge the number of times something has happened can also be studied from a short term perspective in which frequency processing is considered to be a core aspect of an event and is therefore always encoded (Hasher & Zacks, 1979; Zacks & Hasher, 2002). In this context, frequency processing is important at a cognitively lower level, for example in word learning in early childhood; words with a frequently occurring phonetic structure such as 'bat' are learnt with more ease and earlier in development than words with an infrequent structure such as 'tab' (Gonzalez-Gomez, Poltrock, & Nazzi, 2013). Further, the idea that relative frequency encoding is a core skill is supported by research on adaptive functioning within the evolutionary context. The information we receive throughout life is often uncertain and so we utilise relative frequency information to determine the probability of events/outcomes in order to choose how to act (Kelly & Martin, 1994). In the animal kingdom, the actions we choose may be life or death, thus those animals which are sensitive to probability information have an advantage and are likely to thrive (Kelly & Martin, 1994). In humans, this kind of probabilistic reasoning can be seen in a variety of situations from motor performance (Moreno-Bote, Knill, & Pouget, 2011) to word learning (Peña, Bonatti, Nespor, & Mehler, 2002) and is observed in infants and adults alike (Denison, Reed, & Xu, 2012; Denison & Xu, 2014; Téglás et al., 2011).

In a series of studies, Hasher & Chromiak showed that the accuracy with which frequency information was reported was age invariant, and that accuracy did not differ between participants who were given pre-task instructions explaining they would be required to report frequency (and therefore had the opportunity to engage in effortful processing) and those that were not (Hasher & Chromiak, 1977). These findings led Hasher and colleagues to propose that frequency information is encoded automatically, with age invariance and instructional invariance being two tenets of their theory of automaticity (Hasher & Chromiak, 1977; Zacks, Hasher, & Sanft, 1982). More recently, Zacks and Hasher (2002) have acknowledged that the term 'automatic' may be problematic, as even core information such as frequency requires that the person pays attention to the relevant occurrence or event. They argue that attending to an event is a precondition for automatic *and* effortful encoding operations, but that automatic encoding does not make any further demands on attentional resources (Zacks & Hasher, 2002).

As previously stated, Hasher and Zacks (1977) argue that the automatic, or fundamental nature of frequency processing can be investigated by looking for age differences in this skill. Several studies find evidence that frequency information is indeed age invariant and therefore 'automatic' (Ellis, Palmer, & Reeves, 1988; Goldstein, Hasher, & Stein, 1983; Johnson, Raye, Hasher, & Chromiak, 1979). For example, Goldstein, Hasher and Stein (1983) found six to nine year olds' accuracy at judging whether pictures occurred one, two, three or four times was not impacted by age. Further, no age differences were reported in another study with slightly older children of eight to twelve years when judging picture frequency (Johnson et al., 1979). Whilst Ellis et al (1988) report minimal age differences in frequency processing between children of 5 and 8 years of age when judging the frequency of words, they find no reliable age differences when estimating picture frequency. They suggest the developmental effects can therefore be explained by reading ability, and not frequency processing per se and as such consider their data as supportive of Hasher and Chromiak's (1977) hypothesis (Ellis et al., 1988).

However, research is far from conclusive and has found developmental trends irrelevant of stimuli type. For example, Lund, Hall, Wilson and Humphreys (1983) observed higher error rates in younger children (aged five to six years) than older children (seven to eleven years) when asked to make relative judgements about the frequency of previously presented pictures. In a similar study, Chalmers and Grogan (2006) found higher accuracy rates for six year olds than four year olds, once again suggesting a developmental improvement around this age. Furthermore, a study comparing five year olds to adults found children's accuracy rates varied between 50 and 61% whilst the adults varied between 82 and 90%; this demonstrates a significant improvement in performance with age, though this study is unable to tell us much about the progression of this improvement as the age range was very limited (Harris, Durso, Mergler, & Jones, 1990). Finally, Mccormack and Russell (1997) presented children with pictures of common objects; they then had to determine whether these pictures had been presented once or three times. While error rates were similar when pictures had only been presented once, the four year olds were more inaccurate than five to eight year olds when they had been presented three times (Mccormack & Russell, 1997).

1.3 Spatial Representation of Number

There is a strong body of evidence supporting the notion that number representation is spatially organised in adults (Dehaene, Bossini, & Giraux, 1993; Gobel, Shaki, & Fischer, 2011; Hubbard, Piazza, Pinel, & Dehaene, 2005; Marghetis, Núñez, & Bergen, 2014; Sullivan, Juhasz, Slattery, & Barth, 2011). The most commonly reported evidence supporting this idea is the phenomenon whereby Western educated individuals respond to smaller numbers faster with their left hand and vice versa, even when magnitude is irrelevant (Dehaene et al., 1993). This Spatial-Numerical Association of Response Codes (SNARC) effect is proposed to reflect the representation of numbers along a mental number line where numbers increase in ascending order (Dehaene, 1997; Fisher & Shaki, 2014, though see Nunez, 2011).

1.3.1 Origins of Spatial Numerical Associations

It is generally agreed that spatial numerical associations develop over childhood and are a function of an individual's cultural environment (spatial numerical associations in children will be discussed in Chapter 1.3.2). Whilst culture appears to influence the direction of spatial numerical associations, the capacity for these associations is universal; it is seen in multiple populations including Western and Asian participants, as well as indigenous Brazilian and Australian tribes who possess very few number words (Gobel et al., 2011). The pervasive nature of spatial-numerical representation is further shown by research which demonstrates SNARC effects when spatial (and/or numerical) information is implicit and task irrelevant (Gevers, Lammertyn, Notebaert et al, 2006). For example, when numbers are presented merely as background objects they nonetheless impact performance in orientation discrimination tasks (Fias, Lauwereyns, & Lammertyn, 2001). Likewise, small task-irrelevant numbers have been found to reduce detection time to items in the left visual field whilst large task-irrelevant numbers draw attention to the right - thereby demonstrating the automatic activation of number meaning in relation to space (Fischer, Castel, Dodd, & Pratt, 2003). This is also consistent with research suggesting we have the capacity to link space, time and number from birth (de Hevia et al., 2014).

The tight association between number and space is thought to be due to these concepts sharing overlapping neural circuitry in the parietal lobes (Hubbard et al., 2005). As such, repetitive transcranial magnetic stimulation (TMS) over the left angular gyrus in healthy participants impairs performance on both visuo-spatial search tasks and numerical comparison tasks (Hubbard et al., 2005). Furthermore, induced left spatial neglect due to posterior parietal lobe TMS results in a rightward shift of the subjective midpoint in a number line bisection task (Göbel et al., 2006). This is consistent with left spatial neglect patients who demonstrate this rightward shift in numerical and visual line bisection tasks whereby the length of the line is related to the magnitude of the shift (Zorzi et al., 2006). Conversely, in non-numerical tasks this magnitude-length relationship is not observed (Zorzi et al., 2006). Further neurological evidence also highlights shared numerical and spatial deficits. For example, patients with Gerstmann's syndrome (associated with lesions to the left angular gyrus) often have problems such as dyscalculia alongside problems distinguishing left and right (Hubbard et al., 2005). Hubbard et al (2005) review further lines of neurological evidence (from both humans and animals) suggesting that these overlapping neural mechanisms create the capacity for spatial-numerical representations with cultural norms for reading, writing and finger counting direction playing an important role in developing these circuits (see 1.3.4).

1.3.2 Spatial Numerical Associations in Children

Whilst a plethora of research suggests that adults represent number spatially (Dehaene, Bossini, & Giraux, 1993; Gobel, Shaki, & Fischer, 2011; Hubbard, Piazza, Pinel, & Dehaene, 2005; Marghetis, Núñez, & Bergen, 2014; Sullivan, Juhasz, Slattery, & Barth, 2011), much less research exists in the developmental literature despite the importance of spatial numerical associations for mathematical development (White, Szűcs, & Soltész, 2012). Whilst research has shown that very young infants can link number to space, this is in relation to non-symbolic number (de Hevia, Girelli, & Macchi Cassia, 2012), and not symbolic numbers (studied in adults using methodologies such as the SNARC task). A review of the little literature that exists revealed that larger SNARC effects are observed with increasing age (Wood, Willmes, Nuerk, & Fischer, 2008). Notably, in parity judgement tasks where the number magnitude is irrelevant, SNARC effects are only observed at around nine years of age (Berch et al, 1999; Van Galen & Reitsma, 2008). However, SNARC effects have been observed in children as young as seven years of age (Van Galen & Reitsma, 2008; White et al., 2012) and five years of age when they had to judge the colour of a number, but not its magnitude (Hoffmann, Hornung, Martin, & Schiltz, 2013). Further, using a non-symbolic version of the SNARC task, children aged four years were quicker to respond to a smaller number of dots when presented on the left side of the screen than on the right and vice versa (Patro & Haman, 2012). Western four year olds also appear to expect numbers to be ordered ascending spatially from left to right in spatial search tasks and when counting; when they were ordered in the reverse orientation, children struggled to complete the task (Opfer, Thompson, & Furlong, 2010). Given that studies with younger children only find SNARC effects when magnitude is relevant to the task, it is suggested that the automatic activation of number-space mappings occurs when children are approximately nine years old (Van Galen & Reitsma, 2008; White et al., 2012).

Another useful method to study spatial-numerical associations in children is the number line task which requires children to map number on to physical space (Siegler & Opfer, 2003). Number lines are useful for assessing spatial-numerical associations in children as they don't rely on such a robust understanding of the number system (Ebersbach, 2015), nor parity (White et al., 2012). Research with number lines suggests that children's estimates of where numbers belong on a number line become more linear, as opposed to logarithmic, with continued development (Booth & Siegler, 2008; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Siegler & Ramani, 2008). This change becomes apparent in seven year olds, and appears to be relatively complete by eight years of age (Siegler & Booth, 2004). In turn, children's accuracy on the number line is associated with enhanced mathematical skills measured by calculation tests, school based mathematics tests and standardised mathematics batteries (Booth & Siegler, 2006, 2008; Siegler & Ramani, 2008; Sasanguie et al., 2012). Furthermore, Ebersbach (2015) found that Western children's accuracy on the number line is worse when the number line runs from right to left, the reverse direction of Western spatial numerical associations.

This ability to represent number spatially on a line is an aspect of our early number knowledge, a concept defined as our knowledge of numerosity and our understanding of the relationships between numbers; it can include our ability to perceive cardinality, represent number spatially and our knowledge of the words and digits associated with numbers and counting (Östergren & Träff, 2013). It is differentiated from a complex mathematical understanding which is learned in school (Jordan & Kaplan, 2009), this can include knowledge of shapes, fractions and basic algebra (Department of

Education, 2013). The link between these two constructs has been studied using a variety of tasks all demonstrating that early number knowledge influences mathematical skill (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Östergren & Träff, 2013; Stock, Desoete, & Roeyers, 2009). For example, a longitudinal study by Jordan and colleagues created an early number knowledge battery which assessed children's knowledge of relative numerical size and their counting and calculation abilities. The authors found their battery could predict maths achievement in first grade (six to seven years) and third grade (eight to nine years) when measured at multiple time points from five years onwards. Furthermore, growth in early number knowledge was also associated with mathematical performance measured using the Calculation and Applied Problems subtest of the Woodcock Johnson III test battery (Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan & Kaplan, 2009). However, it is worth noting that it has been argued that calculation skills should not be included in measures of early number knowledge as it is then often used as both a predictor and a dependent variable (Östergren & Träff, 2013); this is apparent in the Jordan et al (2007; 2009) studies.

1.3.3 Spatial Numerical Associations and Fine Motor Skills

In Western educated adults, spatial numerical associations appear in the form of number ascending from left to right (e.g. Dehaene et al., 1993). However, this directional effect is not consistent across cultures. For example, reversed SNARC effects (number descending from left to right) are observed in Arabic speaking participants who have been exposed to reading and writing systems that run from right to left (Zebian, 2005). In addition, the SNARC effect is weaker in Iranian participants who read Arabic but have moved to a left to right reading culture (Dehaene et al., 1993). Further, Palestinian participants who read right to left and Western participants who read left to right both showed reading direction consistent SNARC effects, but Israeli participants who read words from right to left, but numbers from left to right showed no SNARC effect (Shaki, Fischer, & Petrusic, 2009). In Chinese participants the SNARC effect is present for Arabic numerals when the task is horizontally aligned and for

Chinese numerals when vertically aligned in a manner consistent with the different reading and writing directions of Arabic and Chinese numerals (Hung, Hung, Tzeng, & Wu, 2008).

It is presumed that these differences in directionality are due to perceptual-motor experience, notably the fine motor skills of reading, writing and finger counting (Dehaene et al., 1993; Fischer, Mills, & Shaki, 2010; Gobel, Shaki, & Fischer, 2011; Hubbard et al., 2005; Fischer & Shaki, 2014). This argument is consistent with embodied cognition where it has been proposed that information is stored in a manner that maps to the neural system (e.g. motor, visual) that originally encoded the information (e.g. Wilson, 2002). Recent research has begun to suggest that it is finger counting which plays the biggest role in the directionality of spatial numerical associations, with reading and writing playing a smaller role (Fischer & Brugger, 2011; Fischer, 2008). Finger counting is used by children to learn numerical concepts, is universal and shows cultural variability consistent with the direction of spatial numerical associations (Fischer & Brugger, 2011). For example, there are multiple lines of evidence (behavioural and neuropsychological) linking finger counting habits with numerical processing (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Fischer & Brugger, 2011; Penner-wilger et al., 2007; Sato, Cattaneo, Rizzolatti, & Gallese, 2007). Furthermore, research has found that Iranian individuals start counting on the right hand, with the little finger representing the number one whilst Western adults start with the left hand with the thumb representing the number one (Lindemann, Alipour, & Fischer, 2011).

Further, it appears that fine motor skills are important in mathematical skills beyond spatial-numerical associations. It is argued that the perfecting of fine motor skills such as reaching and grasping objects allows us to interact successfully with the world and thus provides new learning experiences (Marr, Cermak, Cohn, & Henderson, 2003). This is consistent with Piagetian theory which posits that cognitive abilities stem from sensorimotor activities (Piaget & Inhelder, 1966). It is during Piaget's sensorimotor stage that children begin to make goal directed actions and coordinate sensory input (vision, hearing etc.) with physical output (movement); this in turn provides potential learning opportunities and allows more advanced cognitive skills to develop (Piaget &

Inhelder, 1966). Accordingly poor motor ability can impact on later school outcomes; the Millennium Cohort Study found delays in fine motor and gross motor skills such as crawling and holding objects was associated with delays in cognitive achievement at age five years (Schoon, Cheng, Jones, Joshi, & Dex, 2010). An early review of 74 studies concluded that of those studies which assessed motor skills (over half), most found they could predict mathematics, reading and general achievement (Tramontana, Hooper, & Selzer, 1988). However, these studies vary greatly in the type of motor skills they measure (e.g. gross motor, fine motor or a combination), and in their methods of measurement; only one study measured 'pure' motor skill (Tramontana et al., 1988). More recently, research in to school readiness has observed some relationships between fine motor/perceptual motor skills and maths ability (Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Luo, Jose, Huntsinger, & Pigott, 2007; Pagani, Fitzpatrick, Archambault, & Janosz, 2010; Pagani & Messier, 2012). Studies of children with known motor disorders such as Developmental Coordination Disorder (DCD) or cerebral palsy demonstrate significant delays in mathematical performance also suggesting that fine motor skills may indeed be important for mathematical development (Pieters, Desoete, Van Waelvelde, Vanderswalmen, & Roeyers, 2012; Van Rooijen, Verhoeven, & Steenbergen, 2011). Despite its importance, the contribution of motor skills to mathematics is often neglected (Pagani et al., 2010).

1.3.4 Experimental Work

As the reviewed literature demonstrates, links have been hypothesised between time and number, and space and number. In this thesis, I will present two experiments (Chapters 2 and 3) which assess temporal numerical associations by asking participants to determine the frequency with which events occur, and three experiments (Chapters 4, 5 and 6) which assess our ability to represent number spatially. Across all of these experiments I will also assess whether these temporal numerical/spatial numerical skills are related to other numerical skills, from basic number ability to the more complex mathematical skills taught and measured in schools.

CHAPTER 2

EXPERIMENT 1: CHILDRENS ABILITY TO RECALL EVERYDAY FREQUENCY INFORMATION AND ITS RELATIONSHIP TO NUMERICAL PROCESSING

2.1 Introduction

There is very little research which investigates how well children can recall the frequency of past events. Nevertheless, the few forensic and controlled school based studies which exist suggest that children are often inaccurate and don't always give enumerative (numerical) answers, preferring instead to give qualitative responses such as "many times" (Orbach & Lamb, 2007; Roberts et al., 2015; Sharman et al., 2011; Wandrey et al., 2012). However, whilst one forensic study suggests age (six to ten years) does not impact upon accuracy (Wandrey et al., 2012), two experimental studies suggest older children (six to eight years) are more accurate than younger children (four to five years) (Roberts et al., 2015; Sharman et al., 2011) (See Chapter 1.2.1). Given the importance of being able to recall frequency information, more research is warranted to determine whether age differences are present, and whether children give enumerative answers, the preferred type of response by adults (Brown, 2002; 2008).

The ability to determine the number of times an event has occurred is important in a variety of settings. For example, in forensic settings there is an expectation on children to be able to give event specific information, determine how many events occurred and provide the temporal range in which they occurred (Roberts et al., 2015; Wandrey et al., 2012). It is also important in relation to the '5 a day' scheme introduced by the Government to encourage people to increase their intake of fruit and vegetables (NHS, 2011). Regarding children's intake, frequency estimates will largely rely on the child as parents cannot be sure what the child is eating at school, and the school cannot be sure what the child is eating at home. It is therefore paramount we understand whether children can accurately process this kind of frequency information. To the author's knowledge, there are no studies which currently investigate this.

By their very nature, frequency judgements are numerical – but no research has investigated links between the frequency processing of everyday events and number in children. Whilst the adult literature suggests adults prefer to give enumerative answers to frequency questions, children tend to give qualitative answers (e.g. "lots", "many") or inaccurate quantitative answers (Orbach & Lamb, 2007; Roberts et al., 2015; Sharman et al., 2011; Wandrey, Lyon, Quas, & Friedman, 2012). The developmental findings thus raise the question as to whether or not frequency processing and numerical abilities are related.

In addition, frequency processing is often considered as a subset of *temporal* memory, that is, memory pertaining to time (Orbach & Lamb, 2007; Roberts et al., 2015). Whilst there appears to be no research investigating everyday frequency processing and number, in the temporal memory literature there are a number of studies assessing other temporal attributes such as the duration of an event. For example, in adults numerical processing has been found to interfere with duration processing in a stroop task (Dormal, Seron & Pesenti, 2006). In the animal cognition literature it has been demonstrated that animals utilise basic, non-symbolic counting mechanisms to determine duration (Meck, Church, & Gibbon, 1985; Meck & Church, 1983). Therefore it appears that there are links between the temporal construct of duration processing and numerical processing, but research is currently lacking with regard to frequency processing and numerical skills.

Given the lack of research into children's ability to recall frequency information and the possible links between numerical processing and frequency processing, Experiment 1 aimed to investigate (i) whether children are able to determine the number of times real contextually experienced events have occurred; (ii) whether this ability improves with age and, (iii) whether this type of frequency processing is linked to numerical skills. Given the importance of fruit and vegetable consumption, the experiment was designed such that the results would provide much needed data on whether children can monitor their intake. Therefore, two age groups of children were provided with fruit based snacks each school day for one week, with the frequency of the snacks varying on a daily basis. Children's numerical ability was assessed using a subitizing/dot enumeration task. Subitizing is our ability to rapidly and accurately evaluate a small number of objects (~4) whilst dot enumeration is a slower non-symbolic sequential counting process involving one to one mapping between objects and number words (Gelman & Gallistel, 1978). These are thought to be distinct skills which develop relatively early (Reeve, Reynolds, Humberstone, & Butterworth, 2012; Schleifer & Landerl, 2011) and are presumed to reflect the existence of two separate, but linked, numerical systems (Reeve et al., 2012). Subitizing reflects numerosity, our ability to judge quantity, whilst dot enumeration appears to reflect children's basic counting skills (Gray & Reeve, 2014; Schleifer & Landerl, 2011). Thus, given suggestions that frequency processing may involve a counting strategy to determine the number of times an event has occurred, it was reasoned that dot enumeration performance may be related to children's ability to recall the number of times an event has occurred. In contrast, the ability to subitize appears to develop in very young children even before they are able to count (Benoit, Lehalle, & Jouen, 2004; Feigenson, Carey, & Hauser, 2002) and is thought to be an automatic skill (Trick & Pylyshyn, 1994, though see Pincham & Szűcs, 2012). Nevertheless, subitizing efficiency (shorter response times and a larger subitizing range) increases with age (Reeve, Reynolds, Humberstone, & Butterworth, 2012), such that adult-like subitizing performance may only be present after around 11 years old (Schleifer & Landerl, 2011). Given the proposed automatic nature of subitizing, it may be less likely that this part of the task will correlate with frequency processing, however this is unknown. Further, the evidence that children become more efficient at subitizing with age (e.g. Reeve et al., 2012) may also suggest there is a link.

In addition, children's mathematical achievement was also assessed to determine whether the ability to recall everyday frequency information is related to an applied mathematical understanding; there is currently no research which investigates this. The inclusion of a maths achievement test allowed us to investigate whether mathematics skill is related to subitizing and dot enumeration. Previous research has found that subitizing and dot enumeration are related to calculation skills (Gray & Reeve, 2014; Penner-wilger et al., 2007; Reeve et al., 2012), but to the authors knowledge nobody has tested whether they are also important for the wider range of mathematics skills that are tested in school (e.g. fractions, shapes and figures). This was rectified by using children's scores on the standardised maths tests carried out by the school at the end of each school year. As suggested in Chapter 1.1, numerosity provides a basis for early number knowledge, and these two skills link to mathematics, thus correlations between subitizing, dot enumeration and mathematics would be expected.

Finally, it was investigated whether temporal delay had any impact on children's ability to recall frequency information. This is an important aspect of memory research, given that memory decays over time (Ebbinghaus, 1885). It also has direct relevance to a number of settings in which frequency processing is important. For example, in the forensic setting, disclosure of abuse is often not immediate, and can take place after lengthy delays (Wandrey et al., 2012). The one study which has looked at delay did not find any reduction in performance (Sharman et al., 2011), however, their study involved children being questioned after one week and after five weeks. Whilst this delay may be relevant to the forensic setting, this study was interested in investigating shorter delays given that children are unlikely to need to recall their daily intake of fruit and vegetables for such long periods of time. Children will need to be able to remember this kind of information each day, thus children were asked to recall their intake after one day, but also after one week to determine whether delay does impact children's memory for frequency.

2.2 Methods

2.2.1 Participants

Thirty one children in Year 4 (*M* = 9.4 years; range = 8.9 to 9.8; 15 male) and twenty nine children in Year 6 (*M* = 11.3 years; range = 10.6 to 11.8; 16 male) of the English school system took part in the experiment. The children were mostly of White or South Asian ethnicity (28% White British; 43% Pakistani; 29% other) and attending a primary school in the North of England. Parents were asked to provide information about allergies to ensure that no child would be allergic to the smoothies; they were also given advice about food allergies and how to recognise and treat them.

2.2.2 Materials

Smoothies: A total of 600 smoothies produced by the Organic children's food supplier Ella's Kitchen were used in this experiment. They were chosen as they contain no additives, only fruit purees, and come in small, ready to hand out containers. Each pouch contained one of the children's five a day.

Questionnaires: At the end of each day children were presented with a piece of paper with the question "how many smoothies were you given today?" printed on it. Once they had completed this, they were given a new sheet with the same question, but this time children were given 6 answers (0, 1, 2, 3, 4, and 5); they were asked to circle the one they thought was correct.

Number tasks: A combined subitizing and dot enumeration task was completed on portable tablet computers (Toshiba Portege M700-13P, screen: 257 x 160 mm, 1280 x 800 resolution, 100 Hz refresh rate) which recorded accuracy and reaction times (see Figure 2.1). It was placed at a comfortable position in front of the child, approximately 40-60cm away. This task was created using Pygame software and consisted of 48 randomised trials during which one to eight black dots on a white background appeared on the screen; this resulted in each quantity (1-8) being presented six times (half within the subitizing range of 1-4 and half in the dot enumeration range of 5-8). The arrangement of the dots was random, with the only restriction being that the dots could not be too close to the outer edges of the screen (within 60mm) or too close to each other (within 100mm).

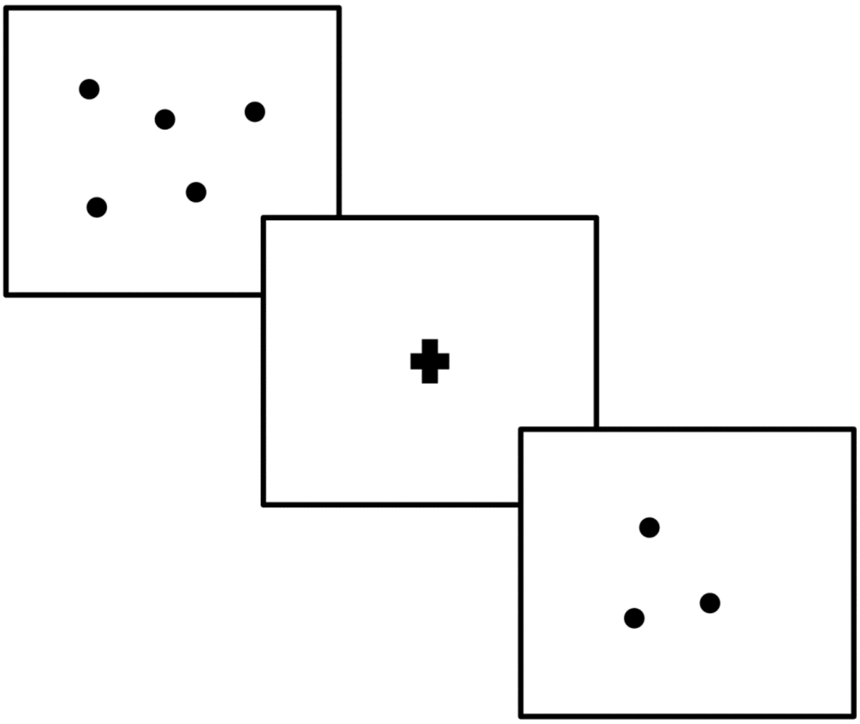

Figure 2.1 A schematic of the subitizing task showing two trials separated by a fixation cross.

2.2.3 Procedure

At the beginning of the school week, children were introduced to the experimenter who told them they would be trying out some new smoothies in school and would be asked questions about them at the end of each day. The smoothies were labelled with the child's name and given to the teacher at the beginning of each day; children were given between zero and four smoothies. Four different flavours were used to stop the children becoming bored with them; they were asked to rate liking on a 5 point Likert scale from "I like it a lot" to "I dislike it a lot". On average, all of the smoothies were rated as being "liked a lot" or "liked a little bit", none were rated as negative.

The teacher was given a protocol explaining when each smoothie should be given and which flavour it should be, these were both pseudo randomised at the group level. When the teacher handed out the smoothie, they told the children to drink as much as they wanted and then collected the pouches back. At the end of each day, children were asked to write down on a question sheet how many smoothies they were given that day. Given the low accuracy observed in previous studies, there was concern that children would perform poorly in this experiment and so they were also given a sheet which asked children to circle the number of smoothies they had been given that day (0-5). Cued recall, or recognition, has been repeatedly shown to be easier than free recall (Anderson & Bower, 1972), thus if children were very poor at free recall, they might nonetheless be able to answer the cued recall questions correctly and therefore improve their accuracy. To assess delay, after one week children were given a new free recall question sheet and asked to write down how many smoothies they had on each day of the previous week.

The following week each child individually completed a combined subitizing and dot enumeration task. During this task between one and eight dots appeared on the computer screen, the children had to determine how many dots were presented as quickly and as accurately as possible. The dots remained on the screen until the child responded by pressing the space bar and simultaneously telling the experimenter the number of dots they thought had appeared. Reaction time was recorded when the space bar was pressed. A fixation cross was presented for 1,500ms between trials. Children were given three practice trials in the same format as the test trials. Finally, maths ability was provided by school assessments based on national norms. These assessments are completed by children at the end of each year and include tests of arithmetic and knowledge of shape and size (Department of Education, 2013). Each child is then assigned to a certain national curriculum level of performance based on their results; children are expected to progress through these levels during schooling (Department of Education, 2013).

2.3 Results

2.3.1 Frequency Recall of Smoothie Intake

The main aim of the study was to determine how well children could recall their smoothie intake, after one day and after one week. Percentages of correct responses displayed in Table 2.1 show that children performed at or near ceiling in the immediate recall condition, with decreased accuracy after a delay.

Table 2.1 *Mean percent correct by age and delay [95% confidence interval]*

	Immediate Recall	Delayed Recall
Year 4	97.24 [92.94, 101.54]	73.79 [62.90, 84.69]
Year 6	86.79 [82.41, 91.16]	56.43 [45.34, 67.52]

A mixed model ANOVA revealed a significant effect of recall type, $F\ (1, 55) = 49.632$, $p < .001$, $\eta^2_p = .474$, a non-significant interaction, $F\ (1, 55) = .818$, $p = .370$, $\eta^2_p = .015$ and a significant effect of age, $F\ (1, 55) = 9.591$, $p < .01$, $\eta^2_p = .148$. These results show that independent of age group, children were most accurate at recalling the smoothies immediately, rather than after a delay; however, this result is interpreted with caution given the ceiling effects in the immediate recall data. Interestingly, the effect of age was driven by Year 6 children being less accurate than Year 4 children. This is likely to be due to problems during testing which resulted in these children not being given the smoothies at the correct time, or at all. For example, unknown to the researcher, children were taken out of class for a morning to complete bicycle competence training and thus missed their scheduled smoothies. Further, the regular class teacher unexpectedly became ill and was replaced by a supply teacher who was not informed about the research resulting in multiple errors in the distribution of the smoothies. Thus there were significant problems with testing which will have interfered with Year 6 children's memory for the smoothies; notably the researcher cannot be sure how many smoothies the children were given and when.

Next, differences in accuracy depending on the frequency of children's smoothie intake were analysed. A mixed model ANOVA was conducted with frequency as a within subjects factor (5 levels; 0, 1, 2, 3, 4) and age as a between subjects factor (2 levels; Year 4, Year 6). There was a significant effect of frequency, F (4, 152) = 5.089, $p < .01$, $\eta^2_p = .118$; the only significant difference between frequencies was that children were more accurate when recalling 0 smoothies than 3 smoothies. Once again there was a significant effect of age, F (1, 38) = 4.921, $p < .04$, $\eta^2_p = .115$, due to the Year 4 children being more accurate. The interaction was non-significant, F (4, 152) = .197, $p = .197$ η^2_p = .041.

A cued recall test was also administered each day after the children had completed their free recall sheets; once again the children performed at ceiling each day. Average accuracy was above 90% for each day, except on the last day when children were given three smoothies. On this day accuracy dropped to 81% for Year 4 children, and 55% for Year 6 children. Whilst it is not clear why this drop in accuracy occurred, it is possible that the children were losing interest in the smoothies. As this was the fifth and final day the children were given the smoothies, it is also possible that the children were starting to get confused about how many smoothies they had been given, resulting in reduced accuracy for this day.

2.3.2 Subitizing and Dot Enumeration

Next the subitizing and dot enumeration data were prepared for analysis. Data were first screened for outliers; any z scores of 3 and above were removed from the data set (Year 4 = 1.5% of all trials, Year 6 = 1.7% of all trials). 3.8% of Year 4 trials and 1.7% of Year 6 trials were removed as errors, as analysis is completed on correct responses only (Piazza et al, 2002; Reeve et al, 2012). Participant's reaction times were then averaged to provide reaction times for each quantity. Figure 2.2 shows comparably flat slopes for dot quantities one to three, and steeper increases from four to eight. Based on previous literature, linear regression lines were fitted to the data to determine the best fit for each age group (Reeve et al, 2012). Figure 2.2 demonstrates that the data is best fit by two different linear regression lines suggesting a subitizing range of one to three with children employing dot enumeration after this point. We then used a mixed model ANOVA to further confirm the point of discontinuity indicated by the regression lines (subitizing 1-3 dots, enumeration 4-8 dots). This revealed a significant effect of numerical processing type (subitizing or dot enumeration), $F\,(1, 57) = 1281.726$, $p < .001$, $\eta^2_p = .957$; subitizing was significantly quicker than dot enumeration. Although there was no effect of age, $F\,(1, 57) = 3.174$, $p = .080$, $\eta^2_p = .053$, there was an interaction, $F\,(1, 57) = 9.025$, $p < .001$, $\eta^2_p = .137$. This was driven by the Year 6 children being faster than the Year 4 children in the dot enumeration range only ($p < .05$).

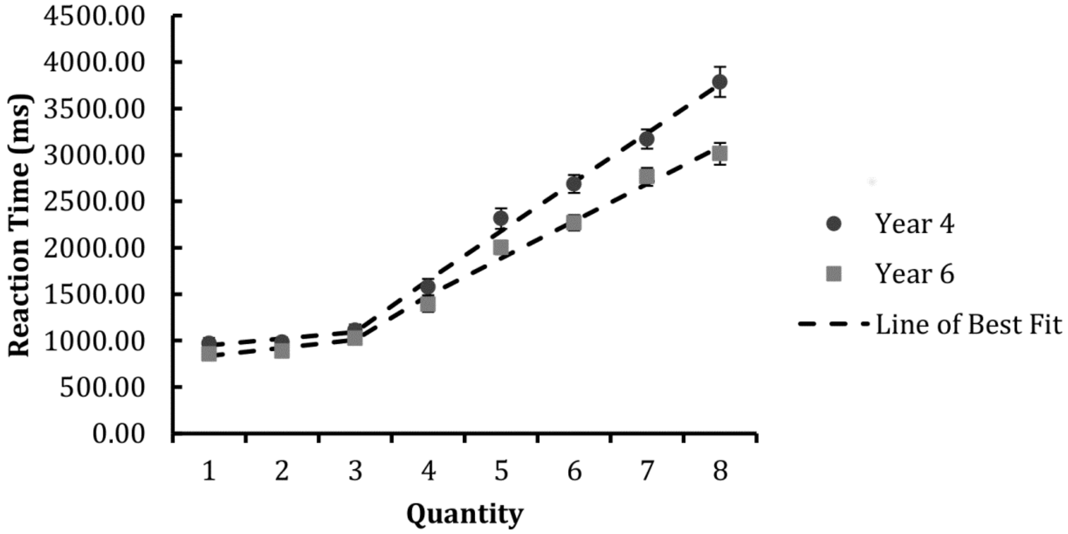

Figure 2.2 Average reaction times for each quantity. Error bars represent ±1 standard error of the mean.

2.3.3 Correlational Analysis

To determine whether recall of event frequency was associated with subitizing, dot enumeration and/or mathematical skills, partial correlations (controlling for age) were conducted with delayed recall, mathematical achievement, subitizing (quantities 1 to 3) and dot enumeration (quantities 4 to 8). Separate correlations for Year 4 and Year 6 were conducted given that there were multiple problems with testing the latter group. Finally, due to the ceiling effects and low variability in the immediate recall data, this analysis was conducted in relation to delayed recall only. These results can be seen in Tables 2.2 and 2.3.

Table 2.2 *Partial correlation coefficients for delayed recall, mathematical achievement, subitizing and dot enumeration for Year 4 children (controlling for age)*

		1	2	3	4
1.	**Delayed Recall**	_			
2.	**Maths Achievement**	.505*	_		
3.	**Subitizing**	.261	-.295	_	
4.	**Dot enumeration**	.092	-.338	.878**	_

Note: *p < 0.05; **p < 0.01.

Table 2.3 *Partial correlation coefficients for delayed recall, mathematical achievement, subitizing and dot enumeration for Year 6 children (controlling for age)*

		1	2	3	4
1.	**Delayed Recall**	_			
2.	**Maths Achievement**	.042	_		
3.	**Subitizing**	.100	-.570*	_	
4.	**Dot enumeration**	-.210	-.656*	.721**	_

Note: *p < 0.05; **p < 0.01.

Notably, delayed recall correlated with maths achievement for the Year 4 children only. Further, whilst subitizing and dot enumeration correlated for both age groups, these skills were only correlated with mathematical achievement for the older children. Given the correlation between delayed recall and mathematics achievement, a regression analyses was also run on the Year 4 data to see if it could explain unique variance in maths achievement, these results can be seen in Table 2.4. The model accounted for 34% of the variance in mathematical achievement, ($R^2_{Adjusted} = .340, F = 4.471, p < .01$); delayed frequency recall was the only significant predictor. However, given the small sample size (N = 31), the results are interpreted with caution.

Table 2.4 *Hierarchical regression analysis predicting mathematical achievement*

	β	t	$R^2_{Adjusted}$
			.340
Age	.608	3.583	
Delayed Recall	-.361**	-1.055	
Subitizing	-.076	-.218	
Dot enumeration	-.067	-.376	

Note: *p < 0.05; **p < 0.01.

2.4 Discussion

This study aimed to examine whether children can recall the number of times an everyday event had occurred. The high accuracy observed after a short delay suggests that children were able to monitor their intake on a day by day basis. However, their accuracy was so high that ceiling effects were observed meaning the immediate recall data were not fully analysed; this level of accuracy was much higher than expected based on previous studies (e.g. Roberts et al., 2015; Sharman et al., 2011; Wandrey et al., 2012). A number of teachers reported to the researchers that the children were very excited by the smoothies and would talk about them to other children, staff and supply teachers; it is possible that the excitement created by the novelty of the smoothies contributed to the observed ceiling effects. This excitement may have resulted in the children being able to retain and recall the information to a much greater degree of accuracy than they might have if the activities had been more mundane. Indeed, research shows we are more likely to remember distinctive (Hunt & McDaniel, 1993) or novel items (Kishiyama & Yonelinas, 2003). Furthermore, autobiographical memory research suggests emotional events are remembered better than non-emotional events in terms of both their vividness and durability (Holland & Kensinger, 2010). This suggests that the type of event that children experience may impact on their ability to recall frequency information. This level of excitement and its potential impact upon performance was something that was not anticipated, and is worth considering in future research.

Whilst age effects were observed, they were in the opposite direction to the authors expectations; younger children were more accurate at frequency recall than the older children. However, as noted in the results, there were a number of issues with testing which can explain these results. The Year 6 class teacher was fully briefed at the beginning of the week about when to give the smoothies, but they were not present on a number of the days meaning a supply teacher who had not been briefed was in charge of giving the children the smoothies. On at least one day, this meant the children received no smoothies when they should have done, on another it meant they received them all at once. Therefore the age effects, and the Year 6 smoothie data in general, are interpreted with extreme caution. It is also possible that the smoothies were less salient to the Year 6 children, and thus less memorable to them. Testing was completed just after the Year 6 children had finished their final primary school exams, thus they were being rewarded with time away from the classroom to prepare for the end of year school play. Given this, the smoothies may have been less exciting to these children.

We also found children's accuracy decreased by 24-30% after a delay of just one week; though accuracy was still high at above 70% in the Year 4 children. These results have important implications in forensic settings whereby children are often questioned after a delay; as yet there is no agreement on what level of accuracy is good enough in the court room, despite the importance of the child's statement to the proceedings. Interestingly, Sharman et al (2011) found that delay had no impact on accuracy, but they questioned the children at different time points. In their study, children were first questioned after a week and then again after five weeks, compared to at the end of the day and after a week in the present study. It is therefore possible that whilst decay occurs within the first week, information that is retained at this time point is then less susceptible to forgetting. Accordingly, whilst research suggests multiple theories of why we forget, the consensus appears to be that forgetting occurs rapidly at first and then eases off, unless conscious efforts (e.g. rehearsal) are made to preserve the memory trace (Ebbinghaus, 1885). Further, the events in Sharman et al's (2011) study took place over a number of weeks. Thus even when the children are first questioned, some of the events will have happened 4 weeks ago, possibly making it harder for children to recall the events. This may also contribute to the low accuracy Sharman et al (2011) observed.

Due to the ceiling effects in the immediate recall data, only the delayed recall data was used in the correlational analysis. Delayed recall did not correlate with subitizing, dot enumeration or mathematical achievement in Year 6 children, however given that the reliability of the Year 6 data was compromised, these results are again interpreted with caution. A correlation between delayed recall and mathematics achievement was observed in the Year 4 children's data, but neither correlated with subitizing or dot enumeration. In fact, delayed recall predicted mathematical achievement, though the sample size is very small. Brown (2002) suggested that: (a) frequency strategies may rely on some form of numerical processing, specifically counting, and, (b) that enumerative strategies are more likely to be used for distinctive events (which the smoothies could be conceived as) (Conrad et al., 1998). However, if that were the case, dot enumeration would be expected to correlate with frequency processing. One possibility is that children are relying on symbolic number knowledge (Arabic digits) as opposed to non-symbolic (e.g. sets of dots), thus explaining why it correlates with mathematics achievement but not dot enumeration. It could also be that the delayed recall of frequency information and mathematical achievement draw upon shared skills such as working memory and executive function. These skills are consistently linked to mathematics achievement (Alloway & Alloway, 2010; Alloway & Passolunghi, 2011; De Smedt et al., 2009; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Holmes & Adams, 2006; Meyer, Salimpoor, Wu, Geary, & Menon, 2010) and are likely involved in the processing of frequency information. For example, working memory has been implicated in the processing of short term frequency of occurrences (Meck & Church, 1983). However, these suggestions would need to be tested further to determine the reason behind the correlation.

In future work it would be interesting to consider asking children how they arrived at their estimates in order to access more detailed information about strategy use, though it is important to note that children often struggle to express information about how they arrived at answers. Nevertheless, if it could be achieved this would provide information about whether children are using strategies, but also what kind of strategies. Brown (2002) suggests adults may use multiple different strategies depending on a number of factors such as the distinctiveness and regularity of the events. For example, they may use simple enumeration, i.e. just counting events, but may also add extra occurrences to compensate for any that may have been forgotten. This strategy arguably requires an understanding that memory decays. Further, adults tend to use rate based strategies by utilising the information of how often they go to something per week to make monthly estimates of event frequency (Brown, 2002). Future research may then be able to determine at what point children are able to utilise the best strategy for a given situation, for example, do they extrapolate when they think they may have forgotten instances of an event, or do they just count all the ones they can remember.

The key focus of this study was to determine whether children could recall frequency information and whether this was related to other numerical skills. However, it also allowed us to assess the development of subitizing and dot enumeration and their potential relationship with mathematical skills. Whilst little research has assessed these skills across age groups, the results corroborated the current findings; reaction times decrease as a function of age and increase as a function of quantity (Reeve et al., 2012). We found the point of discontinuity, that is the change between subitizing and dot enumeration, was 3 dots; reaction times were much faster within the subitizing range. We also found that the two systems were related, as evidenced by the correlation between subitizing and dot enumeration in the present study. Research has shown that subitizing and dot enumeration predict calculation abilities (e.g. addition and subtraction) (Gray & Reeve, 2014; Reeve et al., 2012), and that poor subitizing and dot enumeration skills are associated with problems in mathematical development, such as those observed in dyscalculia (Landerl, 2013). Our results provide some further support for these findings, but only in the Year 6 data. It is unclear why no relationship was observed in the Year 4 data, but it does highlight the importance of more research being conducted into the development of these abilities, especially given that it has been proposed that subitizing abilities could be used as a diagnostic tool for mathematical learning disabilities (Desoete, Ceulemans, Roeyers, & Huylebroeck, 2009).

Experiment 1 has demonstrated that children can recall the frequency of their intake of fruit smoothies with a high degree of accuracy. We also found that their ability to recall this information after a delay was linked to mathematical achievement. However, given the problems with the Year 6 data and the observed ceiling effects, it is hard to draw any firm conclusions from this study. We therefore decided to use a different approach in order to assess the possible links between frequency processing and number in the next chapter.

CHAPTER 3

EXPERIMENT 2: THE DEVELOPMENT OF SHORT TERM FREQUENCY PROCESSING AND ITS RELATIONSHIP WITH NUMERICAL SKILLS

3.1 Introduction

In Chapter 2 it was found that children could process the frequency of everyday events; they were remarkably accurate at recalling their intake of fruit smoothies on a daily basis. However, given that frequency processing can be studied from both short term and long term perspectives, Chapter 3 moves on to investigate frequency processing over much shorter time frames. As with Chapter 2, it was assessed whether children are sensitive to frequency, and whether this improves with age. This is especially relevant to the short term frequency processing literature in which there has been an on-going debate about whether this kind of frequency processing is an 'automatic' process which is age invariant (e.g. Ellis, Palmer, & Reeves, 1988; Goldstein, Hasher, & Stein, 1983; Hasher & Chromiak, 1977), or requires more cognitively penetrable processing and is a skill that increases with age (e.g. Chalmers & Grogan, 2006; Ghatala & Levin, 1973; Lund, Hall, Wilson, & Humphreys, 1983). For example, Hasher & Chromiak (1977) found that neither age nor instructions influenced performance when judging the frequency of presented words. However, Ghatala & Levin (1973) found that children were more accurate at judging both picture and word frequency with age (see section 1.2.2).

Thus research to date has provided mixed evidence for the automatic nature of frequency encoding, at least in relation to developmental effects.

However, this may in part be due to differences in methodology. For example studies differ widely in the type and number of stimuli, and the delay at which frequency judgements are requested. Of note, studies differ in whether or not participants are asked to make absolute (how many times did you see this picture?) or relative judgements (which picture appeared the most). In their review article, Zacks & Hasher (2002) clarify that their original model was related to the automatic encoding of *relative* frequency judgements. This is then consistent with the evolutionary use of frequency information, where it is the knowledge of relative quantity which is key (Kelly & Martin, 1994), for example a predator will be more successful if they frequent areas where there is relatively more prey than another area.

A further issue with the methodologies used to date is the potential for participants to use strategies to complete the task. The standard task for frequency judgements is to present participants with items or pairs of items at a rate of one presentation every few seconds: a time-frame that would enable participants to potentially supplement performance via the use of strategies. It is argued that for a task truly to measure whether or not a process is automatic, participants should not be able to engage in higher order cognitive strategy use (Sanders, Zembar, Liddle, Gonzalez, & Wise, 1989). Indeed, several studies have shown that both understanding the usefulness of strategies, and then being able to implement those strategies successfully, show clear developmental progression (for review see Pressley & Hilden, 2006). Thus, if participants are presented with a frequency processing task which enables the use of strategies, the differences between age groups in the ability to engage strategies effectively may confound the results. Sanders et al (1989) argue that even in studies where participants are not aware they will be asked about frequency, and are presented with a "cover task", more efficient processing of the cover task (via strategy use) could also affect how participants engage with the frequency information.

To assess this Sanders et al (1989) ran two experiments with 7-year-olds, 11-year-olds and adults. In the first, participants were asked to detect patterns within a series of pictures, a task where performance could be improved by using strategies to remember individual pictures. They found that the older children and adults were more accurate than the younger children when subsequently asked about the frequency of individual pictures. The second experiment used a target-absent visual search methodology, where participants had to indicate when a given item was *not* present in a row of items, thus removing the advantage of engaging strategies during task completion. The second study eliminated the age effects. However, the second study also resulted in floor effects across all age groups, and the authors acknowledged that further research would be necessary to test whether or not tasks that prevent strategy use are able to show age invariance in relative frequency processing.

Thus, in order to investigate whether this kind of frequency processing is truly age invariant according to Zacks and Hasher's (2002) criteria, a relative frequency task should be utilised which is too demanding to enable strategy use. Further, previous literature has generally only asked children to distinguish between frequencies of 0 – 4, a relatively small number for a supposedly automatic skill, and often use words or pictures which may require an extra level of processing that is not related to pure frequency processing, but related to the child's familiarity with or labelling of the stimuli. Therefore, a much harder task was devised using simplistic stimuli whereby participants had to judge the relative frequency of a total of 36 shapes (consisting of three difference shapes) in each trial. This increased difficulty is more reflective of frequencies encountered in daily life, for example frequency processing in word learning (Gonzalez-Gomez, Poltrock, & Nazzi, 2013).

As in Chapter 2, it was assessed whether frequency processing is related to numerical processing by investigating the possible links between it and subitizing/dot enumeration. As previously discussed, subitizing is the ability to process small sets of items (generally ≤4) rapidly and accurately, whilst for numbers greater than 4 processing is slower and more effortful, and relates to counting (Arp, Taranne, & Fagard, 2006; Gray & Reeve, 2014; Mandler & Shebo, 1982; Reeve et al., 2012; Trick & Pylyshyn, 1994) (see Chapter 2.1). Some researchers have argued that subitizing is 'automatic' due to the speed with which participants are able to respond, and the fact that response times do not dramatically increase as the number of items increases (Trick & Pylyshyn, 1994, though see Pincham & Szűcs, 2012). The exact nature of this 'automaticity' is unclear and mirrors some of the debate in the frequency literature on exactly what is meant by the term 'automatic' (see e.g. Olivers & Watson, 2008; Pincham & Szűcs, 2012; Railo, Koivisto, Revonsuo, & Hannula, 2008; Trick & Pylyshyn, 1994; Vetter, Butterworth, & Bahrami, 2008). To the authors knowledge, no research has investigated whether relationships exist between short term frequency processing and numerosity judgements. In relation to everyday frequency processing, it was hypothesised that dot enumeration may be a more relevant skill than subitizing. However, it might be expected that subitizing would be more relevant for short term frequency processing than dot enumeration. A correlation with subitizing but not dot enumeration would add weight to the suggestion that frequency processing is automatic.

In accordance with Chapter 2, children's scores on a school based mathematics achievement test were obtained. In the previous chapter, children's performance on this test was related to their ability to recall everyday frequency information after a delay (see Chapter 2.3.3). To the authors' knowledge, only one study has directly investigated the links between short term frequency processing and maths ability. Lund et al (1983) gave a relative frequency processing task to seven to eight year olds, including a group of children who were underachieving in maths. They did not find any differences between typically developing and underachieving children in frequency processing, suggesting that the two abilities are separate, and that frequency processing does not underpin mathematical ability. In contrast, subitizing and dot enumeration have been found to link to later mathematical skills in children (Feigenson et al., 2004; Gray & Reeve, 2014; Landerl, 2013; Penner-wilger et al., 2007; Reeve et al., 2012; Schleifer & Landerl, 2011). For example, Reeve et al (2012) assessed children's numerical skills from age five to eleven years and found that the children could be categorised in to subgroups based on their enumeration abilities; notably group membership remained stable for the six year testing period and could predict maths ability when the children were tested at age nine and eleven years. These findings suggest that whilst quantity processing (e.g. subitizing/dot enumeration) and short term frequency relate to the processing of number, they seem to have different links to mathematical ability; this will be further investigated in the present study.

Finally, children's working memory, that is, the ability to maintain and manipulate information, was assessed (Alloway, 2007). It has been suggested that working memory may play a role in short term frequency processing as it allows us to keep track of the quantity of past stimuli, whilst attending to new stimuli (Meck & Church, 1983). However, if frequency processing is indeed automatic, then these two tasks shouldn't correlate; working memory tasks are cognitively effortful and may indicate that children are using more strategic processing than would be expected from an automatic task – the inclusion of a working memory task allows us to assess this.

In sum, the present study's aims are: (i) to determine whether there are developmental increases in short term frequency processing, (ii) to analyse whether frequency processing is related to core numerical skills and/or more complex mathematical skills, and, (iii) to assess whether frequency processing is related to working memory. To do this children and adults were asked to complete a frequency processing task, a subitizing/dot enumeration task, a working memory task. Children's maths performance was also obtained from the school.

3.2 Method

The frequency task was piloted on a sample of 8 adults (M = 24.6, 5 female). This ensured that the task was neither too hard, nor too easy for participants to complete.

3.2.1 Participants

The sample consisted of 114 children aged between 8 and 11 years. 53 children were in Year 4, (M = 9.4 years; range = 8.9 to 9.8); 53 were in Year 6, (M = 11.3 years; range = 10.6 to 11.9); Half of these children also took part in the study described in Chapter 1. Children were mostly of White or Pakistani ethnicity (32% White British; 28% Pakistani; 12% Black African/Caribbean; 10% Indian;

6% Asian; 4% mixed race; 1% White Eastern European; 1% Bangladeshi). All children attended a primary school in the North of England. Parents gave their children consent to take part prior to the study beginning. Children gave their consent to participate when the study began. The adult sample consisted of 21 participants aged between 18 and 33 years (M = 22.30, SD = 3.78) recruited at the University of Leeds. The gender split was roughly equal (11 females) and all participants were of British descent.

3.2.2 Materials

The subitizing and frequency tasks were completed on four identical portable tablet computers (Toshiba Portege M700-13P, screen: 257 x 160 mm, 1280 x 800 resolution, 100 Hz refresh rate) which recorded accuracy (subitizing and frequency) and reaction times (subitizing). The computers were placed at a comfortable position in front of the participant, approximately 40-60cm away. Both tasks were created and run using Pygame software.

3.2.3 Procedure

All participants completed four tasks in a fixed order: forward digit span, subitizing/dot enumeration, backwards digit span and frequency processing. Both digit span tasks were presented verbally and were preceded by a practice trial. The forward digit span task consisted of 6 blocks of three trials each; the sequence of digits increased by one each time resulting in the first trial having 3 digits and the last having 8 digits. The backwards digit span consisted of strings which ran from 2 digits to 6 digits to reflect the increased difficulty.

After the forward digit span task, participants completed a combined subitizing and dot enumeration task (see Figure 3.1a). This consisted of 48 randomised trials during which one to eight black dots on a white background appeared on the screen; this resulted in each quantity (1-8) being presented six times (half within the subitizing range of 1-4 and half in the dot enumeration range of 5-8). The arrangement of the dots was random, with the only restriction being that the dots could not be too close to the outer edges of the screen (within 60mm) or too close to each other (within 100mm).

Participants were asked to determine how many dots were presented as quickly and as accurately as possible. They responded by pressing the space bar and simultaneously telling the experimenter the number of dots they thought were presented. The dots remained on the screen until the key press. Reaction time was also recorded as this point. For the first stimulus presentation, and after each trial, a fixation cross was presented for 1500ms. Participants were given three practice trials in the same format as the test trials.

The frequency task consisted of 7 trials during which three different shapes (a square, a cross and a triangle) repeated for varying frequencies; a total of 36 shapes appeared in each trial (see Figure 3.1b). The frequency series was pseudo-randomised so that the number of repetitions of a shape varied, for example a square could be the most frequent shape in trial one, but the least frequent in trial two. The frequency series was arranged such that the task became harder with each trial, this was operationalised by decreasing the difference in the number of repetitions of the most frequently presented shape, relative to the other shapes within each trial. For example, at the beginning of the task, the most frequent shape was presented 19 times, the next frequent was presented 12 times and the least frequent was presented 5 times. The number of shape repetitions of the most frequent shape decreased by one with each trial whilst the number of repetitions of the least frequent shape increased by one with each trial. Thus, by the final trial (trial 7), the frequency of shape repetitions was 13, 12 and 11. Each shape remained on the screen for 1 second with a 10ms gap before the next shape appeared.

Participants were told they would see shapes on the screen, some of which would appear more than once. After each trial, a question screen asking which shape they saw the most was presented. This screen contained all three shapes with a number between 1 and 3 underneath. In order to respond, participants had to press the number on the keyboard which corresponded to the shape they thought had occurred the most. Participants were informed they would have to estimate this prior to the study beginning.

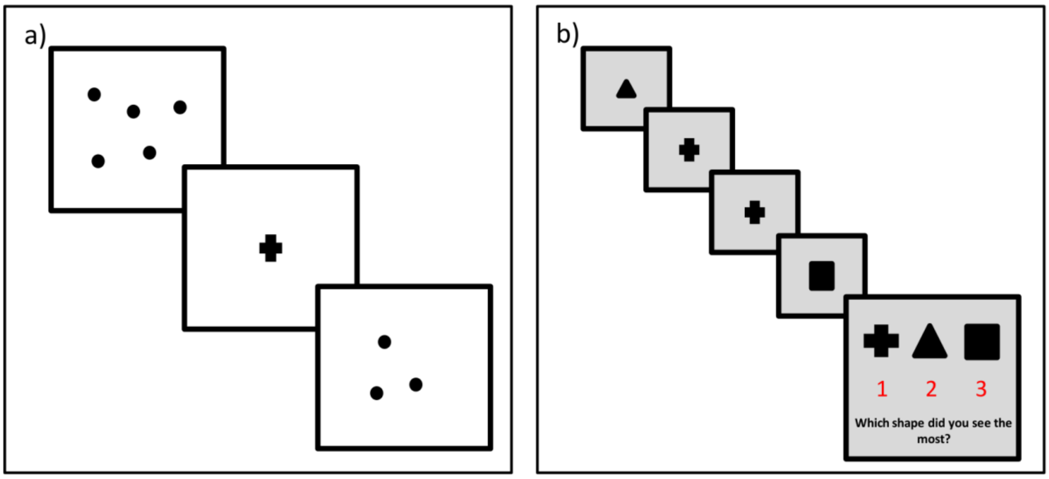

Figure 3.1 (a) Left is a schematic of the subitizing task with two example shape repetitions. (b) Right is a schematic of the frequency task with four example shape repetitions and the answer screen which is presented after 36 shape repetitions.

3.3 Results

3.3.1 Descriptive Analysis

Frequency task: Firstly, data is presented to determine whether there are age differences in children's and adult's ability to process frequency information. The data were coded in two ways, as a span and as an error measure. Given that the task increased in difficulty with each trial, the span variable was calculated as the trial before the participant got two consecutive trials wrong. As there were 7 trials in the task, the maximum span is 7. The error measure is a simple average of the number of errors throughout the task per age group. Once again, the maximum score for the error variable is 7, meaning the participant got every trial wrong.

No significant differences between the age groups were observed using either the span, F (2, 124) = .492, p = .492, η^2_p = .011, or error measure, F (2, 124) = 2.543, p = .083, η^2_p = .039. These results demonstrate a lack of age differences in frequency processing and can be seen in Table 3.1.

Table 3.1 *Average frequency span and frequency error by age group [95% Confidence Interval]*

	Frequency Span	Frequency Errors
Year 4	5.68 [5.22, 6.14]	2.11 [1.83, 2.39]
Year 6	5.89 [5.43, 6.35]	2.21 [1.93, 2.49]
Adult	6.19 [5.46, 6.92]	1.62 [1.18, 2.06]

Subitizing and Dot Enumeration: Once again, linear regression lines were fitted to the data to determine the best fit for each age group; the data was fit best by two different regression lines for all age groups (see Figure 3.2). For the Year 4 and Year 6 children, the subitizing range was one to three, indicated by relatively flat slopes in this range, whilst the dot enumeration range was four to eight, indicated by steeper increases in this range. However, the adults could subitize up to four dots, leaving a dot enumeration range of five to eight.

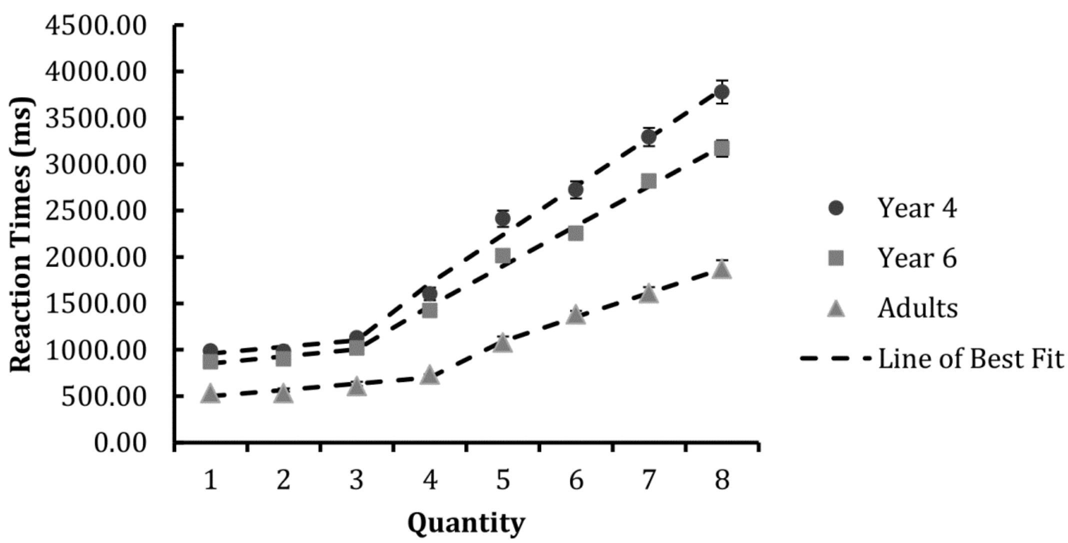

Figure 3.2 Average subitizing and dot enumeration reaction times by age and quantity. Error bars represent ±1 standard error of the mean.

We further explored this point of discontinuity with a mixed model ANOVA (processing type, subitizing and dot counting; age, Year 4, Year 6 and adults). Given that the regression lines revealed different points of discontinuity for adults and children, we used a subitizing range of one to three for children and one to four for adults. This revealed a significant effect of the type of processing, F (1, 124) = 1354.827, p < .001, η^2p = .916, indicating that reaction times for subitizing were significantly quicker than reaction times for dot counting. Further, there was a main effect of age, F (1, 124) = 47.611, p < .001, η^2p = .434 and a significant interaction, F (1, 124) = 37.285, p < .001, η^2p = .376. Pairwise comparisons revealed this interaction was due to reaction times decreasing significantly by increasing age in the dot enumeration range (p < .001), whilst the Year 4 and Year 6 children had similar subitizing reaction times (p = .082) which were slower than the adults (p < .001). These effects demonstrate a discontinuity between subitizing and dot enumeration for all age groups.

Working Memory: There was a significant difference between age groups in terms of forward digit span, F (1, 124) = 19.716, p < .001, η^2 = .241. This was driven by the adults performing better than both the Year 4 and Year 6 children (p < .001). Similarly, backwards digit span improved with age, F (1, 124) = 15.458, p < .001, η^2 = .200, due to the adults performing better than the children (p < .001). These results can be seen in Figure 3.3.

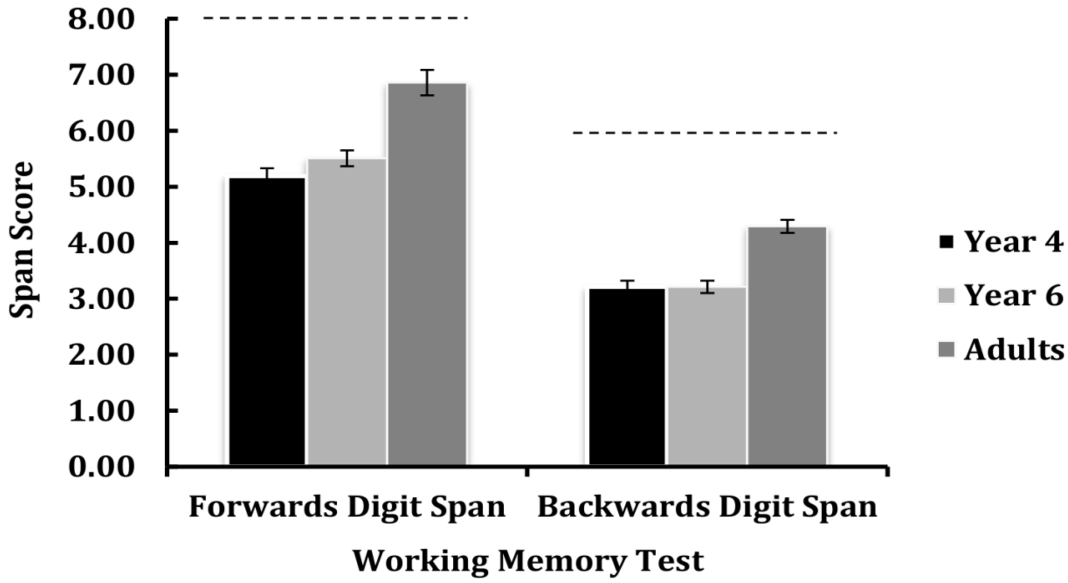

Figure 3.3 Forwards and backwards digit span by age. Error bars represent ±1 standard error of the mean, dotted lines represent the maximum score for each task.

3.3.2 Correlational Analysis

We next explored the relationships between variables in the child sample whilst controlling for age. Frequency span did not correlate with any of the other variables. However, subitizing and dot enumeration correlated with each other and with mathematics achievement, which in turn also correlated with forwards and backwards digit span. These correlations can be observed in Table 3.2.

Table 3.2 *Correlation coefficients for all variables in the child sample controlling for age.*

		1	2	3	4	5	6
1.	**Subitizing**	-					
2.	**Dot Enumeration**	.684**	-				
3.	**Maths Achievement**	-.308*	-.504**	-			
4.	**Forward DS**	-.052	-.217*	.429**	-		
5.	**Backward DS**	-.088	-.319*	.358**	.403**	-	
6.	**Frequency Span[1]**	-.149	-.132	.041	-.124	-.053	-

Note: *$p < 0.05$; **$p < 0.01$.

[1] The results were the same when using the frequency errors measure.

3.4 Discussion

The results lend support to the age invariance hypothesis as frequency processing performance did not differ significantly by age, even when including an adult sample. This is consistent with past research which also reports similar frequency processing abilities in different age groups (Johnson et al., 1979; Ellis et al., 1988; Goldstein, Hasher, & Stein, 1983; Zacks et al, 1982). The present task could be considered as harder than tasks used in past studies; it involved stimulus repetitions of between 4 and 25 and a presentation rate of 1 second compared to repetitions of between 1 and 4 and a stimulus presentation rate of 2-4seconds. This increased task difficulty prevents strategic processing, and therefore builds on past literature by demonstrating age invariance in this context, without the use of a cover task (Sanders et al., 1989). Furthermore, the lack of correlation between frequency processing and the working memory tasks also suggests a lack of strategic processing. It has previously been suggested that working memory is utilised in temporal processing to track numerosities (Meck & Church, 1983), the lack of correlation suggests this strategy is not being utilised here. It may also be considered as further evidence for frequency processing being a more automatic skill, given that working memory tasks are cognitively demanding. Nevertheless, the data is interpreted with some caution given that despite the task difficulty, participants performed near ceiling; the maximum span score for the task was 7, yet on average the present sample had spans of between 5 and 6.

Unlike in Experiment 1, there was no evidence that frequency judgements were related to any kind of numerical processing. Given that subitizing and frequency processing are both 'automatic' and numerically relevant skills, it is interesting that these two skills did not correlate; this may be indicative of these skills reflecting two separate early developed numerical systems. This is perhaps due to frequency processing being an evolutionarily relevant skill (Kelly & Martin, 1994). However, it could also be argued that subitizing has an evolutionary basis; it may serve to allow animals to quickly and accurately determine how many possible predators are in the current environment. Future research may focus further on the similarities and differences between frequency processing and subitizing. Regarding dot enumeration, it is highly likely that it didn't correlate with frequency processing due to the former relying on more effortful forms of counting which may not be utilised in an "automatic" task. It is also possible that neither subitizing nor dot enumeration correlated because the frequency processing task involved numbers outside of the range of the numerical estimation tasks used here. It may be interesting for future research to use larger numbers in the dot enumeration portion of the task to investigate this.

In accordance with the one existing study, frequency processing was not related to level of mathematics performance (Lund et al., 1983); this is in contrast to the relationship with everyday frequency processing that was observed in Chapter 2. It is possible that the ability to monitor number within an everyday task is more relevant to applying number to the problems presented in mathematics tests. However, caution should be applied with regards to maths tests in general given that what is included in the exams can vary by school. Nevertheless, since performance on these exams is what is important for a child's success, they remain an important measure. Consistent with past research, dot enumeration and subitizing were correlated with mathematical achievement (Gray & Reeve, 2014; Hornung, Schiltz, Brunner, & Martin, 2014; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Reeve et al., 2012; Schleifer & Landerl, 2011), providing further support for the suggestion that frequency processing and subitizing/dot enumeration reflect different early developed numerical systems. Alternatively the lack of correlations between frequency processing and subitizing, dot enumeration and mathematics could be due to participants not relying on numerical processing to make their judgements. In fact, Hintzman and Hartry (1990) suggest that relative judgements of frequency rely on familiarity, thus participants may have been utilising feelings of familiarity as opposed to numerical processing to make their judgements; the more familiar something is, the more often you will have presumed to have encountered it. Further, working memory is proposed to link to frequency processing when contextual information is stored (Mutter & Goedert, 1997), thus the lack of correlation between these two constructs could also suggest participants made familiarity based judgements, as familiarity judgements do not require contextual information (Yonelinas, 2002).

Consistent with past literature and the results in Chapter 2, subitizing and dot enumeration appeared to be distinct, yet intertwined skills (e.g. Reeve et al., 2012; Shimomura & Kumada, 2011). Specifically, the two skills were correlated but subitizing was characterised by fast reaction times and a flatter slope whilst dot enumeration was much slower and had a steeper slope. In addition, reaction times decreased with age for dot enumeration, but not consistently for subitizing; the only difference here was between the adults and children, though the gradient of the slopes were the same. Further, working memory correlated with dot enumeration but not subitizing; this is in line with studies which find working memory impacts upon dot enumeration only (Shimomura & Kumada, 2011; Tuholski, Engle, & Baylis, 2001, though see Barrouillet, Lépine, & Camos, 2008). In future it may be important to determine whether different kinds of working memory are related to different numerical skills. For example, subitizing is thought to reflect an object tracking system, thus visuospatial working memory may be the system which allows the tagging of object locations in memory (Shimomura & Kumada, 2011). Accordingly visual working memory has similar capacity limits to subitizing (3-4) items and the two tasks have been found to correlate (Melcher & Piazza, 2011), though this is not always observed (Gray & Reeve, 2014; Shimomura & Kumada, 2011).

Finally, working memory correlated with maths achievement. This is consistent with a large body of research which finds links between working memory and mathematics skills (Alloway & Passolunghi, 2011; Alloway, 2007; De Smedt et al., 2009; Holmes & Adams, 2006; Li & Geary, 2013; Meyer et al., 2010; Simmons, Willis, & Adams, 2012). A recent meta-analysis found that better performance in all aspects of working memory is linked to better maths skill, with verbal updating showing the strongest relationship (Friso-van den Bos et al., 2013).

To sum, Chapter 3 found that children are remarkably accurate at processing frequency information over short time frames; this is consistent with the age invariance hypothesis of frequency processing which posits that it is such a crucial skill it is developed very early (Ellis et al., 1988; Goldstein et al., 1983; Hasher & Chromiak, 1977). We did not find that frequency processing was related to the other numerical skills of subitizing, dot enumeration or mathematical achievement. This suggests frequency processing is not related to these types of numerical skills; it may be completely unrelated to numerical skills, or it may be related to a different type of numerical skill that is not measured here. Overall, Chapters 2 and 3 have found that children are able to process frequency information over both short and long time frames, though their relationship to other forms of numerical processing appears unclear due to problems with ceiling effects and reliability of the Year 6 data (Chapter 2) or with the lack of variability in the data (Chapter 3). The following chapters move on to investigate possible links between spatial and numerical processing.

CHAPTER 4

EXPERIMENTS 3A AND 3B: DIRECTIONAL PREFERENCES IN THE SPATIAL REPRESENTATION OF NUMBER

4.1 Experiment 3a

As previously discussed in Chapter 1.1, time, number and space are argued to be interlinked concepts. The previous two chapters have focused on our ability to link number and time by determining the number of times an event has happened. In this Chapter I move on to investigate the links between space and number using a novel number line task. Given that this task has not been used before, we first tested it in adults to ensure that the task was measuring spatial-numerical associations. This also allowed us to investigate one of the ongoing debates in the spatial-numerical literature: whether these associations are fleeting or inherent.

4.1.1 Introduction

In educated adults, number appears to be oriented in space (Dehaene, Bossini, & Giraux, 1993; Gobel, Shaki, & Fischer, 2011; Hubbard, Piazza, Pinel, & Dehaene, 2005; Marghetis, Núñez, & Bergen, 2014; Sullivan, Juhasz, Slattery, & Barth, 2011). The Spatial Numerical Association of Response Codes (SNARC) is the most widely evidenced example of this type of spatial-numerical coupling (e.g. Dehaene et al., 1993; Fischer, 2003; Shaki et al., 2009; Wood et al., 2008; Zebian, 2005). In a typical SNARC experiment, participants have to judge the magnitude of presented numbers by pressing a button with either their left or right hand. Importantly, participants are quicker to respond to small numbers with the left hand, and large numbers with the right hand (Dehaene et al., 1993; Wood et al., 2008). As discussed in Chapter 1.3.1, this association is thought to derive from numerical and spatial processing sharing overlapping neural circuity in the brain, this is then influenced by cultural norms resulting in a very specific spatially directed organisation of number (Hubbard et al., 2005).

However, this view that the SNARC effect reflects long term representations has recently been challenged by Fischer et al (2010) who argue instead that the directional spatial preferences observed in the SNARC effect are fleeting and reflect transient exposure to a particular relationship between number and spatial position. In other words, directional preferences in spatial numerical associations are not long lasting. Fischer et al (2010) conducted two standard parity judgement tasks with English speaking and Hebrew speaking participants but between tasks asked the participants to read a recipe which had small and large numbers presented either consistently with Western reading and writing direction (small numbers at the start of the line and large at the end) or inconsistently (large numbers at the start of the line, small at the end). In this task, they found that the inconsistent mapping reduced the SNARC effect in English speaking participants and reversed it in the Hebrew participants (Fischer et al., 2010, see also Shaki & Fischer, 2008). Fischer et al (2010) interpreted the rapid impact of the inconsistent condition as reflecting the flexibility of the SNARC effect. In this view, the direction of the SNARC effect can be altered by any form of recent spatial-numerical mapping (Fischer et al., 2010). The idea that the SNARC phenomenon indicates a more flexible and transient associative learning effect is also supported by the observation that a reverse SNARC effect is elicited when participants are trained to represent numbers on a clock face with large numbers are on the left side of space (Bächtold et al., 1998). Finally, Lindemann et al (2008) also questioned the longevity of the SNARC effect finding that learning ascending, descending or random sequences of numbers immediately before making a parity judgement could modulate the effect; the SNARC effect was not present after descending strings of numbers had been presented, but this was only in blocked conditions (i.e. all ascending trials or all descending trials).

Therefore, it can be seen that there are two competing ideas regarding the nature of directional preferences observed in the spatial representation of number. In one account, the direction of the effect reflects a long lasting relationship between numbers and their common cultural spatial representation. In the other account, the effect is a "fleeting" association that can be readily reversed through temporary exposure to a different spatial-numerical arrangement. It was therefore reasoned that it might be possible to dissociate these accounts by observing behaviour under conditions where participants are forced to rapidly select the appropriate action in response to an imperative stimulus. This speeded response means that participants have to rely on a default representation as they have no time to prepare or adapt their response. We therefore designed a study where participants were presented with an unbounded number line above which a number between 1 and 9 would appear. Participants were asked to move a handheld stylus to the point on the line which corresponded to the presented number. The line was presented both normally (for Western educated individuals) i.e. running from 0 to 10, and in a reversed manner, running from 10 to 0 with the colour of the number above the line indicating line direction. It was hypothesised that the neurologically intact adult participants would have the mental flexibility to show minimal impact on their reaction time when the number line is consistently reversed. This level of flexibility would be consistent with the findings of Fischer et al (2010). Nonetheless, the observation of flexibility in stable conditions is not a good test of whether there is a consistent directional preference for number representation. However, a task requiring fast action selection under unstable conditions would reveal the nature of the effect, thus a mixed block of trials was included where line direction changed randomly. This random presentation means that participants cannot rely on previous trials to determine which direction the line is running in, and therefore cannot prepare their responses. This means that if they are relying on a default preference, they should be quicker in responding to number lines consistent with this preference.

Therefore the experimental design involved two groups of participants who both completed two blocked groups of trials followed by one mixed block of trials. The critical difference was that one group of participants completed the normal block of trials first, then the reversed block of trials whilst the second group of participants completed it in the opposite order. If the effect is due to recent exposure and thus is 'fleeting', then the reaction times should differ depending on which block participants did prior to the mixed trials. Specifically, participants who have most recently completed a normal block of trials should show faster reactions to the 'normal' number line in the mixed trials, but those who have most recently completed a reversed block of trials should show faster reactions to the 'reversed' number line in the mixed trials. If the effect is a robust phenomenon then the Western educated adults should show faster reactions to the 'normal' number line in the mixed trials regardless of the direction of the preceding block. This would be consistent with the typically observed SNARC effect, for simplicity results consistent with this framework will also be operationalised as a SNARC effect (i.e. faster responses to the normal number line.

4.1.2 Method

4.1.2.1 Participants

Thirty-nine adults (14 male, mean age 26.4 years, range 18.3 – 56.8 years) participated in the study, with 20 participants in condition A (8 male, mean age 26.9 years, range 22-33 years) and 19 in condition B (6 male, mean age 25.6 years, range 18.3 - 56.8 years). The majority of participants were right handed (n = 34; self-reported) and all spoke English as their first language (reading and writing words from left to right). Participants in the two conditions did not differ in age, F (1, 37) = .24, p = .627, gender, $\chi2(1, N = 39) = .30$, p = .584, or handedness, $\chi2(1, N = 39) = .17$, p = 1.00.

4.1.2.2 Materials

The experimental task was deployed on a touch screen tablet PC (Toshiba Portege M700-13P, 257 x 160 mm, 1280 x 800 resolution, 100 Hz refresh rate). The task was designed on the Clinical Kinematic Assessment Tool (CKAT) software (Culmer, Levesley, Mon-Williams, & Williams, 2009; Flatters, Hill, Williams, Barber, & Mon-Williams, 2014), using the LabView development environment (Version 8.2.1, National Instruments, Austin, TX). The system allows for the presentation of visual stimuli with which the participant can interact using a handheld stylus, in turn providing a number of temporal and spatial kinematic metrics for assessment (for further details see Culmer et al., 2009). The laptop screen was folded back to provide a horizontal surface, which could be interfaced using a stylus as an input device (sampled at a 120 Hz).

The task involved participants moving from a start location shown on the screen to the appropriate location on a horizontal line 110 mm from the start location (see Figure 4.1). The target location was indicated by a number shown above the line (the number was located above the centre of the line). Participants were told that the end of line represented the numbers 0 and 10 and the line itself contained the numbers 1-9 equally spaced along the line. Participants were instructed that the number line ran left to right when the number was shown in red and ran right to left when the number was shown in blue. For the mixed trials, participants were told that line direction would change randomly. Participants learned the colour to line direction correspondence in the blocked trials and were thus primed by number colour in the mixed trials. All participants confirmed that they readily understood the instructions.

Participants were instructed to use their preferred hand (as handedness has no impact on the SNARC effect (Dehaene et al, 1993)) to drag the pen across the screen as fast as possible after the imperative number appeared (500ms after the participant moved into the start box), without removing the stylus from the screen at any point during the movement. This allowed us to record reaction time (RT), movement time (MT) and accuracy when crossing the number line. Participants were seated at a comfortable position in front of the computer, approximately 400-600 mm away.

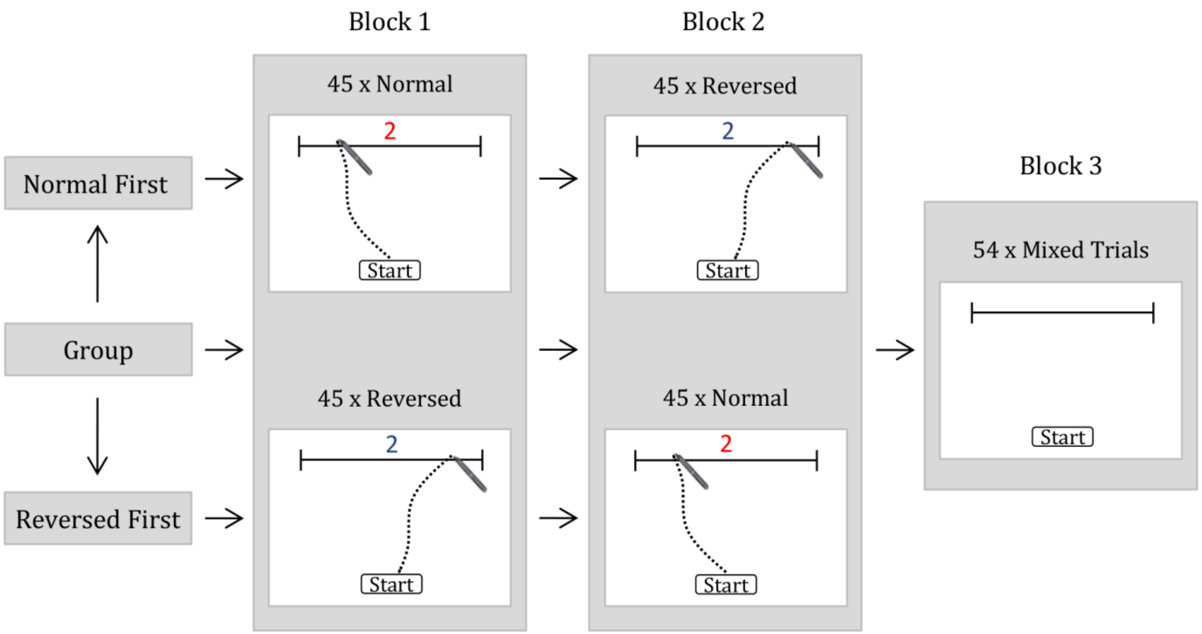

Figure 4.1 The experimental set up of the number line task showing the procedure for each condition. Examples reflect participant data.

4.1.2.3 Procedure

All participants undertook three blocks of trials, with the order of the first two blocks counterbalanced across participants. The three sets comprised one set where the number line always ran left to right ('normal block'), one set where the number line always ran right to left ('reversed block') and a final set where the line direction randomly changed from trial to trial ('mixed block' containing both normal and reversed trials). Participants in the normal first condition completed the normal block first then the reversed block and then the mixed block. Participants in the reversed first condition completed the reversed block first then the normal block and then the mixed block. The normal block consisted of 45 trials, the reversed block consisted of 45 trials and the mixed block consisted of 54 trials. Participants were given two practice trials before the normal block and before the reversed block; no practice trials were given in the mixed block. Participants were told they would complete three blocks of trials, but not what these would entail.

When participants were ready to begin the task, they held the stylus on the start button which triggered a number between 1 and 9 to appear above the line. The numbers were generated in a pseudorandom order; the correct response could not be on the same side more than three times in a row and the same number could not be presented consecutively. The number was red when the line ran from 0-10 (normal), and blue when it was from 10-0 (reversed). Participants used this information to determine line direction in the mixed block and were tasked with instructions to respond as quickly and as accurately as possible and to keep the stylus on the screen whilst responding..

The CKAT software generated (i) reaction times (RTs; the time taken from the appearance of the imperative stimulus to the time the stylus moved from the start position); (ii) the distance the stylus crossed the line from the correct location; (iii) movement times (MTs; the time taken between the stylus moving from the starting location and crossing the number line). All data were processed using MATLAB R2010a. We removed trials where the participant crossed the line on the wrong side (1.53% of trials; significantly fewer errors were made in the blocked trials than in the mixed trials, $t(38) = -5.01$, $p < .001$, but no other influences on these errors reached significance). We also excluded trials (5.3%) if they had negative RTs (i.e. moved before line onset) and/or had movement times longer than 10 seconds. Participants were removed from the experiment if they did not complete at least 50% of the trials correctly in the normal, reversed and mixed blocks. The number 5 was included in all analyses except when number type (small vs large) was used as a variable (when it was excluded - as its median position meant that it did not fit into the small or large category).

4.1.3 Results

4.1.3.1 Data Analysis

Reaction time and movement time data were used to determine the presence of directional spatial numerical associations. They were analysed by condition (whether participants completed the normal trials or the reversed trials first), number type (small vs large) and by trial type. All participants completed four trial types; normal trials where the line ran from 0-10, reversed trials where it ran from 10-0 and normal and reversed trials where the line direction was changed randomly (mixed normal and mixed reversed).

Average distance errors were calculated by analysing the difference between the actual physical location specified by the symbolic number on the number line, and where the participant crossed the line. This allowed us to examine how number was represented on the number line and was analysed by condition (normal first, reversed first), trial type (normal, reversed, mixed normal and mixed reversed) and number type (small vs large). Partial eta squared effect sizes are reported (Cohen, 1988) and the Greenhouse-Geisser correction applied where appropriate.

4.1.3.2 Reaction Time

We first explored the effect of Condition (2 between participant levels: normal first, reversed first) and trial type (4 within participant levels: normal, reversed, mixed normal and mixed reversed) using a mixed model ANOVA. A main effect of trial type was found, F (3, 111) = 81.23, $p < .001$, $\eta^2_p = .69$. Overall, mixed trials showed slower reaction times than blocked trials demonstrating significant switch cost effects. There was no main effect of condition, F (1, 37) = .33, p = .571, η^2_p = .01, but a significant interaction, F (3, 111) = 5.32, p < .05, η^2_p = .13. These effects can be seen in Table 4.1.

This interaction was further explored by first analysing the blocked trials, and then analysing the trials in the mixed block. In the blocked trials there was no main effect of condition, F (1, 37) = .76, p = .388, η^2_p = .02, but there was a main effect of trial type, F (1, 37) = 5.63, p = .023, η^2_p = .13, with normal trials quicker than reversed trials. There was also an interaction between trial type and condition, F (1, 37) = 14.64, p < .001, η^2_p = .28. The SNARC effect (i.e., normal trials quicker than reversed trials) was only found in the reversed first condition (see Table 4.1). This differential presence of a SNARC effect depending on condition can be explained parsimoniously by supposing that there was a small element of task learning at the start of the experiment. During the learning period, RTs would be expected to be marginally longer. When the learning period occurs during the normal block, this would then potentially mask any effect.

When comparing the mixed trials, there was no main effect of condition, F (1, 37) = 1.73, p = .196, η^2_p = .05, but a main effect of trial type, F (1, 37) = 22.80, p < .001, η^2_p = .38. This time the interaction was not significant, F (1, 37) = .00, p = .950, η^2_p = .00: normal trials were responded to faster than reversed trials, regardless of the preceding block. Therefore, under 'unstable' conditions in the mixed block, immediate prior exposure to a reversed number line did not alter the SNARC effect.

Table 4.1 *Reaction times by trial type and condition in seconds [95% confidence interval]*

	Normal First	Reversed First	Total
Normal Block	.83 [.73, .92]	.70 [.61, .80]	.77 [.70, .83]
Reversed Block	.80 [.71, .90]	.81 [.71, .91]	.81 [.74, .88]
Mixed Normal	1.08 [.92, 1.24]	1.23 [1.06, 1.39]	1.15 [1.04, 1.27]
Mixed Reversed	1.21 [1.03, 1.38]	1.36 [1.18, 1.54]	1.28 [1.16, 1.41]

Next, the effect of number on reaction time was explored. Figure 4.2 shows reaction time as a function of target number for the different trial types.

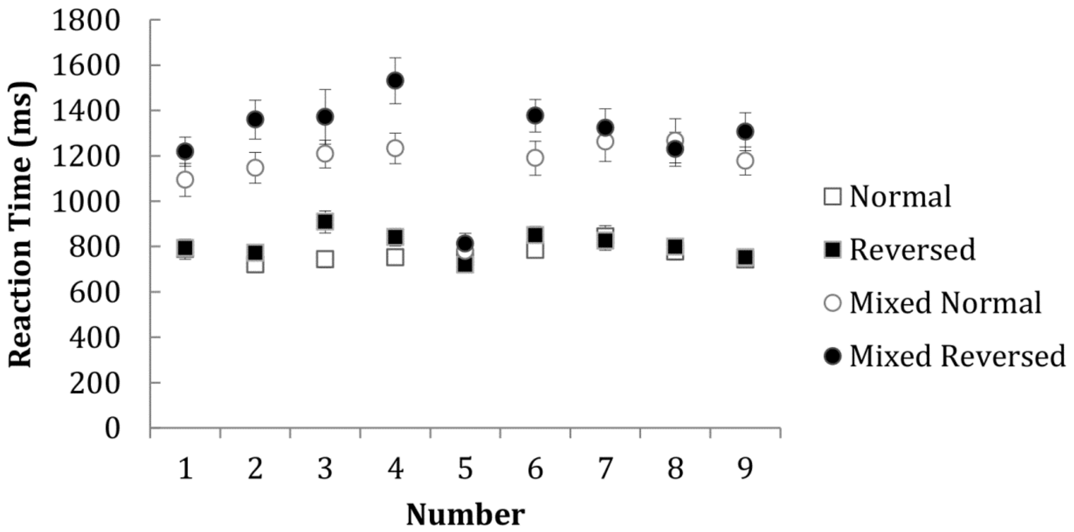

Figure 4.2 Average reaction time (ms) for each number by trial type. Error bars represent ±1 standard error of the mean.

Average RTs were then collapsed across condition into small numbers (1-4) and large numbers (6-9) within trial types.. This resulted in a repeated measures ANOVA with eight levels (normal small, normal large, reversed small, reversed large, mixed normal small, mixed normal large, mixed reversed small, mixed reversed large). The ANOVA showed a significant main effect of number type F (7, 266) = 54.54, p < .001, η^2_p =.59. Pairwise comparisons revealed small numbers in the normal trials had shorter RTs than small numbers in the reversed trials (p = .047), and small numbers in the mixed normal trials had shorter RTs than small (p = .009) or large numbers (p = .028) in the mixed reversed trials demonstrating SNARC effects in both the blocked and mixed trial types (see Table 4.2). However, reaction times to large numbers in the normal or reversed trial types were not significantly different ($p > 0.05$), though the pattern of results suggested participants were quicker to large numbers when presented on the right side of space in both the blocked and mixed trials. Thus these findings provide further support for the notion that small numbers are associated with the left side of space, and hint that large numbers are associated with the right side of space.

Table 4.2 *Reaction times by trial type and number type in seconds [95% confidence interval]*

	Normal	**Reversed**	**Mixed Normal**	**Mixed Reversed**
1-4	.75 [.68, .82]	.83 [.76, .90]	1.17 [1.05, 1.29]	1.37 [1.22, 1.52]
6-9	.79 [.72, .86]	.81 [.73, .88]	1.22 [1.08, 1.37]	1.31 [1.17, 1.45]

4.1.3.3 Movement Time

The results of the MT data essentially mirror those of the RT data. In particular, the mixed measures ANOVA revealed a significant effect of trial type, $F(3, 111)$ = 32.999, $p < .001$, η^2_p = .471 (due to switch costs), a significant interaction between trial type and condition, $F(3, 111)$ = 12.965, $p < .01$, η^2_p = .259 and a non-significant effect of condition, $F(1, 37)$ = .020, p = .888, η^2_p = .001. This interaction was again explored by separating the blocked and the mixed trial types. Unlike with the reaction time data, there was no effect of trial type in the blocked trials, $F(1, 37)$ = 1.348, p = .253, η^2_p = .035, however as with the RT data, there was a significant interaction between trial type and condition, $F(1, 37)$ = 18.930, $p < .001$, η^2_p = .338. Further analysis found that reversed trials were significantly quicker than normal trials in the normal first condition only. Again, this may explained by task learning; in the normal first condition participants start with the easiest trials, but must learn the task resulting in longer MTs. Although the SNARC effect in the reversed first condition is not significant, the means are in the expected direction (see Table 4.3). In the mixed trials there was no main effect of condition, $F(1, 37) = .734$, $p = .397$, $\eta^2_p = .02$ but a main effect of trial type, $F(1, 37) = 23.43$, $p < .01$, $\eta^2_p = .388$. The interaction was not significant, $F(1,37) = .201$, $p = .657$, $\eta^2_p = .005$: as with the RT data, normal trials were responded to faster than reversed trials, regardless of the preceding block.

Table 4.3 *Movement times by trial type and condition in seconds [95% confidence interval]*

	Normal First	**Reversed First**	**Total**
Normal Block	1.74 [1.47, 2.01]	1.31 [1.03, 1.59]	1.53 [1.33, 1.72]
Reversed Block	1.48 [1.25, 1.71]	1.47 [1.23, 1.70]	1.47 [1.31, 1.64]
Mixed Normal	1.71 [1.45, 1.97]	1.86 [1.60, 2.13]	1.79 [1.60, 1.97]
Mixed Reversed	1.86 [1.55, 2.17]	2.04 [1.73, 2.36]	1.95 [1.73, 2.17]

Finally, a significant effect of number type was observed, $F(7, 266) = 23.387$, $p < .001$, $\eta^2_p = .381$. Pairwise comparisons demonstrated significant switch costs ($p < .05$); participants generally moved quicker to small and large numbers in the blocked trials than in the mixed trials (see Table 4.4). There was a significant difference between large numbers in the mixed trial types; larger numbers were responded to quicker in the mixed normal trials than the mixed reversed trials. Whilst not significant, MTs were quicker to small numbers in the mixed normal than the mixed reversed trials.

Table 4.4 *Movement time by trial type and number type in seconds [95% confidence interval]*

	Normal	Reversed	Mixed Normal	Mixed Reversed
1-4	1.57 [1.36, 1.78]	1.53 [1.36, 1.69]	1.86 [1.67, 2.05]	2.05 [1.80, 2.31]
6-9	1.51 [1.31, 1.71]	1.46 [1.30, 1.69]	1.83 [1.62, 2.04]	2.00 [1.78, 2.22]

4.1.3.4 Distance Error

Average distance error was explored by trial type (4 within participant levels: normal, reversed, mixed normal and mixed reversed) and condition (2 group levels: normal first and reversed first) using a mixed model ANOVA. No main effects of either trial type, F (3, 111) = 3.04, p = .052, η^2_p = .08, or condition, F (1, 37) = .32, p = .576, η^2_p = .01, were observed and there was no interaction, F (3, 111) = 1.83, p = .166, η^2_p = .05 (see Table 4.5).

Table 4.5 *Average distance error by trial type and condition in millimetres [95% confidence interval]*

	Normal First	Reversed First	Total
Normal Block	6.43 [5.30, 7.56]	5.36 [4.20, 6.52]	5.90 [5.09, 6.71]
Reversed Block	6.67 [5.52, 7.83]	5.96 [4.78, 7.15]	6.32 [5.49, 7.14]
Mixed Normal	6.95 [5.74, 8.16]	6.57 [5.33, 7.81]	6.77 [5.89, 7.63]
Mixed Reversed	6.55 [5.19, 7.91]	7.01 [5.62, 8.41]	6.78 [5.81, 7.76]

We next explored the effect of number on distance error. Figure 4.3 shows the distance error as a function of target number for the normal and mixed reverse trial types.

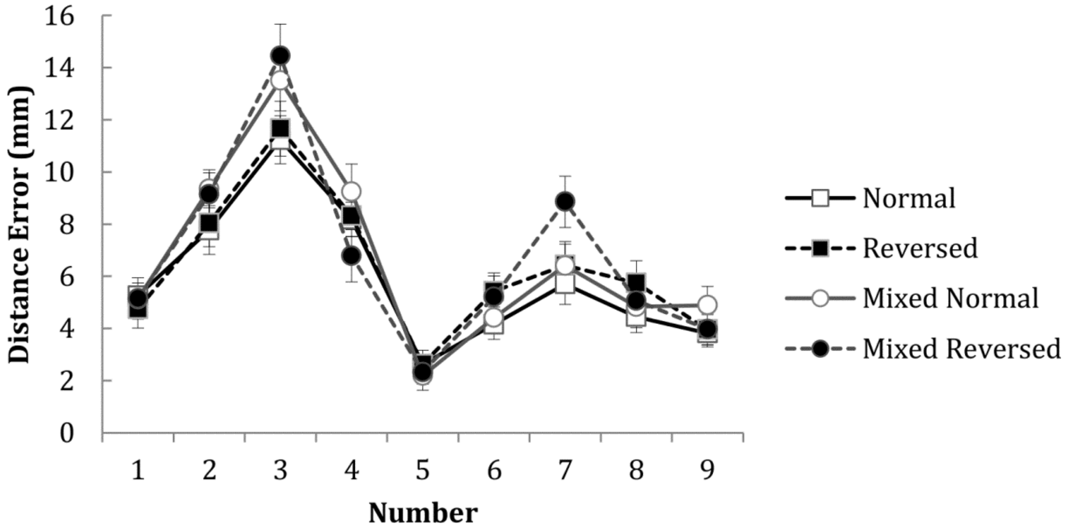

Figure 4.3 Average distance error for each number by trial type. Error bars represent ±1 standard error of the mean. Data points are connected by lines to highlight the pattern of results, not due to the nature of the data.

Average distance errors were collapsed into two groups within trial types; small (numbers 1 to 4) and large (numbers 6 to 9). A repeated measures ANOVA with 8 levels (normal small, normal large, reversed small, reversed large, mixed normal small, mixed normal large, mixed reversed small, mixed reversed large) revealed a significant effect of number type, F (7, 266) = 23.02, p < .001, η^2_p =.38. This was due to bigger distance errors being observed for small numbers than large numbers in all trial types (normal, reversed, mixed normal and mixed reversed; all *p's* < .001) as can be seen in Table 4.6.

Table 4.6 *Distance error by trial type and number type in millimetres [95% confidence interval]*

	Normal	**Reversed**	**Mixed Normal**	**Mixed Reversed**
1-4	8.11 [6.88, 9.34]	8.19 [7.11, 9.27]	9.31 [8.03, 10.59]	8.88 [7.47, 10.30]
6-9	4.53 [3.65, 5.42]	5.12 [4.11, 6.12]	5.13 [4.13, 6.14]	5.78 [4.75, 6.81]

4.1.4 Discussion

The reaction time data in Experiment 3a demonstrate that under unstable conditions (as in the mixed block) adults rely on a default directional preference of number representation (oriented left to right in the Western educated participants), which is not affected by exposing adults to a reversed number line immediately before. This effect was also observed in the number analysis whereby RTs to small numbers were faster when they are associated with the left side of space. The data collected within Experiment 3a therefore suggest that the SNARC effect is not a 'fleeting' phenomenon but rather reflects a reasonably long lasting spatial representation of numbers within the cognitive system.

As well as finding the SNARC effect in the RT data, evidence of this effect was also observed in the mixed blocks when analysing the MT data. This is in line with Fischer (2003), who also found evidence for the SNARC effect extending into the motor execution as well as the motor planning of a task. This is consistent with the framework of embodied cognition, where cognition is not seen as a 'closed' system separate from perceptual input and motor output but rather as an 'open' system where perception and action are considered as essential elements of the system's organisation (Wilson, 2002). In the number line task the cognitive processing takes longer when the required response is not consistent with the default organisation of numerical representation. If cognition were a closed system there would be no reason to suppose that there would be any impact of the SNARC effect once the spatial position has been determined. However, the results from Experiment 3a suggest that the cognitive processes do affect motor execution in a manner predicted by the theory of embodied cognition.

There were some differences in the results of the RT and MT analysis. Notably, no main effect of trial type in the blocked trials of the MT data was observed; participants didn't show significantly faster responses to normal trials over reversed trials, however the means were in this direction in the Reversed First condition. Further, whilst evidence for small numbers being associated with the left side of space was observed in the RT data, the MT data found some evidence that large numbers are associated with the right side of space (in the mixed trials only).

Given the inter-dependency between cognition and action within embodied cognition (Wilson, 2002), it could also be hypothesised that motor performance would influence performance on the number line task. As previously discussed, the fact that a SNARC effect was revealed in the movement times of the mixed trials suggests that the cognitive and motor systems are linked. In particular, when the cognitive demands of the task are increased, as in the unstable mixed block, and the cognitive-motoric system is put under pressure, less proficient motoric ability might have a deleterious effect on number line performance. Thus far, few studies have assessed the SNARC effect in later responses, or considered the embodied cognition approach. However, in the embodied literature there are numerous examples of cognition-motor couplings. For example, participants who are allowed to gesture in a memory task are able to remember more items- postulated to be due to the joint recruitment of both cognitive and perceptual motor systems to aid performance (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001). Specific to numerical processing, it is argued that the sensory-motor activities involved in learning numerical concepts (i.e. finger counting) continue to influence our numerical processing throughout our lives (Tschentscher, Hauk, Fischer, & Pulvermüller, 2012). For example, in adults action planning can be biased by the processing of both symbolic and non-symbolic numbers (Chapman, Gallivan, & Wood, 2014) and conversely, number processing can enhance motor responses (Ranzini et al., 2011). Thus is it possible that adults' level of motor skill proficiency may be linked to their number line performance, Experiment 3b sought to investigate this. Furthermore, given that the number line task is novel, Experiment 3b also attempted to ensure the results we observed are replicable, thus suggesting the findings obtained using this task are reliable.

4.2 Experiment 3b

4.2.1 Introduction

In Experiment 3a it was observed that Western educated adults have a default preference for representing small numbers on the left side of space, and large numbers on the right side of space. This preference was present in both the reaction time and movement time data and was taken as evidence for the inherent nature of spatial numerical associations. Experiment 3b aims to replicate these effects, whilst also further exploring the observed relationship between motoric ability and spatial numerical association, as evidenced by the presence of these associations in the movement time data. This relationship is consistent with the embodied cognition hypothesis of cognition-action inter-dependency (see Chapter 4.1.4). In order to investigate this inter-dependency in the number line task, the present experiment also included measurements of performance on a simple aiming task where the cognitive demands were minimised (as the task only required movements to a physically specified target displayed on the tablet computer screen). The aiming task did not therefore require the manipulation of symbolic information or the memory of the target location. Performance on the aiming task (measured as the average time to move between presented targets) serves as a proxy for motor skill (critically, the relevant motor skill required in the number line task) and has been shown to improve with increasing age over childhood and in line with improvements on other motor tasks (Flatters et al., 2014a; Flatters et al, 2014b). Under stable conditions (blocked trials) adults' motor skill may not play as important a role in completing the number line task given that the system is capable enough to complete the task without recruiting all of it's resources, in this case the cognitive and motor systems together. However, if the embodied account of cognition-action interdependency is correct (e.g., Wilson, 2002), when the cognitive-motoric system is put under pressure (mixed blocks) motoric skill may become increasingly important as the system will need to recruit all of it's resources to complete the task. Therefore, it was hypothesised that performance in the blocked trials would not be related (or only minimally related) to performance on the aiming task, but that there would be a relationship between performance on the aiming task and the mixed block.

4.2.2 Method

4.2.2.1 Participants

Forty-eight adults took part in this study (23 female, mean age 22.3 years, range 20.5 - 47.7 years). Consistent with Experiment 3a, the order in which participants completed the task was counterbalanced with 26 participants in the normal first condition and 21 participants in the reversed first condition. Thirty-six participants were right handed and all spoke English as their first language. Participants in the two conditions did not differ by age, $F(1, 46) = 1.67$, $p = .203$, $\eta^2_p = .04$, gender, $\chi 2(1, N = 48) = .03$, $p = .858$, or handedness, $\chi 2(1, N = 48) = .15$, $p = .696$.

4.2.2.2 Materials

Materials for the number line task were identical to those used in Experiment 3a. For the aiming task, the same tablet computers were used.

4.2.2.3 Procedure

Participants first completed an aiming task with their preferred hand. The task began by participants holding the stylus over a start position marker for 500 ms. This resulted in a green dot appearing; participants were instructed to move the stylus to this dot as quickly and as accurately as possible without lifting the stylus from the screen. Arrival at the target caused the dot to disappear and be replaced by another green dot in a different location- to which participants then aimed towards (see Figure 4.4) The different target locations of the dot was held constant for all participants. This was repeated for a total of 75 trials after which a finish position marker appeared which terminated the task when contacted.

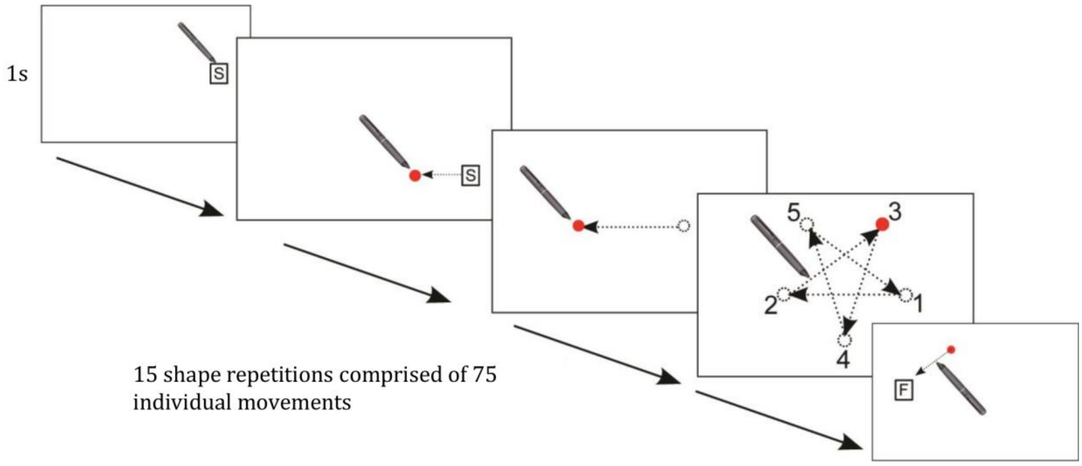

Figure 4.4 Illustration of the aiming task with dotted arrows to demonstrate the movements made by participants during the task. Figure adapted from Flatters et al (2014).

Participants then completed the number line task, the procedure of which was identical to Experiment 3a (see Figure 4.1). Movement time (MT) was computed for the aiming task and RT, MT and accuracy (distance from the correct location) scores were calculated for the number line task. The same exclusion criteria applied in Experiment 3a resulted in the removal of 8.49% trials. The number 5 was included in all analyses except when number type (small vs. large) was used as a variable.

4.2.3 Results

4.2.3.1 Data Analysis

Data analysis in Experiment 3b replicated that of Experiment 3a in order to examine the reproducibility of the SNARC effects observed. One participant was removed from the data set due to being an outlier, resulting in a final sample of 47 adults.

4.2.3.2 Number Line Task – Reaction Time

A mixed model ANOVA with four trial types (normal, reversed, mixed normal and mixed reversed) and two conditions (normal first, reversed first) was conducted. The results replicated Experiment 3a. A main effect of trial type was found, F (3, 135) = 117.48, $p < .001$, $\eta^2_p = .72$; mixed trial types showed slower reaction times than non-mixed trial types demonstrating significant switch cost effects. There was also no effect of condition, F (1, 45) = .29, $p = .593$, $\eta^2_p = .01$. However, this time there was no interaction between trial type and condition, F (3, 135) = .747, $p = .505$, $\eta^2_p = .02$; for both the blocked and mixed trials, normal trials were responded to quicker than reversed trials ($p < .001$). Although, the effect size for the SNARC effect was larger in the mixed trials (η^2_p =.453) than the blocked trials ($\eta^2_p = .364$). These effects can be seen in Table 4.7.

Table 4.7 *Average reaction time by trial type and condition in seconds [95% confidence interval]*

	Normal First	**Reversed First**	**Total**
Normal Block	.71 [.64, .77]	.65 [.58, .73]	.68 [.63, .73]
Reversed Block	.82 [.72, .93]	.79 [.67, .92]	.81 [.73, .89]
Mixed Normal	1.03 [.93, 1.14]	1.05 [.93, 1.17]	1.04 [.96, 1.12]
Mixed Reversed	1.26 [1.14, 1.38]	1.18 [1.04, 1.33]	1.22 [1.13, 1.32]

We next looked at the effect of number (see Table 4.8). We found a significant effect of number on RT, F (7, 315) = 72.724, $p < .001$, $\eta^2_p = .618$ (see table 8). Small numbers were responded to faster in the normal than reversed trials in both the blocked and mixed trials ($p < .05$) providing further evidence for SNARC effects. We also found some evidence that large numbers are associated with the right side of space; large numbers were responded to quicker in the normal trials than reversed trials in blocked trials only ($p < .001$), though this pattern was present in the mixed trials too.

Table 4.8 *Reaction time by trial type and number type in seconds [95% confidence interval]*

	Normal	Reversed	Mixed Normal	Mixed Reversed
1-4	.69 [.63, .74]	.84 [.73, .95]	1.06 [.98, 1.15]	1.33 [1.21, 1.44]
6-9	.70 [.64, .75]	.80 [.73, .88]	1.10 [.99, 1.20]	1.25 [1.15, 1.36]

4.2.3.3 Number Line Task – Movement Time

We found a significant effect of trial type on movement time (MT), F (3, 135) = 35.905, p < .001, η^2_p = .444, this effect was due to switch costs reflecting the increased difficulty of the mixed block. There was also a significant interaction between trial type and condition, F (3, 135) = 3.916, p < .05, η^2_p = .080, but no main effect of condition, F (1, 45) = 2.195, p = .145, η^2_p = .047. Once again the interaction was explored by analysing blocked and mixed trial types separately. In the blocked trials there was a significant effect of trial type, F (1, 45) = 7.789, p < .01, η^2_p = .148, a significant interaction, F (1, 45) = 8.182, p < .01, η^2_p = .154, and no main effect of condition, F (1, 45) = 2.567, p = .116, η^2_p = .054. The interaction was due to the SNARC effect being present in the reversed first condition only; this is consistent with the RT data in Experiment 3a. In the mixed trials, there was a significant effect of trial type, F (1, 45) = 37.256, p < .001, η^2_p = .453, a non-significant interaction, F (1, 45) = 3.358, p = .066, η^2_p = .073, and a non-significant effect of condition, F (1, 45) = 1.420, p = .240, η^2_p = .031; a SNARC effect was observed irrelevant of which trial type was undertaken first. These effects are consistent with those observed in Experiment 3a and can be observed in Table 4.9.

Table 4.9 *Average movement time by trial type and condition in seconds [95% confidence interval]*

	Normal First	Reversed First	Total
Normal Block	1.42 [1.28, 1.56]	1.09 [.93, 1.25]	1.26 [1.15, 1.36]
Reversed Block	1.42 [1.25, 1.58]	1.42 [1.22, 1.61]	1.42 [1.29, 1.55]
Mixed Normal	1.60 [1.46, 1.76]	1.52 [1.34, 1.71]	1.56 [1.44, 1.69]
Mixed Reversed	1.88 [1.70, 2.05]	1.67 [1.47, 1.87]	1.77 [1.64, 1.91]

As with the RT data, there was a significant effect of number on MT, F (7, 315) = 25.709, $p < .001$, $\eta^2_p = .364$. Once again there were no significant differences regarding movement times to small numbers, but the pattern of results are in the expected direction. However, there is evidence that large numbers are responded to quicker in these trials in both the blocked and mixed trial types ($p < .05$). These results are presented in Table 4.10.

Table 4.10 *Movement time by trial type and number type in seconds [95% confidence interval]*

	Normal	Reversed	Mixed Normal	Mixed Reversed
1-4	1.33 [1.22, 1.44]	1.51 [1.35, 1.67]	1.64 [1.51, 1.77]	1.91 [1.76, 2.06]
6-9	1.29 [1.15, 1.43]	1.42 [1.29, 1.55]	1.63 [1.48, 1.77]	1.84 [1.69, 2.00]

4.2.3.4 Number Line Task – Distance Error

In contrast to Experiment 3a, a significant effect of trial type was observed, F (3, 135) = 4.550, $p < .05$, $\eta^2_p = .092$. Pairwise comparisons revealed this was due to larger distance errors occurring during the normal mixed trials relative to either the normal or reversed trials ($p < .05$) (see Table 4.11). Larger errors were also made in the mixed reversed trials, but this did not reach significance. These effects demonstrate that the increased cognitive load in the mixed blocks had some effect on accuracy within the number line task. There was no effect of condition, F (1, 45) = .002, p = .96, η^2_p = .000, and no interaction, F (3, 135) = .383, p = .766, η^2_p = .008.

Table 4.11 *Average distance error by trial type and condition in millimetres [95% confidence interval]*

	Normal First	Reversed First	Total
Normal Block	6.30 [5.59, 7.00]	6.48 [5.67, 7.30]	6.39 [5.85, 6.93]
Reversed Block	6.28 [5.47, 7.09]	6.54 [5.60, 7.49]	6.41 [5.79, 7.03]
Mixed Normal	7.25 [6.33, 8.16]	7.06 [6.00, 8.13]	7.15 [6.45, 7.86]
Mixed Reversed	7.10 [6.24, 7.97]	6.94 [5.93, 7.94]	7.02 [6.36, 7.68]

Consistent with Experiment 3a, a repeated measures ANOVA showed a significant effect of number type, F (7, 315) = 25.334, $p < .001$, η^2_p = .360. Small numbers were associated with bigger distance errors than large numbers in all trial types ($p < .05$), see Table 4.12.

Table 4.12 *Distance error by trial type and number type in milliseconds [95% confidence interval]*

	Normal	Reversed	Mixed Normal	Mixed Reversed
1-4	8.69 [7.67, 9.71]	7.80 [6.81, 8.79]	10.32 [9.00, 11.65]	8.56 [7.50, 9.62]
6-9	5.01 [4.47, 5.56]	5.97 [5.21, 6.73]	5.24 [4.62, 5.85]	6.58 [5.82, 7.33]

4.2.3.5 Number Line Task Performance and Motor Skill Level

We next explored whether a reliable relationship existed between the number line task metrics and the aiming task measures (used as a proxy for motoric ability). The results showed no significant correlations between motor skill level and the blocked trial types for reaction times (normal, $r(47) = .223$, $p = .131$; reversed, $r(47) = .174$, $p = .243$) and movement times (normal, $r(47) = .201$, $p = .176$; reversed, $r(47) = .163$, $p = .275$).

However, motor skill level correlated significantly with reaction times to mixed normal trials, $r(47) = .446$, $p < .01$ and mixed reversed trials, $r(47) = .311$, $p < .05$. Furthermore, aiming correlated with movement times to mixed normal trials, $r(47) = .439$, $p < .001$ and mixed reversed trials, $r(47) = .326$, $p < .05$. Thus, participants with lower motor ability showed increased RTs and MT s within the mixed but not blocked trials.

4.2.4 Discussion

Experiment 3b replicated the effects of Experiment 3a; evidence of directional spatial numerical associations irrelevant of prior exposure was observed. Once again, this was evident in both the participants' reaction times and movement times when analysed by both trial type and number type. As with Experiment 3a, the kinematic data is interpreted as suggesting that the SNARC effect represents a default preference for a left to right orientation of number in Western adults which is present in both movement planning (RT) and execution (MT).

There was a subtle difference in the results of the two experiments – notably in the blocked trials. In the reaction time data there was no interaction between condition and trial type in the blocked trials of Experiment 3b; irrelevant of whether participants started with the normal or reversed trials, a SNARC effect was still evident. Experiments 3a and 3b were identical, except that in the latter participants completed the aiming task before the number line task. It is therefore possible that this resulted in practice effects. Participants in Experiment 3b also have some task specific learning to do in the normal first condition, but they are already familiar with the tablet and moving the stylus across the screen in response to stimuli, thus the learning demands are minimised. It is possible that the reduction in learning in these trials enabled the SNARC effect to be seen irrelevant of condition.

The inclusion of the aiming task in Experiment 3b allowed us to determine the nature of the proposed interdependency between cognition and action. In line with expectations, there was no relationship between the aiming task and the blocked trials, but performance on the aiming task was related to reaction times and movement times in the mixed trials of the number line task. These results demonstrate that when the cognitive-motor system is loaded (as is the case in the mixed block), the capabilities of the motor system become increasingly important. This suggestion is consistent with the movement time data and embodied cognition theory (see General Discussion).

4.3 General Discussion of Experiments 3a and 3b

The results from Experiments 3a and 3b suggest that preferences in the spatial representation of number are a robust phenomenon, with adults showing a preferred default representation under unstable conditions in a variety of tasks. If spatial numerical associations were primarily driven by recent exposure to a particular number-space relationship, then differences should have been found between participants who completed the normal block first and those who completed the reversed block first when they make fast action selections during the mixed trials. However, across two experiments, there were no differences between these groups indicating that the preceding block of trials had no influence on the response time asymmetry. These results are inconsistent with Fischer et al (2010) who were able to influence the SNARC effect in adults. In the Fischer et al (2010) study, adults completed parity judgement tasks under relatively stable conditions, showing that adults *can* adapt their spatial number representation. However, the alteration of representation under stable conditions is not necessarily a robust enough test to reveal default preferences. Unstable, pressured conditions are more likely to show if adults do default to a preferred representation, and whether or not this can be influenced by recent exposure. Across two experiments, the results support the argument that directional preferences in number-space representations are long lasting in adults and therefore not primarily driven by recent visuo-spatial mappings.

Reaction time and movement time by number type (small or large) were also analysed. Notably, across the reaction time data in both experiments, small numbers were associated with the left side of space, but only superficial evidence indicated that large numbers are associated with the right side of space. This is consistent with Fischer's (2003) pointing experiment - people were quicker to initiate responses to small numbers on the left, but not to large numbers on the right. Whilst this finding is not explained by Fischer, it is possible that the strong results for small numbers are due to small numbers being linked to a constant bound of zero. However, 10 is not a constant bound – number lines can go on indefinitely and, as such, representations of these numbers on a number line need to be more flexible, and thus less concrete.

Further, the movement time data provided strong evidence that large numbers are represented on the right, but nothing regarding small numbers. The majority of participants across the two experiments were right handed (80%), therefore dragging the pen across to the right side of the screen will be easier (it is easier to push than pull). Thus when large numbers are presented on the right, participants have a double advantage as not only is this consistent with Western spatial numerical associations, it is also the easier movement. This may explain why evidence for large numbers was only in the movement times, and why no effects were observed with small numbers; whilst the left side of the line would be consistent with spatial numerical associations, it is a harder movement for a large portion of participants.

Overall, these results support the idea that the default number representation for Western educated adults is in the spatial direction predicted by the predominant cultural organisation of numerical information, and are thus consistent with the mental number line hypothesis of spatial numerical associations. Further, the fact that evidence of directional preferences was observed in the movement times as well as the reaction times is consistent with the embodied cognition framework, where an understanding of human behaviour requires a consideration of how cognitive and motor processes interact to achieve a behavioural goal. The fact that MTs were slower in reversed trials shows that this phenomenon extends into the motor execution of a task, and is not limited to the motor planning (something also found by Fischer (2003)). This interdependency between cognition and action was further explored in Experiment 3b by investigating the relationship between participants' motor ability and their performance on the number line task. Embodied cognition theorists have suggested that the rooting of cognitive processes in motoric interactions with the world means that cognitive and motor capabilities must be mutually dependent (e.g. Van Rooijen et al., 2011). This interdependency between cognition and action would be particularly highlighted under unstable conditions where task performance would be more influenced by the underlying capability of the system. We explored this claim by measuring the relevant motor ability (using a simple aiming task) and relating this ability to performance on the number line task. The results showed that there was no reliable relationship between performance on the aiming task and performance on the blocked trials of the number line task. However, under unstable conditions level of motor skill was related to number line performance. This provides further evidence that cognitive and motor processes are intrinsically linked.

These results are consistent with a body of neurophysiological evidence which demonstrates joint recruitment of neural structures for motor and cognitive tasks. For example, the dorsolateral prefrontal cortex (primarily thought of as a cognitive structure) and the neocerebellum (primarily a motor structure) both show increased activation during cognitive tasks and decreased activation during well learned motor tasks (see Diamond, 2000, for review). Furthermore, motor and cognitive deficits frequently co-occur in children. For example, developmental coordination disorder is often coupled with learning difficulties in tasks such as reading and mathematics (Pieters et al., 2012).

Finally, the task created allowed for a consideration of *how* the number is mapped to the line. There were differences in the size of the distance error depending on whether the presented number was small or large – generally, larger errors were observed for small numbers. This can be understood in terms of the numerical size effect where discriminating between two numbers becomes harder as numerical magnitude increases causing a compressed number line as larger numbers appear closer together (Cohen & Blanc-Goldhammer, 2011; Longo & Lourenco, 2007; Siegler & Booth, 2004; Siegler & Ramani, 2008). This is consistent with a body of research showing that the perceived difference between two successive numbers decreases as target number increases (Cohen & Blanc-Goldhammer, 2011). Whether this overlap is due to numbers being logarithmically spaced with fixed variance or linearly spaced with scalar variance (increasing variance) is currently under debate (Cohen & Blanc-Goldhammer, 2011; Huber, Moeller, & Nuerk, 2013).

In conclusion, the results demonstrate that directional preferences in spatial-numerical associations are robust and support the idea that associations reflect a long term exposure to culturally determined directional numerical organisation. In the following experiments, it is investigated whether these preferences are also observed in children, something which is relatively neglected in the literature (White et al., 2012). Whilst number line studies suggest that children's ability to represent number spatially appears to improve with age (Booth & Siegler, 2008; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Siegler & Ramani, 2008), it is not known if and when directional preferences are observed. Children's spatial representation of number is of particular importance given that this ability is linked to later mathematical achievement (Booth & Siegler, 2006, 2008; Siegler & Ramani, 2008; Sasanguie et al., 2012).

CHAPTER 5

SPATIAL NUMERICAL ASSOCIATIONS, FINE MOTOR SKILLS AND NUMERICAL ABILITIES IN CHILDREN

5.1 Introduction

A number of research studies have demonstrated that number is spatially oriented in adults (see General Introduction 1.3). In Chapter 4 it was found that whilst Western Educated adults can adapt the direction of this spatial orientation of number, they have a preference for representing number as ascending from left to right. However, there is very little research on this topic involving children (White et al., 2012). The SNARC effect, which is the most widely reported evidence of spatial-numerical associations in adults, has been observed in children from age five years (Hoffmann, Hornung, Martin, & Schiltz, 2013), but only under certain conditions - leading to suggestions that these associations are not fully developed until around nine years of age (White et al., 2012). Further, it has been suggested that standard SNARC tasks may not be sensitive to assessing spatial-numerical associations in children given their reliance on a full understanding of the number system and parity (Ebersbach, 2015; White et al., 2012). For example, to complete a standard SNARC task children have to understand the meaning of odd and even (parity).

A promising way to assess spatial numerical associations in children is to use a number line task whereby children are asked to place presented numbers where they think they belong on a line and don't need to understand parity. Using this methodology researchers have found that children's accuracy in mapping number spatially improves with age (Booth & Siegler, 2008; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Siegler & Ramani, 2008).

Whilst these studies are informative, they have two major differences to the SNARC task normally utilised with adults. Firstly, they don't assess directional preferences in spatial numerical associations, this is important given that much of the adult literature focuses on this directional effect. For example, the SNARC effect is a bias to responding faster to small numbers on the left side of space and vice versa in Western populations (Dehaene et al., 1993; Viarouge, Hubbard, & Dehaene, 2014). As yet, number line studies only tell us that children *can* represent small numbers on the left side of space and large numbers on the right, but not whether this is their preferred representation as they only test children using one directional arrangement (e.g. 0-10). Secondly, these types of tasks only assess the accuracy with which children place numbers on the line using a pen and paper (e.g. Booth & Siegler, 2006, 2008; Ebersbach, 2015; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Siegler & Ramani, 2008) meaning any motor aspects of the task are not measured. This is in contrast to the SNARC effect in adults which is based on reaction times, with quicker responses indicating a preference for a specific spatio-numerical arrangement. Thus the mental number line task introduced in Chapter 4 was used as a test for directional preferences in spatial numerical associations in children by using both normal (0-10) and reversed (10-0) number lines, allowing us to analyse both accuracy and movement kinematics. The use of this computer based task also improves the sensitivity of the accuracy measures in that the computer can provide a more accurate and objective measure, whereas previous studies measured accuracy using a ruler.

A second focus of the present experiment will be to investigate whether the spatial organisation of number is important in the development of other numerical skills, and the importance of motor skills to numerical development. To do this two types of numerical skills will be assessed: (i) early number knowledge, and, (ii) mathematical attainment. The numerical literature acknowledges a divide between these two numerical skills, with the former being associated with our understanding of quantity (sets of items), how numbers are related (e.g. 5 is bigger than 4), and the words and digits associated with these numbers (Östergren & Träff, 2013), whilst the latter is a more complex mathematical understanding which is learned and tested in school (Jordan & Kaplan, 2009), for example understanding shapes, charts and fractions (Department of Education, 2013). To the authors knowledge, no studies exist which link spatial numerical skills to early number knowledge. Nevertheless, research using number lines has demonstrated a link between mathematical skills and the spatial representation of number in children (Booth & Siegler, 2006, 2008; Siegler & Ramani, 2008; Sasanguie et al., 2012). However, those studies tend to only assess arithmetic skills (e.g. addition and subtraction) as their outcome variable (e.g. Booth & Siegler, 2008), or only utilise correlational analyses (e.g. Siegler & Booth, 2004). Whilst an important aspect of mathematics, successfully achieving the required school grades relies upon much more than just arithmetic, for example children are also expected to be able to count, recite and compare numbers, recognise patterns in objects and shapes, solve word problems etc. (Department of Education, 2013). Furthermore, the mathematical knowledge expected of children changes with age, for example children in Year three are expected to be able to count, read and write numbers up to 1000, whilst Year one children are expected to count, read and write numbers up to 100 (Department of Education, 2013).

As previously stated, current number line studies tell us nothing about directional preferences. Thus, whilst a few studies linking maths and spatial-numerical associations in children exist, only one reports this in relation to directional preferences (Hoffmann et al., 2013). One might presume that showing a directional preference indicates that you have developed a solidified directional representation of number, but this may not be beneficial. It may mean that children find it easier to interact with number lines when used as a pedagogical tool which is especially important given that schools now routinely use number lines in maths lessons. However, numerical reasoning is often very abstract, perhaps it is better to be able to represent numbers on both sides of space (e.g. small on the left and small on the right) and thus demonstrate a more flexible representation of number (Ebersbach, 2015). Nevertheless, it has been suggested that whilst we may all represent number in space, it is the strength of directional preferences which are important in success/failure (Cipora et al., 2015). Thus the influence of directional preferences on mathematics achievement is something which will also be studied here.

Finally the contribution of fine motor skills to spatial numerical associations and numerical skills was assessed. A number of studies have shown that the directional preferences observed in spatial numerical associations are consistent with the cultural direction of fine motor skills such as writing and finger counting (Dehaene et al., 1993; Fischer, Mills, & Shaki, 2010; Gobel, Shaki, & Fischer, 2011; Hubbard et al., 2005; Fischer & Shaki, 2014). In particular, finger counting is thought to be the prime factor, for example, people are quicker to respond when the mapping between magnitude and the finger agrees with the direction of finger counting (for review see Fischer & Brugger, 2011). Nevertheless, despite the consistent predictions of an influence of these fine motor skills on spatial numerical pairings, to the authors' knowledge there is no research which assesses this, except our own in Chapter 4 which found some evidence that motor skills and number line performance are related.

Further, fine motor skills are thought to influence our learning experiences such that children with poor motor skills tend to show delays in cognitive performance (Pieters, Desoete, Roeyers, Vanderswalmen, & Van Waelvelde, 2012; Schoon et al., 2010; Van Rooijen et al., 2011). In particular fine motor skills can predict mathematics performance in typically developing children (e.g. Tramontana, Hooper, & Selzer, 1988) (see Chapter 1.3.3 for further discussion). However, little research exists and most existing studies use very subjective measures of motor control. For example, they use paper and pencil tests (Grissmer et al., 2010) or short teacher/parent questionnaires where fine motor skills may be assessed with just two questions (e.g. "can the child hold a pen appropriately") (e.g. Pagani et al., 2010; Pagani & Messier, 2012). This kind of subjectivity is a flaw which has been criticised in the study of other, related motor assessments of hand-eye coordination (Lee, Junghans, Ryan, Khuu, & Suttle, 2014). Further, it has been suggested that the sensitivity of these types of tests varies depending on the participant sample in question, and who fills out the questionnaire; teacher questionnaires can lack validity in comparison to those filled out by parents (Blank, Smits-engelsman, Polatajko, & Wilson, 2012). For example, teachers' perceptions of motor behaviour are more influenced by factors beyond the skills in question (e.g. gender and classroom behaviour) (Rivard, Missiuna, Hanna, & Wishart, 2007). In addition, some studies (e.g. Luo et al, 2007) use tasks involving drawing from memory which arguably require much more than fine motor skills; drawing a person requires the child to know what features make up a person and what to include – therefore a child may lose points simply by forgetting to draw one aspect of a person (often the neck) (Luo et al., 2007). More importantly, these tests may actually be measuring aspects of functioning beyond motor skills making it hard to be sure of the nature of the relationship between motor skill and mathematical ability. Thus, these tests may not be sensitive enough to truly capture differences in motor control, especially where these are subtle – as they are likely to be in the general population (Culmer et al., 2009).

There is an obvious need for more objective and systematic assessment of motor skills when studying their relationship to mathematics. Standardised assessment batteries such as the Movement ABC (M-ABC) (Henderson & Sugden, 1992) are useful given that they can easily be conducted in a school environment, however they are still flawed in the nature and depth of the information they can provide given that they are pencil and paper tests (Culmer et al., 2009). A promising way to truly capture the complexities of fine motor control is to use digital tablets to record movements as it allows for the assessment of both the speed and quality of movements (Flatters, Hill, et al., 2014). The previously discussed CKAT system (described in Chapter 4.1.2) is run on portable tablets meaning assessments can be carried out quickly and easily in a range of environments. Furthermore, a standardised motor battery run using the CKAT system has previously been shown to be effective in characterising children's performance throughout the school years (Flatters, Hill, et al., 2014).

In sum, it remains to be seen whether spatial numerical associations and the directional preferences within these associations are observed in children, and how these develop with age. We utilised the number line task introduced in Chapter 4 in order to answer these questions. If children show directional preferences, then there should be differences in reaction times depending on which number line they are responding to (normal, 0-10; reversed, 10-0). For directional effects, kinematic data will be of primary interest given that most of the relevant past research focuses on reaction times (e.g. Dehaene et al., 1993; Fischer et al., 2010), however, error data will also be analysed. Furthermore, regardless of directional preferences, based on past research children should become more accurate at placing numbers on the number line with age. This demonstrates an improving ability to represent number spatially, thus (consistent with past studies) error on the number line will be the primary measure for spatial numerical associations irrelevant of directional preferences. It is also explored whether spatial numerical associations are related to two types of numerical skills, early number knowledge and mathematics achievement, both when considering directional preferences and when focusing on accuracy, irrelevant of direction. Finally, CKAT was used to assess children's fine motor skills to determine whether these are related to spatial numerical associations and/or numerical skills.

5.2 Method

5.2.1 Participants

Participants were 91 children recruited from a primary school in the North of England. Eight of these children were either absent on the day of testing, or did not complete all measures leaving a final sample of 83 children. Of these, 27 were in Year 1 (M =6.5 years, range = 6.1 – 6.9, 15 male), 28 were in Year 3 (M =8.3 years, range = 7.9. – 8.8, 13 male) and 27 were in Year 5 (M =10.5 years, range = 9.9 – 10.9, 12 male). Seventy-eight percent of children were right handed. Informed consent was obtained in advance from the schools' Head-teacher and children's parents or guardians; children gave their informed consent verbally on the day of testing.

5.2.2 Spatial-Numerical Associations – Number Line Task

This task was deployed using the Clinical Kinematic Assessment Tool (see Chapter 4.1.2). All tasks were completed on a touch screen tablet PC with the screen folded back to create a horizontal surface (Toshiba Portege M700-13P, 257 x 160 mm, 1280 x 800 resolution, 100 Hz refresh rate).

For this task, children were asked to hold their stylus on a start location at the bottom of the screen; this triggered an unbounded number line to appear near the top of the screen, above which a number between 1 and 9 would appear. Children were required to slide their stylus from the start location to cross the number line where they thought the number belonged, as quickly and as accurately as possible (see figure 5.1). They were told that the number line represented numbers 1 to 9, equally spaced along the line. The task consisted of three blocks of trials; a 'normal' block where the line ran from 0 – 10 and the target numbers were presented in red, a 'reversed block' where the line ran from 10 – 0 and the target numbers were blue, and finally a 'mixed' block where line direction changed randomly. Participants used the colour of the number to determine line direction in the mixed block. Children completed 18 trials (2 of each number) in each of the consistent blocks (normal and reversed) and 36 trials in the mixed block (2 trials per number per line direction). Children were separated into two conditions: they either completed the normal block first or the reversed block first with the mixed block always being completed last. For further methodological information, see Chapter 4. This task provides data on a number of kinematic variables including reaction time (RT) and movement time (MT), as well as accuracy information about where children crossed the line.

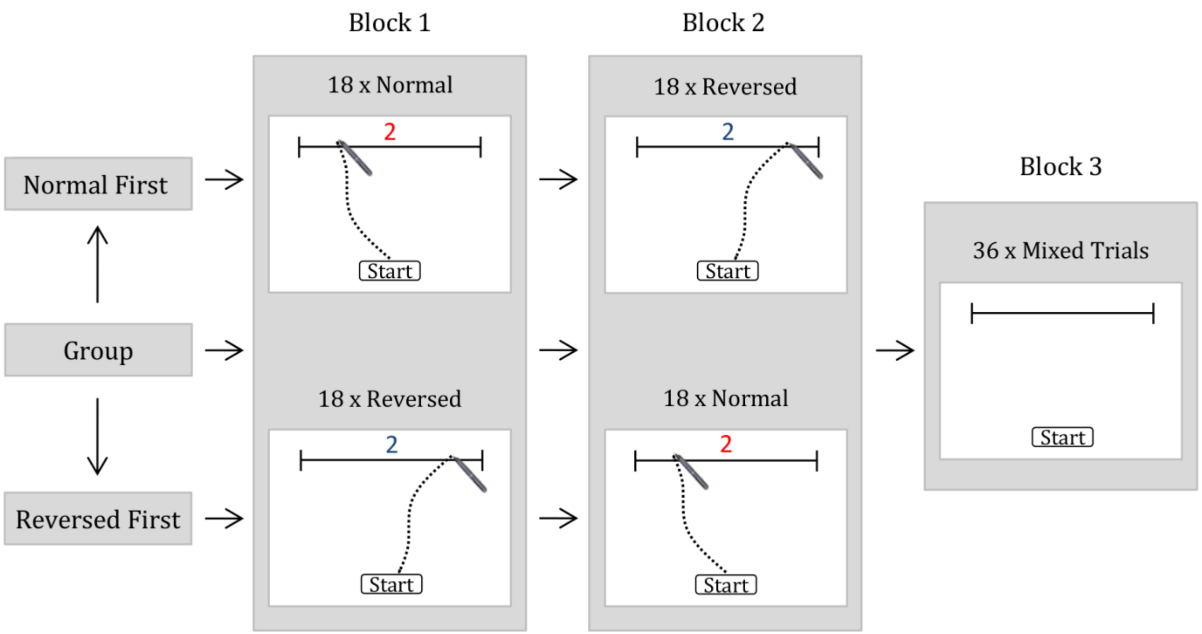

Figure 5.1 The experimental set up of the number line task showing the procedure for each condition. Examples reflect participant data.

5.2.3 Fine Motor Skills Assessment - CKAT

Fine motor skills were also assessed using the Clinical Kinematic Assessment Tool (CKAT). Using this software, children completed a test battery consisting of three tasks: tracking, aiming and tracing. These tasks can be seen in Figures 5.2a, 5.2b and 5.2c respectively. The task procedures will be described below, further details of the tasks are published elsewhere (see Flatters et al., 2014).

Tracking: This task consisted of two parts. First children were asked to track a moving green dot on the screen without a spatial guide, and then with a spatial guide. At the start of both parts, participants were asked to hold the stylus on a stationary green dot, after a delay of 1 second this dot began to move in the shape of a figure 8, repeating 9 times in total (see figure 5.2a). After each three repeats the dot sped up such that all children completed slow (average velocity 41mm/s), medium (average velocity (83.8mm/s) and fast paced trials (average velocity 167mm/s). In the spatial-guide trial, the figure 8 pattern was provided to the child in the form of a black guideline on the screen. A mean value of the root mean square error (RMSE) for all trials (with and without a guide; slow, medium and fast) was calculated for statistical analysis.

Aiming: Participants started this task by placing their stylus on the start position after which a dot appeared at location one, participants had to hit this dot as quickly and accurately as possible by sliding their stylus across the screen. Hitting this dot made it disappear and a new dot appear at location 2. This was repeated for a total of 75 aiming movements including 5 different target locations, the task ended when participants hit the finish position which appeared after the 75th dot had been hit. Of these aiming movements, 50 represent a 'baseline' condition where children completed 10 sequences of aiming to locations 1-5 (resulting in a star shape unknown to participants). The other 25 make up the 'online correction condition' whereby the target (dot) would randomly jump to a new location when the participant was within 40mm of the target, thus requiring online movement correction. Total movement times (MT) for each of the 75 aiming movements were then averaged using the median value. This task was also used in Experiment 3b.

Tracing: Once again, participants started this task by placing their stylus on a start position that triggered a tracing guide path to appear, which led to a finish position at the other end of the screen. The tracing guide path consisted of two black lines separated by a white path which participants followed to complete the tracing task. Participants must try to stay within the black lines of the tracing guide path whilst tracing along the path; feedback was provided in the form of an 'ink trail' produced by the stylus. Children completed six trials, alternating between path A and path B. These paths are geometrically identical, but mirrored vertically. All trials contained a 'pacing' box which was a black transparent box which moved along the tracing path at 5 second intervals; children were asked to try and stay within the box to minimise the impact of variation in the speed/accuracy prioritisation. Average path accuracy adjusted for temporal accuracy (adPA) for all trial types was calculated for analysis. Consistent with Flatters et al (2014) the path accuracy on each trial was inflated by the percentage that participants' movement time deviated from the ideal movement time for the trial, this was set at 36 seconds.

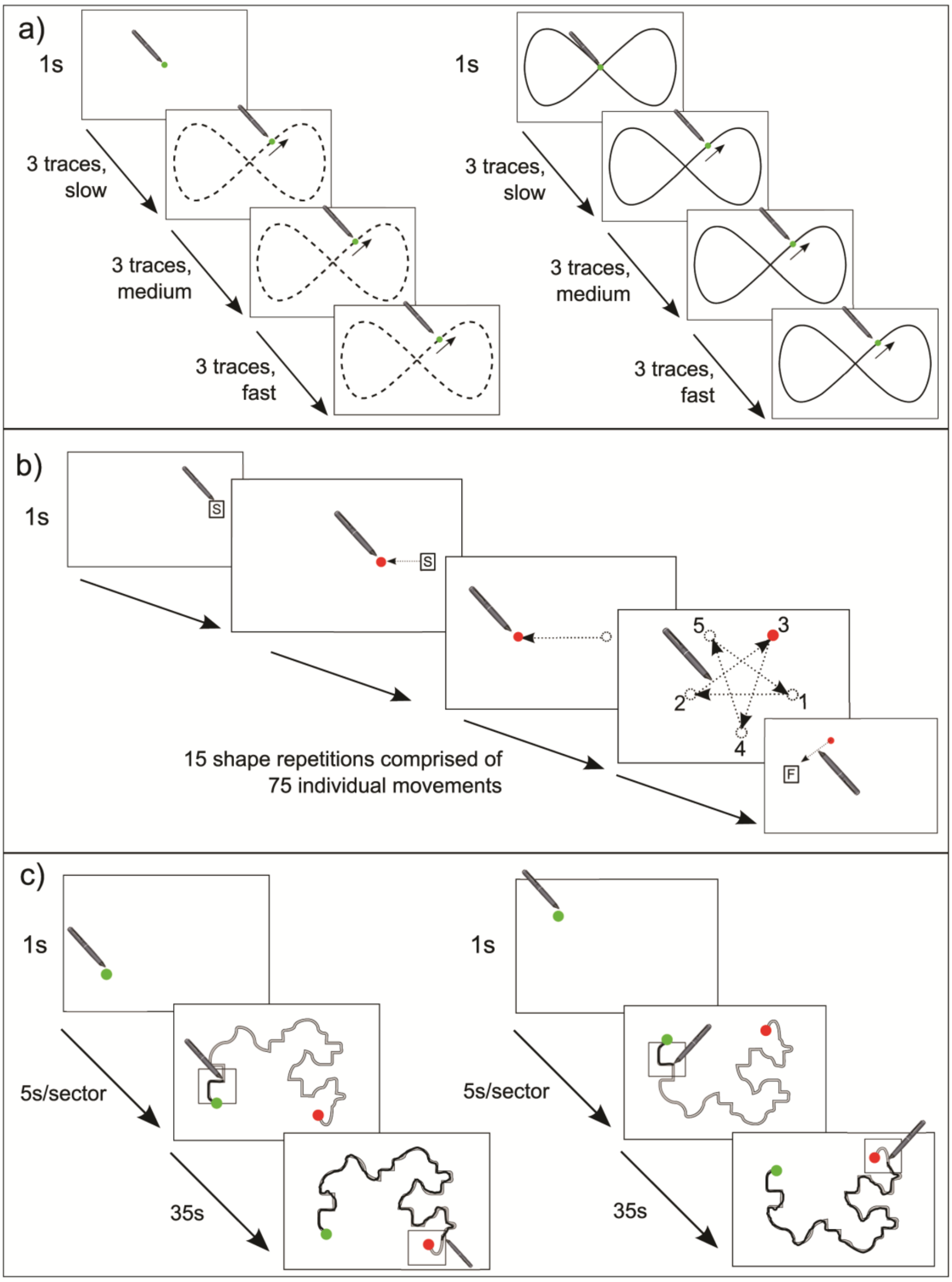

Figure 5.2 (a) Left is a demonstration of a tracking trial without a guideline, right is a demonstration of a tracking trial with a guideline. The dotted line indicates the trajectory of the moving dot. (b) A schematic of the aiming task with dotted lines indicating the trajectory of participants' movements and the dot positioning. (c) A schematic of the tracing task with path A (left) and path B (right). Black lines reflect participant trajectories which are printed to the screen. Figure reproduced from Flatters et al (2014).

5.2.4 Early Number Knowledge

We created an Early Number Knowledge variable made up of 4 tasks; counting forwards, counting backwards, naming the following number and naming the preceding number. These counting and naming skills are thought to represent Early Number Knowledge and have been used in previous research (e.g. Östergren & Träff, 2013). First, children were asked to count forwards from specific numbers said aloud by the experimenter. These numbers were 8, 24, 63 and 85; children were stopped when they had counted forwards by five. Children were then asked to name the number immediately following a specific number (6, 15, 53, 69, and 99). For the counting backwards task children counted backwards by five starting from numbers 10, 15 and 23. Finally, they were asked to name the number prior to a specific number (9, 17, 28, 40, and 80).

5.2.5 Mathematics Achievement

Achievement was measured using standardised tests of mathematics provided by the school. Children complete a number of tests during the school year in order to measure individual progress and to compare the school's progress with others in the UK. The scores used here are those obtained from the most recent assessment the children completed at the time of testing.

5.2.6 Working Memory

Two measures of working memory were obtained; children completed both forwards and backwards digit span tasks. In both tasks, the experimenter read aloud a string of numbers (e.g. 1, 5, 7) which the child had to repeat back to them in the forwards task (1, 5, 7), and repeat backwards to them in the backwards task (7, 5, 1). Both tasks consisted of blocks of 3 trials with the sequence of digits increasing by one for each new block. In the forwards task there were six blocks with trial lengths running from 3 to 8 digits, the backwards task had five blocks where trials ran from 2 to 6 digits.

5.2.7 Procedure

Children were assessed on a number of tests over the course of two sessions. In the first session children completed a motor skills assessment, in the second session they completed the number line task, counting and naming tasks and the working memory tasks. Each session lasted approximately 25 minutes and was completed in a quiet room in the school building where testing stations were set up to allow for simultaneous testing. Children were sat apart from each other, each with an experimenter and faced the walls of the room to reduce disruption.

5.3 Results

5.3.1 Directional Preferences in Spatial Numerical Associations

Trials were excluded if they had a negative reaction time (RT) meaning they responded before stimulus onset, or if they had movement times longer than 10 seconds. This resulted in the loss of 9.73% of trials in total (Year 1 = 16.56%; Year 3 = 10.37%; Year 5 = 4.53%). Trials where participants went to the wrong side of the line (i.e. to the left when the target number was on the right) were excluded from the kinematic and distance error analyses and studied separately, hereafter these are referred to as 'binary errors'. Further, in the kinematic and distance error analyses, we collapsed across all numbers except number 5, due to its median position on the number line.

To examine spatial numerical associations a number of variables were calculated; reaction times (RT's), movement times (MT) and two error variables, i) average distance error which reflects the distance between the numbers ideal location on the line, and the point at which the child crossed it, and ii) total binary error which refers to how many times the child crossed the line on the wrong side (i.e. crossing the line on the right when the number 1 appeared in the Normal condition). There were no main effects of condition in any of these analyses; therefore the data was collapsed across condition.

In order to assess whether directional preferences were present in these variables, the data was analysed with trial type (normal, reversed, mixed normal, mixed reversed) as a within subject factor, in the same way the data were explored in Chapter 4. The hypothesis is that if Western directional preferences are present then children should be quicker in the normal and mixed normal trial types. Much of the past research on directional preferences is based on kinematics, thus the RT and MT data are the main analyses, however error is also reported within this section.

First directional preferences with reaction times (RT) as a function of age (3 group levels; Year 1, Year 3 and Year 5) and trial type (4 within participant levels: normal, reversed, mixed normal and mixed reversed) were analysed (see Figure 5.3). The effect of trial type in the mixed model ANOVA was significant, F (3, 237) = 16.929, $p < .001$, $\eta^2_p = .176$; this was due to switch costs as children were slower to respond in the mixed trials. There was a non-significant effect of age, F (2, 79) = .561, $p = .573$, $\eta^2_p = .014$, but a significant interaction between age and trial type, F (6, 237) = 3.471, $p < .01$, $\eta^2_p = .081$; this was due to switch costs (quicker responses to blocked than mixed trials) being present for children in Year 3 and 5, but not Year 1 children. This is possibly due to the Year 1 children struggling somewhat with understanding the task and thus just setting off very quickly without focusing too much on which direction the line is going in.

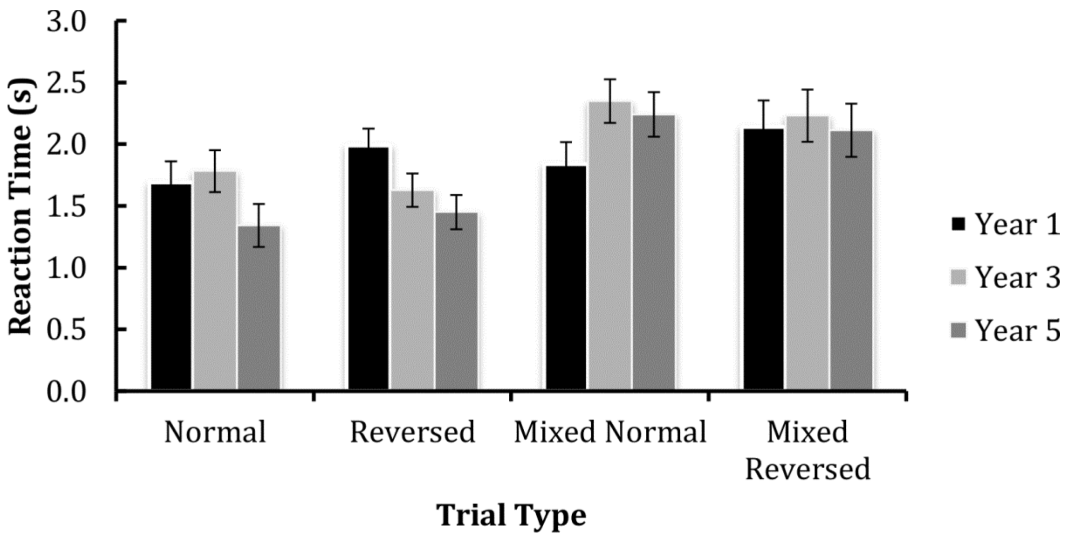

Figure 5.3 Average RTs by trial type and age. Error bars represent ±1 standard error of the mean.

We conducted the same analyses on movement times (MT). Once again there was a significant effect of trial type which was driven by switch costs, F (3, 237) = 17.617, $p < .001$, $\eta^2_p = .182$, and a significant effect of age, F (2, 79) = 5.320, $p < .05$, $\eta^2_p = .119$; Year 5 children had quicker MTs compared to the Year 1 children. The interaction was non-significant, F (6, 237) = 1.401, $p = .215$, $\eta^2_p = .034$. The results can be seen in Figure 5.4.

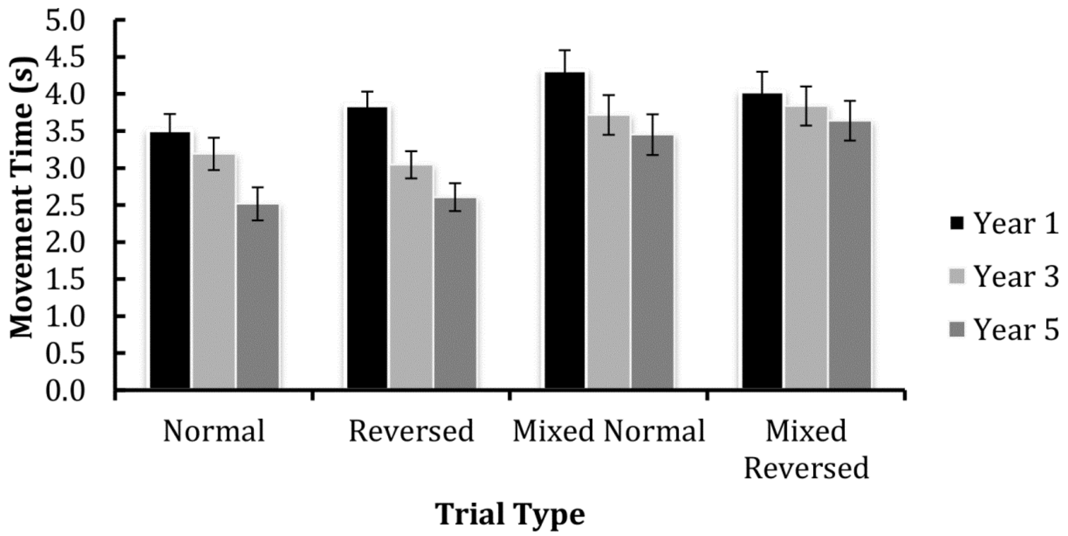

Figure 5.4 Average MTs by trial type and age. Error bars represent ±1 standard error of the mean.

Next average distance error was analysed (see Figure 5.5). The mixed ANOVA revealed a significant effect of trial type, F (3, 237) = 8.920, $p < .001$, $\eta^2_p = .101$; distance error was smaller in the normal trials than either of the mixed trial types ($p < .01$), reversed trials had smaller error than the mixed reversed trials ($p < .05$). A significant effect of age was also observed, F (2, 79) = 15.465, $p < .001$, $\eta^2_p = .281$, signifying that distance error reduces by age group ($p < .05$); the interaction was non-significant, F (6, 237) = .980, $p = .439$, $\eta^2_p = .024$.

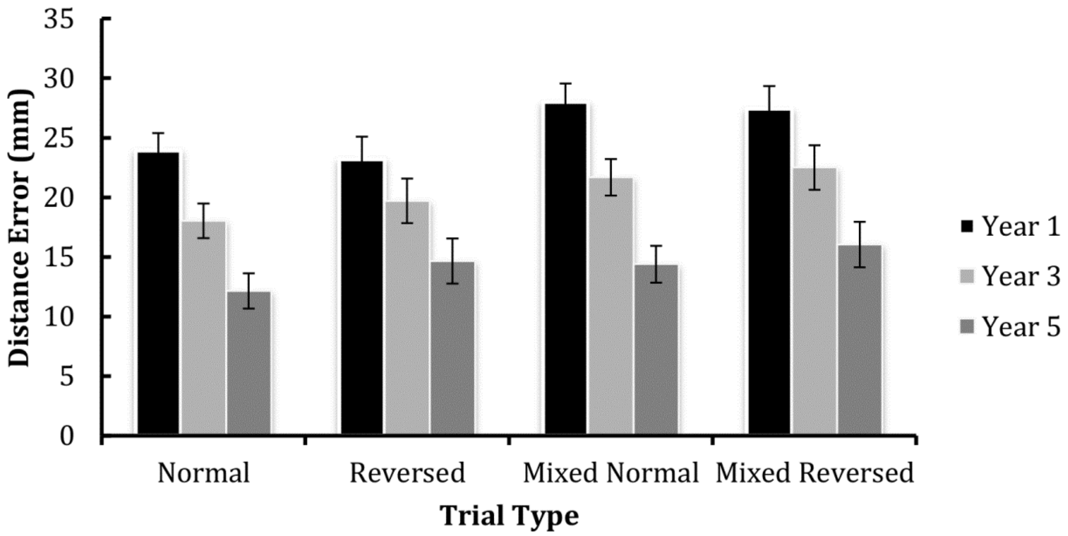

Figure 5.5 Average distance error by trial type and age. Error bars represent ±1 standard error of the mean.

We also analysed average total binary errors; the total number of errors which could be made was 18, thus many children are responding at chance in the mixed trials (see Figure 5.6). A mixed model ANOVA revealed a significant effect of trial type, F (3, 237) = 41.426, $p < .001$, $\eta^2_p = .344$; once again this was due to switch costs. There was also a main effect of age, F (2, 79), 14.718, $p < .001$, $\eta^2_p = .271$, due to Year 5 children making fewer binary errors than the Year 1 or Year 3 children. The interaction was non-significant, F (6, 237) = 1.132, $p = .345$, $\eta^2_p = .028$.

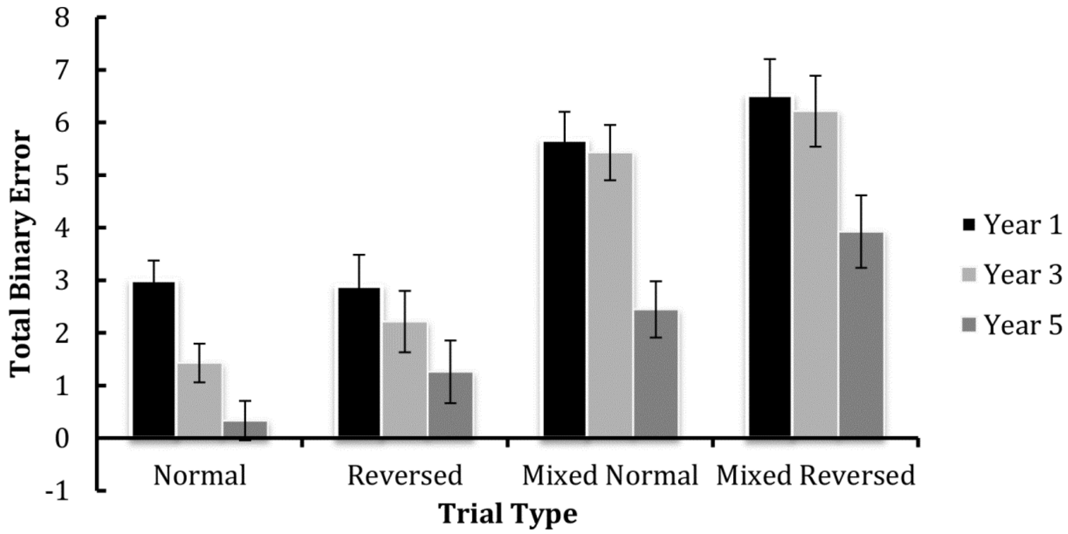

Figure 5.6 Average binary error by trial type and age. Error bars represent ±1 standard error of the mean.

Unlike in adults (see Chapter 4), there was no evidence of a directional preference in spatial numerical associations. However, when looking at the data large individual differences were observed; some children were actually showing a reversed preference, i.e. they were faster to respond and move (total time taken, TT) to the reversed trials than the normal trials. To investigate this, the directional preference of each child was determined by taking away their TT to the reversed trials from their TT to the normal trials (difference score) and then seeing what percentage of children per year was showing a normal or reversed preference (see Table 5.1). Between 35-60% of children were actually showing a reversed preference thus dampening any overall group effects which may be present. Whilst we do not have individual ethnicity data in this study, the school had a large population of Pakistani students. Importantly, Urdu is the national language of Pakistan and is written from right to left; given that past research suggests culture is important in determining the direction of spatial numerical associations, this may be affecting the results observed here. This is further explored in Chapter 6.

Table 5.1 *Percentage of children with normal or reversed directional preferences in the blocked and mixed trials.*

	Blocked Trials		**Mixed Trials**	
	Normal	**Reversed**	**Normal**	**Reversed**
Year 1	66.7%	33.3%	40.7%	59.3%
Year 3	62.1%	37.9%	46.4%	53.6%
Year 5	44.4%	55.6%	51.9%	48.2%

Whilst Table 5.1 demonstrates variability in the number of children showing each directional preference, it does not tell us about the strength of these preferences. For example, a child may have a strong normal preference or they may have a very weak normal preference. Therefore the average difference score between the normal and reversed trial types was assessed, thus a negative score indicates a normal preference and a positive score indicates a reversed preference. The means in Table 5.2 demonstrate that irrelevant of the direction of preference, children's preferences weaken with increasing age (except in the Mixed Normal trials).

Table 5.2 *Mean difference in TT between normal and reversed trial types in the blocked and mixed trials [95% confidence interval]*

	Blocked		**Mixed**	
	Normal	**Reversed**	**Normal**	**Reversed**
Year 1	-1.47 [-1.90, -1.04]	1.15 [.23, 2.07]	-1.47 [-2.28, -.66]	1.37 [.84, 1.90]
Year 3	-1.21 [-1.65, -.76]	1.82 [.99, 2.65]	-.82 [-1.57, -.08]	.85 [.33, 1.38]
Year 5	-.68 [-1.21, -.15]	.46 [-.25, 1.17]	-1.05 [-1.77, -.33]	.73 [.16, 1.30]

5.3.2 Spatial Numerical Associations, Numerical Skills and Fine Motor Skills

The second focus of this chapter was to assess whether improvements in children's ability to represent number spatially (both directional and non-directional spatial numerical associations) is associated with early number knowledge and/or mathematical achievement, and whether motor skills can predict spatial numerical associations, early number knowledge and mathematical achievement. Given the individual differences in directional preference, it was decided to analyse absolute scores which ignore the direction of preference, focusing only on the strength of it. Further, as the pattern of results for RTs and MTs were very similar in the sample, RT and MT were collapsed across to analyse total time taken (TT). This was also due to researchers noticing children using different strategies to complete the task; some children would set off very quickly and decide where the number belonged whilst on the move, whilst other children would decide before they set off and then move very quickly. In the adult sample in Chapter 4 it was useful to separate RT and MT as these appeared to reflect planning and movement separately, however the children do not seem to show this distinction. Creating a composite TT score for the children accounted for these differences in how they approached the task.

5.3.2.1 Developmental Trends

Whilst not the main focus of the study, the following section looks at the developmental trends within the variables. Table 5.3 provides a descriptive summary of the variables included in the following analyses (spatial numerical associations [SNAs], fine motor skills, early number knowledge, working memory and mathematical achievement).

Table 5.3 *Average score for each measure by age [95% confidence interval]*

	Year 1	Year 3	Year 5
SNAs –Distance Error	26.00 [23.04, 28.97]	20.10 [17.19, 23.01]	14. 21 [11.24, 17.17]
SNA's –Binary Error	4.52 [3.84, 5.20]	3.82 [3.16, 4.49]	1.99 [1.31, 2.67]
SNAs -TT	5.76 [5.10, 6.41]	5.45 [4.80, 6.09]	4.82 [4.17, 5.48]
SNAs – Strength score	.97 [.65, 1.28]	.98 [.65, 1.28]	.56 [.24, .88]
CKAT Score	.69 [.443, .940]	-.08 [-.326, .162]	-.60 [-.852, -.355]
Early Number Knowledge	12.07 [10.92, 13.23]	15.11 [13.97, 16.24]	16.52 [15.36, 17.68]
Working Memory	5.74 [4.96, 6.52]	7.89 [8.74, 10.30]	9.51 [8.74, 10.30]
Mathematics Achievement	2.82 [9.09, 3.54]	5.86 [5.15, 6.57]	10.00 [9.28, 10.72]

Spatial Numerical Associations: Past research using number line tasks as a measure of the spatial representation of number uses a distance error measure of performance, thus this measure is also utilised here. Given that no directional preferences were observed, an average was taken across all trial types (normal, reversed, mixed normal, mixed reversed). Using this variable, there was a significant effect of age, F (2, 79) = 15.672, $p < .001$, $\eta^2_p = .284$; as children got older, they became more accurate at placing numbers on the number line ($p < .05$).

Given the nature of the task, binary error and kinematic data were also available and thus explored. There was a non-significant effect of age on TT, F (2, 79) = 2.072, $p = .133$, $\eta^2_p = .05$, but a significant effect of age on binary errors, F (2, 79) = 14.718, $p < .001$, $\eta^2_p = .271$. This was due to Year 5 children making fewer binary errors than the Year 1 or Year 3 children ($p < .01$); the difference between Year 1 and Year 3 children was not significant ($p = .444$).

The TT data also then allowed us to assess whether the strength of children's preference (irrelevant of direction) varied by age. There was a non-significant effect of age, F (2, 79) = 2.166, $p = .121$, $\eta^2_p = .052$; the strength of children's preferences did not vary by age.

CKAT: Children's scores on each of the three CKAT tasks were converted into z scores and averaged to create a CKAT composite score. Univariate analysis confirmed that children's motor skills (as measured by CKAT) improve with age, F (2, 79) = 27.212, $p < .001$, $\eta^2_p = .408$, with all age groups differing significantly ($p < .05$).

Early Number Knowledge: Children's scores on the forwards and backwards counting and naming tasks were added together to produce a total counting score. Once again, developmental increases in performance were observed, F (2, 79) = 15.268, $p < .001$, $\eta^2_p = .279$, but this difference was not significant for the Year 3 and 5 children who performed similarly on these tasks ($p = .262$).

Working Memory: Children's scores on the forwards and backwards digit span task were added together to give a combined score. A significant effect of age was observed, F (2, 79) = 23.456, $p < .001$, $\eta^2_p = .373$; Year 1 children had lower scores than either the Year 3 or 5 children ($p < .01$), and Year 3 children's scores were lower than the Year 5 children's ($p < .05$).

Mathematics Achievement: Children's mathematics achievement significantly improved with age, F (2, 79) = 98.580, $p < .001$, $\eta^2_p = .714$; all year groups were significantly different from each other in ($p < .001$).

5.3.2.2 Relationships between Spatial Numerical Associations, Motor Skills and Mathematics

In this section the aims were to determine i) whether fine motor skills predict spatial numerical associations, and ii) whether spatial numerical associations (SNAs) and/or fine motor skills can predict the numerical skills of a) early number knowledge and b) mathematical achievement. Firstly, Pearson correlation coefficients were calculated (see Table 5.4). These analyses revealed that fine motor skills correlate with the distance error measure of spatial numerical associations but not the kinematic variables. Further, fine motor skills and the error measure of spatial numerical associations also correlated with early number knowledge and mathematical achievement.

Table 5.4 *Partial correlations between variables (controlling for age)*

	1	2	3	4	5	6	7	8
1. SNAs – Distance Error	-							
2. SNAs – Binary Error	.345**	-						
3. SNAs - TT	-.105	-.480**	-					
4. SNAs – Strength Score	.095	.078	.264*	-				
5. CKAT	.416**	.212	-.131	-.043	-			
6. Early Number Knowledge	-.346**	-.193	.142	.032	-.619**	-		
7. Working Memory	-.221	-.180	.057	.005	-.376*	.304*	-	
8. Mathematics Achievement	-.441**	-.133	-.126	-.015	-.398**	.380*	.538**	-

Note: *p < 0.05; **p < 0.01.

Based on the correlational analyses, a number of regression analyses were conducted to assess the study predictions. The 'enter' method was used where age was always entered in step 1 and the predictors entered in step 2. Given that the distance error variable is the one used in the current literature, and that it correlated with the other main variables whilst the kinematic data did not, this is the spatial numerical variable included in the regressions.

Predicting Spatial Numerical Associations: The correlation between fine motor skills and spatial numerical associations (distance error) allowed us to assess whether fine motor skills can actually predict children's performance on the number line task; Table 5.5 summarises the results of the regression analysis. The first model accounted for 30% of the variance in number line ability ($R^2_{Adjusted} = .30, F = 35.236, p < .001$). The second model accounted for 41% of the variance ($R^2_{Adjusted} = .41, F = 29.336, p < .001$); children's CKAT scores predicted their ability to represent number spatially.

Table 5.5 *Hierarchical regression analysis predicting spatial numerical associations*

		β	T	$R^2_{Adjusted}$
1				.297
	Age	-.55**	-5.936	
2				.409
	Age	-.25*	-2.237	
	CKAT	.46**	4.017	

Note: *p < 0.05; **p < 0.01.

Predicting Early Number Knowledge: This regression aimed to determine whether early number knowledge could be predicted by spatial numerical associations (SNAs) and/or fine motor skills. Working memory was also included as a predictor as it correlated with early number knowledge. Once again, age was a significant predictor in the first step, (*standardised* β = .52, p < .001); this first model accounts for 26% of the variance in counting ($R^2_{Adjusted} = .26, F = 29.083, p < .001$). The second model accounts for 52% of the variance ($R^2_{Adjusted} = .52, F = 22.519, p < .001$). This analysis revealed that only CKAT explained unique variance in children's early number knowledge (see Table 5.6).

Table 5.6 *Hierarchical regression analysis predicting Early Number Knowledge*

	B	**t**	$R^2_{Adjusted}$
1			.257
Age	.52**	5.393	
2			.515
Age	.00	.017	
SNAs	-.08	-.732	
CKAT	-.58**	-4.898	
Working Memory	.15	1.456	

Note: **p* < 0.05; ***p* < 0.01.

Predicting Maths Performance: Finally, it was assessed whether fine motor skills and/or spatial numerical associations could predict mathematics performance; working memory and early number knowledge were also included due to their correlation with mathematics achievement. The first model accounts for 75% of the variance in mathematics ability ($R^2_{Adjusted} = .75, F = 243.270, p < .001$). Even after controlling for age, the second model explained 85% of the variance ($R^2_{Adjusted} = .85, F = 92.029, p < .001$); age, working memory and spatial numerical associations all explained unique variance in mathematics achievement (see Table 5.7).

Table 5.7 *Hierarchical regression analysis predicting mathematical achievement*

	β	T	$R^2_{Adjusted}$
1			.749
Age	.87**	15.597	
2			.849
Age	.56**	9.024	
SNAs	-.16**	-2.842	
Early Number Knowledge	.10	1.518	
CKAT	.01	.132	
Working Memory	.28**	4.800	

Note: *p < 0.05; **p < 0.01.

5.4 Discussion

This study aimed to investigate the development of spatial numerical associations in children and whether directional preferences (e.g. smaller numbers associated with the left side of space and large with the right) exist within these associations. We found that accuracy (both binary and absolute measures) improved with age suggesting that children's ability to represent number spatially improves with age. However, unlike the adults in Chapter 4, there was no evidence of a directional preference in the total time taken for children on the number line task; they were just as quick to respond to the number line in its normal direction (0-10) as they were in its reversed direction (10-0). We also found no evidence of a directional preference in the accuracy data. The only other study which utilises a normal vs reversed number line method to assess spatial numerical associations did find some evidence that children were more accurate in the normal trials (Ebersbach, 2015). However, whilst the overall effect of line direction in the mixed model ANOVA (orientation, task order and age) is significant, the alpha value of the t-test was at the six percent level meaning it is non-significant. Further, the impact of line direction was only present in the youngest children when they started with the right to left orientation. It is possible therefore that this effect is mostly driven by practice effects, as observed in the adult data (see Chapter 4). Children start with the harder trials and are learning the task, thus they gain a double advantage when they complete the easiest trials second. There are also a number of other methodological differences between our study and the Ebersbach (2015) study which likely account for the differences, for example they use a non-symbolic bounded 1-100 number line, as opposed to the symbolic unbounded 0-10 number line used in the present study. Whilst previous studies have found directional spatial-numerical associations, these are normally in non-symbolic tasks (de Hevia & Spelke, 2009; Ebersbach, 2015; Opfer et al., 2010). This could suggest a non-symbolic preference develops prior to a symbolic preference – this is consistent with non-symbolic number representation developing much earlier than symbolic representation (Ebersbach, 2015).

In this study it is possible that no directional effects were observed because a number of children were actually showing a reversed preference, thus it is possible that the diversity of directional preferences cancelled out any effects which may have been present in the kinematic data. Why might different preferences have been present? Whilst the data are not clear cut, the sample is from a very mixed ethnicity school with a higher than average number of pupils of Pakistani heritage. Importantly, Urdu is the national language of Pakistan and is written from right to left. Given the proposed cultural influences on spatial numerical associations (see Chapter 1.3.3), it may be expected that these children would show a reversed preference. In fact, this has previously been suggested, but remains to be tested (Ebersbach, 2015). Furthermore, the school has a higher than average percentage of children whose first language is not English. It is therefore possible that they are exposed to different spatial-numerical patterns at home and at school which could reduce any overall effects. Accordingly, past research has found that exposure to different directions in spatial numerical association's results in weaker or non-existent SNARC effects (Shaki & Fischer, 2008; Zebian, 2005).

Whilst no group directional preferences were observed in the data, it was analysed whether the overall strength of preferences (irrelevant of direction) was related to the numerical skills of early number knowledge or mathematical achievement. There was no evidence that the strength of preferences changed with age and this preference was not related to any other variables, suggesting that the strength of directional spatial numerical associations is not important for mathematical achievement. However, to the author's knowledge this is the only study to directly test this in children and follow up work is warranted given findings in the adult literature. For example, research investigating the strength of preferences in adults has tended to use expert mathematicians against a control group. In Dehaene's seminal study, they found a trend for adults with high maths skills to show a smaller SNARC effect (though this was not significant the number of participants in each group was very small (n = 10)) (Dehaene et al., 1993). Using a much larger participant sample, a further study observed that expert mathematicians do not show a SNARC effect at all (Cipora et al., 2015), and weaker SNARC effects have been found in students studying mathematically heavy subjects such as engineering, compared to students studying arts subjects (Hoffmann, Mussolin, Martin, & Schiltz, 2014). It will be important to continue investigating the impact of maths proficiency in the general population as it is possible that differences in representation are only apparent in groups whose mathematical skills vary widely.

There were no significant effects regarding directional preferences, however, consistent with previous findings children's ability to represent number spatially (operationalised as distance error) did predict mathematical achievement (Booth & Siegler, 2006, 2008; Sasanguie et al., 2012; Siegler & Ramani, 2008). The fact that multiple populations appear to represent number spatially in some format could suggest that it is beneficial to us somehow. It is possible that being able to represent number spatially allows children to rely on the mental number line when they are solving complex mathematical problems; they may rely on their spatial representation to cope with task demands. For example, when presented with two addition calculations and asked to determine which calculation produces a bigger sum, they may use knowledge of where the numbers are represented in space to quickly determine that the calculation with more numbers on the right side of space will produce a bigger total. The fact that there was no link between spatial numerical associations and early number knowledge could suggest that for easy problems, the mental number line is not utilised. The counting tasks used in this study were relatively easy and all children were familiar with the number range tested, it is therefore possible that they relied on more semantic knowledge.

Interestingly, there was no evidence that early number knowledge predicted mathematics which is in contrast to some previous studies (Jordan et al., 2007; Jordan & Kaplan, 2009; Östergren & Träff, 2013). However, there are a number of issues with the measurements used in these studies which may explain the differences. Firstly, both studies by Jordan and colleagues included calculation in their early number knowledge measures, even though calculation skills then feature in the mathematics assessment (Jordan et al., 2007; Jordan & Kaplan, 2009). Meanwhile, Östergren and Träff (2013) only used arithmetic skill, not mathematical achievement which is a more general factor consisting of a number of skills, including but not limited to, arithmetic knowledge. Furthermore, they also included a number line task in their early number knowledge measure alongside counting, thus it is possible that the number line task is driving the effect – this is consistent with the finding that number line performance does predict mathematics achievement. Together, these findings suggest that the ability to represent number spatially is important in developing the mathematical knowledge which is required to be successful in school.

Consistent with the study's predictions, fine motor skills predicted spatial numerical associations when measured using the distance error variable. One possibility is that it is due to fine motor skills influencing our early learning experiences (Marr et al., 2003; Piaget & Inhelder, 1966). For example, children often learn about quantities by playing with objects and sorting them in to piles thus creating a link between number and space. Furthermore, it has been proposed that the fine motor skills of reading, writing and finger counting particularly, drive the association between number and space (Dehaene et al., 1993; Fischer, Mills, & Shaki, 2010; Gobel, Shaki, & Fischer, 2011; Hubbard et al., 2005; Fischer & Shaki, 2014). However, it could also be argued that the distance error measure we used actually reflects fine motor skills. Accordingly, motor skills assessments, including the CKAT system used here, often utilise movement error on a given task to determine a person's motor proficiency. In this instance, children who have bigger distance errors may be able to represent number spatially, but have worse motor control. Thus the relationship may be due to the distance error variable and CKAT both assessing motor skill, irrelevant of a child's ability to represent number spatially. Future research should consider this when designing tasks to assess spatial numerical associations in order to ensure motor skill does not confound the results. Nevertheless, it will be interesting for future developmental research to determine how much of an impact the relevant perceptual motor skills (e.g. finger counting, reading, and writing) have on the development of directional effects, as most research to date has been theoretical or correlational. For example, a recent online survey found that Western individuals start counting with their left hand, whilst Middle Eastern individuals start counting with their right hand (Lindemann et al., 2011), but it is not yet known whether these biases form the basis for directional preferences in number representation.

Finally, whilst motor skills correlated with mathematical achievement, they did not predict it. This is inconsistent with some past studies (e.g. Grissmer et al., 2010; Luo et al., 2007; Pagani & Messier, 2012). However, evaluations of mathematics achievement in previous studies often involved aspects of early number knowledge such as counting and reading two digit numerals. Thus it may be fine motor skills relationship with early number knowledge which is driving this effect in the younger children. Further, as fine motor skills are thought to influence mathematical knowledge through the early manipulation of objects e.g. putting blocks in to piles, it is possible that fine motor skills are important early on in development and for more basic numerical abilities, but that other factors are more important later on. Accordingly, Martzog and Stoeger (2011) found the link between fine motor skill and cognition was strongest in young children, with the association weakening with age. Furthermore, in the present study motor skills predicted counting skills, consistent with past research which finds that motor skills predict early number knowledge in both longitudinal (Grissmer et al., 2010; Pagani et al., 2010) and cross sectional studies (Pagani & Messier, 2012). It is also consistent with the theoretical work of Piaget and Inhelder (1966) which posits that fine motor skills enable us to interact with the world in new and varied ways thus allowing us to learn both in the motor and cognitive domains. More specifically, it follows from suggestions that fine motor skills are important in the understanding of number concepts (Luo et al., 2007). Thus, it may be that fine motor skills are a building block for early number knowledge. Previous studies have not always separated early number knowledge from mathematics well enough (see above), therefore perhaps these studies would not have found that fine motor skills predict maths if they were measuring more disparate numerical skills (early number knowledge and mathematics achievement separately).

In sum, Chapter 5 has demonstrated that children's improvements in representing number spatially can predict children's mathematics achievement. Further, we found that spatial numerical associations predicted fine motor skills. However, we note that this link warrants further investigation, given that our distance error variable could actually be measuring fine motor skill. We also found that fine motor skills predict early number knowledge, but not mathematical achievement. In contrast to the adults studied in Chapter 4, there were no directional preferences in spatial numerical associations in children. It was speculated that this may be due to the culturally diverse sample tested. This conjecture will be examined in Chapter 6.

CHAPTER 6

THE IMPACT OF CULTURAL BACKGROUND ON THE DEVELOPMENT OF SPATIAL NUMERICAL ASSOCIATIONS

6.1 Introduction

Few studies have investigated whether spatial numerical associations are present in children, and whether children show directional preferences in these spatial numerical associations (White et al., 2012). For example, do children, like adults, represent number on a mental number line running left to right? In adults, past literature mostly focuses on directional preferences in spatial numerical associations (e.g. Dehaene et al., 1993; Shaki & Fischer, 2008; Treccani & Umiltà, 2011), whilst in children, research tends to just investigate whether they exist, irrelevant of directional preferences (e.g. Booth & Siegler, 2006; Siegler & Ramani, 2008). Whilst both of these are useful, it is important to acknowledge that these are subtly, but importantly, different things. Chapter 5 attempted to investigate both of these issues. Whilst evidence of spatial numerical representations was found, there was no evidence of directional preferences at the group level. This was hypothesised to be due to the mixed ethnicity of the sample; a larger than average number of the pupils were of Pakistani heritage meaning that in their home language they likely read and write from right to left.

As previously discussed in section 1.3.3, one of the main hypotheses of the origin of directional preferences in spatial numerical associations is the influence of cultural background, specifically reading, writing and finger counting experience (Dehaene et al., 1993; Fischer, Mills, & Shaki, 2010; Gobel, Shaki, & Fischer, 2011; Hubbard et al., 2005; Fischer & Shaki, 2014). Accordingly, in adult participants research has found that the direction or existence of the SNARC effect is associated with these perceptual motor skills (Fischer & Brugger, 2011; Fischer, 2008). For example, weaker SNARC effects are observed in participants who have moved from a right to left reading and writing culture, to a left to right reading and writing culture (Zebian, 2005). Given that a large percentage of children in the sample spoke English as an additional language, it is likely that they are being exposed to different directional spatial numerical associations on a daily basis; left to right when at school, and right to left when at home. However, thus far the effect of cultural background on spatial numerical associations in children has been neglected; to the authors knowledge there are no studies which investigate this.

As part of a larger study, the opportunity arose to test in two different schools, one where almost all the pupils were from South Asian backgrounds (predominantly Pakistani) and one where the majority of pupils were from Western backgrounds (predominantly British or Eastern European). Thus these two groups of students were compared to determine whether differences exist in the nature of their spatial representation of number. Further, in the South Asian school, there was also the opportunity to replicate some of the other findings from Chapter 5 as measures of fine motor skills, working memory and mathematical achievement were obtained. Due to time pressures in testing as part of this larger study, an early number knowledge measure was not used. Nevertheless, the tests undertaken allow for the investigation of whether fine motor skills predict spatial numerical associations and whether fine motor skills and/or spatial numerical associations can predict mathematics achievement in a much larger sample.

6.2 Method

6.2.1 Participants

A total of 404 children were included in this study; 230 (55% female) were attending a predominantly Western school, 174 were attending a predominantly South Asian school (53% male). There was a total of 88 children in Year 2 (Western, M = 6.76, range = 6.3 – 7.2; South Asian, M =7.3, range = 6.9 – 7.8), 83 children in Year 3 (Western, M = 7.8, range = 7.2 – 8.2; South Asian, M =8.3, range = 7.7 – 8.9), 102 children in Year 4 (Western, M = 8.8, range = 8.3 – 9.2 ; South Asian, M =9.3, range = 8.9 – 9.8) and 131 children in Year 5 (Western, M = 9.8, range = 9.2 – 10.2; South Asian, M = 10.3, range = 9.9 – 10.8). Both schools are located in areas of similar socio-economic status.

6.2.2 Materials

The number line task and the fine motor skills assessment was completed on the same CKAT software that was used in Chapter 5 using the same touch screen tablet laptops (Toshiba Portege M700-13P, 257 x 160 mm, 1280 x 800 resolution, 100 Hz refresh rate).

6.2.3 Procedure

Participants in both schools completed a similar number line task to that used in Chapters 4 and 5 (see Figure 6.1). For consistency, 'normal' will always refer to the typical Western spatial numerical preference (e.g. 0-10) and reversed will always refer to the opposite of this preference (e.g. 10-0). Children were instructed to press and hold their pen on a start location at the bottom of the screen to begin each trial; this caused an unbounded number line to appear at the top of the screen. When a number between 1 and 9 appeared above this line children were required to drag the pen from the start location to where they thought the number should be on the line as quickly and as accurately as possible. The number line either ran from 0-10 (normal) or 10-0 (reversed). Children completed three blocks of trials; a 'normal' block (0-10), a 'reversed' block (10-0) and finally a mixed block where line direction changed randomly from normal to reversed.

Due to time pressures on testing within the school, and children's boredom with the task, a number of adjustments were made. Firstly, the number of trials in the task was reduced such that the testing session lasted between 10 and 15 minutes. Thus the normal and reversed blocks contained 12 trials each and the mixed block was reduced to 24 trials. There were no trials of number 5, given that this represents the middle of the line and is never included in the analysis. Secondly, the task was not counterbalanced. All children completed the block, followed by the reversed block and finally the mixed block. This was due to there being a lack of effect of condition in the children tested in Chapter 5, and due to the constraints placed upon on us during testing.

Children from the South Asian school also took part in a number of other tests as part of the wider study; this included the CKAT fine motor skills assessment and working memory assessments. Once again, the CKAT battery consisted of tracking, aiming and tracing subtests and the working memory assessment consisted of forwards and backwards digit span tasks (see sections 5.2.3 and 5.2.6). Mathematics achievement was again measured using the child's most recent score on the schools standardised mathematics. As before, testing sessions were set up to allow testing of four children at a time.

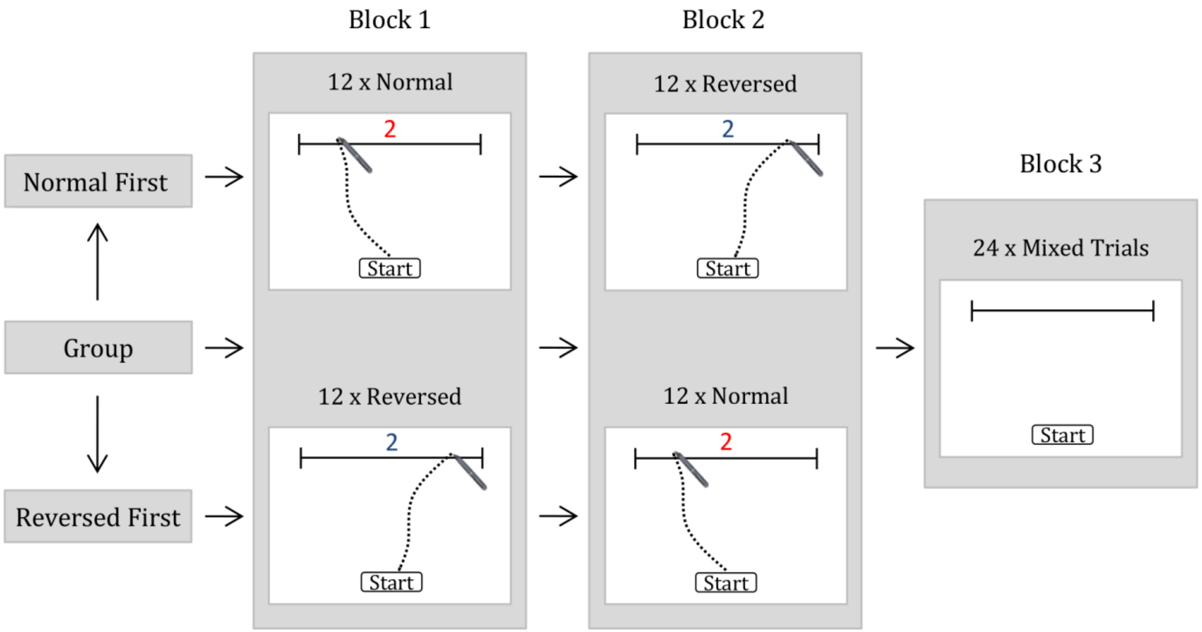

Figure 6.1 The experimental set up for the number line task. Examples reflect participant data.

6.3 Results

First, the results from the South Asian school will be presented to determine whether the spatial numerical effects and/or the predictive relationships observed in Chapter 5 can be replicated. Then there will be a comparison between the South Asian and Western children on the number line task.

6.3.1 Replication of Chapter 5

6.3.1.1 Spatial Numerical Associations

Trials were excluded if they had negative reaction times (RT) or movement times (MT) longer than 10 seconds. Binary errors (trials where participants crossed on the wrong side of the line) were removed from the kinematic and distance error analyses.

Given the observation in Chapter 5 that it was not useful to consider RT and MT separately, they were collapsed across to produce an overall total time (TT) variable. Thus TT, distance errors (the difference between a numbers actual location, and where the child placed the number) and binary errors (where a child crossed the line on the wrong side) were analysed for evidence of spatial numerical associations. In all analyses trial type was assessed as a within subject factor with four levels (normal, reversed, mixed normal, mixed reversed) and age as a between subjects factor with four levels (Year 2, Year 3, Year 4, Year 5) in mixed model ANOVAs.

Finally, as previously stated, normal will refer to a 0-10 number line preference, and reversed will refer to a 10-0 number line preference, irrelevant of participant ethnicity.

Total Time Taken: First, TT was assessed finding a significant effect of trial type, F (3, 513) = 38.265, $p < .001$, $\eta^2_p = .138$, this was due to switch costs in that children were quicker to the blocked trial types than the mixed trial types (see Figure 6.2). Furthermore, children were quicker to respond and move to the reversed trials than the normal trials ($p < .05$). We also found a significant effect of age, F (3, 171) = 7.997, $p < .001$, $\eta^2_p = .123$ as the Year 5 children were quicker than all the other children ($p < .05$). There was no interaction between age and trial type, F (9, 513) = .481, p = .887, η^2_p = .008.

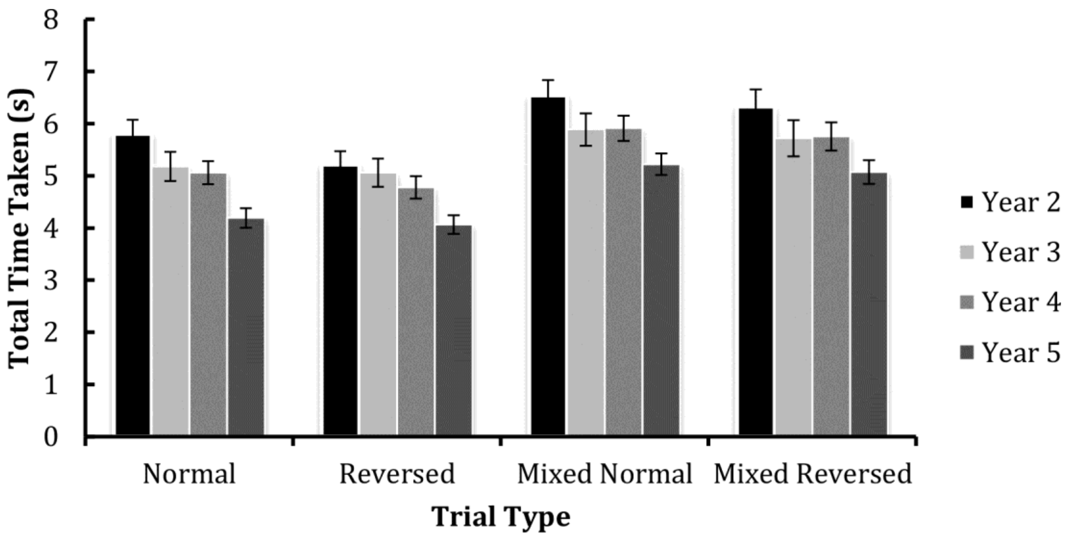

Figure 6.2 Average TT by trial type and age. Error bars represent ±1 standard error of the mean.

Distance Error: For the accuracy data, distance error was first assessed (see Figure 6.3). This revealed a significant effect of trial type, F (3, 513) = 17.825, $p < .001$, η^2_p = .094 and a significant effect of age, F (3, 171) = 10.272, $p < .001$, η^2_p = .153; there was evidence of switch costs and the Year 5 children were more accurate than all other groups ($p < .05$). The switch costs suggest that the difficulty of the mixed trials had an impact on children's accuracy. Once again the interaction was non-significant, F (3, 513) = .915, $p <$ .499, η^2_p = .016.

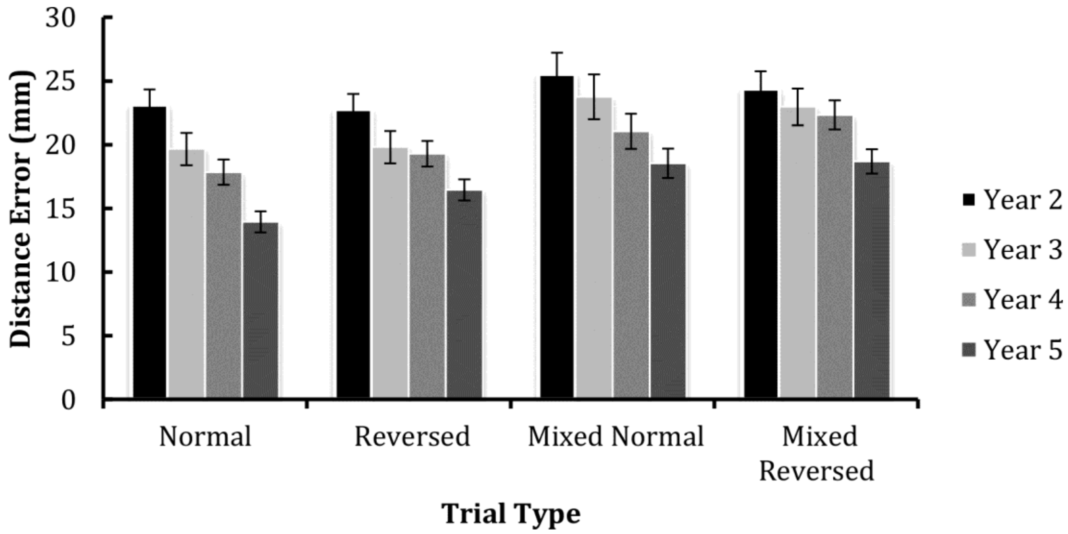

Figure 6.3 Average distance error by trial type and age. Error bars represent ±1 standard error of the mean.

Binary Error: Finally we analysed binary errors. We again found evidence of switch costs, F (3, 678) = 82.080, $p < .001$, $\eta^2_p = .266$ and also found that children made fewer errors to the normal than reversed trial types in the blocked trials ($p < .05$) (see Figure 6.4). The effect of age was significant, F (3, 226) = 3.295, $p < .05$, $\eta^2_p = .042$ but the interaction was not, F (9, 678) = 1.355, $p = .205$, $\eta^2_p = .018$. Overall the Year 5 children made fewer binary errors than the Year 2 children ($p < .05$).

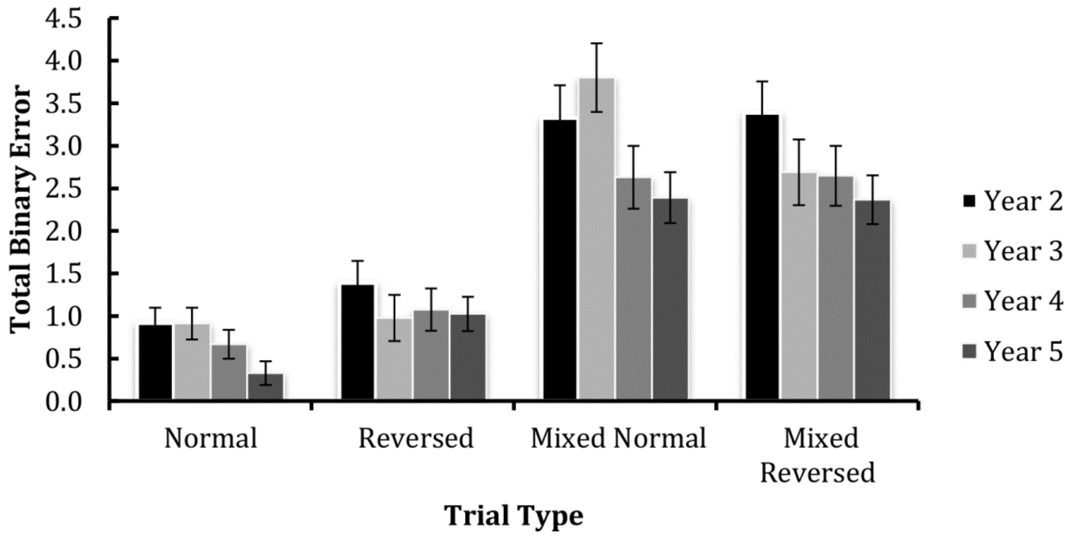

Figure 6.4 Total binary error by trial type and age. Error bars represent ±1 standard error of the mean.

Strength of Associations: Once again total time taken was used to analyse the strength of children's preferences irrelevant of direction by using an absolute difference score (TT to normal trials – TT to reversed trials). This revealed a non-significant effect of age, $F\ (3, 226) = 1.070$, $p = .363$, $\eta^2_p = .014$.

Overall, the pattern of results is similar to the pattern observed in Chapter 5. Notably, there was evidence of age related improvements in all variables except with regard to the strength of spatial numerical associations. However, we also found that children were quicker to respond and move to the reversed trials, possibly suggesting a reversed preference in the South Asian children, though this was not observed in the error data. As in Chapter 5 we observed large individual differences with the percentage of children showing a normal preference varying between 29% and 59% depending on age group (see Table 6.1). Notably, in the blocked trials children from the South Asian school tended to show a reversed preference which would be expected if cultural differences do indeed drive the direction of spatial numerical associations. However, the binary error data suggested a normal preference which may be indicative of a speed/accuracy trade off. In the mixed trials, the percentages are more even between the two preferences, this is possibly due to children finding the mixed blocks harder and so moving without fully considering the line direction. The influence of the mixed trials will be discussed in more depth in section 6.4.

Table 6.1 *Percentage of children with normal or reversed directional preferences in the blocked and mixed trials.*

	Blocked Trials		Mixed Trials	
	Normal	**Reversed**	**Normal**	**Reversed**
Year 2	29.27	70.73	45	45
Year 3	40.54	59.46	40.54	59.46
Year 4	35.42	64.58	52.83	47.17
Year 5	28.17	71.83	51.28	48.72

6.3.1.2 Spatial Numerical Associations, Fine Motor Skills and Mathematics

We were also able to see if we could replicate the findings from Chapter 5. Specifically, we hypothesised that i) fine motor skills would predict spatial numerical associations and ii) spatial numerical associations (SNAs) would predict mathematics. Past literature would lead us to suggest that fine motor skills may predict mathematics, but this was not observed in Chapter 5 thus we again explored this. Firstly, we ran a partial correlation controlling for age. As in Chapter 5 we observed that fine motor skills correlated with the distance error measure of spatial numerical associations and with mathematics achievement. We also found the error measure correlated with mathematics achievement, however this time the kinematic and binary error variable of spatial numerical associations also correlated with mathematics (see Table 6.2).

Table 6.2 *Partial correlations between all variables controlling for age*

	1	2	3	4	5	6	7
1. SNAs – Distance Error	-						
2. SNAs – Binary Error	.545**	-					
3. SNAs - TT	.386**	.080	-				
4. SNAs – Strength Score	.021	.079	-.092	-			
5. CKAT	.155*	.096	-.029	.011	-		
6. Working Memory	-.092	-.172*	.075	.007	-.131*	-	
7. Mathematics Achievement	-.216**	-.336**	.181**	-.080	-.308*	.420**	

Note: *p < 0.05; **p < 0.01.

Predicting Spatial Numerical Associations: Given that the error measure of spatial numerical associations correlated with fine motor skills but neither the kinematic nor binary error variable did, we again we used the distance error measure of the number line task. Consistent with Chapter 5 we found that accuracy was predicted by age and fine motor skills (see Table 6.3). However, this time the variance explained was much lower; the first model accounted for 5% of the variance *($R^2_{Adjusted}$ = .054, F = 14.037, p < .001)*, the second accounted for 7% of the variance *($R^2_{Adjusted}$ = .072, F = 9.943, p < .001).*

Table 6.3 *Hierarchical regression analysis predicting spatial numerical associations*

		β	t	$R^2_{Adjusted}$
1				.054
	Age	-.24**	-3.747	
2				.072
	Age	-.18*	-2.633	
	CKAT	.16*	2.360	

Note: **p* < 0.05; ***p* < 0.01.

Predicting Mathematics Achievement*:* As in Chapter 5, we used distance error, CKAT and working memory to predict mathematics. However, since we also found that binary error and total time taken on the number line task was correlated with mathematics in this experiment, these variables were also included here as measures of spatial numerical associations (SNAs) The first model with only age included accounted for 47% of the variance (*$R^2_{Adjusted}$ = .468, F = 198.821, p < .001)*, the second model accounted for 64% of the variance (*$R^2_{Adjusted}$ = .641, F = 68.013, p < .001)*. Once again, we observed that age and working memory could predict mathematics achievement. Unlike the previous chapter, we did not find that distance error on the number line task explained unique variance in mathematics, but the kinematic and binary error variables did. Furthermore, fine motor skills also contributed to mathematics performance (see Table 6.4)

Table 6.4 *Hierarchical regression analysis predicting mathematics achievement*

	β	t	$R^2_{Adjusted}$
1			.468
Age	.69**	14.100	
2			.641
Age	.50	11.371	
SNAs – Distance Error	-.090	-1.649	
SNAs – Binary Error	-.157*	-3.147	
SNAs - TT	.155*	3.503	
CKAT	-.173**	-3.927	
Working Memory	.25**	5.819	

* $p < .05$, ** $p < .01$

6.3.2 Spatial Numerical Associations in a Predominantly Western School

Total Time Taken: As with the children from the South Asian school we also found a significant effect of trial type due to switch costs, F (3, 432) = 54.741, $p < .001$, $\eta^2_p = .275$. Unlike the South Asian school, we did not find any evidence of directional preferences (see Figure 6.5). The effect of age was non-significant, F (3, 144) = 2.339, $p = .076$, $\eta^2_p = .046$ as was the interaction, F (9, 432) = .945, $p = .472$, $\eta^2_p = .019$.

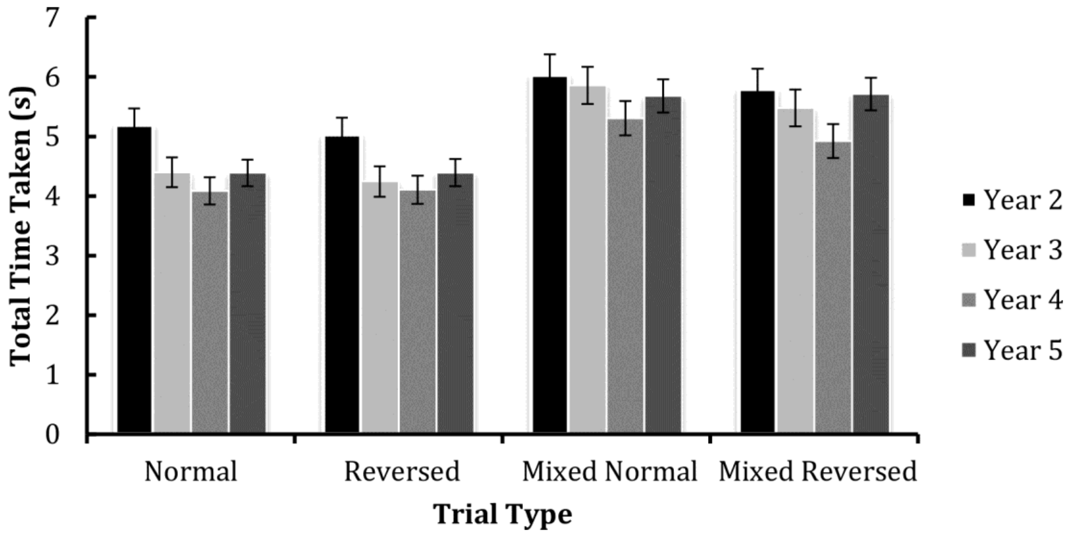

Figure 6.5 Average TT by trial type and age. Error bars represent ±1 standard error of the mean.

Distance Error: Once again there was a significant effect of trial type, F (3, 432) = 8.011, $p < .001$, $\eta^2_p = .053$. This time this was due to children being more accurate in the normal trials than the reversed trials in the blocked trials ($p < .05$) (see Figure 6.6). As with the South Asian school, there was a significant effect of age, F (3, 144) = 6.982, $p < .001$, $\eta^2_p = .127$; the Year 5 children were more accurate than the other year groups. The interaction was non-significant, F (3, 432) = .859, $p = .549$, $\eta^2_p = .018$.

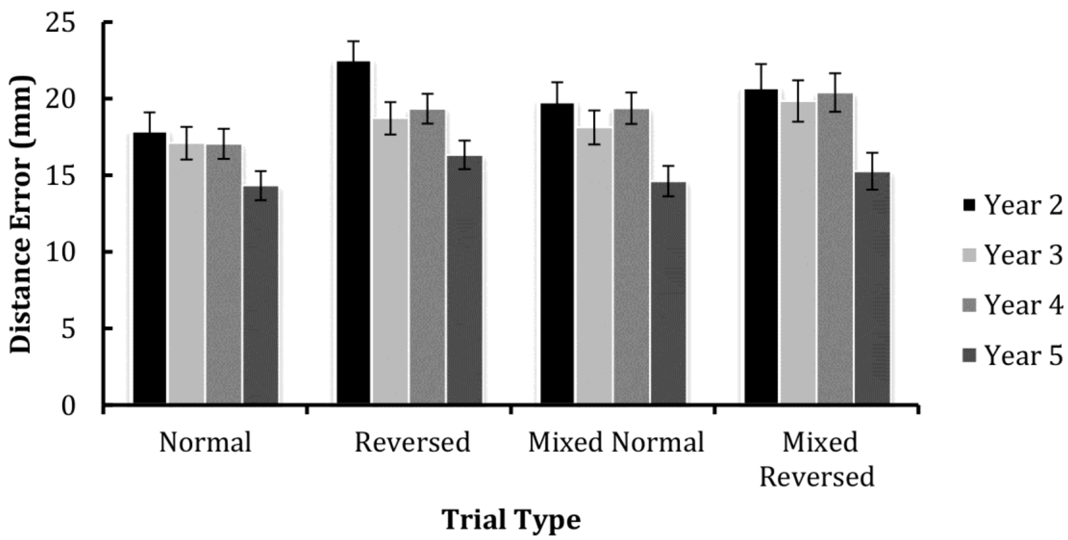

Figure 6.6 Average distance error by trial type and age. Error bars represent ±1 standard error of the mean.

Binary Error: Consistent with the South Asian school, we found a significant effect of trial type, F (3, 510) = 89.244, $p < .001$, $\eta^2_p = .344$; once again this was due to both switch costs and children making fewer errors to the normal (blocked) trials than reversed (blocked) trials (see Table 6.12). This time the effect of age was non-significant, F (3, 170) = .997, $p = .396$, $\eta^2_p = .017$, but there was an interaction, F (9, 510) = 2.284, $p < .05$, $\eta^2_p = .039$. All groups demonstrated switch costs, but the Year 3 and 4 children made fewer errors to the normal than reversed trials ($p < .05$), and the Year 5 children made fewer errors to the mixed reversed than the mixed normal trial types ($p < .05$).

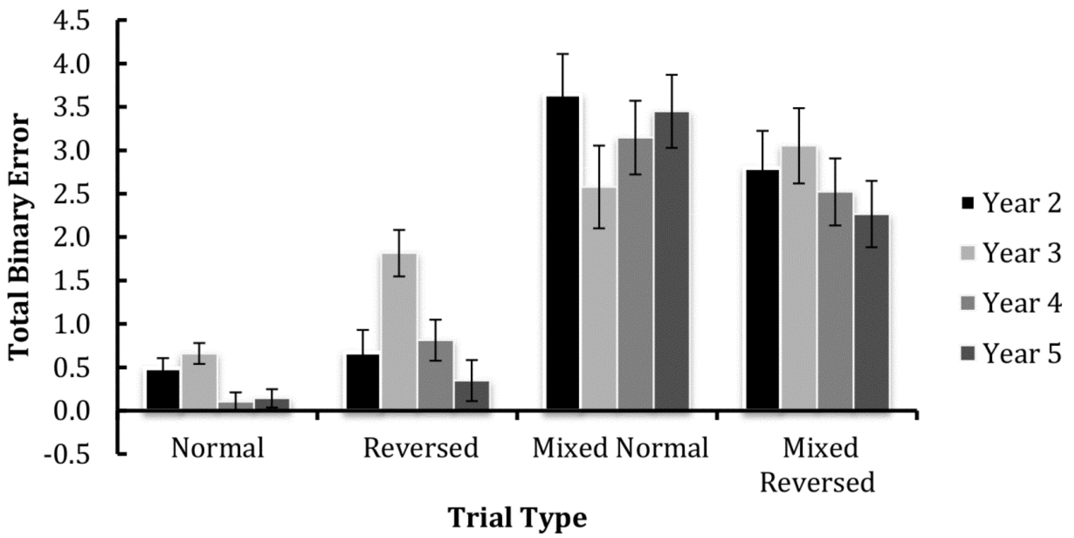

Figure 6.7 Total binary error by trial type and age. Error bars represent ±1 standard error of the mean.

Overall, children from the Western school were just as quick to respond and move to the reversed trials as the normal trials, however in general they made smaller distance errors and fewer binary errors to the normal than reversed trials. Once again, we also looked at the percentage of children in each year group who show either a normal or reversed preference (see Table 6.5). Unlike the children from the South Asian school, the children from the Western school were split relatively evenly in terms of whether they showed a normal or reversed preference.

Table 6.5 *Percentage of children with normal or reversed directional preferences in the blocked and mixed trials.*

	Blocked Trials		**Mixed Trials**	
	Normal	**Reversed**	**Normal**	**Reversed**
Year 2	47.06	52.94	43.75	56.25
Year 3	38.89	61.11	33.33	66.67
Year 4	52.27	47.73	37.78	62.22
Year 5	48.89	51.11	50	50

6.3.3 Comparison between the South Asian and the Western School

We collapsed across age and compared TT to each trial type (normal, reversed, mixed normal, mixed reversed) between the two schools (South Asian, Western). We observed a significant effect of trial type, F (3, 963) = 103.426, $p <$ .001, η^2_p = .244; this was due to switch costs (see Figure 6.8). The effect of school was non-significant, F (1, 321) = 7.216, $p <$ .01, η^2_p = .022 as was the interaction, F (1, 321) = 1.879, p = .171, η^2_p = .006.

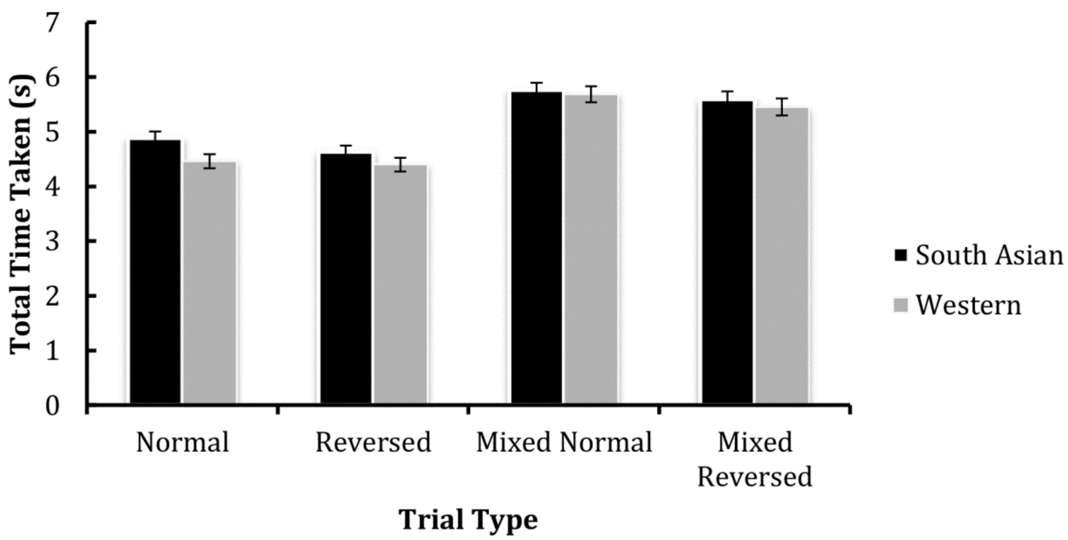

Figure 6.8 Average TT by trial type and school. Error bars represent ±1 standard error of the mean.

We also analysed distance errors by trial type and school type. There was a significant effect of trial type, F (3, 963) = 21.121, $p < .001$, $\eta^2_p = .062$, a significant effect of school, F (1, 321) = 7.216, $p < .01$, $\eta^2_p = .022$, and a significant interaction, F (3, 963) = 7.227, $p < .001$, $\eta^2_p = .022$. Overall children were more accurate on the normal trials than any of the other trial types ($p < .05$), and more accurate on the reversed trials than the mixed reversed trials ($p < .05$). The effect of school was due to the children from the Western school being more accurate than those from the South Asian school. Pairwise comparisons revealed that children from both schools were more accurate in the normal trials than the reversed trials in the blocked trials, but children from the South Asian school also showed switch costs whereas the children from the Western school did not. These results can be seen in Figure 6.9.

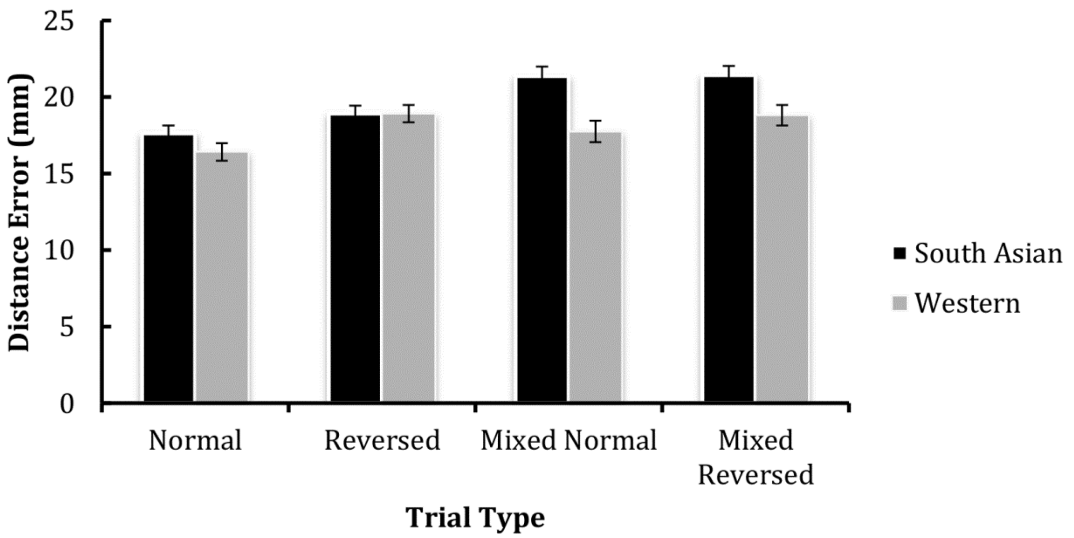

Figure 6.9 Average distance error by trial type and school. Error bars represent ±1 standard error of the mean.

The binary error analysis revealed a significant effect of trial type, F (3, 1206) = 172.011, $p < .001$, $\eta^2_p = .300$. Neither the effect of school, F (1, 402) = .373, $p = .542$, $\eta^2_p = .001$, nor the interaction was significant, F (3, 1206) = 2.047, $p = .124$, $\eta^2_p = .005$. Overall, children made fewer errors in the blocked trials than the mixed trials (see Figure 6.10). They also made fewer errors to the normal trials than the reversed trials, but fewer errors to the mixed reversed trials than the mixed normal trials ($p < .05$).

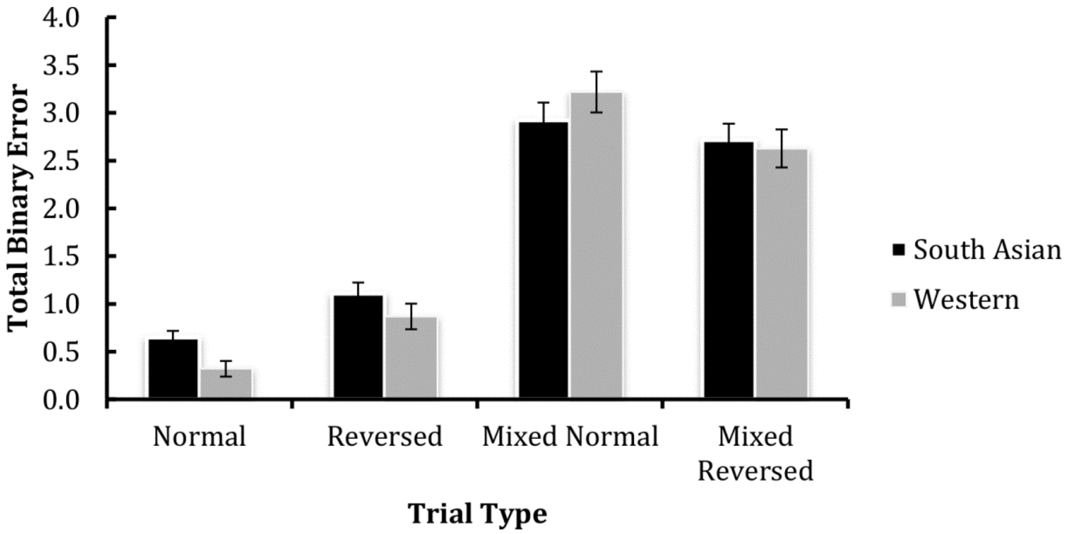

Figure 6.10 Total binary errors per trial type and school. Error bars represent ±1 standard error of the mean.

Finally, children were separated by whether they showed a normal or reversed preference by taking their total time taken to the reversed trials away from their total time taken to the normal trials; the percentage of children showing each preference can be seen in Table 6.1 (South Asian children) and Table 6.5 (Western children). This also allowed us to look at the strength of children's preferences as it could be that children are showing a weak preference towards the reversed trials but a strong preference to the normal trials or vice versa. We looked at these preferences by age group and school; a negative score suggests a normal preference and a positive score suggests a reversed preference (see Table 6.6). Interestingly, in the blocked trials, the strength of the normal preference appears to be similar for both schools, but in both the blocked and mixed trials the strength of the reversed preference appears to be smaller in the children from the Western school. This appears most apparent in the younger age groups. We analysed these differences statistically, but there were no significant effects of age, F (3, 195) = 1.592, p = .193, η^2_p = .024 or school, F (1, 195) = 2.534, p = .113, η^2_p = .013 and there was no interaction, F (3, 195) = .320, p = .811, η^2_p = .005.

In the mixed trials, the strength of the normal preference appears stronger in the Western children in Years 2 and 3, but is then stronger in the South Asian children in Years 4 and 5. However, once again when we analysed this statistically there were no significant effects of age, F (3, 156) = .937, p = .424, η^2_p = .018 or school, F (1, 156) = .018, p = .892, η^2_p = .000 and there was no interaction, F (3,156) = .861, p = .463, η^2_p = .016. We also analysed for differences between children showing a reversed preference in the mixed blocks by age and school, but again there were no significant effects of age, F (3, 196) = 1.465, p = .225, η^2_p = .022 or school, F (1, 196) = 1.884, p = .171, η^2_p = .010 and there was no interaction, F (3,196) = .502, p = .681, η^2_p = .008.

Table 6.6 *Mean difference in TT between trial types in the blocked and mixed conditions by age group and SNA direction [95% confidence interval]*

	Blocked				**Mixed**			
	Normal		**Reversed**		**Normal**		**Reversed**	
	Asian	**Western**	**Asian**	**Western**	**Asian**	**Western**	**Asian**	**Western**
Year 2	-.61 [-.97, -.24]	-.61 [-.96, -.26]	1.17 [.83, 1.50]	.99 [.62, 1.36]	-.11 [-1.55, -.58]	-.99 [-1.48, -.49]	1.63 [1.20, 2.05]	1.15 [.72, 1.58]
Year 3	-.80 [1.09, -.51]	-.84 [-1.21, -.46]	1.18 [.75, 1.60]	.80 [.46, 1.13]	-.87 [-1.39, -.36]	-1.39 [-1.92, -.86]	1.24 [.80, 1.67]	1.10 [.73, 1.47]
Year 4	-.62 [-.90, -.35]	-.67 [-.97, -.38]	.93 [.59, 1.28]	.72 [.38, 1.07]	-.84 [-1.26, -.41]	-.67 [-1.12, -.23]	1.18 [.80, 1.55]	1.05 [.70, 1.39]
Year 5	-.68 [-.92, -.44]	-.73 [-1.10, -.49]	.75 [.48, 1.02]	.71 [.39, 1.05]	-1.11 [-1.47, -.76]	-.93 [-1.30, -.55]	.99 [.69, 1.29]	.98 [.72, 1.57]

6.4 Discussion

Chapter 6 aimed to replicate the results of Chapter 5, and test whether directional preferences in spatial numerical associations differ depending on a child's cultural background. Firstly, with regard to the replication, the pattern of results in the South Asian school was similar to the pattern of results observed in Chapter 5; children did improve with age. However, this time we also found that the children from the South Asian school were quicker to respond and move to the reversed trials than the normal trials, though they made fewer binary errors to the normal trials. Once again, there were high levels of individual variability. One possible explanation for this is that the children in the South Asian school may be being exposed to differing spatial-numerical relationships (e.g. reading, writing and finger counting) given the high percentage of children for whom English is an additional language. For example, children may be exposed to a normal number line at school and a reversed number line at home. The extent of these experiences may also differ greatly depending on the family background or when the family moved to the UK; a child who has moved recently will have much less experience with a normal number line compared to a child who has lived here for many years. It is also highly likely that some parents do not speak English at home, whilst others may speak only English and others may have a mix of English and Urdu.

Nevertheless, consistent with Chapter 5 it was observed that children's spatial numerical representations could be predicted by age and fine motor skills, thus providing evidence (and in a much larger sample size) that fine motor skills are important in the development of these representations. Once again, this is interpreted to reflect the suggestion that the involvement of fine motor skills during play may help develop the link between number and space. This is further consistent with suggestions that fine motor skills drive the direction of spatial numerical associations (Dehaene et al., 1993; Fischer, Mills, & Shaki, 2010; Gobel, Shaki, & Fischer, 2011; Hubbard et al., 2005; Fischer & Shaki, 2014). Nevertheless, we also acknowledge there is an alternative interpretation; that spatial numerical associations and fine motor skills correlate because the distance error variable may actually be measuring motor control, a skill which we would expect to correlate with a fine motor skill assessment (see Chapter 5.4).

However, in contrast to Chapter 5, we did not observe that spatial numerical associations predicted mathematics achievement when using the distance error variable which is often used in the literature. This time the total time taken and binary error measures of spatial numerical associations both explained unique variance in mathematics achievement. At present we are unsure why distance error was the important variable in Chapter 5 whilst total time taken and binary error were the most important in the present chapter. The task does appear to be useful at tapping in to spatial numerical associations, but this is coming out in different ways. This may be related to speed accuracy trade-offs (Fitts, 1954); some children may prioritise moving quickly over accuracy, whilst others may prioritise accuracy over speed. This may mean that spatial numerical associations are evident in kinematic variables for some children, and error variables for others. Finally, whilst fine motor skills correlated with mathematics attainment in Chapter 5, they did not predict it – but they do in Chapter 6. In Chapter 5 it was hypothesised that the lack of predictive relationship was due to fine motor skills being a building block for early number knowledge, rather than a direct contributor to mathematical attainment. The relationship here might suggest that actually there is a need for a larger sample size to detect this relationship.

In the comparison between the South Asian and Western school, there was some evidence of a reversed preference in spatial numerical associations in the South Asian school in the kinematic data, but evidence of a normal preference in the binary error data. Once again we observed large individual variability and suggested this could be due to the South Asian children being exposed to differing spatial numerical mappings (South Asian at home, Western at school). However, we also found large variability in the directional preferences in the children from the Western school; whilst some of these children do speak English as an additional language, these are mostly European languages and thus written left to right (meaning the number to space mappings are not mixed). Nevertheless, there was some evidence of a directional preference for the normal number line in the predominantly Western school; children made less binary errors and were more accurate on the normal number line than the reversed number line in the blocked trials. With regard to the mixed trials, the only real effect in both schools was the evidence of switch costs demonstrating that overall children found these trials harder. In adults, the mixed trials allow us to observe default preferences in spatial-numerical representation (see Chapter 4), however in children it is possible that these trials are too hard as they rely on the children remembering which direction the line goes in and the colour associated with the specific line orientation. Together these two factors increase the cognitive load of the task, meaning children have to focus very hard on the task, or decide it is too hard and thus pay little attention to line direction, thus meaning default preferences cannot be observed. Thus task difficulty may also be contributing to a lack of strong conclusions regarding directional preferences. One way to reduce this load would be to bound the number line such that children know which way the line is going. However, it is thought that bounded number lines makes participants use proportion estimation strategies, rather than being a measure of spatial numerical associations per se (Barth & Paladino, 2011; Cohen & Blanc-Goldhammer, 2011).

Despite the differences observed in the separate school analyses, no differences in directional spatial numerical associations were observed when statistically comparing the two schools; overall all children were more accurate in the normal than reversed trials in that they made fewer binary errors and had smaller distance errors. It is possible that children have just not yet developed a strong enough preference, perhaps this preference develops later; studies have shown that larger SNARC effects are observed with increasing age (Wood et al., 2008). Research into this is sparse and thus there are differential findings regarding the development of spatial numerical associations. For example, some developmental studies demonstrate SNARC effects in children as young as 4 or 5 years old (Hoffmann et al., 2013; Patro & Haman, 2012), whilst others have not observed effects in children younger than 7 years (Van Galen & Reitsma, 2008; White et al., 2012). However, these studies tend to differ in methodology with regards to the nature of the stimuli (e.g. symbolic or non-symbolic) and the to-be-made judgement (e.g. parity or colour judgement), thus suggesting that the task employed may have large impacts on whether or not SNARC effects are observed. Nevertheless, it is again noted that there was some evidence of different preferences was observed in the individual school analyses, therefore a number of other possible explanations for the lack of group differences arise. It is possible that the South Asian children's exposure to the normal number line through formal schooling has reduced the cultural effects such that their representation is now much closer to that of the Western children, but has not yet fully changed to reflect a 0-10 number line. It would therefore be interesting to develop a test simple enough for younger children to complete to determine if culturally biased directional effects are present before formal schooling. It will also be important for future studies to attain individual information about both ethnicity and the language spoken at home. Whilst group ethnicity was used as a proxy, this provides no specific information about the child's cultural background. It is entirely possible that some of the South Asian children experience much stronger culturally influenced preferences than others. In future work it may also be possible to assess spatial numerical associations in Western children living in the UK and South Asian children living in their home country (e.g. Pakistan) in order to determine how much enculturation influences these associations. This has been tested in adults (Shaki & Fischer, 2008; Zebian, 2005), but not children.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1 Introduction

Time and space are physical realities whilst number is an abstract concept. Nevertheless, there appears to be a causal link between human interactions with the physical world and the development of abstract mathematical concepts including the representation of quantity and time (Cohen Kadosh et al., 2008; de Hevia et al., 2014). However, there is a dearth of research that investigates the relationship between quantity, time and space in children. To date, much of the temporal-numerical research involves very young children, focusing mostly on duration estimates rather than other temporal constructs (e.g. Srinivasan & Carey, 2010). Further, spatial-numerical research mostly focuses on adults (e.g. Dehaene, Bossini, & Giraux, 1993; Fischer, Mills, & Shaki, 2010; Shaki & Fischer, 2008; Zebian, 2005). Thus, this thesis sought to assess: (i) the development of children's ability to link time and number using frequency processing tasks, and (ii) children's ability to link space and number. In this chapter I provide an overview of the main findings and discuss the theoretical and applied implications of these.

7.2 Review of Findings

7.2.1 Temporal Representation of Number

The thesis assessed the temporal representation of number by analysing whether children could recall the frequency of both everyday events (Chapter 2) and short term events (Chapter 3), and whether these skills were related to numerical processing. Firstly, in Chapter 2 it was observed that children aged between eight and eleven years of age could recall their daily intake of fruit smoothies with a high degree of accuracy. Furthermore, their ability to recall their intake after a delay of one week was related to their mathematical achievement, but not the more basic numerical skills of subitizing and dot enumeration. Secondly, Chapter 3 revealed that children (and adults) are also remarkably accurate at recalling the frequency of short term events, namely multiple presentations of different shapes. This is consistent with past literature investigating short term frequency processing (Ellis et al., 1988; Goldstein et al., 1983; Hasher & Chromiak, 1977). However, in contrast to everyday frequency recall, short term frequency processing was not related to any type of numerical skill. In addition, across both experiments, subitizing and dot enumeration were related to mathematical achievement, which is consistent with the few existing studies that have investigated this issue (Gray & Reeve, 2014; Reeve et al., 2012).

7.2.2 Spatial Representation of Number

In Chapter 4, a novel number line task was introduced to assess spatial numerical associations. This task demonstrated that Western educated adults have a default preference for representing number in a left to right direction with small numbers on the left side of space, and large numbers on the right. This preference was observed in both reaction times and movement times, suggesting that the impact of space on numerical processing lasts beyond the movement planning stage. This was discussed within the embodied cognition framework which posits that cognitive and motor systems interact with each other and the environment. In this way cognition is conceptualised as an open system (Wilson, 2002). Further support of this was evidenced by finding a correlation between adults' motor skills and their reaction times on the number line task.

In Chapter 5 it was observed that whilst children became more accurate on the number line, there was no evidence of the default directional preferences in spatial numerical associations that were present in the adult data. However, there was a large amount of individual variability which was hypothesised to be due to the diversity of the sample; a large number of children were from South Asian backgrounds and thus may have been exposed to right to left spatial-numerical associations given that the national language (Urdu) is written and read in this direction. Chapter 6 investigated whether cultural background influenced spatial numerical associations by comparing number line performance between children in a predominantly South Asian school and children in a predominantly Western school. Whilst there were no significant group differences, there was some evidence of a reversed preference (right to left) in the South Asian children, and a normal preference (left to right) in the Western children. Finally, across Chapters 5 and 6, there was evidence that fine motor skills predicted spatial numerical associations, and that both of these factors predicted mathematical achievement.

7.3. Future Directions

7.3.1 Temporal Representation of Number

To the author's knowledge, this is the first study to demonstrate that children can accurately recall their fruit intake, and that this ability is related to mathematical competence. This ability is crucial in a number of settings, but particularly in health and legal environments. The current work can further inform researchers and professionals working in these fields about the accuracy with which they can expect children to be able to recall everyday frequency information. However, it is noted that the 'to-be-recalled' event may have a large impact on accuracy, thus it is important to consider this in future work and in applied settings. For example, whilst children are able to monitor their fruit intake (an important skill given the emphasis on the Government's '5 a day' scheme), it is likely that the novelty of the fruit smoothies increased accuracy. Furthermore, this study is not able to tell us anything about children's actual intake, since fruit smoothies were provided. In future research it will be important to consider monitoring children's normal intake, and then assessing whether they can recall the frequency of this, though this will involve the consideration of a number of methodological issues (e.g. how to accurately measure children's normal intake in the first place). It will also be interesting to try and replicate the relationship between frequency recall and mathematical achievements in future studies, and further consider why this relationship might exist.

Chapter 3 added to the debate of whether short term frequency processing is an age invariant skill as proposed by Hasher & Chromiak, (1977). Children were as accurate as adults despite the use of a much harder task consisting of more shape repetitions than previous studies. Whilst it not argued that frequency processing is necessarily ‘automatic’, performance wasn’t related to working memory suggesting that it may be a low level, and non-strategic skill. It will therefore be important for research to move towards investigating *how* we determine frequency. Whilst working memory may not play a role, this is the first study to investigate this issue. Further, even if it is not related, it may be that other strategies are used. Investigating variables which may impact our frequency accuracy (e.g. attention), and variables which may or may not link to it (e.g. strategic processing) will further our understanding of just how ‘automatic’ frequency processing may be.

7.3.2 Spatial Representation of Number

In Chapter 4, the novel number line task demonstrated that adults have a default preference to represent number from left (small numbers) to right (large numbers). This evidence was also observed in movement times, something which has remained relatively unexplored in the current literature despite the implications for numerical processing, and the insights it can give us to embodied cognition (see Chapter 7.4.2). In future research more attention should be paid to the relationship between spatial numerical associations on motor performance. In fact, recent research has begun to consider how to measure movement in numerical processing (Fischer & Hartmann, 2014) and how spatial numerical associations are an embodied phenomenon (Fischer, 2012).

Unlike the adults, there was no evidence that children had any directional preferences in their spatial representation of number, though they did become more accurate at representing number on a number line with a Western direction (left to right). At present there is very little research investigating directional preferences in spatial numerical associations in children. Future work should aim to address this especially given that research with adults has suggested that successful mathematicians may have a more flexible or abstract representation of number, as indicated by a weaker SNARC effect (Cipora et al., 2015; Dehaene et al., 1993; Hoffmann et al., 2014). If this is the case, it may be beneficial to try and encourage flexible representation in children. Currently schools use number lines as a pedagogical tool, but only in the typically Western direction (0-10). It might be useful to also use reversed number lines during teaching (10-0).

This thesis has also provided some evidence that cultural background influences the direction of spatial numerical associations (Chapter 6). Given the suggested importance of culture in the development of these associations (see Chapter 1.3.3); future work should try and further explore the impact of culture. The only cultural information available for this study was school based ethnicity data. Whilst this is informative, future work should improve on this by gaining measures which takes in to account the level of exposure children have had to cultural norms of spatial-numerical relationships. This may be especially important for those children who exhibit a reversed preference as it may then be harder for them to adapt to the normal number lines utilised in the classroom if they are still experiencing reversed associations at home.

7.4 Further Considerations

7.4.1 Number in Time

Overall, children appear to be remarkably accurate at recalling the frequency of both an everyday event occurring multiple times during the day, and a computer based event occurring multiple times within a 10-15 minute period. Interestingly, whilst both types of frequency processing involve a certain understanding of quantity, only children's recall of the frequency of an everyday event was related to any of the other numerical skills we tested. Specifically frequency recall correlated with, and even predicted, mathematical attainment. It could be argued that both everyday frequency processing and the mathematical achievement measured by school tests require a more applied understanding of number. In contrast, subitizing and dot enumeration appear to rely on more basic skills. For example, the ability to subitize is thought to reflect our innate sensitivity to numerosity, and both subitizing and dot enumeration are thought to reflect a non-symbolic number system which is present before language skills develop (Feigenson et al., 2004; Hyde, 2011). Thus, whilst these skills predict mathematical achievement, it is possible that they reflect too basic a representation of number to be useful for everyday frequency processing.

It has been argued that the kind of short term frequency processing assessed in Chapter 3 is an age invariant, evolutionarily relevant skill which is thus developed early in life (Kelly & Martin, 1994; Zacks & Hasher, 2002), and as such it can be considered a basic numerical skill. Therefore the lack of correlation with either subitizing or dot enumeration suggests that it reflects a different kind of early developed sensitivity to numerosity. Specifically, short term frequency processing reflects our ability to remember the quantity of a set of items over time, whilst subitizing and dot enumeration both involve determining quantity when a set of constant items are present. The suggestion that frequency processing and subitizing/dot enumeration reflect different types of early developed numerical systems is further supported by the lack of correlation between frequency processing and mathematics achievement.

7.4.2 Number in Space

The ability to represent number along a number line can be considered as one aspect of early number knowledge, more broadly defined as a variety of relatively simple numerical skills which develop through childhood with practice and formal instruction (Östergren & Träff, 2013). This ability predicted mathematical achievement, but was not related to children's ability to count, another type of early number knowledge. Given that counting is relatively easy for the children in the age range tested (six to eleven years), whilst mathematics tests are designed to be a hard test of children's skills, this could suggest that the number line is only utilised for complex problems.

A further consideration raised by the investigation of spatial numerical associations relates to the theory of embodiment. Traditionally cognition and action have been considered as two separate entities. However, recent work has begun to consider both brain and body as influencing each other, whilst also considering the impact an individual's environment can have on functioning (Anderson, 2003; Smith & Gasser, 2005; Wilson, 2002). The findings in Chapter 4 are a prime example of such research; spatial numerical associations are seen not only in the motor planning stage (the "cognitive" stage) but also in the movement phase (the "motor" stage), and performance in both stages is related to adults' general motor performance. Furthermore, in Chapters 5 and 6, there was evidence that fine motor skills could predict spatial numerical associations. Perceptual motor skills are normally considered to influence spatial numerical associations in terms of directionality, i.e. reading, writing and finger counting experience is thought to determine whether small numbers are associated with the left side of space and large with the right, or vice versa (e.g. Dehaene et al., 1993; Gobel, Shaki, & Fischer, 2011). Even though there was no evidence of group directional effects, it still appears that fine motor skills were influential in individual directional preferences and spatial numerical associations more generally. These findings are consistent with a body of work which has begun to find further evidence of the embodiment of spatial numerical associations (Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Fischer, 2012; Sato et al., 2007). Additionally, it was observed that fine motor skills can predict early number knowledge in the form of counting. It is thought that playing with and counting objects physically (for example, organising toy blocks in piles) may help children develop an early knowledge of number (Pagani & Messier, 2012). This further demonstrates the importance of children's motoric and environmental surroundings to the development of numerical concepts. Finally, in Chapter 6 it was observed that fine motor skills predicted mathematical achievement (although these factors only correlated in Chapter 5), once again demonstrating a tight link between cognition and action.

7.5 Concluding Remarks

The overarching theme of this thesis was primary school children's representation of number in both time and space. This investigation of number representation has furthered our understanding of the extent to which different numerical concepts interact, from the basic understanding of number that we share with non-human animals, to the uniquely human understanding of early number knowledge and mathematics. Whilst the field of numerical cognition is still in its infancy, the enormous contribution of numerical understanding to society is without question. It is therefore hoped that the insights and questions raised in this thesis will influence further research, so that we may fully understand how we represent and make sense of something so abstract as number.

REFERENCES

Alloway, T. P. (2007). Working memory, reading, and mathematical skills in children with developmental coordination disorder. *Journal of Experimental Child Psychology*, *96*(1), 20–36. doi:10.1016/j.jecp.2006.07.002

Alloway, T. P., & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, *106*(1), 20–9. doi:10.1016/j.jecp.2009.11.003

Alloway, T. P., & Passolunghi, M. C. (2011). The relationship between working memory, IQ, and mathematical skills in children. *Learning and Individual Differences*, *21*(1), 133–137. doi:10.1016/j.lindif.2010.09.013

Anderson, J., & Bower, Gordon, H. (1972). Recognition and Retrieval Processes in Free Recall. *Psychological Review*, *79*(2).

Anderson, M. L. (2003). Embodied Cognition: A field guide. *Artificial Intelligence*, *149*(1), 91–130. doi:10.1016/S0004-3702(03)00054-7

Arp, S., Taranne, P., & Fagard, J. (2006). Global perception of small numerosities (subitizing) in cerebral-palsied children. *Journal of Clinical and Experimental Neuropsychology*, *28*(3), 405–19. doi:10.1080/13803390590935426

Aunola, K., Leskinen, E., Lerkkanen, M.-K., & Nurmi, J.-E. (2004). Developmental Dynamics of Math Performance From Preschool to Grade 2. *Journal of Educational Psychology*, *96*(4), 699–713. doi:10.1037/0022-0663.96.4.699

Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. *Neuropsychologia*, *36*(8), 731–5.

Barrouillet, P., Lépine, R., & Camos, V. (2008). Is the influence of working memory capacity on high-level cognition mediated by complexity or resource-dependent elementary processes? *Psychonomic Bulletin & Review*, *15*(3), 528–534. doi:10.3758/PBR.15.3.528

Barth, H. C., & Paladino, A. M. (2011). The development of numerical estimation: evidence against a representational shift. *Developmental Science*, *14*(1), 125–35. doi:10.1111/j.1467-7687.2010.00962.x

Benoit, L., Lehalle, H., & Jouen, F. (2004). Do young children acquire number words through subitizing or counting? *Cognitive Development*, *19*(3), 291–307. doi:10.1016/j.cogdev.2004.03.005

Blank, R., Smits-engelsman, B. C. M., Polatajko, H. J., & Wilson, P. H. (2012). European Academy for Childhood Disability (EACD): recommendations on the definition, diagnosis and intervention of developmental coordination disorder (long version). *Developmental Medicine and Child Neurology*, *54*(1), 54–93. doi:10.1111/j.1469-8749.2011.04171.x

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, *42*(1), 189–201. doi:10.1037/0012-1649.41.6.189

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*(4), 1016–31. doi:10.1111/j.1467-8624.2008.01173.x

Brown, N. R. (2002). Encoding, Representing and Estimating Event Frequencies: A Multiple Strategy Perspective. In P. Sedlmeier & T. Betsch (Eds.), *Frequency Processing and Cognition*. Oxford: Oxford.

Brown, N. R. (2008). How metastrategic considerations influence the selection of frequency estimation strategies. *Journal of Memory and Language*, *58*(1), 3–18. doi:10.1016/j.jml.2007.09.004

Butterworth, B., & Laurillard, D. (2010). Low numeracy and dyscalculia: identification and intervention. *International Journal of Mathematics Education*, *42*(6), 527–539. doi:10.1007/s11858-010-0267-4

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition*, *106*(2), 579–593. doi:10.1016/j.cognition.2007.03.004

Chalmers, K. a., & Grogan, M. J. (2006). Developmental differences in judgments of recency and frequency: Quantitative or qualitative? *Cognitive Development*, *21*(1), 72–79. doi:10.1016/j.cogdev.2005.11.001

Chapman, C., Gallivan, J., & Wood, D. (2014). Counting on the motor system: Rapid action planning reveals the format-and magnitude-dependent extraction of numerical quantity. *Journal of Vision*, *14*(3), 1–19. doi:10.1167/14.3.30.doi

Chen, Q., & Verguts, T. (2010). Beyond the mental number line: A neural network model of number-space interactions. *Cognitive Psychology*, *60*(3), 218–40. doi:10.1016/j.cogpsych.2010.01.001

Cipora, K., Hohol, M., Nuerk, H.-C., Willmes, K., Brożek, B., Kucharzyk, B., & Nęcka, E. (2015). Professional mathematicians differ from controls in their spatial-numerical associations. *Psychological Research*. doi:10.1007/s00426-015-0677-6

Cohen, D. J., & Blanc-Goldhammer, D. (2011). Numerical bias in bounded and unbounded number line tasks. *Psychonomic Bulletin & Review*, *18*(2), 331–8. doi:10.3758/s13423-011-0059-z

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Cohen Kadosh, R., Lammertyn, J., & Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology*, *84*(2), 132–147. doi:10.1016/j.pneurobio.2007.11.001

Conrad, F. G., Brown, N. R., & Cashman, E. R. (1998). Strategies for estimating behavioural frequency in survey interviews. *Memory*, *6*(4), 339–366.

Crawford, C., & Crib, J. (2013). Reading and maths skills at age 10 and earnings in later life: a brief analysis using the British Cohort Study. Retrieved November 4, 2013, from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190625/Reading_and_maths_skills_at_age_10_and_earnings_in_later_life.pdf

Culmer, P. R., Levesley, M. C., Mon-Williams, M., & Williams, J. H. G. (2009). A new tool for assessing human movement: the Kinematic Assessment Tool. *Journal of Neuroscience Methods*, *184*(1), 184–92. doi:10.1016/j.jneumeth.2009.07.025

De Hevia, Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(13), 4809–13. doi:10.1073/pnas.1323628111

De Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: origins of the mental number line. *Frontiers in Psychology*, *3*(October), 466. doi:10.3389/fpsyg.2012.00466

De Hevia, M. D., & Spelke, E. S. (2009). Spontaneous mapping of number and space in adults and young children. *Cognition*, *110*(2), 198–207. doi:10.1016/j.cognition.2008.11.003

De Hevia, M. D., & Spelke, E. S. (2010). Number-space mapping in human infants. *Psychological Science*, *21*(5), 653–60. doi:10.1177/0956797610366091

De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Working memory and individual differences in mathematics achievement: a longitudinal study from first grade to second grade. *Journal of Experimental Child Psychology*, *103*(2), 186–201. doi:10.1016/j.jecp.2009.01.004

Dehaene, S. (1997). *The Number Sense*. Oxford: Oxford University Press.

Dehaene, S. (2011). *The Number Sense: How the Mind Creates Mathematics* (Revised an.). Oxford: Oxford University Press.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The Mental Representation of Parity and Number Magnitude. *Journal of Experimental Psychology: General*, *122*(3), 371–396.

Denison, S., Reed, C., & Xu, F. (2012). The emergence of probabilistic reasoning in very young infacts: Evidence from 4.5- and 6-month-olds. *Developmental Psychology*, 1–22.

Denison, S., & Xu, F. (2014). The origins of probabilistic inference in human infants. *Cognition*, *130*(3), 335–347.

Department of Education. (2013). *Mathematics programmes of study: Key stages 1 and 2 National curriculum in England*.

Desoete, A., Ceulemans, A., Roeyers, H., & Huylebroeck, A. (2009). Subitizing or counting as possible screening variables for learning disabilities in mathematics education or learning? *Educational Research Review*, *4*(1), 55–66. doi:10.1016/j.edurev.2008.11.003

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*(1), 44–56.

Domahs, F., Moeller, K., Huber, S., Willmes, K., & Nuerk, H.-C. (2010). Embodied numerosity: implicit hand-based representations influence symbolic number processing across cultures. *Cognition*, *116*(2), 251–66. doi:10.1016/j.cognition.2010.05.007

Ebbinghaus, H. (1885). *Über das Gedächtnis*. Leipzig: Dunker.

Ebersbach, M. (2015). Evidence for a Spatial–Numerical Association in Kindergartners Using a Number Line Task. *Journal of Cognition and Development*, *16*(1), 118–128. doi:10.1080/15248372.2013.805134

Ellis, N. R., Palmer, R. L., & Reeves, C. L. (1988). Developmental and intellectual differences in frequency processing. *Developmental Psychology*, *24*(1), 38–45. doi:10.1037//0012-1649.24.1.38

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: object files versus analog magnitudes.

Psychological Science : A Journal of the American Psychological Society / APS, *13*(2), 150–156. doi:10.1111/1467-9280.00427

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*(7), 307–14. doi:10.1016/j.tics.2004.05.002

Fias, W., Lauwereyns, J., & Lammertyn, J. (2001). Irrelevant digits affect feature-based attention depending on the overlap of neural circuits. *Brain Research. Cognitive Brain Research*, *12*(3), 415–23.

Fischer, M. (2003). Spatial representations in number processing--evidence from a pointing task. *Visual Cognition*, *10*(4), 493–508. doi:10.1080/13506280244000186

Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, *44*(4), 386–392. doi:10.1016/j.cortex.2007.08.004

Fischer, M. H. (2012). A hierarchical view of grounded, embodied, and situated numerical cognition. *Cognitive Processing*, *13 Suppl 1*, S161–4. doi:10.1007/s10339-012-0477-5

Fischer, M. H., & Brugger, P. (2011). When digits help digits: spatial-numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology*, *2*(October), 260. doi:10.3389/fpsyg.2011.00260

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience*, *6*(6), 555–6. doi:10.1038/nn1066

Fischer, M. H., & Hartmann, M. (2014). Pushing forward in embodied cognition: may we mouse the mathematical mind, *5*(November), 1–4. doi:10.3389/fpsyg.2014.01315

Fischer, M. H., Mills, R. a, & Shaki, S. (2010). How to cook a SNARC: number placement in text rapidly changes spatial-numerical associations. *Brain and Cognition*, *72*(3), 333–6. doi:10.1016/j.bandc.2009.10.010

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, *47*(6), 381–391.

Flatters, I., Hill, L. J. B., Williams, J. H. G., Barber, S. E., & Mon-Williams, M. (2014). Manual control age and sex differences in 4 to 11 year old children. *PloS One*, *9*(2), e88692. doi:10.1371/journal.pone.0088692

Flatters, I., Mushtaq, F., Hill, L. J. B., Holt, R. J., Wilkie, R. M., & Mon-Williams, M. (2014). The relationship between a child's postural stability and manual dexterity. *Experimental Brain Research*, 2907–2917. doi:10.1007/s00221-014-3947-4

Friso-van den Bos, I., van der Ven, S. H. G., Kroesbergen, E. H., & van Luit, J. E. H. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review*, *10*, 29–44. doi:10.1016/j.edurev.2013.05.003

Gelman, R., & Gallistel, C. (1978). *The child's concept of number*. Cambridge, MA: Harvard University Press.

Gevers, W., Lammertyn, J., Notebaert, W., Verguts, T., & Fias, W. (2006). Automatic response activation of implicit spatial information: Evidence from the SNARC effect. *Acta Psychologica*, *122*(3), 221–33. doi:10.1016/j.actpsy.2005.11.004

Ghatala, E. S., & Levin, J. R. (1973). Developmental Differences in Frequency Judgements of Words and Pictures. *Journal of Experimental Child Psychology*, *507*, 495–507.

Göbel, S. M., Calabria, M., Farnè, A., & Rossetti, Y. (2006). Parietal rTMS distorts the mental number line: simulating "spatial" neglect in healthy subjects. *Neuropsychologia*, *44*(6), 860–8. doi:10.1016/j.neuropsychologia.2005.09.007

Gobel, S. M., Shaki, S., & Fischer, M. H. (2011). The Cultural Number Line: A Review of Cultural and Linguistic Influences on the Development of Number Processing. *Journal of Cross-Cultural Psychology*, *42*(4), 543–565. doi:10.1177/0022022111406251

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining Math: Gesturing Lightens the Load. *Psychological Science*, *12*(6), 516–522. doi:10.1111/1467-9280.00395

Goldstein, D., Hasher, L., & Stein, D. K. (1983). Processing of occurrence-rate and item information by children of different ages and abilities. *The American Journal of Psychology*, *96*(2), 229–41.

Gonzalez-Gomez, N., Poltrock, S., & Nazzi, T. (2013). A "bat" is easier to learn than a "tab": effects of relative phonotactic frequency on infant word learning. *PloS One*, *8*(3), e59601. doi:10.1371/journal.pone.0059601

Gray, S. a., & Reeve, R. a. (2014). Preschoolers' dot enumeration abilities are markers of their arithmetic competence. *PLoS ONE*, *9*(4). doi:10.1371/journal.pone.0094428

Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: two new school readiness indicators. *Developmental Psychology*, *46*(5), 1008–17. doi:10.1037/a0020104

Harris, J. F., Durso, F. T., Mergler, N. L., & Jones, S. K. (1990). Knowledge base influences on judgments of frequency of occurrence. *Cognitive Development*, *5*(2), 223–233. doi:10.1016/0885-2014(90)90028-R

Hasher, L., & Chromiak, W. (1977). The Processing of Frequency Information : An Automatic Mechanism ? *Journal of Verbal Learning and Verbal Behaviour*, *184*, 173–184.

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General*, *108*(3), 356–388. doi:10.1037/0096-3445.108.3.356

Henderson, S., & Sugden, D. (1992). *The Movement Assessment Battery for Children*. London: Psychological Corporation.

Hintzman, D., & Hartry, A. (1990). Item effects in recognition and fragment completion: Contingency relations vary for different subsets of words. *Journal of Experimental Psychology: Learning, Memory and Cognition1*, *16*(6), 955.

Hoffmann, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number-space associations: SNARC effects using a color discrimination task in 5-year-olds. *Journal of Experimental Child Psychology*, *116*(4), 775–91. doi:10.1016/j.jecp.2013.07.013

Hoffmann, D., Mussolin, C., Martin, R., & Schiltz, C. (2014). The impact of mathematical proficiency on the number-space association. *PloS One*, *9*(1), e85048. doi:10.1371/journal.pone.0085048

Holland, A. C., & Kensinger, E. a. (2010). Emotion and autobiographical memory. *Physics of Life Reviews*, *7*(1), 88–131. doi:10.1016/j.plrev.2010.01.006

Holmes, J., & Adams, J. W. (2006). Working Memory and Children's Mathematical Skills: Implications for mathematical development and mathematics curricula. *Educational Psychology*, *26*(3), 339–366. doi:10.1080/01443410500341056

Hornung, C., Schiltz, C., Brunner, M., & Martin, R. (2014). Predicting first-grade mathematics achievement: The contributions of domain-general cognitive abilities, nonverbal number sense, and early number competence. *Frontiers in Psychology*, *5*(APR), 1–18. doi:10.3389/fpsyg.2014.00272

Hubbard, E. M., Diester, I., Cantlon, J. F., Ansari, D., Opstal, F. Van, & Troiani, V. (2008). The evolution of numerical cognition: from number neurons to linguistic quantifiers. *The Journal of Neuroscience : The Official Journal of* *the Society for Neuroscience*, *28*(46), 11819–11824. doi:10.1523/JNEUROSCI.3808-08.2008

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews. Neuroscience*, *6*(6), 435–48. doi:10.1038/nrn1684

Huber, S., Moeller, K., & Nuerk, H.-C. (2013). Dissociating number line estimations from underlying numerical representations. *Quarterly Journal of Experimental Psychology*, *0*(0), 1–13. doi:10.1080/17470218.2013.838974

Hung, Y., Hung, D. L., Tzeng, O. J.-L., & Wu, D. H. (2008). Flexible spatial mapping of different notations of numbers in Chinese readers. *Cognition*, *106*(3), 1441–50. doi:10.1016/j.cognition.2007.04.017

Hunt, R. R., & McDaniel, M. A. (1993). The Enigma of Organization and Distinctiveness. *Journal of Memory and Language*, *32*(4), 421–445.

Hyde, D. C. (2011). Two systems of non-symbolic numerical cognition. *Frontiers in Human Neuroscience*, *5*(November), 150. doi:10.3389/fnhum.2011.00150

Johnson, M. K., Raye, C. L., Hasher, L., & Chromiak, W. (1979). Are There Developmental Differences in Reality-Monitoring? *Journal of Experimental Child Psychology*, *27*(1), 120–128.

Jordan, N. C., & Kaplan, D. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology*, *45*(3), 850–867. doi:10.1037/a0014939.Early

Jordan, N. C., Kaplan, D., Locuniak, M. N., & Ramineni, C. (2007). Predicting First-Grade Math Achievement from Developmental Number Sense Trajectories. *Learning Disabilities Research & Practice*, *22*(1), 36–46. doi:10.1111/j.1540-5826.2007.00229.x

Jordan, N. C., Kaplan, D., Nabors Oláh, L., & Locuniak, M. N. (2006). Number sense growth in kindergarten: a longitudinal investigation of children at risk for mathematics difficulties. *Child Development*, *77*(1), 153–75. doi:10.1111/j.1467-8624.2006.00862.x

Kaufmann, L., Mazzocco, M. M., Dowker, A., von Aster, M., Göbel, S. M., Grabner, R. H., … Nuerk, H. C. (2013). Dyscalculia from a developmental and differential perspective. *Frontiers in Psychology*, *4*(AUG), 1–5. doi:10.3389/fpsyg.2013.00516

Kelly, M. H., & Martin, S. (1994). Domain-general abilities applied to domain-specific tasks: Sensitivity to probabilities in perception, cognition, and language. *Lingua*, *92*, 105–140. doi:10.1016/0024-3841(94)90339-5

Kishiyama, M. M., & Yonelinas, A. P. (2003). Novelty effects on recollection and familiarity in recognition memory. *Memory & Cognition*, *31*(7), 1045–51.

Kroesbergen, E. H., Van Luit, J. E. H., Van Lieshout, E. C. D. M., Van Loosbroek, E., & Van de Rijt, B. A. M. (2009). Individual Differences in Early Numeracy: The Role of Executive Functions and Subitizing. *Journal of Psychoeducational Assessment*, *27*(3), 226–236.

Landerl, K. (2013). Development of numerical processing in children with typical and dyscalculic arithmetic skills-a longitudinal study. *Frontiers in Psychology*, *4*(July), 459. doi:10.3389/fpsyg.2013.00459

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: a study of 8-9-year-old students. *Cognition*, *93*(2), 99–125. doi:10.1016/j.cognition.2003.11.004

Lee, K., Junghans, B. M., Ryan, M., Khuu, S., & Suttle, C. M. (2014). Development of a novel approach to the assessment of eye-hand coordination. *Journal of Neuroscience Methods*, *228*, 50–56. doi:10.1016/j.jneumeth.2014.02.012

Li, Y., & Geary, D. C. (2013). Developmental gains in visuospatial memory predict gains in mathematics achievement. *PloS One*, *8*(7), e70160. doi:10.1371/journal.pone.0070160

Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Numerical approximation abilities correlate with and predict informal but not formal mathematics abilities. *Journal of Experimental Child Psychology*, *116*(4), 829–38. doi:10.1016/j.jecp.2013.08.003

Lindemann, O., Abolafia, J. M., Pratt, J., & Bekkering, H. (2008). Coding strategies in number space: memory requirements influence spatial-numerical associations. *Quarterly Journal of Experimental Psychology (2006)*, *61*(4), 515–24. doi:10.1080/17470210701728677

Lindemann, O., Alipour, a., & Fischer, M. H. (2011). Finger Counting Habits in Middle Eastern and Western Individuals: An Online Survey. *Journal of Cross-Cultural Psychology*, *42*(4), 566–578. doi:10.1177/0022022111406254

Longo, M. R., & Lourenco, S. F. (2007). Spatial attention and the mental number line: evidence for characteristic biases and compression. *Neuropsychologia*, *45*(7), 1400–7. doi:10.1016/j.neuropsychologia.2006.11.002

Lund, A. M., Hall, J. W., Wilson, K. P., & Humphreys, M. S. (1983). Frequency judgment accuracy as a function of age and school achievement (learning disabled versus non-learning-disabled) patterns. *Journal of Experimental Child Psychology*, *35*(2), 236–47.

Luo, Z., Jose, P. E., Huntsinger, C. S., & Pigott, T. D. (2007). Fine motor skills and mathematics achievement in East Asian American and European American kindergartners and first graders. *British Journal of Developmental Psychology*, *25*(4), 595–614. doi:10.1348/026151007X185329

Lyons, I. M., & Beilock, S. L. (2012). Mathematics anxiety: Separating the math from the anxiety. *Cerebral Cortex*, *22*(9), 2102–2110. doi:10.1093/cercor/bhr289

Maloney, E. a, Ansari, D., & Fugelsang, J. a. (2011). The effect of mathematics anxiety on the processing of numerical magnitude. *Quarterly Journal of Experimental Psychology (2006)*, *64*(1), 10–16. doi:10.1080/17470218.2010.533278

Mandler, G., & Shebo, B. J. (1982). Subitizing: an analysis of its component processes. *Journal of Experimental Psychology. General*, *111*(1), 1–22. doi:10.1037/0096-3445.111.1.1

Marghetis, T., Núñez, R., & Bergen, B. K. (2014). Doing arithmetic by hand: Hand movements during exact arithmetic reveal systematic, dynamic spatial processing. *The Quarterly Journal of Experimental Psychology*, *0*(0), 1–18. doi:10.1080/17470218.2014.897359

Marr, D., Cermak, S., Cohn, E. S., & Henderson, A. (2003). Fine motor activities in Head Start and kindergarten classrooms. *The American Journal of Occupational Therapy : Official Publication of the American Occupational Therapy Association*, *57*(5), 550–7.

Martzog, P., & Stoeger, H. (2011). The relevance of fine motor skills for the cognitive development of preschoolers. In *Twentieth Conference of the Developmental Psychology Section of the German Association of Psychology*.

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PloS One*, *6*(9), e23749. doi:10.1371/journal.pone.0023749

Mccormack, T., & Russell, J. (1997). The development of recency and frequency memory: is there a developmental shift from reliance on trace-strength to episodic recall? *Journal of Experimental Child Psychology*, *66*(3), 376–92. doi:10.1006/jecp.1997.2380

Meck, W. H., & Church, R. M. (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology. Animal Behavior Processes*, *9*(3), 320–34.

Meck, W. H., Church, R. M., & Gibbon, J. (1985). Temporal integration in duration and number discrimination. *Journal of Experimental Psychology. Animal Behavior Processes*, *11*(4), 591–597. doi:10.1037/0097-7403.11.4.591

Melcher, D., & Piazza, M. (2011). The role of attentional priority and saliency in determining capacity limits in enumeration and visual working memory. *PLoS ONE*, *6*(12). doi:10.1371/journal.pone.0029296

Meyer, M. L., Salimpoor, V. N., Wu, S. S., Geary, D. C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences*, *20*(2), 101–109. doi:10.1016/j.lindif.2009.08.004

Moreno-Bote, R., Knill, D. C., & Pouget, A. (2011). Bayesian sampling in visual perception. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(30), 12491–6. doi:10.1073/pnas.1101430108

Mutter, S. a, & Goedert, K. M. (1997). Frequency discrimination vs frequency estimation: adult age differences and the effect of divided attention. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *52*(6), P319–P328. doi:10.1093/geronb/52B.6.P319

NHS. (2011). Why 5 a day? Retrieved from http://www.nhs.uk/Livewell/5ADAY/Pages/Why5ADAY.aspx.

Numeracy, N. (2014). Facts and figures. Retrieved November 4, 2013, from http://www.nationalnumeracy.org.uk/what-the-research-says/index.html

Núñez, R., & Cooperrider, K. (2013). The tangle of space and time in human cognition. *Trends in Cognitive Sciences*, *17*(5), 220–229. doi:10.1016/j.tics.2013.03.008

Olivers, C. N. L., & Watson, D. G. (2008). Subitizing requires attention, (MAY 2008). doi:10.1080/13506280701825861

Opfer, J. E., Thompson, C. a, & Furlong, E. E. (2010). Early development of spatial-numeric associations: evidence from spatial and quantitative performance of preschoolers. *Developmental Science*, *13*(5), 761–71. doi:10.1111/j.1467-7687.2009.00934.x

Orbach, Y., & Lamb, M. E. (2007). Young Children ' s References to Temporal Attributes of Allegedly Experienced Events in the Course of Forensic Interviews. *Child Development*, *78*(4), 1100–1120.

Östergren, R., & Träff, U. (2013). Early number knowledge and cognitive ability affect early arithmetic ability. *Journal of Experimental Child Psychology*, *115*(3), 405–21. doi:10.1016/j.jecp.2013.03.007

Pagani, L. S., Fitzpatrick, C., Archambault, I., & Janosz, M. (2010). School readiness and later achievement: a French Canadian replication and extension. *Developmental Psychology*, *46*(5), 984–94. doi:10.1037/a0018881

Pagani, L. S., & Messier, S. (2012). Links between Motor Skills and Indicators of School Readiness at Kindergarten Entry in Urban Disadvantaged Children. *Journal of Educational and Developmental Psychology*, *2*(1), 95–107. doi:10.5539/jedp.v2n1p95

Patro, K., & Haman, M. (2012). The spatial-numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology*, *111*(3), 534–42. doi:10.1016/j.jecp.2011.09.006

Peña, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech processing. *Science (New York, N.Y.)*, *298*(5593), 604–607. doi:10.1126/science.1072901

Penner-wilger, M., Fast, L., LeFevre, J., Smith-Chant, B. L., Skwarchuk, S. L., Kamawar, D., & Bisanz, J. (2007). The Foundations of Numeracy: Subitizing , Finger Gnosia , and Fine Motor Ability. In D. S. McNamara & J. G. Trafton (Eds.), *Proceedings of the 29th Annual Cognitive Science Society* (pp. 1385–1390). Austin, TX.

Piaget, J., & Inhelder, B. (1966). *La psychologie de l'enfant [the psychology of the child]*. Paris, France: Presses Universitaires de Franc.

Pieters, S., Desoete, A., Roeyers, H., Vanderswalmen, R., & Van Waelvelde, H. (2012). Behind mathematical learning disabilities: What about visual perception and motor skills? *Learning and Individual Differences*, *22*(4), 498–504. doi:10.1016/j.lindif.2012.03.014

Pieters, S., Desoete, A., Van Waelvelde, H., Vanderswalmen, R., & Roeyers, H. (2012). Mathematical problems in children with developmental coordination disorder. *Research in Developmental Disabilities*, *33*(4), 1128–35. doi:10.1016/j.ridd.2012.02.007

Pincham, H. L., & Szűcs, D. (2012). Intentional subitizing: exploring the role of automaticity in enumeration. *Cognition*, *124*(2), 107–16. doi:10.1016/j.cognition.2012.05.010

Pressley, M., & Hilden, K. (2006). Cognitive Strategies. In D. Kuhn & R. Siegler (Eds.), *Handbook of Child Psychology: Cognition, Perception and Language* (6th Ed., pp. 511–556). Hoboken, NJ: Wiley & Sons.

Railo, H., Koivisto, M., Revonsuo, A., & Hannula, M. M. (2008). The role of attention in subitizing. *Cognition*, *107*(1), 82–104. doi:10.1016/j.cognition.2007.08.004

Ranzini, M., Lugli, L., Anelli, F., Carbone, R., Nicoletti, R., & Borghi, A. M. (2011). Graspable objects shape number processing. *Frontiers in Human Neuroscience*, *5*(December), 147. doi:10.3389/fnhum.2011.00147

Reeve, R., Reynolds, F., Humberstone, J., & Butterworth, B. (2012). Stability and change in markers of core numerical competencies. *Journal of Experimental Psychology. General*, *141*(4), 649–66. doi:10.1037/a0027520

Rivard, L. M., Missiuna, C., Hanna, S., & Wishart, L. (2007). Understanding teachers' perceptions of the motor difficulties of children with developmental coordination disorder (DCD). *The British Journal of Educational Psychology*, *77*(Pt 3), 633–648. doi:10.1348/000709906X159879

Roberts, K. P., Brubacher, S. P., Drohan-Jennings, D., Glisic, U., Powell, M. B., & Friedman, W. J. (2015). Developmental Differences in the Ability to Provide Temporal Information About Repeated Events. *Applied Cognitive Psychology*, *417*.

Sanders, R. E., Zembar, M. J., Liddle, C. L., Gonzalez, E. G., & Wise, J. L. (1989). Developmental Effects in the Processing of Event Frequency. *Journal of Experimental Child Psychology*, *47*, 142–159.

Sasanguie, D., De Smedt, B., Defever, E., & Reynvoet, B. (2012). Association between basic numerical abilities and mathematics achievement. *The British Journal of Developmental Psychology*, *30*(Pt 2), 344–57. doi:10.1111/j.2044-835X.2011.02048.x

Sato, M., Cattaneo, L., Rizzolatti, G., & Gallese, V. (2007). Numbers within our hands: modulation of corticospinal excitability of hand muscles during numerical judgment. *Journal of Cognitive Neuroscience*, *19*(4), 684–93. doi:10.1162/jocn.2007.19.4.684

Schleifer, P., & Landerl, K. (2011). Subitizing and counting in typical and atypical development. *Developmental Science*, *14*(2), 280–291. doi:10.1111/j.1467-7687.2010.00976.x

Schoon, I., Cheng, H., Jones, E., Joshi, H., & Dex, S. (2010). Millenium Cohort Study Briefing 4: Resilience in children ' s development. *http://www.cls.ioe.ac.uk/library-media%5Cdocuments%5Cbriefing4_print(2).pdf*.

Shaki, S., & Fischer, M. H. (2008). Reading space into numbers: a cross-linguistic comparison of the SNARC effect. *Cognition*, *108*(2), 590–9. doi:10.1016/j.cognition.2008.04.001

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review*, *16*(2), 328–31. doi:10.3758/PBR.16.2.328

Sharman, S. J., Powell, M. B., & Roberts, K. P. (2011). Children's ability to estimate the frequency of single and repeated events. *International Journal* *of Police Science & Management*, *13*(3), 234–242. doi:10.1350/ijps.2011.13.3.243

Shimomura, T., & Kumada, T. (2011). Spatial working memory load affects counting but not subitizing in enumeration. *Attention, Perception & Psychophysics*, *73*(6), 1694–1709. doi:10.3758/s13414-011-0135-5

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, *75*(2), 428–44. doi:10.1111/j.1467-8624.2004.00684.x

Siegler, R. S., & Opfer, J. E. (2003). The Development of Numerical Estimation: Evidence for Multiple Representations of Numerical Quantity. *Psychological Science*, *14*(3), 237–250. doi:10.1111/1467-9280.02438

Siegler, R. S., & Ramani, G. B. (2008). Playing linear numerical board games promotes low-income children's numerical development. *Developmental Science*, *11*(5), 655–61. doi:10.1111/j.1467-7687.2008.00714.x

Simmons, F. R., Willis, C., & Adams, A.-M. (2012). Different components of working memory have different relationships with different mathematical skills. *Journal of Experimental Child Psychology*, *111*(2), 139–55. doi:10.1016/j.jecp.2011.08.011

Smith, L., & Gasser, M. (2005). The development of embodied cognition: six lessons from babies. *Artificial Life*, *11*(1-2), 13–29. doi:10.1162/1064546053278973

Srinivasan, M., & Carey, S. (2010). The long and the short of it: On the nature and origin of functional overlap between representations of space and time. *Cognition*, *116*(2), 217–241. doi:10.1016/j.cognition.2010.05.005

Statistics, N. C. for E. (2013). *A First Look: 2013 Mathematics and Reading*. *National Assessment Of Educational Progress At Grades 4 And 8*. doi:NCES 2014-451

Stock, P., Desoete, a., & Roeyers, H. (2009). Predicting Arithmetic Abilities: The Role of Preparatory Arithmetic Markers and Intelligence. *Journal of Psychoeducational Assessment*, *27*(3), 237–251. doi:10.1177/0734282908330587

Sullivan, J. L., Juhasz, B. J., Slattery, T. J., & Barth, H. C. (2011). Adults' number-line estimation strategies: evidence from eye movements. *Psychonomic Bulletin & Review*, *18*(3), 557–63. doi:10.3758/s13423-011-0081-1

Téglás, E., Vul, E., Girotto, V., Gonzalez, M., Tenenbaum, J. B., & Bonatti, L. L. (2011). Pure reasoning in 12-month-old infants as probabilistic inference. *Science (New York, N.Y.)*, *332*(6033), 1054–9. doi:10.1126/science.1196404

Tramontana, M. G., Hooper, S. R., & Selzer, S. C. (1988). Research on the preschool prediction of later academic achievement: A review. *Developmental Review*, *8*(2), 89–146. doi:10.1016/0273-2297(88)90001-9

Treccani, B., & Umiltà, C. (2011). How to cook a SNARC? Space may be the critical ingredient, after all: a comment on Fischer, Mills, and Shaki (2010). *Brain and Cognition*, *75*(3), 310–5; discussion 316–8. doi:10.1016/j.bandc.2010.11.006

Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review*, *101*(1), 80–102. doi:10.1037/0033-295X.101.1.80

Tschentscher, N., Hauk, O., Fischer, M. H., & Pulvermüller, F. (2012). You can count on the motor cortex: finger counting habits modulate motor cortex activation evoked by numbers. *NeuroImage*, *59*(4), 3139–48. doi:10.1016/j.neuroimage.2011.11.037

Tuholski, S. W., Engle, R. W., & Baylis, G. C. (2001). Individual differences in working memory capacity and enumeration. *Memory & Cognition*, *29*(3), 484–492. doi:10.3758/BF03196399

Vale´rie Dormal Mauro Pesenti, X. S. (2006). Numerosity-duration interference:A Stroop experiment. *Acta Psychologica*, *121*, 109–124. doi:10.1016/j.actpsy.2005.06.003

Van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: a study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology*, *101*(2), 99–113. doi:10.1016/j.jecp.2008.05.001

Van Rooijen, M., Verhoeven, L., & Steenbergen, B. (2011). Early numeracy in cerebral palsy: review and future research. *Developmental Medicine and Child Neurology*, *53*(3), 202–9. doi:10.1111/j.1469-8749.2010.03834.x

Vetter, P., Butterworth, B., & Bahrami, B. (2008). Modulating attentional load affects numerosity estimation: Evidence against a pre-attentive subitizing mechanism. *PLoS ONE*, *3*(9), 1–6. doi:10.1371/journal.pone.0003269

Viarouge, A., Hubbard, E. M., & Dehaene, S. (2014). The Organization of Spatial Reference Frames Involved in the SNARC Effect. *Quarterly Journal of Experimental Psychology (2006)*, *0*(0), 1–16. doi:10.1080/17470218.2014.897358

Von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology*, *49*(11), 868–873.

Vukovic, R. K., Kieffer, M. J., Bailey, S. P., & Harari, R. R. (2013). Mathematics anxiety in young children: Concurrent and longitudinal associations with mathematical performance. *Contemporary Educational Psychology*, *38*(1), 1–10. doi:10.1016/j.cedpsych.2012.09.001

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*(11), 483–488. doi:10.1016/j.tics.2003.09.002

Wandrey, L., Lyon, T. D., Quas, J. A., & Friedman, W. J. (2012). Maltreated children's ability to estimate temporal location and numerosity of placement changes and court visits. *Psychology, Public Policy and Law*, *18*(1), 1–25. doi:10.1037/a0024812.MALTREATED

White, S. L. J., Szűcs, D., & Soltész, F. (2012). Symbolic number: the integration of magnitude and spatial representations in children aged 6 to 8 years. *Frontiers in Psychology*, *2*(January), 392. doi:10.3389/fpsyg.2011.00392

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–36.

Wood, G., Willmes, K., Nuerk, H., & Fischer, M. H. (2008). On the cognitive link between space and number : a meta-analysis of the SNARC effect. *Psychological Science Quarterly*, *50*(4), 489–525.

Wu, S. S., Barth, M., Amin, H., Malcarne, V., & Menon, V. (2012). Math anxiety in second and third graders and its relation to mathematics achievement. *Frontiers in Psychology*, *3*(JUN), 1–11. doi:10.3389/fpsyg.2012.00162

Yonelinas, A. P. (2002). The Nature of Recollection and Familiarity: A Review of 30 Years of Research. *Journal of Memory and Language*, *46*(3), 441–517. doi:10.1006/jmla.2002.2864

Zacks, R. T., & Hasher, L. (2002). Frequency Processing: A Twenty-Five Year Perspective. In P. Sedlmeier & T. Betsch (Eds.), *ETC. Frequency Processing and Cognition* (pp. 21–36). Oxford: Oxford University Press.

Zacks, R. T., Hasher, L., & Sanft, H. (1982). Automatic Encoding of Event Frequency. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *8*(2), 106–116.

Zebian, S. (2005). Linkages between Number Concepts, Spatial Thinking, and Directionality of Writing: The SNARC Effect and the REVERSE SNARC Effect in English and Arabic Monoliterates, Biliterates, and Illiterate Arabic Speakers. *Journal of Cognition and Culture*, *5*(1), 165–190. doi:10.1163/1568537054068660

Zorzi, M., Priftis, K., Meneghello, F., Marenzi, R., & Umiltà, C. (2006). The spatial representation of numerical and non-numerical sequences: evidence from neglect. *Neuropsychologia*, *44*(7), 1061–7. doi:10.1016/j.neuropsychologia.2005.10.025