Influences of visuospatial mental processes and cortical excitability on numerical cognition and learning

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Abstract

Numerical cognition has been shown to share many aspects of spatial cognition, both behavioural and neurological. However, it is unclear whether a particular type of spatial cognition, visuospatial mental imagery (VSMI), may play a role in symbolic numerical representation. In this thesis, I first show that mental rotation, a form of VSMI, is related to two measures of basic numerical representation. I then show that number-space synaesthesia (NSS), a rare type of VSMI involving visualised spatial layouts for numbers, does not show an advantage in mental rotation, but shows interference in number line mapping. I next present a study investigating links between NSS and the ability to learn novel numerical symbols. I demonstrate that NSS shows an advantage at learning novel numerals, and that transcranial random noise stimulation, which increases cortical excitability, confers broadly similar advantages that nonetheless differ in subtle ways. I present a study of transcranial alternating current stimulation on the same symbol learning paradigm, which fails to demonstrate effects. Lastly, I present data showing that strength of numerical representation in these newly-learnt symbols is correlated with a measure of mental rotation, and also with visual recognition ability for the symbols after, but not before, training. All together, these findings suggest that VSMI does indeed play a role in numerical cognition, and that it may do so from an early stage of learning symbolic numbers.

Chapter 1: Introduction

Numbers are arguably one of humans' greatest technologies. Formal numerical systems have enabled us to create systems of mathematics and physics, replace barter systems with money, engineer complex structures and explore outer space, and even quantify and record the functioning of the human brain. However, these great accomplishments have humble bases. Human infants and animals are thought to share a basic representation of quantity, known as the approximate number system (ANS), which allows them to discriminate between different numerosities (Cantlon & Brannon, 2006; Cantlon, Platt, & Brannon, 2009; Feigenson, Dehaene, & Spelke, 2004; Lipton & Spelke, 2003). This system works with increasingly lower precision at higher quantities, possibly due to less precise tuning curves in their neural representations (M. Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). In addition to the ANS, numerate human children and adults are thought to possess an exact number system (ENS), which allows them to represent and compare even large quantities with high precision (Buckley & Gillman, 1974; Castronovo & Gobel, 2012). The ENS is a symbolic system, operating through verbal and visual symbolic numbers (i.e., number words and numerals), and children show signs of increased use of ENS over ANS through development, e.g. in number line tasks (Siegler & Opfer, 2003) and Stroop-like paradigms testing the automaticity of symbolic number processing (Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). It is with this number system that my thesis is primarily concerned.

Research suggests that the ENS appears to have its foundations in the ANS, for example, by showing that ANS ability can predict later mathematics ability (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013), and by showing activation in an identical area of the intraparietal sulcus (IPS) in both symbolic and non-symbolic numbers (Piazza, Pinel, Le Bihan, & Dehaene, 2007). On the other hand, some researchers have suggested that ENS arises first, as part of a 'number module' that allows development of the concepts of exact numerosities (Butterworth, 1999). Either way, several theoretical accounts have suggested that human use of numbers (i.e., ENS) may have arisen from evolutionarily more ancient cognitive functions, such as spatial cognition (Anderson, 2010; Cohen Kadosh, Lammertyn, & Izard, 2008; Dehaene & Cohen, 2007). Accordingly, investigations into the relationship between spatial and numerical cognition formed the impetus for the research I will present in this dissertation.

Numbers and Space

A large body of research has demonstrated links between numerical and spatial cognition (Cohen Kadosh et al., 2008; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Hubbard, Piazza, Pinel, & Dehaene, 2005; van Dijck, Ginsburg, Girelli, & Gevers, 2014; Walsh, 2003). One of the first instances of this was demonstration of the distance effect (Moyer & Landauer, 1967), in which performance in a magnitude comparison task is worse when comparing numbers separated by smaller numerical distance (e.g., 2 and 3) than when comparing numbers separated by large numerical distance (e.g., 2 and 8). This effect is found in both ANS (e.g., comparing arrays of dots) and ENS (e.g., comparing Arabic numerals), although performance on the two tasks is not correlated within individuals (Maloney, Risko, Preston, Ansari, & Fugelsang, 2010). The distance effect has been interpreted as evidence that humans represent numbers spatially (Dehaene et al., 1998); on the other hand, it might arise merely as an artefact of the topographical spatial aspect of neuronal coding for numbers (Harvey, Klein, Petridou, & Dumoulin, 2013; Van

Opstal, Gevers, De Moor, & Verguts, 2008). That is, it does not necessarily imply that spatial *cognition* is involved in the ENS.

A stronger piece of evidence to the latter point comes from a seminal, often-replicated finding termed the spatial-numerical association of response codes (SNARC) effect (Dehaene, Bossini, & Giraux, 1993). The SNARC effect demonstrates that participants respond more quickly and accurately to smaller magnitude numbers with the left hand, or on the left side of space, and respond to larger numbers more efficiently with the right hand, or on the right side of space. This effect remains even in number judgement tasks that are unrelated to numerical magnitude or that are performed with eye movements (saccades) instead of manual response (Schwarz & Keus, 2004). The SNARC effect is similarly flexible according to the range of numbers used, and to manipulations in spatial imagery (Bachtold, Baumuller, & Brugger, 1998; Price, 2009), and even to non-numerical sequences, such as months or the alphabet (Gevers, Reynvoet, & Fias, 2003; Jonas, Taylor, Hutton, Weiss, & Ward, 2011). Neurological findings have suggested that the SNARC effect arises in response selection, rather than stimulus encoding or motor planning, which suggests that it arises from some aspect of the numerical representation (Keus, Jenks, & Schwarz, 2005). Furthermore, SNARC-like effects on grip aperture, with smaller grip size facilitating response to smaller numbers, demonstrate that numbers are cognitively connected to not only spatial orientation, but also spatial measurements of size or distance (Andres, Davare, Pesenti, Olivier, & Seron, 2004).

Another facet of the relationship between numerical and spatial cognition lies in investigations into the use of number lines. Siegler and Opfer (2003) asked children to map numbers onto a physical line, and demonstrated that the pattern of their placement of numbers initially showed logarithmic compression of larger numbers, similar to visual compression of space. Number line training, including training involving kinaesthetic interaction with space, has been shown to improve children's understanding of numbers, supporting the idea that spatial functions can interact with numerical cognition (U. Fischer, Moeller, Bientzle, Cress, & Nuerk, 2011). Tasks in adults have similarly showed a link between spatial lines and numbers, suggesting the presence of a spatially-moderated mental number line. For instance, line bisection was found to be spatially biased when the line was composed of numerals (M. H. Fischer, 2001), showing a leftward bias for small-value numerals and a rightward bias for large-value numerals. Operations on numbers have also shown patterns similar to analogous spatial tasks. For example, healthy participants tend to show a leftward bias, or "pseudoneglect," when asked to bisect a physical line (Jewell & McCourt, 2000). Similarly, healthy participants also show a left pseudoneglect when asked to find the middle number of a numerical interval (e.g., answering that 5 is halfway between 3 and 9; Lourenco & Longo, 2009).

Evidence for the spatial nature of this effect is bolstered by studies of patients with leftward neglect caused by right parietal lesions (Zorzi, Priftis, Meneghello, Marenzi, & Umilta, 2006). The attentional neglect of leftward space causes such patients to show a marked rightward bias when they bisect physical lines, but also causes a bias toward larger numbers when they are asked to name the halfway points of numerical intervals. Conversely, a patient with the rarer condition of rightward spatial neglect, caused by left hemisphere damage (Pia, Corazzini, Folegatti, Gindri, & Cauda, 2009), showed the opposite spatial biases in bisection of both physical lines and numerical intervals. This evidence together suggests that spatial attention influences not only perception, but the representation of the mental number line as well. It should be noted that the body of neuropsychological evidence does not necessarily imply a simple or unitary link between spatial and numerical representations. Dissociations within some types of line and number interval bisection in neglect patients suggest that a mental spatial representation of number is not simply a single, left-to-right ascending-value number line, but may be characterised by more complex interactions of number and space (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; van Dijck et al., 2014).

The neuropsychological evidence reviewed in the previous paragraph implicates a role of the parietal cortex in the mediation between number and space. Both monkey and human physiological investigations have supported this link. For instance, Nieder and Miller (2004) identified neurons tuned for specific numerosities in the IPS of rhesus macaque monkeys. Later research found that similar areas also code for temporal and spatial processes in monkeys, and even demonstrated the existence of neurons that coded for both specific numerosity and physical line length (Tudusciuc & Nieder, 2007). Although single-neuron recording is not currently feasible in humans, neuroimaging studies have found links between cognition of space and number in the parietal cortex (Cohen Kadosh et al., 2008). Multiple studies have found areas in the IPS that appear to code quantity information about both symbolic numbers and non-symbolic spatial stimuli, such as lines and shapes (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Piazza et al., 2007). Similarly, studies such as Kaufmann, et al. (2005) have found that the IPS appears to modulate conflicts between numerical and spatial aspects of stimuli, as in the numerical Stroop paradigm, which measures the interference between physical size and numerical value in pairs of numbers whose physical and numerical magnitudes are either congruent (e.g., 2 8) or incongruent (e.g., 2 8).

Visuospatial mental imagery

Evidence amassed from a variety of sources—such as the SNARC effect, spatial neglect patients, and neuroimaging studies—all seems to suggest that the ENS is not merely organised in a similar way to spatial cognition (nor merely located in nearby but functionally unrelated areas), but rather, that symbolic number representation actually engages mechanisms of spatial cognition. As noted above, much of the evidence gathered so far has focused on mechanisms of motor response, spatial perception, and spatial attention. However, comparatively little work has addressed the possibility that one of the spatial mechanisms involved in numerical representation may be visuospatial mental imagery (VSMI). In this thesis, I define VSMI as the creation and manipulation of visuospatial mental representations of concrete objects or abstract concepts (Kosslyn, Thompson, & Ganis, 2006). As I refer to it throughout this dissertation, VSMI involves a visual representation that includes spatial orientation, ordering, and/or magnitude, and it serves as a referent for an object or scene that may or may not be physically present.

Mental Rotation

One well-studied example of VSMI is mental rotation, the process of imagining an object in a different spatial orientation to its normal or depicted form. Early research by Shepard and Metzler (1971) found that time required to recognise depictions of differently-oriented 3-dimensional objects increased parametrically with the angle of rotation between them, suggesting that mental rotation is done by imagining actual rotation movement. Cooper and Shepard (1973) found the same pattern in rotations of 2D alphanumeric characters within the vertical plane. More recent research has confirmed Shepard and Metzler's finding as a robust aspect of mental rotation tasks, and furthermore has suggested that this visuospatial process of rotation is not easily cognitively penetrable. For instance, Borst, Kievit, Thompson, and Kosslyn (2011) found that participants' performance on a standard 3D mental rotation task (comparing pairs of rotated objects) was affected neither by explicit instructions for imagery strategies nor by implicit influences of observing rotation examples. However, the process of mental rotation does not appear to be automatic; mere presentation of a rotated familiar stimulus (e.g., alphanumeric characters) is not enough to evoke neural metabolic responses typical of rotation (Weiss et al., 2009). Furthermore, mental rotation on objects recalled from memory shows similar patterns to mental rotation of visually presented objects, suggesting that the process of mental rotation can be accessed voluntarily (Just, Carpenter, Maguire, Diwadkar, & McMains, 2001).

Visual and spatial processes have both been implicated in mental rotation (e.g., both visual and spatial working memory; Hyun & Luck, 2007; Kaufman, 2007). However, a great deal of neuroimaging research has focused on the spatial aspects of the task (Zacks, 2008). For instance, fMRI studies have shown that bilateral IPS activation increases with increases in rotation angle (Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Gogos et al., 2010). Similarly, (Weiss et al., 2009) found parametric activation of IPS, along with other areas, in rotation (but not identification) of alphanumeric characters. Transcranial magnetic stimulation (TMS) studies have also shown the varying roles of both right and left posterior parietal cortex, in both 2D (Harris & Miniussi, 2003) and 3D mental rotation (Feredoes & Sachdev, 2006). These findings are intriguing for the possibility that VSMI, and mental rotation ability in particular, may be engaged in numerical cognition, as both IPS and PPC have been widely implicated in an array of spatial-numerical tasks (Cohen Kadosh et al., 2008).

Like numerical and mathematical ability (Dowker, 2008), mental rotation ability shows wide individual differences (Just & Carpenter 1985, Peters 2007). These are possibly due to differences in strategy (e.g., Heil & Jansen-Osmann, 2008), but also depend on physiological fluctuations in hormones such as testosterone and estradiol (Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000) and likely other innate and environmental influences (e.g., level of education and age; Peters, Manning, & Reimers, 2007).

Number-Space Synaesthesia

In contrast to mental rotation, VSMI also may take forms more clearly related to numerical cognition, as in depicting number lines. There are a multitude of cultural examples of numbers presented in a (usually sequential) spatial layout: rulers, clocks, calendars, and even house numbers. In line with this, school curricula often teach VSMI as an explicit strategy for learning number magnitudes and arithmetic (Ernest, 1985). Additionally, experimental paradigms have shown that instructing participants to use VSMI of clocks or rulers can influence their spatial responses to numbers, as measured by the SNARC effect (Bachtold et al., 1998; Price, 2009). There is much debate about the cultural influences of spatial associations with numbers. In most Western cultures, in which reading occurs left-to-right, numbers are usually culturally presented in the same left-to-right orientation (although not always, as seen with analogue clocks and compasses.) Therefore, many studies have implicated cultural influences of writing and symbolic number notation on spatial-numerical associations (Shaki & Fischer, 2008; Shaki, Fischer, & Petrusic, 2009; Zebian, 2005). However, recent research has shown that monkeys demonstrate a left-to-right directional bias when transferring vertically-learned ordinal sequences to horizontal orientations (Drucker & Brannon, 2014), suggesting there may be an evolutionary root to this widespread cultural bias.

As noted above, cultural instantiations of numbers can be voluntarily used in VSMI. However, some individuals exhibit VSMI for numbers in an involuntary and automatic manner, in a condition termed number-space synaesthesia (NSS). Individuals with NSS automatically and consistently associate numbers to a specific visuospatial layout, reported as either in peripersonal space or in their "mind's eye" (Galton, 1880; Gertner, Henik, & Cohen Kadosh, 2009; Sagiv, Simner, Collins, Butterworth, & Ward, 2006; Seron, Pesenti, Noel, Deloche, & Cornet, 1992). This visuospatial layout (hereafter called a "number form" or "spatial form," interchangeably) is idiosyncratic to the synaesthete, and can vary widely across individuals. NSS is one of many types of sequence-space synaesthesia (SSS), a condition broadly defined as automatic visualisation of spatial layouts for sequences such as days of the week, months, or the alphabet (Eagleman, 2009). Relatively rare, NSS is thought to affect up to 10-20% of the population, equally in males and females, and often co-occurs in individuals with other forms of SSS (Sagiv et al., 2005; Sagiv et al., 2006; Seron et al., 1992).

Evidence is mixed as to whether SSS, including NSS, relies predominantly on visual or spatial cognitive processes. For instance, two studies, testing 20 spatial-sequence synaesthetes in total, found that participants with time-space variants of SSS outscored controls on mental rotation paradigms, which would seem to implicate spatial ability as a key component of SSS (Brang, Miller, McQuire, Ramachandran, & Coulson, 2013; Simner, Mayo, & Spiller, 2009). However, other findings have argued that SSS is based more in visual than spatial imagery. For instance, (Rizza & Price, 2012) reported that 9 synaesthetes with at least two forms of sequence-space synaesthesia (weekdays, months, and/or number) scored no better than controls on spatial tasks, such as box-folding and mental rotation, and in fact scored higher than controls on the visual object portion, but not the spatial portion, of an imagery questionnaire. However, this latter result may be due to several questions on the visual (but not spatial) portion of the questionnaire that measured the involuntariness or automaticity of imagery (a hallmark of NSS) rather than its visual versus spatial elements *per se* (e.g., whether respondents "experience many spontaneous vivid images" or whether images are "difficult to ignore").

SSS is accompanied by a host of both benefits and costs in cognition. In addition to advantages at mental rotation, time-space synaesthetes have shown heightened ability to recall past events and learn new spatial forms for months (Brang et al., 2013; Simner et al., 2009). Synaesthetes with some combination of NSS and spatial forms for time were found to show advantages over controls in visuospatial working memory (Hale, Thompson, Morgan, Cappelletti, & Cohen Kadosh, in press). Additionally, some authors have hypothesised that SSS may be the basis of superior recall or calculation abilities in some savants (Murray, 2010; Simner et al., 2009). On the other hand, NSS has also been associated with worse performance at addition and multiplication problems, possibly due to their use of number forms rather than the potentially faster method of answering solely by rote memory (J. Ward, Sagiv, & Butterworth, 2009). NSS also appears to interfere with speed at numerical judgements when spatial aspects of the task conflict with spatial aspects of an individual's number form (Gertner, Henik, Reznik, & Cohen Kadosh, 2013; Hubbard, Ranzini, Piazza, & Dehaene, 2009).

Although the two are confounded in numerical systems, ordinality, rather than magnitude, appears to govern the organisation and operation of spatial forms in NSS. One piece of evidence for this is the high prevalence of SSS for sequences that are characterised by over-learned orders (e.g., days of the week, or the alphabet) that have no inherent magnitude properties (Sagiv et al., 2006). Furthermore, neurological and behavioural differences have been found between processing of ordinal and magnitude information in NSS. A neuroimaging study found that participants with NSS showed additional activation in bilateral IPS compared to controls when they engaged in a numerical task involving ordinal information, but activation did not differ from controls in a task requiring magnitude information (Tang, Ward, & Butterworth, 2008). Similarly, a battery of behavioural tasks assessing spatial, temporal and numerical abilities found that a group of synaesthetes with SSS (either time-space, NSS, or both) outperformed controls on judgements concerning order but not magnitude (Hale et al., in press). This is consistent with neurological evidence in typical and patient populations that order and magnitude of numbers are processed differently (Turconi, Jemel, Rossion, & Seron, 2004; Turconi & Seron, 2002). Furthermore, the importance of ordinality in NSS concurs with findings in typical populations that the predictive power of ANS performance for later ENS ability is mediated by ordering ability (Lyons & Beilock, 2011).

Similarities of NSS to numerical and spatial cognition in typical populations has led some authors to suggest that NSS may simply be a more explicit version of implicit spatial numerical representations that underlie typical numerical cognition ((Cohen Kadosh, Gertner, & Terhune, 2012; Cohen Kadosh & Henik, 2007; Eagleman, 2009). Participants with NSS show SNARC effects according to their particular spatial forms, in the same way that typical populations show SNARC effects according to cultural number line orientations (Hubbard et al., 2009; Jarick, Dixon, & Smilek, 2011). Additionally, areas implicated in NSS by neuroimaging are those also highly implicated in normal numerical and spatial cognition (Tang et al., 2008). A final piece of evidence offers the only documented case of a sudden loss of NSS. Over half a century ago, Spalding and Zangwill (1950) described an individual who suffered damage to the left parietal cortex and subsequently showed profound impairments in both the ability to do simple arithmetic and the ability to access his synaesthetic number form. Intriguingly, the pattern of his arithmetic impairment suggests that his calculation abilities may have relied on his number form (Cohen Kadosh et al., 2012). However, despite these hints, the extent to which NSS may reflect the role of spatial mechanisms in numerical cognition is still largely an open question.

Modulating neural substrates

In the previous two sections, I suggested through several pieces of evidence that the *anatomical* underpinnings of VSMI and numerical representation may overlap (especially in the IPS and other regions of the parietal cortex). This begs the question: does the *functioning* of these regions govern numerical cognition and VSMI similarly? In other words, will functional changes to these regions modulate processes of mental imagery and numerical representation in similar ways?

An ideal way to investigate this is by modulating neural activity in an experimentally controlled way. Transcranial electrical stimulation, or tES, is a non-invasive brain stimulation method that can modulate large-scale neural activity by passing small amounts of electrical current through the brain via electrodes placed on the scalp. tES has been used in a wide variety of cognitive paradigms, to enhance or investigate cognition (Cohen Kadosh, 2013; Jacobson, Koslowsky, & Lavidor, 2012; Beatrix Krause & Cohen Kadosh, 2013; Kuo & Nitsche, 2012). The most common form of tES to date is transcranial direct current stimulation (tDCS), which delivers current in a given direction, flowing from the positively charged electrode (anode) to the negatively charged electrode (cathode). This polarity between the electrodes results in differential electrical properties induced in brain tissue underlying the two electrodes. In tDCS, the constant level of current modulates the transmembrane potential in neurons, thereby changing individual neural firing patterns by increasing (cathodal stimulation) or decreasing (anodal stimulation) the residual level of synaptic neural activity needed to bring the neuron beyond threshold for inducing action potentials (Antal, Nitsche, & Paulus, 2001; Nitsche & Paulus, 2000). TDCS has demonstrated the importance of underlying brain function in fields of cognition as varied as executive processing, mathematical cogniton, and social cognition (Cohen Kadosh, Soskic, Iuculano, Kanai, & Walsh, 2010; Dockery, Hueckel-Weng, Birbaumer, & Plewnia, 2009; Santiesteban, Banissy, Catmur, & Bird, 2012).

Transcranial alternating current stimulation (tACS), as opposed to tDCS, delivers current in an oscillatory pattern, changing the direction of current flow at a fixed temporal frequency (e.g., at theta band, alpha band, or gamma band) (Antal et al., 2008). This oscillating current is thought to entrain temporally-synchronous oscillations of cortical activity in the large-scale neuronal populations in areas targeted by stimulation (Neuling, Rach, & Herrmann, 2013; Struber, Rach, Trautmann-Lengsfeld, Engel, & Herrmann, 2013). Depending on how closely the frequency and phase of the alternating current match those of the targeted neuronal population in a particular cognitive process, this can either increase signal-to-noise ratio, thus facilitating cognitive processes underway, or alternatively, it can increase interference, thus impairing cognitive processes (Zaehle, Rach, & Herrmann, 2010). TACS has been used to demonstrate the role of frequency-specific oscillations and neural synchrony in cognitive abilities such as working memory and fluid intelligence (Jausovec & Jausovec, 2014; Jausovec, Jausovec, & Pahor, 2014; Polania, Nitsche, Korman, Batsikadze, & Paulus, 2012).

Transcranial random noise stimulation (tRNS) is a relatively new form of tES, first introduced to the literature in 2008 (Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). Instead of direct or fixed frequency alternating current, tRNS delivers a constantly-changing random level of current generated according to a fixed Gaussian probability curve. This produces an electrical signal corresponding to "white noise," in which all frequencies up to 640Hz are represented. Because the probability function of the random current levels is usually centered on 0, each electrode carries equal amounts of negative and positive current when averaged over time; therefore, there are no polarity effects as in tDCS. TRNS can be further specified to deliver only high-frequency (hf-tRNS; 100-640 Hz) or low-frequency (lf-tRNS; 0.1-100 Hz) currents. Currently more evidence has pointed to effectiveness of hf-tRNS (Fertonani, Pirulli, & Miniussi, 2011; Snowball et al., 2013). In motor studies, tRNS has been found to be excitatory under both electrodes (Terney et al., 2008). Although the mechanisms of tRNS are still not well-understood, they may operate through principles of stochastic resonance, employing random noise to amplify weak neural signals (Moss, Ward, & Sannita, 2004). Whereas direct current only shifts membrane potential once, at the beginning of stimulation, random current may affect neuronal activity by allowing small continual depolarization effects to keep occurring over time (Schoen & Fromherz, 2008; Terney et al., 2008). TRNS has been shown in recent training studies to improve training on numerical abilities, i.e., numerosities, when applied to parietal areas (Cappelletti et al., 2013), and arithemetic calculation, when applied to prefrontal cortex (Snowball et al., 2013).

One of the main advantages of investigating cognition through tES, rather than neuroimaging, is that by systematically manipulating neural activity, it can causally demonstrate the role of the affected brain area in the resultant behavioural (or biological) measures of cognition. Such a causal demonstration of neural function resembles the empirical revelations of lesion studies, but with three obvious advantages: 1) brain stimulation, unlike lesions, can be ethically and reversibly applied to healthy human participants, and unlike the chance nature of clinical lesions, it can be systematically localised and modulated in its temporal duration and severity; 2) the experimenter is able to examine cognitive processes in the intact brain, rather than in the atypical brain, which might have undergone unknown processes of reorganisation and compensation (Robertson & Murre, 1999); 3) perhaps less obviously, another advantage over lesion studies is that tES can impair, but also can *increase*, efficacy of neuronal activity.

Although the effects of tES are relatively diffuse compared to methods such as TMS (Bikson, Rahman, & Datta, 2012; DaSilva, Volz, Bikson, & Fregni, 2011), this can be an advantage when the underlying networks involved in a targeted task are diffuse as well. The continual, low levels of current in tES also make it ideally suited for use in training paradigms, such as the ones I use in the latter chapters of this thesis. Modulating cortical excitability or endogenous oscillations over diffuse brain areas and long periods of time can allow time for neural pathways to be strengthened in learning, and may potentially even mimic or model functional differences in atypical brains. For instance, by applying cathodal tDCS to the right parietal cortex and anodal tDCS to the left, (Cohen Kadosh et al., 2010) found that the changes of hemispheric balance during training in a novel numerical system resulted in numerical cognitive effects resembling those of dyscalculic populations. Although not a perfect model of functionally atypical brains, the effects of stimulation can shed light on functional processes that may be underlying atypical cognition.

Research questions

In summary, numerical cognition has been shown to share many aspects of spatial cognition, both behavioural and neurological (Cohen Kadosh et al., 2008). However, it is unclear whether humans merely encode numbers in a *similar manner* to how we encode space, or whether basic numerical representation in fact recruits *actual mechanisms* of spatial cognition. If the latter explanation is true, VSMI might be one way through which numerical representation engages spatial cognitive mechanisms. An example of this can already be found in one atypical population, NSS, in which individuals form and automatically access visuospatial imagery of numbers when engaged in numerical tasks. This led me to a number of research questions.

In chapter 2, I ask the question: is VSMI related to numerical representation in typical (non-NSS) populations? Chapter 3 investigates the question of how spatial aspects of number representation differ between NSS and non-NSS populations. In chapter 4, I ask: in typical and atypical (NSS) populations, is VSMI just another strategy to help humans work with numbers, or does it influence the formation of basic numerical representation? Furthermore, can modulating the cortical substrates of VSMI and numerical cognition cause changes in newly learnt numerical representations? Chapter 5 asks whether brain stimulation effects on numerical learning can be further pinpointed to specific frequencies of neural oscillations. Lastly, in chapter 6 I ask how the visuospatial representation of numerals is linked to the understanding of their semantic (numerical) associations. Together, these chapters contribute to answering the question of how VSMI may play a role in numerical representation and learning.

Chapter 2: The link between mental rotation ability and basic numerical representations

Although mental rotation has been linked to higher-level mathematical skills, to date it has not been shown whether mental rotation ability is linked to the most basic mental representation and processing of numbers. To investigate the possible connection between mental rotation abilities and numerical representation, I tested 43 participants on four tasks: 1) a standard pen-and-paper mental rotation task; 2) a multi-digit number magnitude comparison task assessing the compatibility effect, which indicates separate processing of decade and unit digits; 3) a number-line mapping task, which measures precision of number magnitude representation; and 4) a random number generation task, which yields measures both of executive control and of spatial number representations. Results show that mental rotation ability correlated significantly with both size of the compatibility effect and with number mapping accuracy, but not with any measures from the random number generation task. Together, these results suggest that higher mental rotation abilities are linked to more developed number representation, and also provide further evidence for the connection between visuospatial mental imagery and numerical abilities.

Introduction

A strong connection has long been noted between mathematical and spatial cognitive abilities. Studies of developmental, individual, and sex differences among cognitive skills have consistently shown that spatial and mathematical aptitude tend to align (Bull, Cleland, &

Mitchell, 2013; Geary, Saults, Liu, & Hoard, 2000; Reuhkala, 2001). However, it is unclear whether this connection exists solely with high-level mathematical abilities or if it is founded upon a deeper overlap between visuospatial abilities and basic numerical cognition. Most of the current evidence has established connections between visuospatial abilities and high-level numerical abilities, such as mathematical abilities (e.g., Dumontheil & Klingberg, 2012). The relationship of visuospatial ability to more basic mathematical abilities, such as arithmetic, is less clear. For instance, Delgado and Prieto (2004) found that mental rotation ability predicted performance in algebra and geometry, but not arithmetic. Similarly, a meta-analysis found that arithmetic ability was better predicted by verbal than by spatial abilities (Friedman, 1995).

Individual and task differences further complicate the observed relationship between spatial and mathematical abilities. For instance, there is conflicting evidence as to the relative importance of visuospatial versus verbal working memory in younger versus older children's arithmetic ability, with some studies implicating a greater role of visuospatial working memory in arithmetic in older versus younger children (McKenzie, Bull & Gray, 2003) and others finding the reverse (Meyer, Salimpoor, Wu, Geary & Menon, 2010). Furthermore, disparate numerical and mathematical abilities may rely upon visuospatial ability to differing degrees. For instance, Simmons, Willis & Adams (2012) found visuospatial working memory to predict unique elements of variance in magnitude judgment and number writing ability, but not arithmetic. Nevertheless, it is possible that connections between mathematical and spatial ability are partially based on a more fundamental link between visuospatial abilities and basic numerical abilities that serve as the building block for high level numerical abilities (Butterworth, 2010).

Despite the common intuition that numbers are represented purely abstractly (for a review see Cohen Kadosh & Walsh, 2009), numerical cognition has been shown to incorporate a vigorous visuospatial component; for instance, spatial influences have been shown on numerical tasks such as number interval bisection, parity judgment, and numerical value comparison, whereas irrelevant but automatically-processed numbers have been shown to influence visuospatial tasks such as attentional cueing and physical line bisection (e.g., de Hevia, Vallar, & Girelli, 2008; Vallar & Girelli, 2009). Space is a powerful conceptual framework for learning number properties of ordering and magnitude, as illustrated in the embodied cognition account of Lakoff and Nunez (2000), and as evidenced in the widespread use of visual number lines in early mathematics education (Ernest, 1985). Additionally, lesion and imaging studies have implicated common areas in the parietal cortex for both visuospatial (e.g., physical line bisection, spatial attention and orientation) and numerical (e.g., number comparison, numerosity and magnitude judgment) abilities, suggesting that they may recruit shared neural circuits (for reviews see Cantlon et al., 2009; Cohen Kadosh et al., 2008; Hubbard et al., 2005; Walsh, 2003). It follows, then, that numerical representation may be closely linked to visuospatial functions, such as VSMI. In this chapter I investigate one particular VSMI ability, mental rotation, and its links to numerical representation.

It may not be immediately obvious how ability in mental rotation, which involves 2- or 3-dimensional spatial representations, would be relevant to spatial representations of number, which are primarily presumed to 1-dimensional (i.e., linear). However, one need only look at various multi-dimensional cultural representations of numbers, such as calendars, analogue clocks or abacuses, for a clue as to how number representation could include multiple dimensions. Indeed, Moeller, Pixner, Kaufmann & Nuerk (2009) suggest that children's performance on number line estimation tasks may reflect a combination of number representations more spatially complicated than 1D number lines. Similarly, the 2D and 3D number layouts reported by number-space synaesthetes also suggest that number representation is not limited to a single dimension.

Mental rotation is a computationally complex process of VSMI, with performance varying widely across individuals irrespective of other intelligence measures (Borst et al., 2011; Johnson & Bouchard, 2005; Shepard & Metzler, 1971). Mental rotation has been shown to correlate with other tests of spatial abilities, such as mental paper-folding tasks, space relations tests, and spatial working memory (Just & Carpenter, 1985; Kaufman, 2007; Reuhkala, 2001), suggesting that it may indicate, at least to some degree, more general visuospatial skills of a participant.

Like mental rotation, basic number representation has been widely investigated. By "number representation" or "numerical representation", I simply mean the mental organisation and framework within which information about the semantic concept of numbers is stored. Thus number representation is the most basic level of numerical cognition upon which other (more complex) numerical and mathematical thinking builds. Whilst this basic number representation must ultimately have a neuronal basis (Harvey et al., 2013; Nieder & Miller, 2004), it is important to remember that representation and neuronal organisation are not necessarily the same thing, and that a particular proposed system of number representation could have many possible neuronal manifestations. In this thesis, it is equally important to distinguish what I will refer to as "number processing": the nature of processing necessarily relies upon the underlying representation of the concepts and percepts being acted upon, but it is not a synonym for representation. Rather, it refers to the *act of engaging* mental representations, in order to use this numerical information for number-related tasks or other cognitive processes, as well as providing input for the numerical representation (e.g., grapheme recognition). Therefore, since number representation is not accessible by any means other than number processing, observation of number processing is the only way to infer aspects of the underlying representation.

It is similarly worthwhile to emphasise here the distinction between, on the one hand, *numerical* skills, abilities, or processing, and on the other hand, *mathematical* skills, abilities, or processing. The relationship between these two concepts is a nested one; numerical skill is only one component part of mathematical skill. In this model, numerical skills necessarily rely heavily—perhaps primarily—upon numerical representation, with few other basic sub-processes mediating their outcomes, such as visual recognition of numerals. On the other hand, mathematical skills additionally rely upon (and therefore can be amplified or attenuated by) a greater number, degree, and complexity of sub-skills and sub-processes, such as logical inference, memorisation of calculation procedures, working memory, etc. For instance, factors such as working memory have been shown to predict later mathematical performance in a longitudinal developmental study (Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011). Thus, to investigate numerical representation I utilised tasks that engage numerical, rather than mathematical, skills, as mathematical measures may be affected by a multitude of these non-numerical factors.

Details of number representation have been inferred from several types of tasks, including number line mapping and numerical comparisons (Cohen Kadosh et al., 2008). Numerical comparison tasks ask participants to indicate which of two numbers is larger in magnitude (or sometimes, smaller in magnitude). This requires participants to access mental representations of the numerical magnitude of each number, and to perform comparative processes on these representations. Such tasks show several reliable behavioural effects, each shedding light on the inner workings of number processing and underlying representation. One of the effects, the unit-decade compatibility effect, arises from the decimal place-value structure of symbolic Arabic numbers. It provides evidence for decomposed processing of multi-digit numbers, thereby challenging a previous suggestion that numbers are represented by a single holistic representation, i.e., as an integrated entity which does not retain place-value information (Dehaene, Dupoux, & Mehler, 1990). The compatibility effect reflects a performance cost for trials in which the magnitude decision between unit digits of the two numbers is incompatible with (that is, opposite to) the magnitude decision between the decade digits (e.g., for a 'compatible' trial, such as 42 vs. 57, 4 < 5 and 2 < 7; but for an 'incompatible' trial, such as 37 vs. 52, 3 < 5 but 7 > 2; Nuerk, Weger, & Willmes, 2001). The performance cost for incompatible trials suggests that the unit digits of two-digit numbers are automatically processed, even when they are irrelevant to the task.

Further evidence using eye-tracking supports this interpretation, indicating that participants showed more eye fixations on unit digits than decade digits, and especially so for incompatible trials (Moeller, Fischer, Nuerk, & Willmes, 2009). This pattern has been interpreted as reflecting the need to inhibit magnitudes of unit digits for incompatible trials only, as the (irrelevant) unit comparison interferes with the decade and overall comparison; therefore the data are most consistent with a model in which both digits are processed separately (see Moeller et al., 2009, for a detailed version of that argument including hypothetical eye fixation patterns for various models and conditions). Such separate processing requires the activation of multiple representations, at least one for decade and one for unit in the case of two-digit numbers. Thus the compatibility effect can serve as a quantifiable measure indicating the robustness of simultaneous processing of multiple (i.e., decomposed-digit) numerical representations (for a review, see Nuerk, Moeller, Klein, Willmes, & Fischer, 2011). This would seem to indicate that larger compatibility effects would accompany a more complex, advanced system of number representation; indeed, developmental studies of the compatibility effect have shown it to increase with age and numerical experience (Mann, Moeller, Pixner, Kaufmann, & Nuerk, 2011) and to predict later arithmetic ability (Moeller et al., 2011).

Another type of numerical task, the number line mapping task (also termed number line estimation task), has been widely utilised in the last decade as a measure of internal spatial representations of number in both children and adults (Cohen Kadosh et al., 2010; Karolis, Iuculano, & Butterworth, 2011; Siegler & Opfer, 2003). In its commonly used number-to-space version, the paradigm typically presents participants with a horizontal line segment labelled with a numerical value at either end (usually 0 at the left, and 10, 100, or 1000 at the right), and asks them to mark the place at which a target number should be located on the line. The deviation of this mark from the true position of the number on a linear equidistance line is assessed, and both absolute deviations as well as the form of these deviations are modelled to explore the possible underlying magnitude representation (see Moeller, Pixner et al., 2009; Siegler & Opfer, 2003; Slusser, Santiago, & Barth, 2012 for different suggestions). Developmental studies show that children's mean absolute error percentages on number line tasks drop below a threshold of 10% by age 8 for numbers 0-100, and by age 10 for numbers 0-1000, and that performance in this task predicts later arithmetic learning (Booth & Siegler, 2006, 2008). In addition, numerate adults are so accomplished at this number-mapping task that their results often show strong ceiling effects (Karolis et al., 2011; Siegler & Opfer, 2003). However, these can be ameliorated by the task format, for instance by varying the endpoints of the line to values other than 0 or exponents of 10. This reduces the efficacy of algorithms that can partition lines according to the overlearned concept of decimal structure, rather than relying upon the internal spatial number representation (Karolis et al., 2011).

In a less explicit fashion, random number generation (RNG) tasks have also been shown to reveal elements of fundamental number representation, through the form of inherent spatial biases. Specifically, when asked to produce a string of numbers between a specified minimum and maximum, in as random an order as possible, participants show a small but reliable bias to produce a greater proportion of relatively small numbers (Bachmann, Fischer, Landolt, & Brugger, 2010; Loetscher & Brugger, 2007). Loetscher, Schwarz, Schubiger, and Brugger (2008) found that this small-number bias (SNB) is especially pronounced with the experimental manipulations of asking participants to turn their heads to the left, and/or to imagine the numbers on a (left-to-right) ruler. This suggests that the basic representation of numbers, as accessed in the RNG task, incorporates a highly spatial aspect, and that this task may reflect the strength with which individuals represent numbers spatially (left-to-right). In addition to SNB, further reflections on number-space interaction in the RNG task can also be gleaned through additional, more complex measures of how the changing pattern of response choices "moves" along the number line (Loetscher & Brugger, 2009).

As its name suggests, the RNG task also provides various measures of response randomness, in which the sequence of random numbers produced by the participant is analysed for similarity to actual random (or pseudo-random) sequences. In contrast to the other numerical tasks, or the spatial RNG indices, measures of randomness in RNG do not require and are not thought to directly reflect upon any explicit numerical magnitude representations (Brugger, 1997). Rather than relying on numerical skills, success at this measure is interpreted to rely mainly upon more general executive function, namely the ability to suppress response preferences created by one's own previous output (Brugger, 1997; Peters, Giesbrecht, Jelicic, & Merckelbach, 2007; Terhune & Brugger, 2011).

The present study

Surprisingly, despite extensive research on both mental rotation (for reviews see: Peters & Battista, 2008; Zacks, 2008) and basic number processing (for reviews see: Cohen Kadosh et al., 2008; Cohen Kadosh & Walsh, 2009), there is a lack of previous research satisfactorily explaining how these two cognitive faculties may relate to one another. Given the observed anatomical (Cantlon et al., 2009; Cohen Kadosh et al., 2008; Hubbard et al., 2005; Walsh, 2003) and behavioural (de Hevia et al., 2008; Dumontheil & Klingberg, 2012; Vallar & Girelli, 2009) overlap between numerical and spatial processing, it seems likely that spatial and numerical cognition may share common neurocognitive mechanisms, or did so at an earlier developmental (de Hevia, Girelli, & Macchi Cassia, 2012; Johnson, 2011), or evolutionary stage (Anderson, 2007, 2010; Dehaene & Cohen, 2007). Therefore, the present study set out to investigate whether the well-studied spatial faculty of mental rotation may indeed show cognitive links to basic numerical representation. As spatial abilities almost certainly evolutionarily predate cognition of symbolic numbers, one likely possibility driving such proposed links is that mental rotation and basic numerical skills both rely upon—or have developmentally derived from—shared spatial representation mechanisms. If this is the case, one would expect to see correlations between individual differences in spatial and numerical tasks that recruit such mechanisms.

Moreover, observing the types of measures that correlate should yield clues as to the more specific nature of these general posited mechanisms. To analyse these clues, however, one must also take into account the nature of the numerical representation. Namely, numerical representation can be characterised separately in terms of quality, or precision of representations, and in terms of quantity, or the feasibility of holding multiple simultaneous representations. Highly precise—that is, highly detailed and accurate—spatial representations should offer an advantage in mental rotation tasks, by helping to choose between response alternatives that may differ only in small details of feature orientation or length. They should also enhance accuracy in number-mapping tasks, because when spatial representations are more accurate, then individuals should be able to produce more accurate mappings in physical space. Therefore, spatial deviations should be less pronounced and consequently performance in the number line mapping tasks, which is measured by such spatial deviations, should be better. However, highly precise spatial representations should not show any discernible effect on tasks which compare the differential weight of holistic versus decomposed representation of multi-digit numbers, since both of these types of representations should similarly benefit from extra precision (by improving accuracy and processing time). Lastly, highly precise spatial representation of numbers might be expected to result in more pronounced spatial measures on RNG tasks, such as stronger small number bias or more complex patterns of response choice “moving” along the mental number line.

Ability to hold multiple simultaneous spatial representations should help in mental rotation tasks, as the task requires participants to represent and compare spatial features of two or more objects. Although strategies at this task may differ (Butler et al., 2006; Heil & Jansen-Osmann, 2008), both holistic object rotation and piecemeal feature-by-feature comparison require the comparison of two or more spatial representations; therefore, ability to hold multiple simultaneous spatial representations ought to aid in performance at this task. Additionally, this ability should be associated with a higher compatibility effect, as the effect arises from presence of multiple simultaneous (i.e. decomposed) representations of spatially separated digits in multi-digit numbers. It is unlikely, however, to affect accuracy of number line mapping, as the task is designed to reflect a single, holistic representation of numerical magnitude. Similarly, the RNG task does not seem likely to recruit multiple spatial representations of number, as it utilises only single digits that are processed unidimensionally across time.

Therefore, if some individuals can create more precise *and* multiple spatial representations, this would predict a confluence of 1) better performance at spatial tasks, such as mental rotation, which require holding multiple 3-D representations with minimally different spatial features, 2) worse performance on tasks that evoke processing of irrelevant extraneous numerical representations (i.e., a larger compatibility effect), 3) better performance at spatial-numerical tasks, such as number line mapping, and 4) more pronounced effects of the spatial measures of RNG tasks.

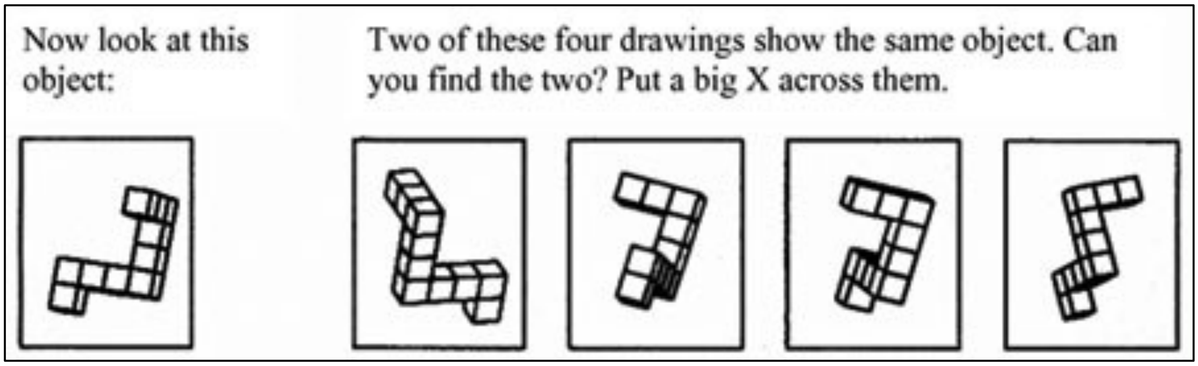
Methods

Participants

Forty-three university students (mean age 21.26 years, *SD* = 2.94, 34 female, 5 left-handed) participated in the following four tasks: 1) the redrawn Vandenberg & Kuse pen-and-paper Mental Rotation Test (Peters et al., 1995); 2) a computerised numerical comparison task (Nuerk et al., 2001); 3) a computerised number-line mapping task (Cohen Kadosh et al., 2010); and 4) a verbal random-number-generation task (Loetscher & Brugger, 2007). All participants had normal or corrected-to-normal vision. Participants completed the four tasks in a single experimental sitting with order of tasks balanced across participants by a Latin square design.

Mental Rotation Task.

Participants were administered a pen-and-paper version of the Peters, et al. (1995) redrawing of the Vandenberg & Kuse Mental Rotation Test, consisting of 24 questions each showing several 2-D drawings of a 3-D block object, and asking participants to choose which two out of four drawings on the right could be rotated to match the target drawing on the left (See Fig. 1). Participants were given three minutes to finish each 12-question section. According to the preferred scoring method suggested by Peters, et al. (1995), to minimise effects of guessing, a point was awarded for a question only if both responses for that question were correct. Thus possible scores ranged from 0, which indicates poor mental rotation abilities, to 24, which indicates high mental rotation abilities.


Now look at this object:

Two of these four drawings show the same object. Can you find the two? Put a big X across them.

Figure 1: Example question from the Vandenberg & Kuse mental rotation test

Numerical Comparison Task

Stimuli were displayed on a 19-inch flat-screen Dell monitor in Arial size 50 font, at a distance of ~55 cm. The two numbers in each trial were arranged horizontally, one on the left and one on the right, each at 2.1 degrees visual angle from centre. Participants completed 480 trials of a dichotomous forced-choice, speeded numerical comparison task in which they indicated which of a pair of two-digit numbers was numerically larger. Participants responded by key-press with right or left index finger on the side of the chosen number (P or Q on QWERTY keyboard). They were instructed to respond as quickly and as accurately as possible. Each trial began with a fixation cross presented in the middle of the screen for 300ms, followed by the number pair 300ms after the offset of the fixation cross. The number pair remained on the screen until either P or Q was pressed, up to a maximum of 5000ms. A new trial began 200ms after the participant's response, and a participant-terminated break occurred after each 120 trials.

Number pairs were adapted from Moeller, Fischer, et al. (2009) and were balanced such that both relevant groups of stimuli (i.e. compatible versus incompatible trials) yielded statistically similar measures of multiple factors including overall numerical distance, unit distance, decade distance, problem size, correct hand response, and within-pair direction of numerical ordering. Half of the stimuli were within-decade comparisons (e.g., 51 vs. 58) to ensure that the unit digits were equally as relevant as decade digits in making the numerical comparisons throughout the task; however, as is typical for this paradigm, only between-decade number pairs were later analysed. Between-decade pairs were classified as compatible or incompatible. The compatible condition comprised number pairs for which separate comparisons of tens and units yielded the same decision (e.g., 23 vs. 46; $2 < 4$ AND $3 < 6$); in contrast, the incompatible condition comprised pairs for which these single digit-comparisons differ in their direction (e.g., 26 vs. 53; $2 < 4$ BUT $6 > 3$). The frequency of compatible condition and incompatible condition was equal.

Number Line Mapping Task.

Each trial presented a blue horizontal axis stretching from left to right, centred vertically on a black background screen and labelled with an anchor number on each end, always with the numerically smaller anchor on the left (See Fig. 2). To avoid centre- or side-bias, target numbers were displayed in both upper-left and upper-right corners above the numerical anchors (e.g., -1000 and 1000). To differentiate between target and anchor numbers, target numbers appeared in yellow. Participants completed 60 trials of the task, in which they indicated by mouse click where on the given number line a given target number should be mapped. Each trial was presented immediately following the mouse click of the previous. Trials were not restricted in terms of time, but participants were instructed to reply as accurately as possible while still going at a “reasonably fast pace,” which based on observation was rarely more than 20 sec (1.7% of trials) and never more than 40 sec. Half the trials displayed a fixed range from -1000 to 1000. The other half of trials had variable axis ranges (e.g., 20 to 85, -100 to 400).

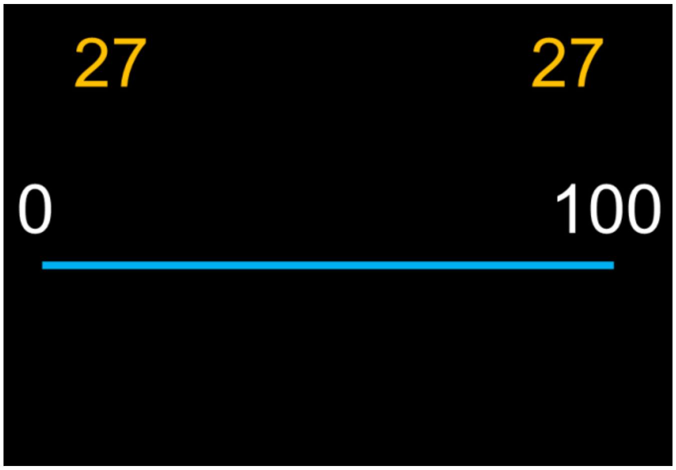


Figure 2: An example trial from the number line mapping task

Random-number-generation task.

Participants heard an auditory stimulus of electronic beeps, with one beep per second, created with the software *Audacity* and played on a MacBook Pro laptop speaker. The task asked participants to verbally produce a string of random numbers between 1 and 6 inclusive, to the rhythm of an auditory stimulus playing beats at a rate of 1Hz. Participants were exhorted to give numbers as random as possible, as if rolling a die. The experimenter notated the produced numbers by hand to collect a total of at least 66 valid responses. Invalid responses (e.g., “0” or “7”) were infrequent (0.15% of responses) and were excluded from the analysis. Both invalid responses and skipped beats were tallied and recorded as separate variables. The number strings produced were examined according to the methods of Towse and Neil (1998) for their similarity to true randomly generated number sequences, by analysing individual response frequency, first-order differences, repetition distance, and response phase.

Results

Mental Rotation Task

Results were scored according to Peters, et al. (1995), as described in Section 2.2, resulting in a score between 0 and 24. Scores were normally distributed, and the mean score across all participants was 11.58 (*SD*: 4.82), in line with previous findings of means around 11 (e.g., for comparison to a large student sample see Peters et al., 1995).

Numerical Comparison Task

Mean reaction times (RTs) and error rates were analysed separately, following the convention of earlier findings (e.g., Nuerk et al., 2001). A measure combining both RTs and error rate (inverse efficiency score) yielded similar results to separate RT and error rate analyses. RTs were calculated on correct trials only (mean error rate: 4.27%). Error rates were arcsine transformed before analysis to ensure that they approximated a normal distribution. Reproducing earlier findings (Nuerk et al., 2001; Nuerk, Weger, & Willmes, 2004), I found a significant main effect of compatibility (incompatible versus compatible trials) for both RTs ($t(42)=17.26, p<.001$, Cohen's $d=2.63$) and accuracy ($t(42)=8.14, p<.001$, Cohen's $d=1.24$). I computed the compatibility effect for each individual participant by subtracting the mean score of all compatible trials from that of all incompatible trials. The correlation of mental rotation score (MRS) and compatibility effect using RTs was not significant ($r=.04, p=.81$). However, the correlation of MRS and compatibility effect measured by accuracy was significant ($r=.4, p<.01$; see Fig. 3). Furthermore, this correlation was still significant even when controlling for RT in a partial correlation ($r=.4, p<.01$), indicating that it was not due to a speed-accuracy trade-off.

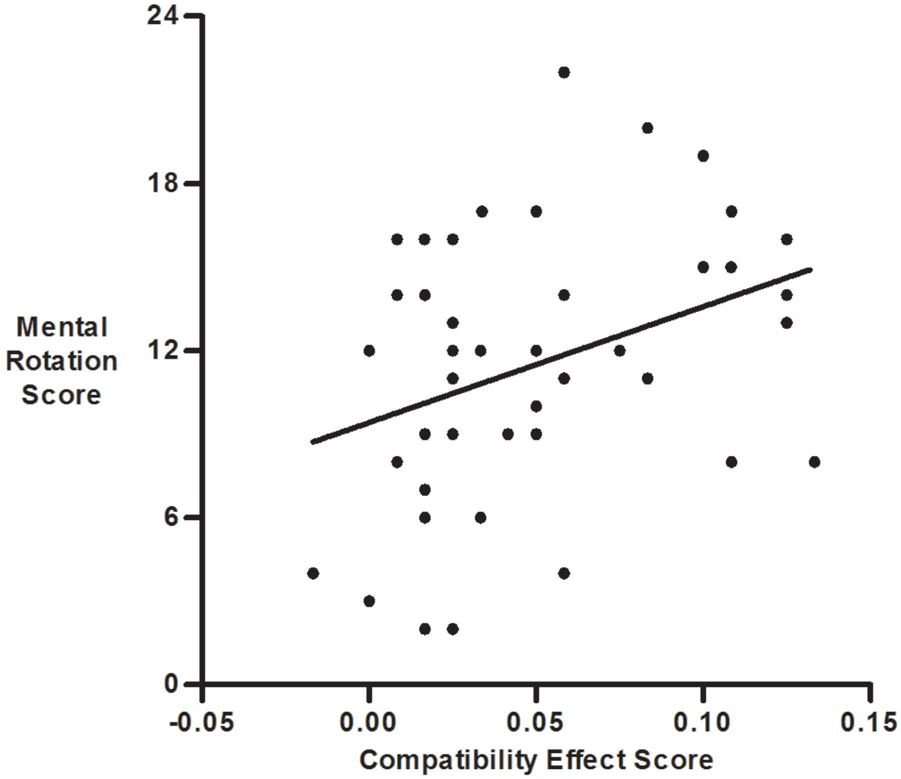


Figure 3: Mental rotation score correlates positively with size of the compatibility effect as measured by accuracy. The higher the mental rotation score the higher the compatibility effect, a measure which indicates higher degree of decomposed (separate-digit) processing of multi-digit numbers.

Number Line Mapping Task

Average RT was 6.87 seconds (*SD*: 2.64). There was no correlation between RT and MRS (*r*=.05, *p*=.77). A percentage deviation score was calculated for each participant by dividing the absolute deviation of their response from target value by the length of the numerical span represented on the axis (|subjective mapping - objective mapping|/ numerical length of the axis; as in Booth & Siegler, 2006). This ensured that all trials were weighed equally in the analysis, regardless of the numerical axis length. A Pearson correlation revealed that the percentage deviation score was significantly negatively correlated with MRS (r= -0.35, $p < .05$; see Fig. 4), indicating that a more accurate number mapping (lower deviation) tended to co-occur with higher MRS. To ensure that the correlation between MRS and percentage deviation score did not arise from a speed-accuracy trade-off, I confirmed that the same relationship of percentage deviation score to MRS was still noted in a partial correlation controlling for RT (r=-.4, p<.01).[1]

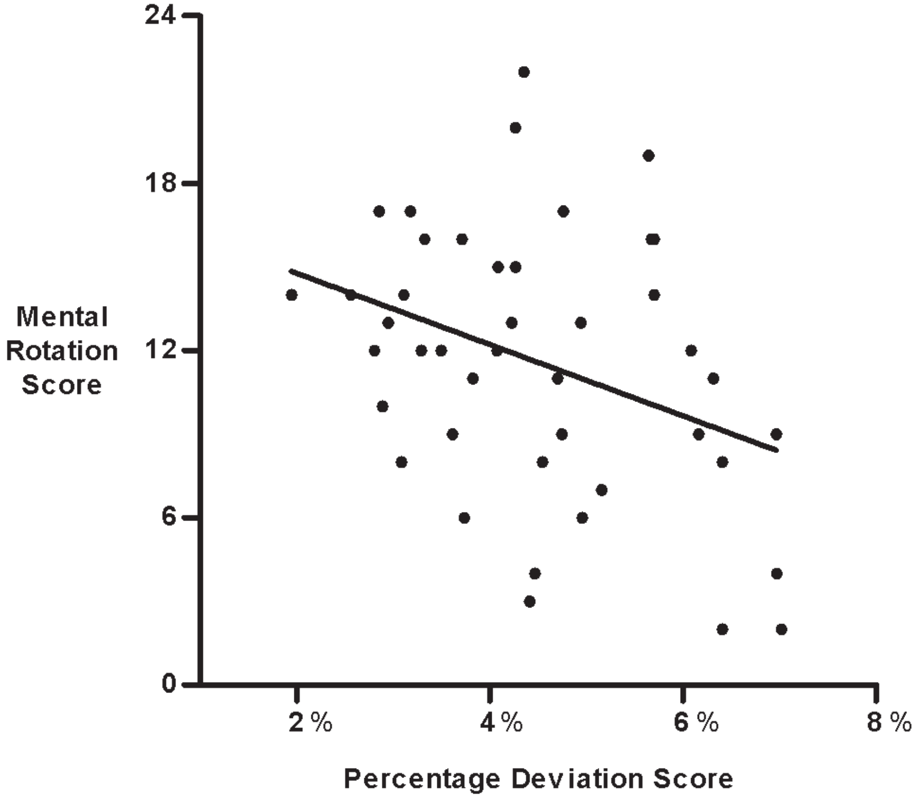


Figure 2: Mental rotation ability is negatively correlated with percentage of error (percentage deviation score) in mapping numbers on a number line.

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[1] Due to well-documented sex differences in mental rotation and other number-related abilities (Geary et al., 2000; W. Johnson & Bouchard, 2007; Kucian, Loenneker, Dietrich, Martin, & Von Aster, 2005; Peters, Manning et al., 2007), I ascertained that neither MRS nor number line scores differed by sex (*ps*>.12). I furthermore ran multiple regression analyses (using the enter method) to assess the fit of MRS and sex as predictors of both compatibility effect and number line mapping deviation. For both dependent variables, sex was not a significant predictor (compatibility effect: Beta=-.11, p=.44; number line mapping: Beta=-.19, p=.21), whereas MRS *was* a significant predictor (compatibility effect: Beta=.45, p<.01; number line mapping: Beta=-.38, p<.05), thus suggesting that the results of my observed correlations were not driven by sex differences.

Location-marking tasks, such as line bisection, often show an effect referred to as pseudoneglect: namely, participants tend to point to the left of the actual target location, analogous to behaviour observed in perceptual hemispheric neglect (for a meta-anlaysis and review, see Jewell & McCourt, 2000). To ensure that my deviation score did not simply reflect effects of pseudoneglect rather than actual overall accuracy, for each participant I also calculated mean percentage deviation scores from the non-absolute (raw percentage) values of deviation, which includes information about direction (negative values for leftward deviation, and positive values for rightward deviation.) Analysis of these data revealed a small but significant pseudoneglect effect, with mean leftward deviation of 0.72% of the given line (one-sample *t*(42)= 4.27, *p*<.001, Cohen's *d*=1.30). However, as this measure was uncorrelated with MRS (*r*=.007, *p*=.97), I conclude that the precision of number-mapping, rather than systematic leftward pseudoneglect, is linked to mental rotation ability.

Although accuracy on the number-mapping task and size of compatibility effect were both significantly correlated with MRS, these two measures were not significantly correlated to each other (*r*=.13, *p*=.40).

Random Number Generation Task

For each participant's set of 66 responses, several separate measures of random number generation were calculated, using the RgCalc program created by Towse and Neil (1998). I analysed three measures of randomness. Redundancy of responses (R score) measures how often participants repeat each response choice; a score of 0% represents perfect equality of frequency among all choices, and 100% represents complete repetition of one choice. The RNG index measures the distribution of digrams, i.e., any given pair of consecutive response choices; a score of 0 represents perfect equality of digram frequency among all possible 36 combinations, and a score of 1 represents complete repetition of one choice. The RNG2 index is similar to the RNG index, but calculates it instead with pairs of digrams. None of these three measures correlated significantly with MRS: (R score: *r*=-.12, *p*=.44; RNG index: *r*=-.02, *p*=.92; RNG2 index: *r*=-.12, *p*=.42).

Additionally, I analysed three spatial measures of RNG performance. Small number bias (SNB), as mentioned in Section 1.2, reflects a bias to spontaneously produce more small numbers than large numbers. SNB was thus calculated by finding the numerical difference between number of relatively "small" responses (1,2, or 3) and number of "large" responses (4,5, or 6). First-order differences (FODs) refer to the mathematical difference between each randomly generated number and the previous response. Thus positive FODs indicate a rightward direction of responses along the mental number line (e.g., 3 followed by 5 gives an FOD of +2) and negative FODs indicate a leftward shift (e.g., 6 followed by 1 gives an FOD of -5). Similarly to the SNB index, a measure of FOD differential was calculated by taking the numerical difference between number of "rightward" (positive) FODs and number of "leftward" (negative) FODs. Lastly, the turning point index (TPI) measures the number of changes in direction (positive or negative) of FODs compared to the expected number of such changes. For instance, the sequence 1-2-5-3-1 would show one such change, at response "5": from ascending (positive) to descending (negative) sequences. Thus, the TPI measures how relatively often an individual "changes direction" along the mental number line within their string of responses. Neither SNB nor FOD measures were significantly different from 0 across the population (SNB: one-sample *t*(42)=1.48, *p*=.15, Cohen's *d*=0.45; FODs: one-sample *t*(42)=1.40, *p*=.17, Cohen's *d*=0.43). Mean TPI was 93.86, significantly less than the standard of 100 (one-sample *t*(42)=3.73, *p*<.01, Cohen's *d*=1.14), indicating that participants switched between ascending and descending sequences slightly less than expected by chance. However, none of these three measures correlated significantly with MRS: (SNB: *r*=-.04, *p*=.80; FODs: *r*=-.20, *p*=.21; TPI: *r*=-.002, *p*=.99).

Table 1: Values of correlation coefficients between measures from four tasks: Mental Rotation, Numerical Comparison, Number Mapping, and RNG

		Mental Rotation Score	Compatibility Effect Score	Number Mapping Accuracy	Small Number Bias	First Order Differences	Turning-Point Index	Redundancy Score	RNG Index	RNG2 Index
Mental Rotation Score	**r**	1	**.405****	**-.353***	.040	-.196	-.002	-.124	-.017	-.127
	p		**.007**	**.020**	.801	.207	.992	.435	.915	.422
Compatibility Effect Score	**r**		1	.065	.214	.031	-.233	**-.308***	-.195	**-.370***
	p			.677	.174	.842	.143	**.047**	.215	**.016**
Number Mapping Accuracy	**r**			1	-.093	-.131	-.191	-.150	.122	.015
	p				.558	.402	.232	.343	.441	.923
Small Number Bias	**r**				1	-.126	-.071	.214	-.273	.069
	p					.428	.659	.175	.080	.664
First Order Differences	**r**					1	.132	-.091	-.097	-.113
	p						.411	.567	.540	.475
Turning-Point Index	**r**						1	.120	.262	.126
	p							.455	.097	.433
Redundancy Score	**r**							1	.267	**.422****
	p								.088	**.005**
RNG Index	**r**								1	.108
	p									.495
RNG2 Index	**r**									1
	p									

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

Discussion

This study endeavoured to examine the link between mental rotation abilities and basic numerical representations, specifically investigating the hypothesis that both recruit detailed spatial representation abilities. To do so, I assessed both 1) mental rotation abilities and 2) basic numerical skills that tap the underlying numerical representations of the mental number line and the place-value structure of the Arabic number system (Loetscher & Brugger, 2007; Nuerk et al., 2001; Siegler & Opfer, 2003). I found a correlation between mental rotation performance (which relies heavily upon spatial representation and processing) and both 1) size of the compatibility effect, a measure which indicates the tendency to represent two-digit numbers by using multiple representations for tens and units, rather than a single holistic representation (Moeller, Fischer et al., 2009; Nuerk et al., 2001); and 2) accuracy of number line mapping, which is suggested to reflect precision of spatial number representation (Karolis et al., 2011; Siegler & Opfer, 2003). In contrast, performance in the mental rotation task did not correlate with measures of either randomness or spatial aspects in the random number generation task.

Although these null findings regarding the RNG measures ran counter to my original prediction, they are nevertheless easily reconciled with that initial hypothesis. Whereas the numerical comparison task and number line mapping task explicitly tap number magnitude representations, elicitation of number magnitude in the RNG task is purely implicit, meaning that the relationship of these effects to spatial representation may have been too subtle to measure in a correlation with mental rotation skills. This is consistent with previous research from Priftis, Zorzi, Meneghello, Marenzi, and Umilta (2006) showing that spatial-numerical impairments in neglect are only found in tasks drawing on explicit number knowledge (e.g., mental number line bisection) but not implicit number knowledge (e.g., spatial-numerical association of response codes, or SNARC). Therefore, together, the foremost and most parsimonious interpretation of my aggregate data is that a greater ability to process multiple, precise spatial representations subserves both superior mental rotation ability and more advanced (i.e. more closely approximating the adult end of the developmental trajectory) number representations. The observation that size of compatibility effect and accuracy of number-line mapping both correlated with mental rotation performance, but not with each other, fits neatly with my initial predictions: namely, that these two measures may each primarily recruit separate aspects of spatial representation (precision versus quantity) which are both utilised in mental rotation.

My proposed explanation notwithstanding, one might suggest alternative explanations for an observed link between mental rotation and basic numerical skills. One possibility is that individuals who perform better at both skills simply exhibit better cognitive control. In this case, better mental rotation scores should predict less interference at numerical tasks that feature an automatically-processed irrelevant dimension which must be effortfully ignored (i.e. a smaller compatibility effect in the numerical comparison task). However, the relationship I observed between the MRS and the compatibility effect was exactly the opposite of this alternative prediction, thus suggesting that cognitive control was not the factor explaining this correlation. This is supported by findings from developmental studies which show that with age and experience (and better overall performance), the compatibility effect in children increases, suggesting that experience with numbers outweighs improved cognitive control (Mann et al., 2011; Nuerk, Kaufmann, Zoppoth, & Willmes, 2004). Additionally, no link was found between the MRS and measures of response randomness from the RNG task, which are considered to rely upon executive control (Brugger, 1997; Peters, Giesbrecht et al., 2007). Although the compatibility effect showed a significant correlation to randomness measures in the RNG task (see Table 1), this is not surprising, since both measures reflect some influence of executive function (Brugger, 1997; Nuerk & Willmes, 2005). In fact these findings render the cognitive control explanation even less plausible, by confirming that smaller compatibility effect was associated with better executive control (i.e. lower R or RNG index score, indicating better suppression of previous response selection). Together, these findings make it highly unlikely that cognitive control is the mediating factor underlying the connection in question. While it is not tenable to exclude the possibility that there are other mediating factors, the primary goal of the current study was to uncover the potential link between mental rotation abilities and basic numerical skills, and more specifically numerical representation.

The present study was not without its limitations. Firstly, although the sample size of 43 was relatively large for a cognitive experiment, the statistical power of correlations dips rapidly under samples of 100. However, the predictable (normal, fat-tailed) distribution of MRS, along with the high number of observations included in the calculation of compatibility effect and number line estimation scores (240 and 60, respectively), suggest that the obtained correlations are not particularly likely to reflect Type I error. Secondly, it should be noted that a recent study by Macizo and Herrera (2011) compared mental rotation performance to the compatibility effect and found a relationship seemingly inconsistent with the results of the present study: namely, individuals in their experiment who exhibited a larger compatibility effect showed poorer mental rotation ability. However, the mental rotation task used by Macizo and Herrera (2011) differs fundamentally from the task I used in several ways: type of rotation object (graphemes versus "3-dimensional" block objects), dimensions of rotation (vertical plane versus horizontal plane), and response paradigm (forced-choice versus multiple choice). (See Peters & Battista, 2008, for a further overview of the differences between these two tasks, and the consequent implications.)

Given these extreme differences, it is possible that the two variations of the task capture minimally overlapping facets of mental rotation ability. Additionally, Macizo and Herrera (2011) measured the compatibility effect using response times (versus accuracy in my study) and analysed the results of both compatibility effect and mental rotation by splitting scores into high versus low ability groups (rather than using correlation, as in my study). Such an approach (Extreme Group Approach) may affect findings in terms of many important factors, including reliability (Preacher, Rucker, MacCallum, & Nicewander, 2005). These discrepancies may partially account for the disparate findings between the two studies. However, given the various differences between the two studies (types, dimensions, measures), the determinants of the observed correlations should be examined further in future studies using different mental rotation tasks.

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Chapter 3: The link between number-related synaesthesias and basic numerical representations

Number-space synaesthesia and grapheme-colour synaesthesia are rare neurological conditions in which individuals automatically and involuntarily associate numbers with either a particular layout in space (NSS) or with particular colours (GCS). NSS has been shown to have costs in arithmetic processing, but it is unclear how either NSS or GCS is related to an individual's level of ability at basic numerical representation. This experiment tested non-synaesthete controls against groups of syanesthetes with either NSS, GCS, or both, in two tests of basic numerical representation (a number line mapping task and a measure of decomposed processing of two-digit numbers), as well as an executive control task (random number generation) and a spatial mental imagery task (mental rotation). NSS were slower than non-NSS participants in number line mapping, but especially for numbers which overlapped with their synaesthetic mental number lines. GCS showed a pattern of results on the two-digit number comparison task that suggested they processed numbers in a more decomposed manner, potentially due to the effects of experiencing different synaesthetic colours for each numeral. These results suggest that presence of number-related synaesthesia may be related to differences in basic numerical cognition.

Introduction

Synaesthesia is a benign, relatively rare neurological condition in which stimuli in one sensory modality or cognitive category will automatically and involuntarily elicit an experience in another (Banissy & Ward, 2007; Cohen Kadosh & Henik, 2007; Simner & Ward, 2006). Of the great many recorded types of synaesthesia, several are elicited by the concept of numbers. For instance, number-space synaesthesia (hereafter called 'NSS') describes the involuntary association of numbers to a "number form": an ordered number line perceived in space or in the "mind's eye" (Galton, 1880). Number forms range from simple orthogonal horizontal lines to very complex and idiosyncratic 3-dimensional layouts with corners, undulations and breaks. Synaesthetes typically report that their number forms have not changed much, if any, from childhood, and describe the range from 0 to 100 as being the most easily accessible and vivid (Eagleman, 2009; Galton, 1880; Sagiv et al., 2006). Number forms are reported to arise involuntarily in response to reading or hearing numbers; in fact, most synaesthetes report that they cannot do simple mental arithmetic or number comparisons without spontaneously seeing the numbers on their number form (Jarick et al., 2011). In addition to this seemingly automatic evocation, synaesthetes typically can recall and examine their number form at will, and many synaesthetes report that they can mentally manipulate the form, e.g. by "zooming in," or moving their perspective along the line (Galton, 1880; Seron et al., 1992).

Another form of number-elicited synaesthesia, known as grapheme-colour synaesthesia (hereafter, 'GCS'), describes the association or perception of colours in response to numbers and letters. Synaesthetes typically describe their colour associations existing as far back as they can remember, and they likewise tend to show consistency of these colour-grapheme associations over time (however, some researchers have raised objections that this attribute may be misleadingly self-selected by research paradigms; c.f. Simner, 2012). Like NSS, GCS produces highly heterogeneous and idiosyncratic experiences; for instance, synaesthetes may experience the associated colours either as projected into locations in physical space, as existing in their "mind's eye," or as mere associations with no specific location (J. Ward, Li, Salih, & Sagiv, 2007). Elicited colours may range from extremely specific shades with precise hue, saturation, and luminance (and even perceived colour patterns or textures), to more general impressions of colour categories. Although some weak trends are found across synaesthetes in terms of actual grapheme-to-colour pairings (e.g. larger magnitude digits, such as 9, tend to have darker colours), for the most part a synaesthete's set of grapheme-colour associations is highly idiosyncratic (Beeli, Esslen, & Jancke, 2007; Cohen Kadosh, Henik, & Walsh, 2007; Simner et al., 2005; Smilek, Carriere, Dixon, & Merikle, 2007). Although overall prevalences of NSS and GCS are relatively low (estimated at about 10-15% and 1-2%, respectively), co-occurrence of these two conditions is unexpectedly high (approximately 60% of individuals with GCS were reported to have NSS), suggesting that the two phenomena might be neurologically related (Sagiv et al., 2006; Simner et al., 2006).

This brings me to the motivating question of this study: how do number-elicited synaesthesias interact with or affect number cognition, specifically at the representational level? Research to date has largely circumvented this question, although some experiments have investigated the link between numbers and synaesthesia in the context of simple mathematical operations. For instance, previous studies have shown number-space synaesthetes to exhibit disadvantages at some simple number tasks (such as multiplication or division) which rely primarily on rote memory rather than manipulation of numbers (Ward et al., 2009). Presumably, this performance cost is due to their automatic evocation of a number form, which is irrelevant to the task at hand. However, other research has suggested that explicit visuospatial representations of systems such as numbers may actually confer a performance benefit at tasks which typically require high levels of processing (such as large sums) (Cohen Kadosh et al., 2012; Murray, 2010;

Simner et al., 2009). Studies of GCS and numbers have largely focused on bidirectionality of colour-number associations, e.g. demonstrating that stimuli coloured congruently to synaesthetic colours may facilitate a synaesthete's performance on arithmetic problems or single-digit number comparisons, (Cohen Kadosh et al., 2005; Ghirardelli, Mills, Zilioli, Bailey, & Kretschmar, 2010)), or that synaesthetic colours show spatial-numerical effects analogous to their corresponding numerical values (Brugger, Knoch, Mohr, & Gianotti, 2004). However, few studies have examined how GCS interacts with number cognition in the more ecologically valid context of purely achromatic visual numerical stimuli.

Therefore, I examined numerical representation in synaesthetes and non-synaesthetes of both NSS and GCS, by presenting them with two numerical tasks intended to examine number representations, and two controls tasks (one spatial, one executive). I hypothesised that presence of NSS or GCS would be associated with different patterns of performance on these numerical tasks, based on theoretical assumptions about these two types of synaesthesia.

Number Line Mapping Task.

Because NSS offers an explicit, endogenous representation of spatial layout for numbers, NSS may also be expected to interfere with tasks that utilise exogenous presentations of spatial number layouts (e.g. number-mapping tasks). GCS, however, would not be expected to influence spatial number mapping ability. To test these hypotheses, I included a number-line task designed to reflect precision of ordinal number representations. The number line task has been used widely in both children and adults to reflect underlying number magnitude representation (Booth & Siegler, 2006; Siegler & Opfer, 2003). It is generally executed with extremely high accuracy by adults, therefore suggesting that response times may be the most likely source of group differences (Karolis et al., 2011).

Numerical Comparison Task

Because NSS involves an explicit spatial representation of numbers, in formats similar to those hypothesised for holistic representation of multi-digit numbers, NSS might reasonably be expected to be associated with task performance indicating predominantly holistic number representation. (See the discussion of holistic and decomposed number representation in Chapter 2). GCS, on the other hand, may be associated with more digit-decomposed representations of numbers if individuals associate or perceive different colours for each separate numeral, even when these numerals comprise multi-digit numbers (all of the GCS participants reported this phenomenon). To assess these hypotheses, I utilised a two-digit number comparison task designed to measure holistic versus decomposed representation of multi-digit numbers (Nuerk et al., 2001).

The two-digit number comparison task excels at picking apart the representation of numerical magnitude of multi-digit numbers in reference to digits and decimal place-value structure. Particularly, this task has shown a vigorous effect introduced and oft-replicated in the past 10 or so years: the unit-decade compatibility effect, or simply, compatibility effect (CE) (Moeller, Fischer et al., 2009; Nuerk, Kaufmann et al., 2004; Nuerk et al., 2011; Pixner, Moeller, Hermanova, Nuerk, & Kaufmann, 2011; Thompson, Nuerk, Moeller, & Cohen Kadosh, 2013). This effect relies upon the fact that trials in two-digit number comparison tasks can either yield the same comparison for both pairs of decade digits and unit digits (compatible trials: e.g. for 32 vs. 47, $3<4$ AND $2<7$), or the opposite comparison for decade digits as for unit digits (incompatible trials: e.g. for 37 vs. 52, 3<5 BUT 7>2). In other words, the irrelevant unit digits may either conform to the task decision determined by the decade digits, or may oppose it. This leads to impaired performance for incompatible trials, in which the units decision opposes the decades decision, compared to better performance on compatible trials, in which both unit and decade decisions concur. Such a performance cost for incompatible trials suggests that the irrelevant dimension, i.e. units digits in these trials, evoke a representation separate from the representation of decades digits or the overall semantic magnitude representation. Eye-tracking evidence for the two-digit number comparison task supports this conclusion, suggesting that participants process both digits separately and in parallel (Moeller, Fischer et al., 2009).

This evidence of decomposed digit-by-digit representation diverges significantly from the holistic number representation model put forth by Dehaene, et al. (1990), which hypothesised that number magnitudes are mentally represented on a single continuous scale, impervious to influence from separate composite digits. Given the strong evidence for both holistic and decomposed models, and the inability of either model to completely explain empirical findings, it seems highly likely that the answer lies in a hybrid model which incorporates both types of number representation (although other explanations have been given; cf. Moeller, Pixner, Kaufmann, & Nuerk, 2009b). In this case, individual differences in behavioural measures of holistic versus decomposed number representation could be explained by differential strengths of one representational mode over the other. That is, although evidence suggests that all normal individuals represent numbers both ways (Nuerk et al., 2011), some may favour holistic over decomposed representations, or vice versa, depending on a whole host of underlying factors, either cognitive, developmental, environmental, or chance.

Given, then, the likelihood of a hybrid holistic-decomposed model for number magnitude representation, I took the size of an individual's compatibility effect as a rough measure of the relative dominance of decomposed compared to holistic number representation. That is, the stronger the decomposed representation in an individual, the stronger compatibility effect I would expect to see in a multi-digit number comparison task. Conversely, an individual with a hypothetically near-complete dominance of holistic representation of numbers should show almost no effects of unit-decade compatibility in such a task.

Methods

Participants

The participant group comprised 48 university students: 13 with number-space synaesthesia but no other number-related synaesthesia (mean age 21.62, *SD*=3.41, 3 male, 1 left-handed); 12 with grapheme-colour synaesthesia but no other number-related synaesthesia (mean age 22.33, *SD*=2.56, 3 male, 0 left-handed); 10 with both number-space and grapheme-colour synaesthesias (mean age 20.90, *SD*=2.07, 1 male, 2 left-handed); and 13 controls matched for age, sex, and handedness (mean age 21.31 years, *SD*=3.36, 3 male, 2 left-handed). Given the rarity of synaesthetes, these sample sizes are relatively large for synaesthesia studies, many of which are case studies or include only a few participants (e.g., Gertner et al., 2009; Smilek et al., 2011; Terhune et al., 2011). However, it must be noted that compared to typical cognitive psychological investigations these sample sizes remain relatively small.

All synaesthetes were verified by a 30-minute personal interview, which assessed automaticity, consistency, and phenomenology. All synaesthetes reported that their synaesthetic experiences dated from childhood or “as long as [they] could remember,” and that their specific experiences had changed little, if at all, since then. During the interview number-space synaesthetes were asked to describe and/or draw their number form in detail, and grapheme-colour synaesthetes were asked to choose colours for each numeral 0-9 in the computer programme Microsoft Paint, which were then recorded by RGB value. All grapheme-colour synaesthetes reported that each digit within multi-digit numbers would elicit its own colour, identical or very similar to the colour elicited by the given digit when presented or thought of alone. While interviews sought to eliminate self-report bias via a thorough and systematic battery of questions, the experiential nature of synaesthesia makes it difficult to assess exactly how successful this screening measure was. Screening eliminated 7 of 42 possible synaesthetes whose descriptions of their experiences did not match criteria of either consistency or phenomenology. Furthermore, a subset of synaesthetes (11 GCS, 9 NSS and 6 NSS-GCS) were surprise-retested for consistency after at least 4 weeks, and all were assessed to be at least 90% consistent with previous reports of their synaesthetic experiences. For GCS, consistent responses were deemed those falling within the same boundaries of 11 basic colours. For NSS, each description of direction for a particular range of numbers was considered a consistent response only if it matched as categorised by horizontal, vertical, and depth axes.

All participated in the following tasks, identical to those described in the preceding chapter: 1) a number line mapping task (Cohen Kadosh et al., 2010; Siegler & Opfer, 2003); 2) a numerical comparison task (Nuerk et al., 2001); 3) a random-number-generation task (Brugger, 1997); and 4) the Vandenberg & Kuse Mental Rotation Task (Peters et al., 1995). All participants had normal or corrected-to-normal vision. Participants completed the four tasks in a single experimental sitting, and order of tasks was counterbalanced across participants by a Latin square design.

Results

In all subsequent analyses, an alpha level of .05 is assumed. Decomposition of interactions are not corrected for multiple comparisons given the *a priori* assumptions of directions of the interactions.

Number line mapping task

Two types of axis ranges were represented in the task trials. The static-range axis presented number lines labelled from -1000 to 1000. The variable-range axes presented number lines with various limits; these fell entirely within the area that most synaesthetes report as visualised on their mental number form (i.e. between 0 and 100). Error scores for each trial were calculated by dividing the absolute difference between guess and correct answer by the numerical axis length, as according to Booth and Siegler (2008). Trials with error scores above 50% of the number line (0.33% of trials) were automatically discarded as more likely being accidental clicks than legitimate guesses. Trials with error scores above 25% were hand-checked, and those with obvious polarity mistakes (e.g. guessing 377 for -365) were discarded (0.79% of trials).

Both error scores and mean RT data were separately subjected to a repeated-measures ANOVA with the within-subject factor of axis range (static versus variable) and 2 between-subjects factors: NSS (those with number-space synaesthesia versus those without it) and GCS (those with grapheme-colour synaesthesia versus those without it). The error scores analysis showed no significant results (all Fs<2.71, ps>.10) apart from a marginally significant main effect of NSS, indicating that number-space synaesthetes were slightly more accurate overall

($F(1,44)=3.21$, $p=.080$). However, the RT analysis revealed two significant results. Number-space synaesthetes ($M=7.86$ s) were significantly slower than controls ($M=5.72$ s) overall at mapping numbers ($F(1,44)=7.99$, $p=.007$, $\eta\rho^2=.15$), and there was a significant interaction between number-space synaesthesia and axis range ($F(1,44)=5.80$, $p=.020$, $\eta\rho^2=.12$; see Fig. 1). Decomposing this interaction by axis range revealed that number-space synaesthetes were significantly slower than those without NSS both in static-range axis ($t(31.86)=2.52$, $p=.017$, Cohen's $d=.74$) and even more so in the variable-range axes ($t(30.74)=2.79$, $p=.009$, Cohen's $d=.82$). As the NSS group were both slower than controls and more accurate overall, I ran correlation analyses between RTs and accuracy across both groups and within each group to check whether these results might be explained by a speed-accuracy trade-off. Although RT and accuracy showed a significant negative correlation overall ($r= -.41$, $p=.004$), when I inspected this relationship within each group, the correlation was significant only in the control group ($r= -.51$, $p=.009$), but not in the NSS group ($p=.18$). This suggests that whilst the results must be taken with caution, they are not likely to be entirely the product of a speed-accuracy trade-off.

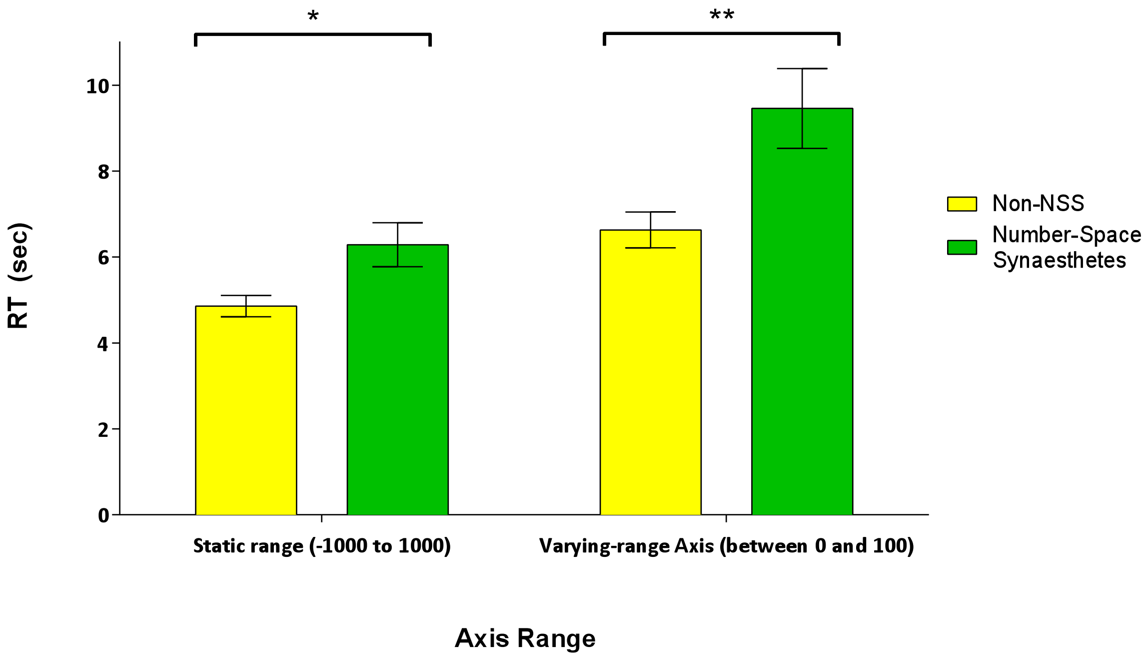

Figure 1: Participants with NSS were much slower at mapping numbers on the varying axes, which fall within the range of their synaesthetic number lines.

Numerical comparison task

Response times (RTs) were trimmed to include only those within ±2 SD of the participant's mean RT. Mean RT (from correct trials only) and accuracy were calculated for each participant for each condition. Accuracy and RT measures were then subjected to a 5-way mixed-model analysis of variance (ANOVA). The within-subject variables manipulated were: units distance (small vs. large), decades distance (small vs. large), and unit-decade compatibility (incompatible vs. compatible). Additionally, there were 2 between-subjects factors of group: NSS (those with number-space synaesthesia versus those without it, regardless of GCS) and GCS (those with grapheme-colour synaesthesia versus those without it, regardless of NSS). This yielded a 2×2×2×2×2 factorial design.

Consistent with previous findings from two-digit number comparison tasks (Nuerk et al., 2001; Nuerk, Weger et al., 2004), I found significant within-subjects main effects of both RT and error measures for both decade distance (RT: $F(1,44)=430$, $p<.001$, $\eta\rho^2=.91$; Error: $F(1,44)=104$, $p<.001$, $\eta\rho^2=.70$) and unit-decade compatibility (RT: $F(1,44)=300$, $p<.001$, $\eta\rho^2=.87$; Error: $F(1,44)=76.38$, $p<.001$, $\eta\rho^2=.63$), as well as a significant main effect of unit distance for error measures only ($F(1,44)=47.36$, $p<.001$, $\eta\rho^2=.56$). Additionally, there were two higher interactions of within-subjects RT measures and two of error measures, all following the general pattern (observed in previous findings of two-digit number comparison tasks) of especially slow RTs and especially high error rates when trials are a combination of incompatible (versus compatible), small decade distance (versus large decade distance), and large unit distance (versus small unit distance). For details of all interactions see Table 1 at the end of this chapter.

Neither main effect of NSS nor GCS was significant for RT ($Fs<2.40$, ps>.12) or for errors (Fs<2.85, ps>.098). Interactions of NSS by GCS were not significant for either RT or error measures (Fs<0.40, ps>.53). For RT measures, no other interactions with group reached significance, apart from a four-way interaction of unit distance, decade distance, compatibility, and GCS ($F(1,44)=4.09$, $p=.049$, $\eta\rho^2=.08$). This four-way interaction is presented in Figure 2.

Examining the interaction separately at each level of compatibility yielded no simple three-way interaction in the incompatible condition ($p=.39$), but did reveal a simple three-way interaction in the compatible condition ($F(1,46)=4.31$, $p=.043$, $\eta\rho^2=.09$). Decomposing this further by unit distance revealed no significant interaction for small decade distance ($p=.91$), but a significant simple-simple two-way interaction for large unit distance($F(1,46)=9.93$, $p=.003$, $\eta\rho^2=0.18$). The source of this two-way interaction was revealed to be a significant group difference (between GCS and non-GCS) in the small decade distance trials ($t(46)=2.15$, $p=.037$, Cohen's *d*=0.62), versus no significant group difference in the trials with large decade distance (*p*=.32).

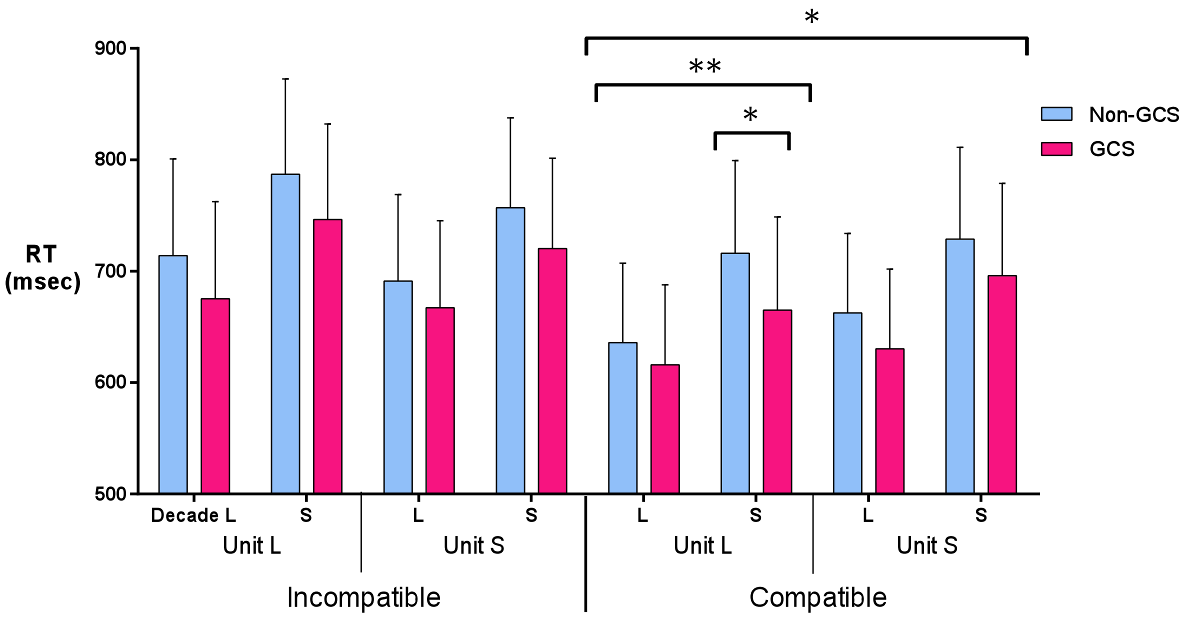

Figure 2: RT measures reveal a 4-way interaction between GCS, unit distance, decade distance, and compatibility. Error bars represent one standard error mean.

For error measures, there were no significant higher-order mixed interactions, although the interaction of compatibility by GCS reached marginal significance (*F*(1,44)=3.01, *p*=.085, $\eta\rho^2$=.066). Decomposing this interaction by compatibility revealed that although error rates did not significantly differ between GCS and non-GCS groups on compatible trials (*p*=.42), on incompatible trials they did differ marginally (*t*(46)=1.80, *p*=.078, Cohen's *d*=0.52), due to a higher error rate in the GCS group (*M*=9.02%) than non-GCS (*M*=6.25%). To check whether any of these results might be explained by a speed accuracy trade-off, I confirmed that there was no correlation between RTs and accuracy either in overall scores or within the compatible or incompatible conditions (*p*s>.26).

Random number generation task

For each participant's set of responses, several separate measures of random number generation were calculated, using the RgCalc program created by Towse and Neil (1998). For each of these measures, ANOVAs testing group differences were non-significant (all *Fs*<2.23, *p*s>.14) at the level of both main effects and interactions.

Mental rotation task

The Vandenberg & Kuse mental rotation test was administered in order to verify that any of the differences in the abovementioned tasks are not due to significant differences in mental rotation abilities between groups (control, NSS, GCS, NSS-GCS). Indeed, there were no significant group differences of mental rotation ability (all *F*s<1.20, *p*s>.28, in a 2-way univariate ANOVA), thus indicating that mental rotation ability was not a confounding factor driving main effects or interactions that involved the factor of group.

Discussion

The experiment examined differences in number cognition between individuals with and without 2 types of number-related synaesthesia: number-space synaesthesia (NSS) and grapheme-colour synaesthesia (GCS). Participants completed four separate tasks, two of which (number line task and two-digit number comparison task) measured separate aspects of number representation, and two of which (mental rotation task and random number generation task) were used as controls for other cognitive capacities (i.e. mental rotation ability and executive function). These two latter tasks revealed that neither mental rotation ability nor random number selection (repetition suppression, an executive function) varied systematically across groups according to presence of either type of synaesthesia. Although the sample size is too small to make sweeping judgments on general similarities between synaesthetes and non-synaesthetes in these two abilities, these results do confirm that group differences in the number comparison and number line estimation tasks in the current study do not likely arise from *a priori* group differences in abilities for executive control or visuospatial object manipulation. This is an important consideration, as both of these abilities may figure prominently in the execution of the number tasks I tested: executive control especially in ignoring the irrelevant units dimension of the number comparison task, and visuospatial object manipulation especially in interacting with the spatial number placement in the number line task.

In contrast to the control tasks, results from the number line task and number comparison task both showed group differences of synaesthesia.

Number Line Mapping Task

The number line data indicated that individuals with NSS performed differently from those without it, regardless of presence of GCS. Particularly, number-space synaesthetes exhibited longer response latencies on trials in which axis ranges overlapped with their internal explicit number line representations. This especially pronounced slowing of NSS in the variable-range axes suggests that the internal number forms of number-space synaesthetes may impede their use of other number-task strategies when spatially mapping numbers within this visualised range.

However, response times were so lengthy overall that it is difficult to determine whether this RT difference may in fact reflect non-representational aspects of response such as differences in task strategy, or simply a greater interest in inspecting this part of the number line. Future studies may improve upon this paradigm by introducing tighter RT constraints, or incorporating eye tracking to assess different strategies. Nevertheless, this group difference suggests that the presence of an internal number form, rather than synaesthesia *per se*, impairs performance as compared to non-NSS individuals.

Numerical Comparison Task

In the numerical comparison task, I found support for the prediction that grapheme-colour synaesthetes would exhibit more decomposed processing of multi-digit numbers. This conclusion is based on two results: 1) In the error rates analysis, a marginally significant interaction of unit-decade compatibility and GCS revealed that participants with GCS made more errors than their non-GCS controls, but only in the incompatible trials. In other words, the GCS group showed a larger overall unit-decade compatibility effect than non-GCS. In literature to date, this type of compatibility effect is widely interpreted as reflecting decomposed processing of digits (Nuerk et al., 2001; Nuerk & Willmes, 2005; Pixner et al., 2011). 2) A significant 4-way interaction in the RT analysis revealed that participants with GCS responded especially fast compared to those without GCS in one specific condition: compatible trials with small decade distance and large unit distance. This pattern, although more nuanced than the simple compatibility effect, is also indicative of decomposed processing of multi-digit numbers, as I will explain here.

Given that all participants showed an extremely strong overall compatibility effect in the RT analysis (as expected of educated adult participants), it follows that the slight differences I sought to uncover within their overall high levels of decomposed digit processing would likely be more pronounced within sub-conditions of the task which favour one group and disadvantage another. For instance, sub-conditions of small overall distance, unit-decade compatibility, and large unit distance will broaden the performance gap between mainly holistic and mainly decomposed processors. That is, according to the distance effect, small overall distance will especially penalise individuals with mainly holistic processing (in my hypothesis, non-GCS). Unit distance should not make a difference to holistic processors because overall holistic distance is kept, on average, constant. Participants relying mainly on decomposed representations of separate digits, however (in my hypothesis, GCS), should show greater effects of the irrelevant unit dimension. Specifically in the compatible condition, large unit distance should aid performance more than small unit distance; this is because, although both will strengthen the preference for the correct answer, according to the distance effect the larger distances will be easier to process. That is, decomposed processors will process the task-irrelevant units digit, and the large-distance, i.e. easy, decision for the unit digits will help point to the compatible, i.e. correct, decision for the decades digits.

Therefore, since the group relying on decomposed representation (GCS) is already on average faster than the holistic representation group (albeit, non-significantly), one would expect to see the most pronounced group differences in the condition that will make the fast group

(GCS) faster, and the slow group (non-GCS) even slower. This is exactly what I found: in the condition of trials with small decade distance (i.e. difficult for non-GCS) but compatible, large unit distance (i.e. helpful for GCS), participants with GCS are especially fast compared to those without. This suggests that grapheme-colour synaesthetes, as a group, tend to process magnitude of multi-digit numbers in a fashion that favours decomposed representation of separate digits over a single holistic representation.

It is important to reiterate that, as all groups showed a strong overall compatibility effect, this indicates that all groups showed some measure of decomposed representation of separate unit and decade digits. Similarly, the main effect of decade distance (which necessarily coincides with overall distance) indicates some degree of holistic representation of numerical magnitude across all groups. These observations, coupled with the fact that group differences surfaced only in certain susceptible sub-conditions of the task, suggest that group differences in the balance of holistic and decomposed number magnitude representation are relatively slight. This is of course to be expected, given that all participants were highly educated and received years of numerical and mathematical training in relatively homogenised Western schooling system.

Conclusions

In summary, results from two tasks reflecting separate aspects of basic numerical cognition suggest that number-related synaesthesia is associated with atypical numerical magnitude representation. The explicit mental number line of individuals with NSS seems to interfere with use of standardised, external number lines in the same range. The separate colours experienced for digits by individuals with GCS may affect their processing of multi-digit numbers such that they are processed in a more decomposed, rather than holistic, manner. As all of the participants reported their synaesthesia as a congenital condition, it is impossible to infer causality in how their numerical cognition and synaesthesia may have developed side by side; however, these findings suggest the possibility that synaesthesia may affect the very basic aspects of number cognition investigated in this experiment.

Table 1: ANOVA results for RT(mean) and error in Number Comparison experiment. Between-subjects factors were NSS group and GCS group, and within-subjects factors were unit distance (small or large), decade distance (small or large), and compatibility (compatible or incompatible).

	RT			**Error**		
Effect	***F***	***p***	$\eta\rho^2$	***F***	***p***	$\eta\rho^2$
Unit	0.022	.882	.001	**11.989**	**.001**	**.214**
Unit * NSS	0.411	.525	.009	0.783	.381	.017
Unit * GCS	2.222	.143	.048	0.032	.859	.001
Unit * NSS * GCS	0.005	.946	0	2.372	.131	.051
Decade	**430.476**	**0**	**.907**	**103.975**	**0**	**.703**
Decade * NSS	2.333	.134	.05	1.61	.211	.035
Decade * GCS	3.368	.073	.071	0.867	.357	.019
Decade * NSS * GCS	2.021	.162	.044	0.055	.816	.001
Compatibility	**300.14**	**0**	**.872**	**76.378**	**0**	**.634**
Compatibility * NSS	0.056	.815	.001	1.611	.211	.035
Compatibility * GCS	0.031	.862	.001	3.106	.085	.066
Compatibility * NSS * GCS	0.923	.342	.021	0.001	.976	0
Unit * Decade	1.673	.203	.037	0.192	.663	.004
Unit * Decade * NSS	2.468	.123	.053	0.503	.482	.011
Unit * Decade * GCS	1.279	.264	.028	1.525	.223	.034
Unit * Decade * NSS * GCS	0.112	.739	.003	0.402	.529	.009
Unit * Compatibility	**110.26**	**0**	**.715**	**27.921**	**0**	**.388**
Unit * Compatibility * NSS	0.127	.723	.003	1.336	.254	.029
Unit * Compatibility * GCS	0.662	.42	.015	1.18	.283	.026
Unit * Compatibility * NSS * GCS	1.047	.312	.023	1.827	.183	.04
Decade * Compatibility	**0.009**	**.924**	**0**	**44.289**	**0**	**.502**
Decade * Compatibility * NSS	0.188	.667	.004	0.05	.824	.001
Decade * Compatibility * GCS	0.938	.338	.021	0.65	.424	.015
Decade * Compatibility * NSS * GCS	0.633	.43	.014	1.448	.235	.032
Unit * Decade * Compatibility	1.849	.181	.04	3.609a	.064a	.076
Unit * Decade * Compatibility * NSS	0.111	.741	.003	2.672	.109	.057
Unit * Decade * Compatibility * GCS	**4.089**	**.049**	**.085**	**0.041**	**.84**	**.001**
Unit * Decade * Compatibility * NSS * GCS	0.651	.424	.015	0.209	.65	.005

Bold values indicate significance, $p < .05$

Chapter 4: Influences of transcranial random noise stimulation and number-related synaesthesias on numerical symbol learning

Number-related synaesthesias have been associated with various costs and benefits in numerical cognition, but it is unclear whether these group differences arise early on in the learning of numerical systems, or whether they emerge only later, after practice. Transcranial random noise stimulation (tRNS) is a non-invasive brain stimulation method that may enhance cognition by increasing cortical excitability. To investigate the roles of number-space synaesthesia (NSS) and grapheme-colour synaesthesia (GCS) in numerical learning, as well as the roles parietal and occipital cortex, I trained NSS, GCS and non-synaesthete control groups on a set of novel numerical symbols in a five-day learning paradigm, whilst they received either real or sham tRNS to the bilateral parietal or occipital cortices each day. In addition to the learning task, participants completed tasks measuring the strength of numerical representation (distance effect and number line mapping) at various points during the training. Results showed that both NSS and parietal stimulation appeared to confer overall benefits in numerical learning, although the patterns of these benefits were not identical. Additionally, stimulation appeared to affect control and synaesthete groups differently, with a benefit of parietal stimulation in the GCS group, occipital stimulation in the control group, and no stimulation effects in the NSS group.

Introduction

The experiments in this dissertation so far have investigated one central question: how does visuospatial mental imagery (mental rotation, chapter 2; number-elicited synaesthesia, chapter 3) relate to numerical representation? Chapter 2 found that mental rotation ability was related to two measures of numerical representation, and chapter 3 found that two types of number-related synaesthesia were associated with separate, atypical patterns of numerical representation. Together, they suggest that individual differences in visuospatial mental imagery may affect number cognition. However, these experiments examined both mental imagery and numerical cognition as already-established cognitive abilities, with no way to disentangle the influences of one on the other, or to establish any patterns of causation. Therefore, this chapter sought to tackle the issue of causation in the relationship between visuospatial mental imagery and numerical representation, asking the question of how visuospatial mental imagery and its underlying neurological basis *affect* numerical representation.

In the current experiment, I targeted the problem of causation in two ways. First, I removed the confound of already-established numerical abilities by training participants on a novel set of symbols with numerical properties of ordinality and magnitude (as in Tzelgov, Yehene, Kotler, & Alon, 2000). This paradigm had the benefit of being able to precisely control exposure to the numerical symbols being tested, allowing me to discount possible confounds between ability and practice. Furthermore, this design offered the additional benefit of being able to control the relative order of development for mental imagery abilities and novel-symbol "numerical" abilities (ensuring that mental imagery abilities were already well established before introduction of the novel symbols). Especially relevant to the case of synaesthesia, learning completely novel numerical symbols would thus avoid confounds of any existing visuospatial (synaesthetic) associations with numbers (or specifically, Arabic numerals). Instead, it would isolate the effects of synaesthetes' neurological profiles or cognitive traits leading to the propensity to form these associations, rather than the associations themselves, which are known to be affected by varying environmental influences (Eagleman, 2009; Simner et al., 2005; Witthoft & Winawer, 2013).

The second way in which this experiment addressed causality was by manipulating neural substrates of visuospatial and numerical cognition. The first question this raises is: what are the neural substrates of visuospatial mental imagery and numerical cognition? The parietal cortices are considered to be one of the core areas of numerical representation in humans (Cohen Kadosh, Cohen Kadosh et al., 2007; Harvey et al., 2013; Kaufmann, Wood, Rubinsten, & Henik, 2011). Parietal areas are also implicated in spatial mental imagery, for instance, Carpenter, et al. (1999) found parametric activation in intraparietal sulcus (IPS) for increasing object rotation during a mental rotation task. Some research has suggested NSS may access parietal areas (Tang et al., 2008), and certainly the component mechanisms it recruits (i.e., spatial and numerical processes) are strongly implicated to involve those regions (Hubbard et al., 2005; Walsh, 2003). The occipital cortex, as the seat of visual processing, is also highly relevant to visuospatial mental imagery. Occipital (e.g., V4) and nearby inferior temporal cortex are implicated in GCS (Banissy et al., 2012; Rouw, Scholte, & Colizoli, 2011). Furthermore, GCS is associated with abnormally high occipital (V1) cortical excitability (Terhune, Tai, Cowey, Popescu, & Cohen Kadosh, 2011). Areas bordering occipital cortex are also implicated in numerical cognition; for instance, a study using the invasive method of electrocorticography (ECoG) in humans found a ‘visual number form’ area in the fusiform gyrus (Shum et al., 2013). The recruitment of this area for recognition of numerals may be phylogenetically rooted, as rhesus macaque monkeys trained to associate quantities to numerical symbols showed reliable activation in homologous areas of inferior temporal cortex (Srihasam, Mandeville, Morocz, Sullivan, & Livingstone, 2012). Intriguingly, specialised areas for visual recognition of these numerals arose only in juvenile monkeys trained on this task, but not in adult monkeys, suggesting an important role of the physiology and organisation of the developing brain in numeral recognition.

Given that parietal and occipital cortices may be important neural substrates for visuospatial mental imagery and numerical cognition, how can one manipulate neural activity in these areas? Transcranial random noise stimulation (tRNS) is a relatively new, non-invasive method of brain stimulation, which is thought to increase cortical excitability through processes of stochastic resonance (Terney et al., 2008). Unlike tDCS, tRNS is excitatory at all stimulation sites, making it ideal to use when targeting multiple cortical areas simultaneously (such as bilateral parietal or bilateral occipital cortex). When applied to a site relevant to the task, tRNS has been found to enhance performance a variety of tasks (e.g., numerosity: Cappelletti et al., 2013; visual: Fertonani et al., 2011; calculation: Snowball et al., 2013; and motor: Terney et al., 2008). Enhancement of ability through tRNS to a particular area can thereby implicate the causal role of that area to a particular task. Furthermore, it speaks to the role of cortical excitability in that task (i.e., in this experiment, numerical learning). Cortical excitability has been hypothesised to play an important developmental role in GCS (Terhune et al., 2011), and it is possible that, analogously, cortical excitability in parietal cortex may play a similarly important role in NSS.

The current experiment

In order to assess the main and interactive effects of both synaesthesia and tRNS on numerical learning, I applied a combinatorial design of these two factors in a training task using novel numerical symbols (Cohen Kadosh et al., 2010; Tzelgov et al., 2000). In addition to NSS, I tested two types of controls: both non-synaesthetes, and synaesthetes with GCS. Because the GCS group was also a specially-recruited population, this would help to account for any effects that might arise from motivation differences in a specially-recruited group. Given that a wealth of evidence implicates the parietal cortices in numerical cognition and the occipital cortices in both synaesthesia and visual numerical processing, as detailed in the paragraphs above, I decided to test whether externally modulating neuronal activity in these areas could improve numerical symbol-learning performance. I tested tRNS to both of these areas, as well as sham tRNS to control for placebo effects of stimulation. To test how group differences would affect transfer of the symbol learning from the trained task to other contexts, I included measures of distance effect and “number line” mapping of the symbols as well.

This design led to a number of hypotheses concerning the outcome of symbol learning. Because NSS involves the tendency to spatially visualise magnitude or ordinality, I hypothesised that it would improve numerical learning, from the beginning of the learning process. I further hypothesised that, because number-space synaesthetes create an explicit visuospatial referent that records order of the symbols, NSS would especially improve learning of symbols in the middle of the symbol hierarchy, which otherwise require keeping track of many magnitude relationships. However, given the interference effects of NSS on number line mapping that I found in chapter 3, I predicted that NSS would show worse mapping performance on line orientations incongruent with their spatial forms (most likely in ‘backward’ orientations of increasing magnitude right-to-left). The condition of GCS also concerns numerical symbols, but as it does not offer the obvious benefits of explicit spatial ordering of symbols, I predicted that performance in this group would differ little, if at all, from non-synaesthetes.

Concerning overall effects of tRNS, I hypothesised that parietal tRNS would improve learning compared to sham (Cappelletti et al., 2013). TRNS is thought to operate by boosting weak neural signals, therefore in the continual Hebbian processes of neural reinforcement in learning (Moss et al., 2004), I would expect this improvement to manifest cumulatively across days (Alonzo, Brassil, Taylor, Martin, & Loo, 2012). As tRNS has previously been shown to improve calculation procedures more than memorisation (Snowball et al., 2013), I further hypothesised that parietal tRNS would help in learning symbols requiring more on-line calculation. I predicted that occipital tRNS, on the other hand, would result in small improvements compared to sham, due to better visual learning of the symbols. However, because the symbols were highly visually distinct, and there were only 7 of them, I expected that this improvement would not be as high as the one hypothesised for parietal tRNS.

Methods

Participants

In total, 61 Oxford graduate or undergraduate students took part. One participant was excluded from analysis due to misunderstanding the instructions of the learning task. The 60 remaining participants were allocated randomly to stimulation groups (sham, parietal, or occipital TRNS) within their synaesthesia groups (NSS, GCS, or control). Synaesthesia groups and stimulation groups were matched for age, gender, and numerical competence (WIAT mathematics composite standardised score; all *p*s>.22; see Table 1). All participants were healthy volunteers and were screened each day before participation to rule out any possible contraindications to electrical stimulation, including current or previous neurological conditions, drug or alcohol use, or lack of sleep. (For the full list of screening questions, see Appendix). Number-space synaesthetes (*N*=15) and grapheme-colour synaesthetes (*N*=15) were verified by an in-depth structured interview, and all were confirmed to have only one of these two types. Six of the NSS participants and 5 of the GCS participants had also already participated in the experiment from chapter 3, which investigated number representation and mental rotation in synaesthetes. Non-synaesthete controls were screened by a simple set of questions to check that they had neither NSS nor GCS. All participants were self-reported right handed, apart from one left-handed individual with GCS, who was included due to the relative rarity of the condition. To ensure that possible differences in cortical organisation did not affect brain stimulation, this individual was allocated to the sham stimulation group.

The small sample sizes in the synaesthesia groups compared to non-synaesthete controls was due to difficulty of recruiting synaesthetes who were both willing and able to take part in a training-tRNS study. Overall, 81 potential synaesthetes were interviewed to confirm synaesthesia and were approached to take part in the study, but of these, 11 were excluded due to having both NSS and GCS, 5 stated they were not comfortable with the idea of brain stimulation (one of these due to past unpleasant experiences with TMS), and 23 declined to participate either due to logistical reasons such as not wishing to commit to a week of daily sessions, or for reasons they did not share. Of the 42 synaesthetes who agreed to participate, 10 GCS and 2 NSS candidates did not pass medical screening measures for tRNS. Although sample sizes of 5-10 per group are not uncommon for synaesthesia or tES studies (e.g., Cohen Kadosh et al., 2010; Terhune et al., 2011), these small sample sizes nevertheless place strong limitations on the statistical power and generalisability of the findings, and therefore I suggest that findings should be interpreted cautiously as a proof-of-concept rather than strong evidence.

Table 1: *Stimulation and synaesthesia groups by gender, age, and WIAT mathematics composite score*

				Age (years)		**WIAT Maths Composite**	
Stimulation	**Synaesthesia**	***N***	**Gender (F:M)**	***Mean***	***SD***	***Mean***	***SD***
Sham	Non-syn	10	7:3	23.40	3.84	115.30	8.22
	NSS	5	3:2	21.60	2.88	122.80	6.06
	GCS	5	4:1	22.80	2.17	118.40	6.80
Parietal	Non-syn	10	7:3	22.50	2.80	115.10	10.91
	NSS	5	4:1	22.40	1.95	114.80	11.03
	GCS	5	4:1	23.00	2.65	118.20	17.43
Occipital	Non-syn	10	8:2	22.70	4.30	117.30	11.77
	NSS	5	3:2	23.60	3.72	114.20	8.08
	GCS	5	4:1	22.60	0.55	113.00	14.46

Design

The centrepiece of this experiment was an intensive symbol learning paradigm, spread over five sessions on consecutive days. Participants wore a TRNS electrode setup throughout the learning task, and received stimulation each of the 5 days, starting concurrently with the task. On the first, third and fifth (last) day, after the learning session, participants also used the learnt symbols in a "number line" spatial mapping task. This was designed to evaluate their spatial-numerical understanding of the symbols outside of the context of the learning task. Before and after this entire process, participants were additionally pre- and post-tested on control measures of attention and working memory. These measures served dual purposes: to check whether any cognitive gains after training 1) could be attributed to general, rather than training-specific, cognitive improvements, or 2) were offset by cognitive costs in other functions (e.g., Iuculano & Cohen Kadosh, 2013). Participants completed the pre-test session up to one week before the start of the learning paradigm, and completed the post-tests directly after symbol assessments on the last day of the learning paradigm.

Symbol learning task

The symbol learning task required participants to learn relative magnitudes of seven artificial abstract symbols, based on trial-and-error with visual feedback. The symbols were adapted from figures created by Gibson (1963). To ensure that results were contaminated as little as possible by any accidental visual similarities of the symbols to extant letters or numerals, I developed 18 candidate symbols and distributed them in a survey to 25 individuals, none of whom later participated in any symbol learning experiments for this thesis. From the survey participants' 1-7 Likert scale responses, I chose the 7 symbols that were rated least similar to other known alphanumeric characters. I ordered these randomly and assigned each a value 1-7, with 1 as the smallest and 7 the greatest magnitude (see Fig. 1). I will refer to the symbols by their assigned numeric values throughout this chapter.

Figure 1:The 7 symbols used in the symbol learning task, ordered from smallest assigned magnitude (value '1') at left to largest assigned magnitude (value '7') at right

Stimuli consisted of pairs of these symbols, presented horizontally such that one was in left visual field and one in right visual field. Participants were seated ~60cm from the 43cm presentation screen, and symbols were on average 4cm tall, separated laterally by 15cm centre to centre. Participants saw a total of 2580 trials, organised into 86 blocks of 30 trials each and split over five days (days 1, 3, and 5: 16 blocks, days 2 and 4: 22 blocks). All learning trials showed pairs of adjacent-magnitude symbols (e.g., 1 & 2, 2 & 3, etc.), with each block presenting each of the 6 possible pairs 5 times. Each pair was presented 60% of the time with the smaller magnitude on the left and larger magnitude on the right (a 'forward' orientation according to Western reading direction), to introduce an implicit spatial orientation bias in the learning of the symbols, similar to the bias present in the everyday Western Culture (Cohen Kadosh & Henik, 2007).

Participants were told that the symbols were artificially created and that each of them had been randomly assigned a relative magnitude in comparison to the others, completely unrelated to its physical attributes. At no time were numbers mentioned. Participants were instructed that on each trial, they must guess which of the symbols represented the larger magnitude. Halfway through the session, they were re-instructed to now choose the smaller magnitude, with the order of ‘larger’ versus ‘smaller’ response sections swapping daily, to help counterbalance response-lateralisation effects. Both ‘larger’ and ‘smaller’ responses were given by pressing a key on the side of the chosen symbol with the corresponding hand (Q or P on a QWERTY keyboard). This ensured that despite the spatial orientation bias, an equal number of left-hand and right-hand responses were given on each day.

Each trial began with a 200ms fixation cross, followed by 300ms blank screen, followed by a response-terminated presentation of the stimulus, up to 5000ms. After the participant response (or time-out), visual feedback was presented for 500ms: either “correct,” “incorrect,” or “no response.” After a 200ms blank screen interval, the next trial began. See Fig. 2 for a visual depiction of this process.

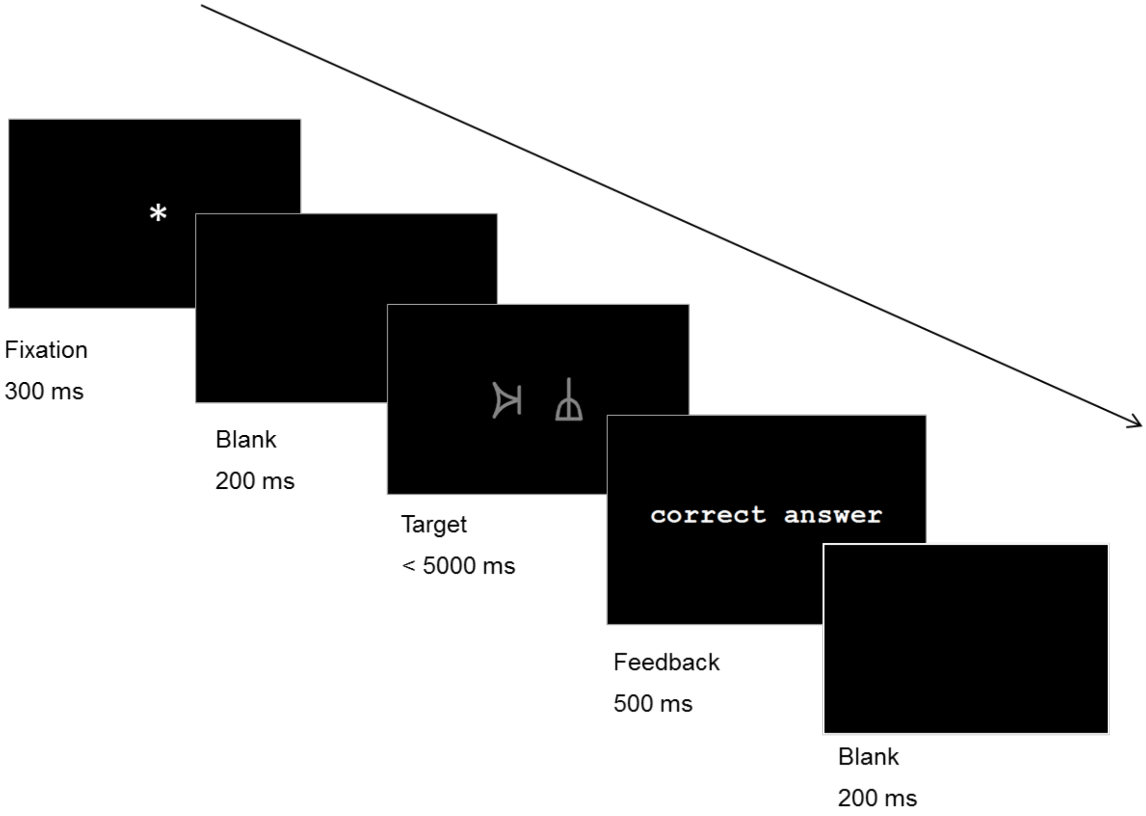

Figure 2: The order of slide presentation for each trial in the symbol learning task

Distance transfer task

Directly after the last symbol learning session, participants completed a test of all possible pairings of symbols to assess the transfer of magnitude understanding from adjacent pairs to greater numerical 'distance' pairs (as in Tzelgov et al., 2000). This "distance transfer" task presented every possible pairing of the 7 symbols (21 pairings in total) 6 times in each of the 2 possible spatial orientations (i.e., smaller symbol on left or right). As in the learning task, participants were first instructed to choose the larger magnitude symbol, and halfway through the task were re-instructed to choose the smaller magnitude symbol. Trials were identical to the learning task, except that no feedback was given. To ensure that the results truly reflected transfer of numerical knowledge rather than rote memory, all adjacent-magnitude trials (numerical distance of 1) were excluded, and only previously-unseen pairings (numerical distance 2 to 6) were included in the analysis.

Line mapping task

On days 1, 3, and 5 after the learning task, participants completed a spatial line mapping task analogous to a number line assessment (adapted from Cohen Kadosh et al., 2010). At the top left or right corner of the screen, one of the symbols 2-6 was presented, and participants were asked to click with the computer mouse where they thought it "belonged" on a centred horizontal line anchored at either end by the symbols 1 and 7. The direction of the line could be either 'forward,' (i.e., symbol 1 on the line's left end and 7 on the right end), or 'backward.' Participants completed 60 trials each session (5 possible symbols × 2 directions × 2 symbol locations (left or right upper corner) × 3 times each) in a randomised order. Participants were explicitly warned that the symbols at either end of the line would switch from trial to trial, although it was never mentioned which magnitudes the anchor symbols represented. See Fig. 3, below, for an example of a trial from this task.

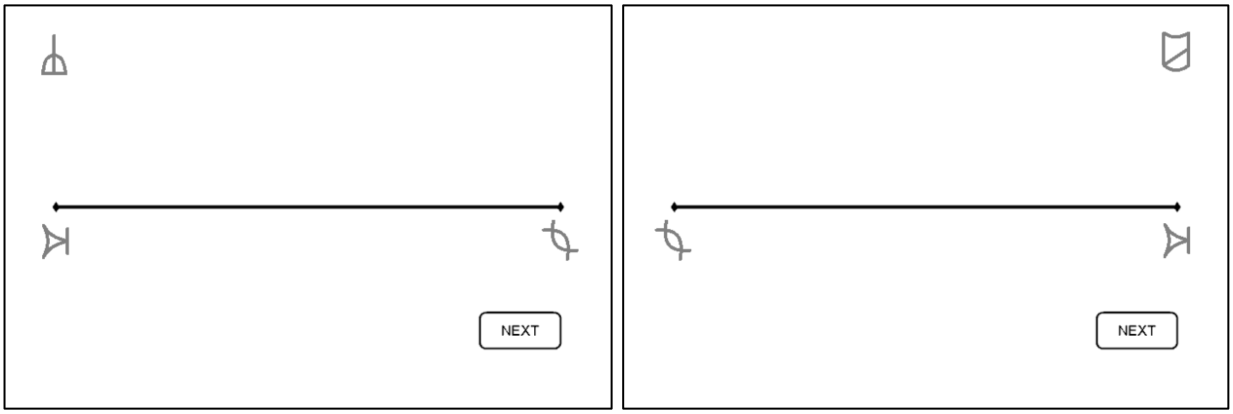

Figure 3: Two examples of trials in the line mapping task. On the left is a forward-direction trial with stimulus (symbol '2') in the upper left corner. On the right is a backward-direction trial with the stimulus (symbol '6') in the upper right corner. The correct mapping position for both of these trials would be one-sixth of the total line length inward from the left endpoint.

Control tasks

Participants completed six control tasks during the pre-test session, and repeated four of them as post-tests at the end of the final learning session (see Table 2). The 3D mental rotation task was the same as that administered for the experiments in Chapters 2 and 3 of this dissertation. The 2D mental rotation task included both Roman alphabet letters and novel symbols from the current experiment. Both rotation tasks are analysed and discussed in further detail in Chapter 6. The verbal working memory (digit span) test required participants to repeat, either in forward or reverse order, increasingly long strings of digits spoken in a flat tone in 1-second intervals by the experimenter. Digit strings were taken from the Wechsler Adult Intelligence Scale, edition III (Wechsler, 1981). To test visuospatial working memory, I administered the standard Corsi block tapping test (Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000). Like the digit span test, this required participants to observe the experimenter tapping increasingly long sequences of blocks in a 9-block array, then repeat the sequences in forward or reverse order by tapping the blocks themselves. I adapted the attention network test (ANT) directly from Fan, McCandliss, Sommer, Raz, and Posner (2002), merely reducing the number of trials to one-third the original (from 288 to 96), to fit into a more reasonable time period (the original experiment lasted 30 minutes). Even at this shorter length, inter-session re-testing reliability remained high (*r*=.84, p<.001), supporting my use of this shorter version. Lastly, participants also completed the mathematics component of the Wechsler Individual Achievement Test, edition II, United Kingdom (Wechsler, 2005), which included sub-tests of numerical operations and mathematical reasoning.

Table 2: A catalogue of pre- and post-tests administered as controls for the TRNS symbol learning experiment

Task	Times tested	Administration	Source
3D mental rotation	Pre	Paper and pen (6min)	Peters et al., 1995
2D mental rotation	Pre & Post	Computerised (10 min)	Cooper & Shepard, 1973
Digit span	Pre & Post	Verbal (4min)	WAIS-III, 1997
Corsi blocks	Pre & Post	Visual-motor (5min)	Pearson Assessment, 2011
Attention Network Test	Pre & Post	Computerised (10min)	Fan et al., 2002
WIAT-II^{UK} Mathematics	Pre	Paper and pen (40min)	Pearson Education, 2005

TRNS

Stimulation was administered by a battery-powered wireless Magstim DC Stimulator Plus transcranial electrical stimulation device (Neuroconn GmbH, Ilmenau, Germany), through two square rubber electrodes measuring 25cm^2 each. Electrodes were housed in saline-soaked sponge pockets to reduce electrical impendence and potential skin irritation, and were secured in place on the scalp by a silicone band. Electrodes were placed over either bilateral parietal or bilateral occipital cortices; in the international 10-10 EEG measurement system these corresponded to P3 and P4 for parietal stimulation, and halfway between PO7 and PO9 and halfway between PO8 and PO10, respectively, for occipital stimulation. Each day, starting concurrently with the learning task, participants in the real stimulation groups (parietal or occipital) received 20 minutes of TRNS, whereas participants in the sham group received 30 seconds of TRNS, all with 15 seconds ramp-up and ramp-down. Stimulation was 1 milliamp peak-to-peak with no DC offset, and the signal included only high-frequency noise (101-640Hz), as this range has previously been shown to improve perceptual learning compared to lower-frequency or full-spectrum noise (Fertonani et al., 2011). Participants in the sham group were randomized to have electrodes placed at either parietal or occipital sites, consistent across all sessions. Allocation of real and sham stimulation was double-blind-like; both the primary experimenter (who explained and administered the tasks) and the participants were blind to assignment, whilst a secondary experimenter (who did not interact with the participants) was brought in to control and monitor the Neuroconn device during stimulation.

Results

All trials with RTs more than ±2 *SD* from the mean (by participant and session) were excluded from analysis (symbol learning, 4.67% of trials; distance transfer, 5.57%; line mapping, 4.31%). Incorrect trials were excluded from RT analyses (symbol learning, 9.05% of trials; distance transfer, 4.61%). When Mauchly's test of sphericity was significant ($p<.05$) I used Greenhouse-Geisser values. As the focus of this chapter was to investigate group differences due to synaesthesia or TRNS, I report in depth only those results including a factor of either synaesthesia or stimulation group (all within-subjects results are nonetheless noted).

Symbol learning task

To examine the effects of stimulation on symbol learning, I conducted mixed-model ANOVAs on both accuracy and RT of the symbol learning task. The 3×3×5×2×3 design included between-subjects factors of stimulation group (sham, parietal, occipital) and synaesthesia group (non-synaesthete, NSS, GCS), and within-subject factors of session (days 1 through 5), orientation of symbol pair ('forward,' i.e., larger symbol on the right, versus 'backward,' i.e., larger symbol on the left), and pair type (outermost, i.e. pairs 1&2 and 6&7; midway, i.e. pairs 2&3 and 5&6; or innermost, i.e. pairs 3&4 and 4&5). The organisation of pair type into these bins was deemed appropriate for two reasons: firstly, the outermost pairs differed from the other stimuli, in that they contained a symbol that was always the largest or always the smallest, and therefore ought to be easiest to learn; and secondly, I hypothesised that learning of the non-outer pairs, which must be algorithmically computed by inferring their relationships to the outermost pairs, would proceed from the pairs closest to the outer pairs (i.e., the midway pairs), and thence to the innermost pairs. All results of the ANOVAs are reported in Table 3, below, and I discuss the most relevant results (i.e., highest-order group effects and interactions) below.

Table 3: ANOVAs for RT and accuracy measures of the main symbol learning task, including between-subjects factors of stimulation and synaesthesia groups, and within-subjects factors of day, orientation of magnitude direction, and symbol pair.

	RT				**Accuracy**			
Effect	**df**	***F***	***p***	ηp^2	**df**	***F***	***p***	ηp^2
Stim	2,51	1.50	.23	.06	2,51	**5.54**	**0.007**	**0.18**
Syn	2,51	2.87	.066	.10	2,51	1.1	0.34	0.04
Stim * Syn	4,51	0.36	.83	.03	4,51	**3.53**	**0.013**	**0.22**
day	2.25,114.54	**153.81**	**<.001**	**.75**	1.30,66.30	**49.94**	**<.001**	**.50**
day * Stim	4.49,114.54	**2.73**	**.027**	**.10**	2.60,66.30	0.81	.48	.03
day * Syn	4.49,114.54	0.62	.67	.02	2.60,66.30	1.13	.34	.04
day * Stim * Syn	8.98,114.54	0.74	.67	.06	5.20,66.30	0.51	.77	.04
orient	1,51	**226.77**	**<.001**	**.81**	1,51	**105.21**	**<.001**	**.67**
orient * Stim	2,51	2.92	.063	.10	2,51	**7.62**	**.001**	**.23**
orient * Syn	2,51	2.81	.069	.10	2,51	1.67	.20	.06
orient * Stim * Syn	4,51	0.62	.65	.05	4,51	**3.86**	**.008**	**.23**
pair	1.53,78.13	**188.10**	**<.001**	**.79**	2,102	**53.84**	**<.001**	**.51**
pair * Stim	3.06,78.13	0.92	.44	.03	4,102	2.18	.076	.08
pair * Syn	3.06,78.13	**2.90**	**.026**	**.10**	4,102	1.41	.24	.05
pair * Stim * Syn	6.13,78.13	1.11	.36	.08	8,102	1.24	.29	.09
day * orient	3.00,152.78	0.54	.66	.01	3.07,156.73	**6.45**	**<.001**	**.11**
day * orient * Stim	5.99,152.78	0.93	.48	.04	6.15,156.73	1.39	.22	.05
day * orient * Syn	5.99,152.78	0.84	.54	.03	6.15,156.73	1.87	.088	.07
day*orient*Stim*Syn	11.98,152.78	0.61	.83	.05	12.29,156.73	0.40	.96	.03
day * pair	2.7,137.58	**6.86**	**<.001**	**.12**	4.51,229.87	**3.10**	**.013**	**.06**
day * pair * Stim	5.4,137.58	1.56	.17	.06	9.01,229.87	**2.79**	**.004**	**.10**
day * pair * Syn	5.4,137.58	0.86	.52	.03	9.01,229.87	1.16	.32	.04
day*pair*Stim*Syn	10.79,137.58	0.33	.98	.02	18.03,229.87	1.03	.43	.07
orient * pair	1.79,91.29	**3.35**	**.044**	**.06**	2,102	**10.31**	**<.001**	**.17**
orient * pair * Stim	3.58,91.29	0.40	.79	.02	4,102	0.88	.48	.03
orient * pair * Syn	3.58,91.29	2.01	.11	.07	4,102	1.19	.32	.04
orient*pair*Stim*Syn	7.16,91.29	0.70	.68	.05	8,102	1.63	.13	.11
day * orient * pair	5.84,297.88	2.05	.061	.04	5.74,292.55	**4.42**	**<.001**	**.08**
day*orient*pair*Stim	11.68,297.88	0.96	.49	.04	11.47,292.55	1.14	.33	.04
day*orient*pair*Syn	11.68,297.88	0.86	.59	.03	11.47,292.55	1.41	.16	.05
day*orient*pair*Stim* Syn	23.36,297.88	0.86	.66	.06	22.95,292.55	1.11	.33	.08

Significant effects and interactions (p<.05) are in **bold**

Effects of interest, which are discussed in the text, are shaded in grey

The accuracy ANOVA produced two group interactions of note. The first was the three-way interaction of orientation, stimulation and synaesthesia (*F*(4,51)=3.86, *p*=.008, ηp^2=.23; see Fig. 4). Breaking this interaction down by stimulation group, the simple interaction of synaesthesia by orientation was significant only in the sham group (*F*(2,17)=4.21, *p*=.033, ηp^2=.33). This simple interaction was due to smaller orientation effects in sham non-synaesthetes (*F*(1,9)=13.13, *p*=.006, ηp^2=.59) than in sham NSS (*F*(1,4)=18.75, *p*=.012, ηp^2=.82) or sham GCS (*F*(1,4)=17.70, *p*=.014, ηp^2=.82). The parietal and occipital groups showed no simple interactions (*p*s>.13), but both showed simple main effects of orientation with an advantage for forward orientation (*F*s>19.41, *p*s<.001), and the occipital group showed a simple main effect of synaesthesia (*F*(2,17)=8.03, *p*=.004, ηp^2=.49), with an advantage for non-synaesthetes over NSS (*t*(13)=2.18, *p*=.048, Cohen's *d*=1.19) and GCS (*t*(4.91)=3.21, *p*=.024, Cohen's *d*=2.22) but no difference between NSS and GCS (*p*=.17).

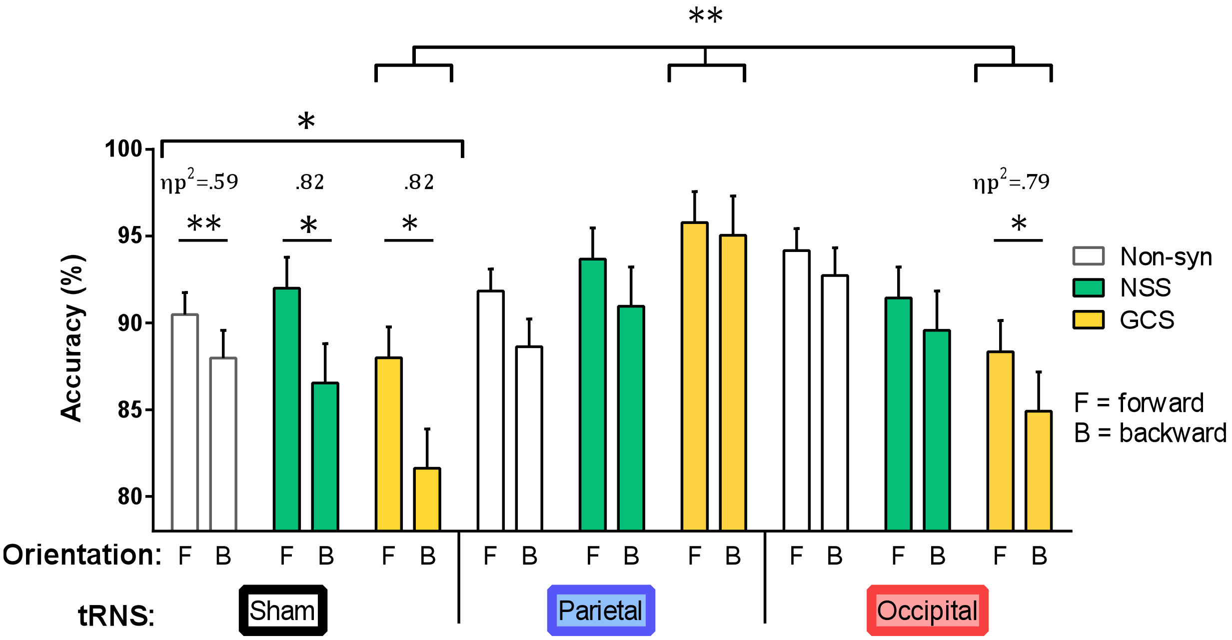

Figure 4:The ANOVA for symbol learning task accuracy yielded a significant interaction of orientation by stimulation group by synaesthesia group. Within the GCS group, in both orientations, those with parietal TRNS were more accurate than those with either sham or occipital TRNS. However, in the non-synaesthete group, in backward orientation only, the occipital TRNS group was more accurate than both sham and parietal.

To better understand the three-way interaction in terms of orientation effects by group, I decomposed it again in a different manner. Decomposing the interaction first by synaesthesia group showed a simple interaction between stimulation and orientation only in the GCS group (F(2,12)=7.37, p=.008, ηp^2=.55). This was due to a lack of orientation effect in the GCS parietal group (p=.15), whereas large effects were found in both GCS sham (F(1,4)=17.70, p=.014, ηp^2=.82) and GCS occipital (F(1,4)=15.28, p=.017, ηp^2=.79). The non-synaesthete and NSS groups showed no simple interactions (ps>.13), but both showed main effects of orientation, with an advantage for forward (Fs>23.02, ps<.001), and the non-synaesthetes showed a marginal main effect of stimulation (F(2,27)=2.74, p=.083, ηp^2=.17), due to better performance in the occipital non-synaesthete group compared to sham non-synaesthetes (t(12.51)=2.65, p=.020, Cohen's d=1.18) and marginally compared to parietal non-synaesthetes (t(12.07)=1.84, p=.090, Cohen's d=0.83).

The second group interaction from the accuracy ANOVA was an interaction of stimulation, day and pair type (F(9.01,229.87)=2.79, p=.004, ηp^2=.10; see Fig. 5). Decomposing this by pair type revealed the simple interaction of day by stimulation was not significant for outer or midway pairs (ps>.19). These pair types showed only simple main effects of day (Fs>48.89, ps<.001) and marginal or significant simple main effects of stimulation type (outermost: F(2,57)=2.81, p=.068; midway: F(2,57)=5.26, p=.008). These simple main effects of stimulation were due to better accuracy in parietal versus sham in both pair types (outermost: t(38)=2.36, p=.023, Cohen's d=0.75; midway: t(38)=2.51, p=.017, Cohen's d=0.79) and better accuracy in occipital versus sham in the midway pairs only (t(29.38)=2.90, p=.007, Cohen's d=0.92; all other comparisons p>.19). However, the simple interaction of day by stimulation *was* significant for innermost pairs (F(8,228)=2.22, p=.027, ηp^2=.07). Breaking this down further by day, I found that accuracy on innermost pairs did not differ by group on days 1 through 3 ($ps>.19$), but it did marginally differ on day 4 ($F(2,57)=2.98$, $p=.059$, $\eta p^2=.10$) and on day 5 ($F(2,57)=2.82$, $p=.068$, $\eta p^2=.09$). Post hoc tests revealed that these group differences on days 4 and 5 were due to higher accuracy on innermost pairs in the parietal compared to sham group (day 4: $t(38)=2.58$, $p=.014$, Cohen's $d=0.82$; day 5: $t(38)=2.63$, $p=.014$, Cohen's $d=0.83$), whereas no other groups significantly differed ($ps>.15$).

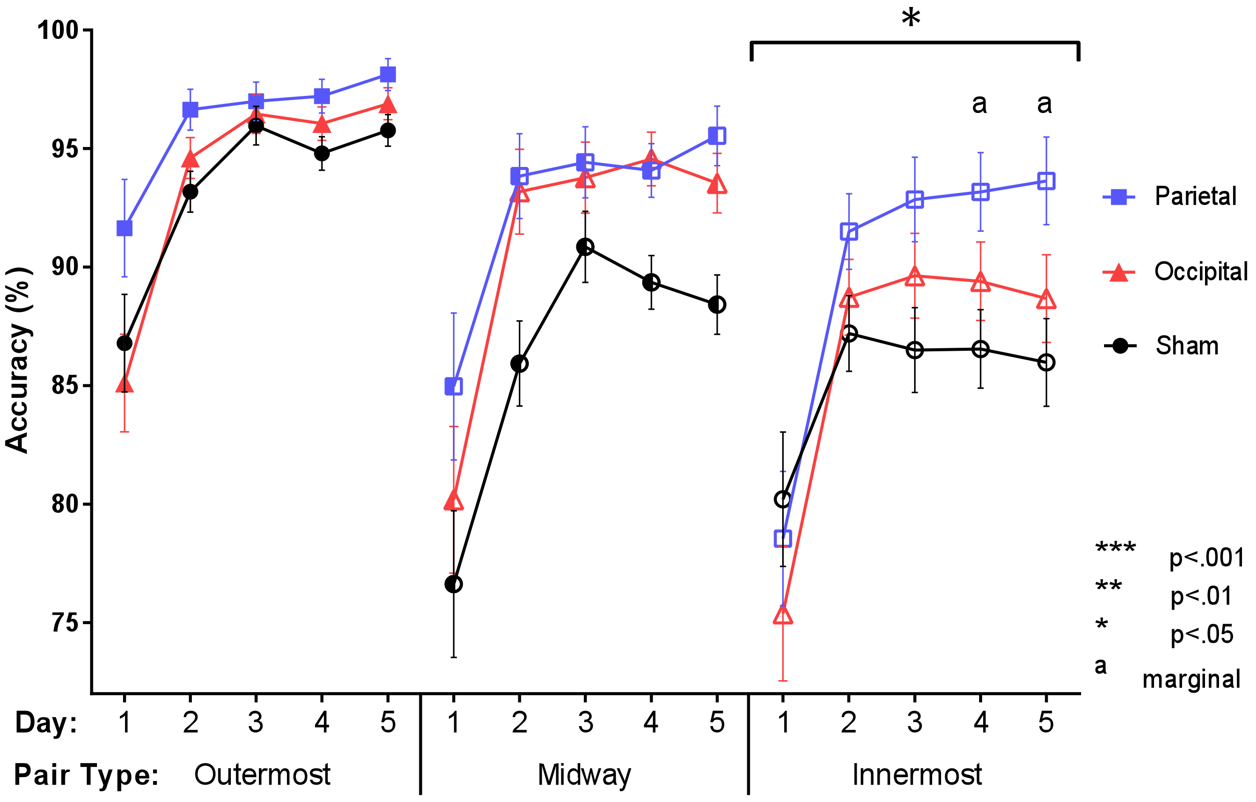

Figure 5: The ANOVA for accuracy on the symbol learning task yielded an interaction of stimulation by day by pair type. Breaking down by pair type, only innermost pairs produced a simple interaction of day by stimulation. This was due to higher accuracy in the parietal group compared to sham on the later days only.

The ANOVA of RTs produced two group interactions of note. Firstly, the interaction of synaesthesia group by pair type was significant (*F*(3.06,78.13)=2.90, *p*=.026, ηp^2=.10; see Fig.6). Breaking this interaction down by pair type revealed no significant simple main effect for the outermost pairs (*p*=.11), but a marginally significant simple main effect for the midway pairs (*F*(2,57)=2.61, *p*=.082, ηp^2=.08), and a significant simple main effect for the innermost pairs (*F*(2,57)=4.06, *p*=.022, ηp^2=.12). Post hoc tests revealed that the latter two simple main effects were driven by faster RTs in the NSS versus the non-synaesthete group in both midway (*t*(41.26)=2.80, *p*=.008, Cohen's *d*=0.75) and innermost pairs (*t*(39.21)=3.32, *p*=.002, Cohen's *d*=0.92), whereas no other comparisons were significant (*p*s>.12).

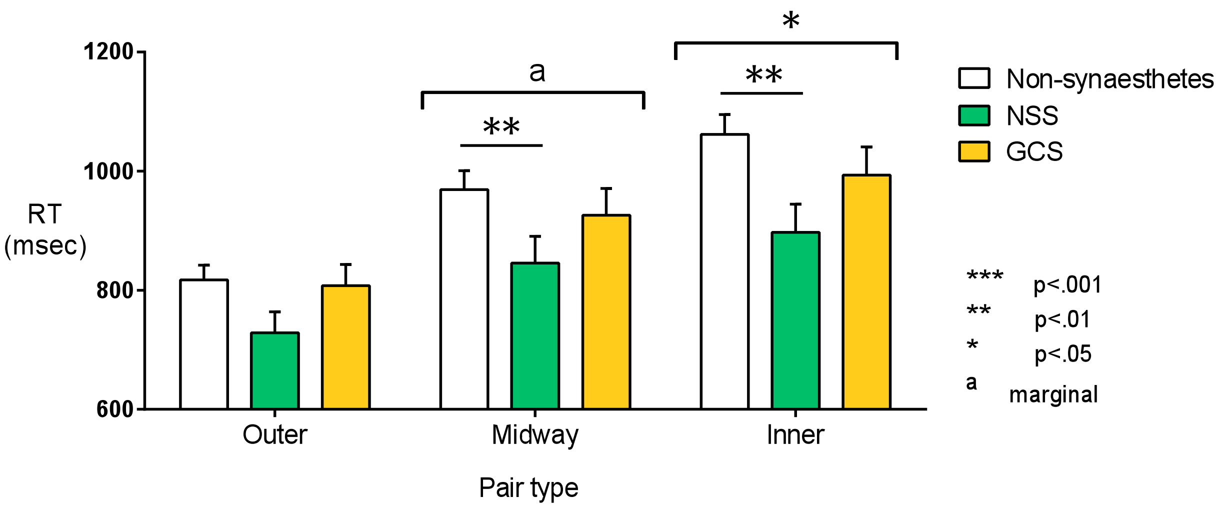

Figure 6: The ANOVA for RT on the symbol learning task produced a significant interaction between synaesthesia group and pair type. The interaction was driven by faster performance by the NSS group compared to non-synaesthetes on innermost (and marginally, midway) pairs.

Second, the interaction of stimulation group by day was significant for RT (*F*(4.49,114.54)=2.73, *p*=.027, ηp^2=.10; see Fig. 7). Decomposing this interaction by day revealed a significant simple main effect of stimulation type for day 1 (*F*(2,57)=4.04, *p*=.023, ηp^2=.12) but for none of the later days (*p*s>.25). Post hoc tests revealed that the occipital stimulation group was slower than both sham (*t*(38)=2.61, *p*=.013, Cohen's *d*=0.83) and parietal (*t*(41.26)=2.22, *p*=.032, Cohen's *d*=0.70), whereas sham and parietal did not differ (*p*=.59).

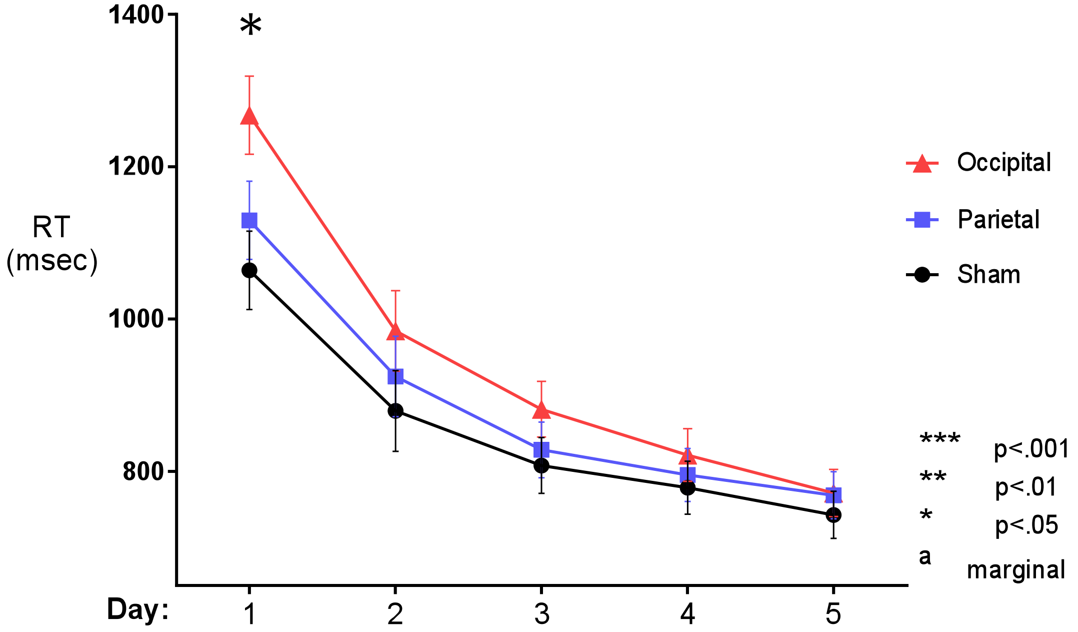

Figure 7: The ANOVA for RT on the symbol learning task produced an interaction between stimulation group and day, arising from slower responses in the occipital group compared to both sham and parietal on day 1.

I also modeled individual learning curves based on a power law function (Newell & Rosenbloom, 1981),

$$RT = \beta * N^{-\alpha}$$

in which RT is the mean reaction time in a given block, β represents initial performance (reaction time on the initial block), N represents the number of a given block, and α represents the exponential slope of learning trajectory (i.e., the learning rate) . This yielded measures of α, learning rate, and β, initial speed, for each participant. I analysed each of these variables in univariate ANOVAs with between-subjects factors of stimulation and synaesthesia group. Both learning rate and initial speed showed a main effect of stimulation (learning rate: *F*(2,51)=3.18, *p*=.050, ηp^2=.11; initial speed: *F*(2,51)=5.54, *p*=.007) and no other effects (*p*s>.33). Post hoc tests revealed that in both measures, occipital stimulation was higher than both sham (learning rate: (*t*(38)=2.62, *p*=.013, Cohen's *d*=0.83; initial speed: *t*(38)=3.71, *p*=.001, Cohen's *d*=1.18) and parietal (learning rate: *t*(38)=2.05, *p*=.048, Cohen's *d*=0.65; initial speed: *t*(38)=2.23, *p*=.031, Cohen's *d*=0.71), whereas sham and parietal did not differ (*p*s>.22). The higher learning rates in the occipital group may have simply been due to higher initial speeds, offering more room for improvement (Jolles & Crone, 2012). However, because both measures showed stimulation group effects, neither could be used as a covariate for each other in an analysis of covariance (ANCOVA) of stimulation groups, as this would violate ANCOVA assumptions of equal variance across groups. To investigate whether the occipital group was simply slower at responding to computer tasks, I compared RTs by group in the only computer-administered pre-test, the ANT. There was no difference in RT by stimulation for this task in either the pre-test (*p*=.23) or post-test (*p*=.27), suggesting that the slow initial speeds could have been due to occipital stimulation (as stimulation was given from the very start of the symbol learning task). These results mirror the ANOVA results for RTs, which showed a stimulation by day interaction following the same pattern (see Fig. 5).

Distance transfer test

I conducted a 3×3×2×5 mixed-model ANOVA on the distance transfer test for both RT and accuracy. The between-subjects factors were stimulation group (sham, parietal, or occipital) and synaesthesia group (non-synaesthete, NSS, GCS), and the within-subjects factors were orientation (forward or backward) and numerical distance (2, 3, 4, 5, or 6). The analysis for RT produced only one significant effect, namely, the main effect of numerical distance (*F*(2.13,108.66)=70.35, *p*<.001, ηp^2=.58; all other *p*s>.12), indicating that all participants showed a strong distance effect in RT. The accuracy analysis produced a main effect of distance ($F(2.97,151.60)=15.43$, $p<.001$, $\eta p^2=.23$), and interactions between orientation and distance ($F(3.51,179.04)=3.06$, $p=.023$, $\eta p^2=.06$), and stimulation and distance ($F(5.95, 151.60)=2.22$, $p=.045$, $\eta p^2=.08$; see Fig. 8). No other effects were significant (*p*s>.38).

Decomposing the latter interaction by numerical distance, I found that simple main effects of stimulation were significant for distances of 2 ($F(2,57)=3.45$, $p=.039$, $\eta p^2=.011$) and 3 ($F(2,57)=6.52$, $p=.003$, $\eta p^2=.18$), but not for the larger distances (all *p*s>.35). Further post hoc tests revealed that at distances of 2, parietal was more accurate than sham ($t(38)=2.43$, $p=.020$, Cohen's $d=0.77$), but the other comparisons were not significant (*p*s>.14), and that at distances of 3, both parietal ($t(38)=3.49$, $p=.001$, Cohen's $d=1.11$) and occipital ($t(38)=2.36$, $p=.023$, Cohen's $d=0.75$) were more accurate than sham, but parietal and occipital did not differ from each other ($p=.39$). The interaction thus depicted a larger distance effect, measured in accuracy rates, for sham compared to parietal tRNS.

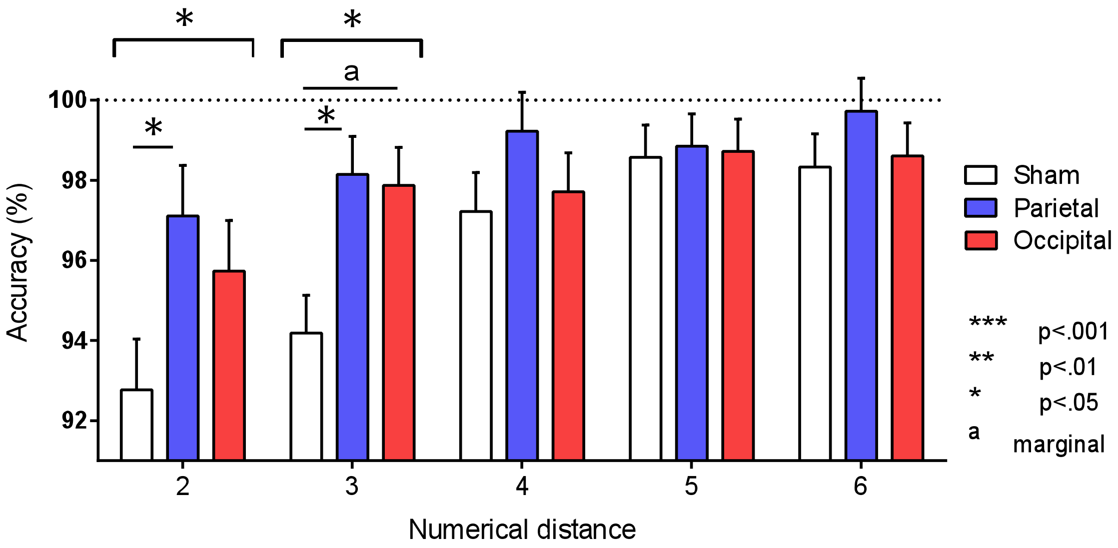

Figure 8: In the distance transfer test, the ANOVA on accuracy yielded an interaction of TRNS group with numerical distance of stimulus pairs. At greater distances, accuracy did not differ between groups, but at smaller distances, the parietal TRNS group was more accurate than sham.

To check whether these distance effect results might reflect a speed-accuracy trade-off, I ran two correlation analyses between the size of the distance effects in RTs and accuracy across all participants. I calculated distance effect for each individual in two different ways: by taking the difference (in RT or in accuracy) between distance 2 and distance 6, respectively, or between the average of distances 2 and 3, and the average of distances 4, 5, and 6, respectively. Neither method of calculation yielded significant correlations between RT and accuracy scores (r=-.15, p=.25, and r=-.10, p=.44, respectively). The correlations remained non-significant even when dividing RT distance effects by the RT for smaller distances, to account for individual differences in overall RT (r=-.16, p=.23, and r=-.11, p=.42, respectively), as done in Holloway and Ansari (2009). Furthermore, these were not caused by opposite correlation values in different stimulation groups, as all four correlations remained non-significant when run separately for each of the three stimulation groups (ps>.12).

As noted above, in the original ANOVAs no main group effects reached significance. However, because there were many more small distance pairs (e.g. 1&3,2&4,3&5,4&6,5&7) than large distance pairs (e.g., 1&7), distance categories contained vastly different numbers of trials. Therefore, to ensure that averaging over distance categories in the original analysis did not give misleading results, I re-ran the ANOVAs without distance as a factor (i.e., giving each trial equal weight). For accuracy, two additional main effects became significant: orientation ($F(1,51)=5.03$, p=.029, $\eta p^2=.09$), showing better accuracy for ‘forward’ orientation, and stimulation group ($F(2,51)=4.00$, p=.024, $\eta p^2=.14$). Post hoc tests showed that the parietal group was more accurate overall than sham ($t(38)=3.01$, p=.005, Cohen’s d=0.95; other comparisons ps>.11). No other effects or interactions on accuracy were significant (ps>.10). In the ANOVA on RTs, only the main effect of synaesthesia group neared significance ($F(2,51)=2.71$, p=.076,

ηp^2=.10; other *p*s>.16). Post hoc tests revealed this was due to NSS being faster than both non-synaesthetes (*t*(43)=2.36, *p*=.023, Cohen's *d*=0.75) and GCS (*t*(28)=2.10, *p*=.045, Cohen's *d*=0.76), whereas non-synaesthetes and GCS did not differ (*p*=.82).

Line mapping task

To measure precision in the line mapping task, I calculated a measure of absolute deviation for each trial, similar to that of the number line task in chapters 2 and 3 (i.e., I subtracted the actual position from the guess and took the absolute value of the result). Because the direction of the line changed across trials, polarity mistakes were common, as confirmed by spontaneous anecdotal self-report. Similarly, accidental mouse-clicks occurred with somewhat high frequency. Therefore, responses of absolute deviation greater than 33%[2] were classed as probable polarity mistakes and discarded (5.27% of trials). However, if over half of the valid trials in any particular category of day × orientation × symbol (at least 3 trials) were deemed polarity mistakes, I retained those trials. This was based on the assumption that such a high percentage of "mistakes" more likely indicated a true intention to place the symbol far from its linear position, rather than multiple polarity mistakes or errant mouse clicks.

The resulting deviation measures, as well as RTs, were subjected to mixed-model 3×3×3×2×5 ANOVAs with between-subjects factors of stimulation (sham, parietal, or occipital) and synaesthesia (non-synaesthetes, NSS, or GCS), and within-subjects factors of day (1, 3, or

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[2] I chose a consistent cutoff value, rather than using individual cutoffs computed using standard deviations, because size of *SD*s varied so widely across individuals that no multiple of *SD*s was functionally useful as a cutoff point to catch polarity mistakes. That is, high multiples of *SD*s left in obvious polarity mistakes in some participants, whereas multiples of *SD*s low enough to exclude the aforementioned mistakes cut out a great deal of valid-seeming data in other participants. The particular cutoff value of 33% was chosen because it represented the distance of the smallest perfect polarity mistake (i.e. the distance between correct and polarity-reversed placement for symbol 3 or 5).

5), line direction (forward or backward) and symbol (2, 3, 4, 5, or 6). The RT analysis showed several within-subjects effects: the main effects of day (*F*(1.17,59.83)=38.99, *p*<.001, ηp^2=.43) and symbol (*F*(3.30,168.00)=59.46, *p*<.001, ηp^2=.54), and interactions of day by symbol (*F*(4.51,229.85)=4.074, *p*=.002, ηp^2=.07) and line direction by symbol (*F*(3.47,176.79)=2.71, *p*=.076, ηp^2=.10). More relevantly to the focus of this chapter, the ANOVA on RTs also showed an interaction of stimulation by symbol (*F*(6.59,168.05)=2.64, *p*=.015, ηp^2=.09; see Fig. 9). Decomposing this interaction by symbol revealed that simple main effects of stimulation reached (or neared) significance only for symbols 3 (*F*(2,57)=3.30, *p*=.044) and 5 (*F*(2,57)=2.95, *p*=.058; other *p*s>.22). Further tests found that for both of these symbols, the parietal group was significantly or marginally slower than sham (symbol 3: *t*(26.12)=2.21, *p*=.033, Cohen's *d*=0.70; symbol 5: *t*(38)=2.01, *p*=.051, Cohen's *d*=0.64), but no such differences arose between parietal and occipital (*p*s>.090), nor between sham and occipital groups (*p*s>.39). No other group effects or interactions were significant for the RT analysis (*p*s>.13).

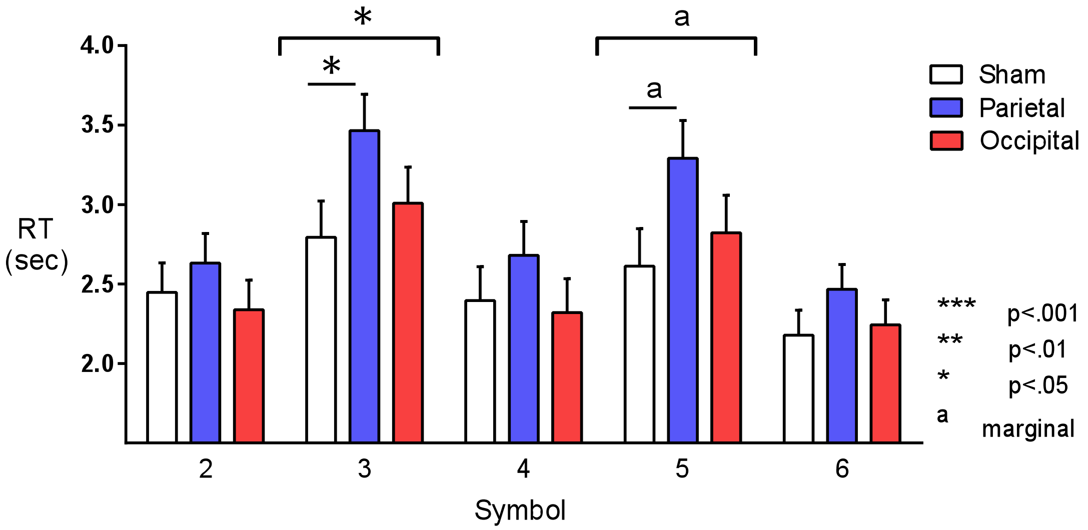

Figure 9: The ANOVA on RTs for the line mapping task revealed a significant interaction of stimulation group by symbol, in which the parietal group was slower than the sham group to map symbols 3 and 5. These symbols were the most difficult to map, as they were the farthest symbols from the anchor values at the endpoints (apart from symbol 4, which could be mapped simply by bisecting the line).

The ANOVA for absolute deviation used the same factors as the ANOVA for RT. In addition to main effects of day ($F(1.43, 73.15)=27.40$, $p<.001$, $\eta p^2=.35$) and symbol ($F(2.30,117.19)=4.56$, $p=.009$, $\eta p^2=.08$), I found an interaction between synaesthesia group and day ($F(2.87,73.15)=4.05$, $p=.011$, $\eta p^2=.14$; see Fig. 10). No other effects were significant (*p*s>.12). Broken down by day, the interaction revealed that only on day 1 did the synaesthesia groups differ in absolute deviation ($F(2,59)=3.36$, $p=.042$; other *p*s>.38). Post hoc tests further revealed that, on day 1, the NSS group plotted the symbols more precisely than the GCS group ($t(28)=2.61$, $p=.014$, Cohen's $d=0.95$) and marginally more precisely than the non-synaesthete group ($t(28)=1.83$, $p=.074$, Cohen's $d=0.58$). The GCS and non-synaesthete groups did not differ ($p=.28$). Thus it appears that all groups eventually reached the same degree of precision, but the NSS group started off with greater mapping precision than the others.[3]

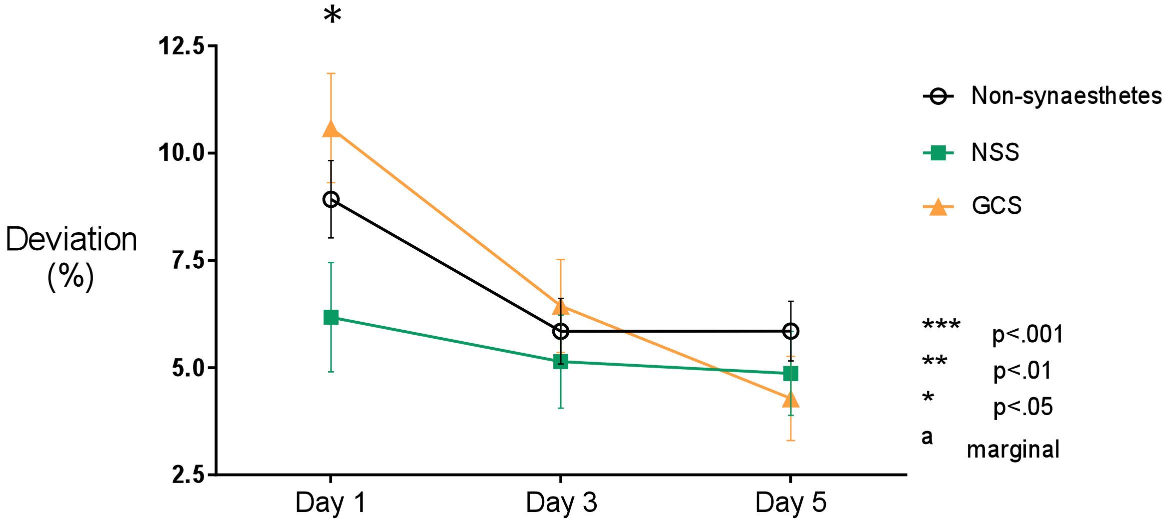

Figure 10: The ANOVA on absolute deviation for the line mapping task revealed a significant interaction of synaesthesia group by day, arising from the finding that the NSS group was more accurate than the other groups at mapping symbols on day 1.

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[3] This is all the more impressive when considering that two of the NSS group (but no other participants) reported in a post-experiment debriefing interview that they had visualised the "symbol line" in a non-linear fashion, and had mapped it accordingly. The mean deviations for these participants on day 1 were 18% and 14%, respectively, whereas the mean for the NSS group on day 1 after excluding them dropped from 6.16% to 4.65%.

Control tasks

To assess whether the control measures showed group differences *a priori,* I conducted univariate or mixed-model ANOVAs on these measures with synaesthesia and stimulation groups as between-subjects factors, and any sub-measures as within-subjects factors. To assess whether control measures changed as a function of group from pre- to post-test, I conducted these same ANOVAs with the addition of session (pre or post) as a factor. For the attention network task, neither RT nor accuracy measures showed any group effects or interactions, either in the pre-test (*p*s> .16) or across sessions (*p*s>.27). For the visuospatial working memory span tests, (Corsi block tapping test) there were no group effects or interactions, either in the pre-test (*p*s>.20) or across sessions (*p*s> .10).

For the digit span working memory tests, scores on day 1 showed a marginal interaction between synaesthesia group and span direction, ($F(2,51)=2.85$, $p=.067$, $\eta p^2=.10$) but no other group interactions or effects (*p*s>.30). Decomposing this marginal interaction revealed that the GCS group had a slightly smaller cost of reversing span direction ($F(1,14)=17.50$, $p=.001$, $\eta p^2=.56$) compared to non-synaesthetes ($F(1,29)=60.36$, $p<.001$, $\eta p^2=.68$) and NSS ($F(1,14)=45.63$, $p<.001$, $\eta p^2=.70$).

When analysed across both pre- and post-tests, the digit span working memory measures also showed a three-way interaction of stimulation group, session, and span direction ($F(2,51)=3.37$, $p=.042$, $\eta p^2=.12$), but no other group interactions or effects (*p*s>.11). Decomposing this interaction by session revealed no simple interaction of stimulation and span direction on the pre-test ($p=.29$), but a marginal interaction of those variables on the post-test, ($F(1,57)=3.02$, $p=.057$, $\eta p^2=.10$). Further decomposing by span direction revealed no group differences on the post-test for forward digit span ($p=.67$), but a group difference on the post-test of reverse digit span (*F*(2,59)=4.79, *p*=.012, ηp^2=.14), due to a higher score for parietal stimulation compared to both sham (*t*(38)=3.07, *p*=.004, Cohen's *d*=0.97) and occipital (*t*(38)=2.58, *p*=.014, Cohen's *d*=0.82), with no difference between sham and occipital (*p*=.99). This suggests the source of the interaction was higher reverse digit span scores for parietal stimulation in the post-test, therefore suggesting that parietal stimulation may have offered an unintended side benefit of improved reverse digit span in working memory. Alternatively, as tRNS is known to affect cortical excitability for up to 90 minutes after the end of stimulation (Terney et al., 2008), residual effects of tRNS may have enhanced working memory (which was tested approximately 60-75 minutes post-stimulation).

Discussion

In summary, the symbol learning task and its auxiliary tests of symbol understanding revealed an array of effects by stimulation and synaesthesia groups. The most complex finding, which I will tackle here first, concerned a three-way interaction of orientation by stimulation by synaesthesia, expressed in accuracy rates on the main symbol learning task. It can best be understood by separately addressing both how different synaesthesia types appeared to affect stimulation efficacy, and how different types of stimulation may have affected the various synaesthesia groups.

Presence, but not type, of synaesthesia appeared to influence the efficacy of stimulation on symbol learning. In those receiving sham stimulation, both synaesthete groups (NSS and GCS) showed a larger orientation effect than non-synaesthetes. Parietal tRNS appeared to engender an orientation effect across all synaesthesia types. Occipital stimulation also appeared to produce an orientation effect across synaesthesia types, but more importantly, it also appeared to cause better performance in non-synaesthetes than in synaesthetes of both types (NSS and GCS). Together, these results suggest that NSS and GCS, compared to non-synaesthetes, may share neurological attributes that both bias them to internalise implicit visuospatial cues (orientation frequencies) and to nullify benefits of occipital tRNS whilst learning numerical symbols. Given that concurrence of NSS and GCS is high (Sagiv et al., 2006; Simner et al., 2006), these similarities between the two synaesthete groups may support the possibility that NSS and GCS share underlying neurological similarities.

Type of stimulation appeared to affect synaesthete groups differently. In non-synaesthetes, occipital stimulation increased accuracy compared to sham (and, marginally, compared to parietal), especially when responding to pairs in the backward orientation. A potential explanation for this pattern might be that occipital stimulation biased the balance of cortical activation in favour of visual regions necessary for recognition and discrimination of the symbols (i.e. occipito-temporal regions) and away from regions implicated in processing spatial aspects (i.e. parietal regions). The NSS group did not show any differential effects of stimulation, although it did show an overall effect of orientation. This suggests that the presence of NSS may have had a sufficiently strong effect on learning strategy and novel numerical processing to mask any effects of stimulation. The GCS group showed a large advantage for parietal stimulation, further characterised by a lack of orientation effect with parietal stimulation, compared to larger orientation effects and poorer overall performance in the other stimulation conditions.

Thus the results indicate a dissociation between parietal and occipital stimulation effects in GCS versus non-synaesthetes; non-synaesthetes improved only with occipital stimulation, whereas GCS improved only with parietal stimulation. This dissociation makes sense in context of the findings by Terhune, et al. (2011), which demonstrated that GCS is associated with abnormally high cortical excitability in occipital cortex. Given that tRNS has been found to increase cortical excitability (Terney et al., 2008), tRNS to occipital cortex might be expected to have little effect on the already high cortical excitability in GCS participants (Terhune et al., 2011), relative to sham. This idea runs in line with a recent model that explains the efficacy of brain stimulation as a function of excitability (B. Krause, Marquez-Ruiz, & Cohen Kadosh, 2013). However, parietal tRNS in GCS may have resulted in high cortical excitability across both occipital and parietal regions, both of which were expected to be instrumental in the learning task. This would neatly explain the high accuracy performance in the GCS parietal stimulation group.

The group interactions with pair type on the learning task revealed further detail of the mechanisms of learning during the task. Quite apart from overall performance, analyses of pair type gave an insight into how participants performed relatively on pairs requiring only rote memory (the outermost pairs, which could be answered by merely by recognising one of the outermost symbols) versus pairs requiring more algorithmic processing to calculate their magnitude (midway or innermost pairs). Whereas overall accuracy appears to have been differentially affected by stimulation within the three synaesthesia groups, accuracy of pair types differed by stimulation across the board. Specifically, parietal stimulation boosted accuracy on inner pairs on the later days, suggesting it conferred a cumulative training advantage on pair types requiring the most calculation. These results are consistent with findings from Snowball, et al. (2013), who reported that tRNS (to prefrontal areas) improved long-term retention of ability on arithmetic calculation problems in comparison to rote memorization problems.

Intriguingly, a similar pattern was observed in RTs for the NSS group, which performed better on midway and inner pairs than their non-synaesthete or GCS counterparts. These results echo findings of previous research showing advantages for NSS in numerical tasks requiring high levels of calculation (Cohen Kadosh et al., 2012; Murray, 2010; Simner et al., 2009) versus those relying on memory (Ward et al., 2009). Notably, unlike the results for parietal tRNS, the interaction for the NSS group did not involve day, suggesting that their advantage was present from the start of the training. This is consistent with many NSS participants' self-report that they began to visualise spatial forms for the symbols starting from the first day.

The lack of day-by-day changes in NSS performance also highlights the difference between the nature of the performance advantages I observed for NSS and for parietal tRNS. Advantages of NSS presumably relied upon explicit visualisation of magnitude order, and seemed to remain consistent throughout the week. That is, once the spatial form of symbol order was established, it appeared to confer the same benefit throughout the week of training. Advantages of parietal tRNS, however, grew over the course of training, and especially emerged later in the training. This is consistent with findings in the tES literature that excitatory stimulation may benefit performance disproportionately *after* neural pathways for a particular task have been established (see: Dockery et al., 2009; although this must be interpreted cautiously, as the paper in question concerns tDCS, which is thought to involve different mechanisms from tRNS). The small differences between the patterns of performance for parietal tRNS and NSS (e.g., onset of advantage, emergence in RT versus accuracy) support the conclusion that an increase in parietal cortical excitability is not equivalent to, nor a sufficient condition for, developing NSS (at least in adults). However, the broad similarities between the two patterns of performance suggest that cortical excitability may indeed be a fruitful avenue of research for investigating the causes of NSS in development.

Results from the learning task also suggested an overall effect of occipital tRNS, manifesting in slower RTs for the occipital group on the first day only. This pattern was reflected both in ANOVA investigating results day by day, and in modeling of response times block by block across the week in a power law function. The fact that the occipital group did not show slower RTs compared to other groups in pre-test tasks suggests that their slow responses in the learning task were due to stimulation. The findings from Dockery, et al. (2009) may help to explain this pattern; they found that increasing cortical excitability (applying anodal tDCS to prefrontal areas for a planning task) improved performance only in later sessions, when neural pathways were presumably already entrenched. Since the process of recognising and discriminating the visual symbols would have been especially relevant on the first day, it is possible that this increase in cortical excitability simply added noise to the process of visually learning the stimuli at first.

The distance transfer task demonstrated that participants showed a clear (RT) distance effect across all groups. However, the distance effect in accuracy was more pronounced in the sham group versus parietal. What does this say about the relative strength of numerical symbol representations in these two groups? Although the distance effect is found in adults (Moyer & Landauer, 1967) as well as children (Holloway & Ansari, 2009), its size has been found to negatively correlate with mathematical achievement (Holloway & Ansari, 2009) and to decrease over time in development, even taking into account changes in domain-general stimulus processing ability (Holloway & Ansari, 2008). Therefore, if numerical training in adults follows developmental trajectories, my results suggest that parietal tRNS during symbol training appears to accelerate learning effects compared to sham stimulation. Specifically, the parietal tRNS group showed a smaller distance effect, which has been associated with better numerical understanding (Butterworth, 2005; Holloway & Ansari, 2009). These results must be interpreted cautiously, as the high overall accuracy levels, especially in the parietal group, suggest that distance effects could be blunted by ceiling effects that speak to a speed-accuracy trade-off. However, I found no interaction of group and distance in RTs, and no correlation between individuals' distance effects in RTs and accuracy; together, these suggest that distance effects in the parietal group was not simply obscured by speed-accuracy trade-off.

The number line task revealed differences in performance across synaesthete groups, with the NSS group showing higher mapping precision compared to the other groups on the first day of symbol training (but not later days). Notably, these results differ from those of Chapter 3, which found that NSS participants were slower to map numbers within the range of their mental number forms. As suggested by self-report of several synaesthetes during a post-experiment debriefing session, this may have been due to the NSS group in the current experiment spontaneously visualising spatial forms, or “symbol lines,” that were congruent to the line presented during the task (in terms of spacing, if not necessarily line direction). At least one NSS participant reported spontaneously visualising a vertical spatial form for the symbols, which helped equally with mapping symbols on forward- and backward-direction lines.

In the analysis of RTs, the number line task yielded differences of stimulation group, with the parietal group responding slower than sham to symbols 3 and 5. Furthermore, the lack of stimulation effects or interactions in the deviation measure suggests this is unlikely to be the result of a speed-accuracy trade-off. Symbols 3 and 5 appeared to be the most difficult to map in all stimulation groups; indeed, if following the popularly reported mapping strategy of placing each symbol in reference to an endpoint or midpoint, 3 and 5 ought to be the slowest because they require multiple steps of first determining the midpoint, then measuring from there. Therefore, it is not surprising that group difference arose only in these symbols. However, because tRNS has previously improved performance when applied to appropriate areas for visual (Fertonani et al., 2011) and numerical (Cappelletti et al., 2013; Snowball et al., 2013) tasks, and because parietal areas are highly implicated in both numerical and spatial processing (Hubbard et al., 2005; Walsh, 2003), I predicted that parietal tRNS would cause improvement, rather than impairment, in the line mapping task. It may be that the parietal group was *a priori* less facile at spatial mapping in general, although this potential explanation is made less appealing by the fact that control tasks found no group differences in pre-tests of mental rotation, visuospatial working memory, attention, or mathematics achievement. Another potential explanation is that parietal tRNS, whilst conferring benefits to training-relevant tasks of symbol comparison, caused impairment to tasks less similar to the training paradigm, such as line mapping. Iuculano and Cohen Kadosh (2013) found similar results with parietal tDCS and symbol learning, finding that the stimulation condition that most benefitted training performance led to costs in a different task paradigm (measuring automaticity).

However, all results from the line mapping task should be taken with caution, given the difficulty of interpreting the deviation results. It is an unfortunate limitation of this task that there is no clear way to discriminate polarity mistakes versus misinterpretation of a symbol's magnitude. Because polarity mistakes can result in extremely high deviation scores, but nonetheless can be difficult to detect, they add a great deal of noise to the deviation data, potentially obscuring significant results.

In conclusion, the results from this chapter suggest that parietal tRNS and NSS may both confer advantages at learning novel numerical symbols, although the nature of these advantages differs. The symbol learning task and distance transfer test showed advantages of parietal tRNS during symbol training, although results from the line mapping task suggest that these advantages might be accompanied by slight impairments of symbol cognition in different cognitive contexts. Results from the symbol learning task and the line mapping task both showed advantages in numerical symbol learning for NSS that were apparent from the first day of training. Results from the symbol learning task suggest that tRNS may affect synaesthete groups differentially, with large advantages of parietal tRNS seen in the GCS group and more modest advantages of occipital tRNS apparent in the non-synaesthete group, whereas stimulation did show significant effects on overall performance in the NSS group.

Chapter 5: Influences of transcranial alternating current on numerical symbol learning

Transcranial alternating current stimulation (tACS) is a non-invasive brain stimulation method that can be used to investigate cognition by entraining endogenous large-scale oscillations of neural activity in the brain. In this experiment, I applied synchronous tACS to left frontal and parietal cortex of adult volunteers in either theta- or gamma-band frequencies, or a sham condition, during three subsequent days of training on novel numerical symbols. At the end of training, participants were tested on their numerical representations of the novel symbols in tasks measuring numerical distance effect, numerical magnitude priming, and automaticity of numerical magnitude. Although all participants showed within-subjects effects of learning the symbols, neither gamma nor theta tACS groups showed any differences from sham in these behavioural measures of numerical learning. Possible reasons for these null findings are discussed in detail.

Introduction

The previous chapter investigated the effects of excitatory brain stimulation (tRNS) during the learning of novel numerical symbols. Methods such as tRNS may be particularly helpful when the set of neural processes underlying a particular function are thought to be diverse, or the frequencies are not known. In such a case, simply excitatory or inhibitory methods such as tRNS and tDCS may theoretically be able to alter neural processing efficacy across many frequencies of neural activity. However, transcranical electrical stimulation is not limited to unilateral excitation or inhibition of cortical activity. Transcranial alternating current stimulation (tACS) is an increasingly popular stimulation method, in which an oscillating current is passed through the brain, periodically alternating between positive and negative current. Although a few studies have compared effects of tRNS and tDCS (e.g., Fertonani et al., 2011), so far there is a dearth of research directly comparing effects of tRNS versus tACS on cognitive performance.

Although tACS at some frequencies can induce cortical excitability (e.g. in motor cortex, Chaieb, Antal, & Paulus, 2011; Zaghi et al., 2010), its primary use in cognitive stimulation paradigms is to entrain large-scale frequency-specific neural oscillations in the cortical areas underlying its application, in order to enhance or inhibit functions thought to rely upon these frequencies (Antal & Paulus, 2013). Measurement methods such as electroencephalography (EEG) and magnetoencephalography (MEG) have long allowed researchers to observe the presence of neural oscillations at various frequencies, and to link them to particular types of cognitive activity; however, it is difficult to disentangle whether these oscillations are instrumental in such activity, or merely an epiphenomenon. TACS allows researchers one step closer to the basis of causality through its ability to directly but noninvasively modulate the oscillatory activity of neural populations (Ali, Sellers, & Frohlich, 2013; Helfrich et al., 2014; Herrmann, Rach, Neuling, & Struber, 2013; Zaehle et al., 2010).

Accordingly, tACS has been used in several cognitive paradigms to manipulate large-scale neural oscillations at specific frequencies, therefore demonstrating the importance of those oscillation frequencies in cognition. For instance, theta stimulation of the parietal cortex was found to improve working memory (Jausovec & Jausovec, 2014; Jausovec et al., 2014) and theta stimulation to left dorsolateral prefrontal cortex was found to increase risk-taking in decision making (Sela, Kilim, & Lavidor, 2012). So far, these studies have been helpful in showing the causality of frequency-specific oscillations in single cortical regions. However, complex cognitive processes, such as numerical tasks, necessarily engage an increasingly complex network of multiple cortical regions, and moreover, require them to work in harmony (Kaufmann et al., 2011; Menon, 2014; Micheloyannis, Sakkalis, Vourkas, Stam, & Simos, 2005). The interregional synchrony of cortical oscillations has long been implicated as important for cognitive processes, and may be the mechanism allowing this harmonious interaction (Fries, 2005; L. M. Ward, 2003). A recent study was the first to causally demonstrate the importance of remote cortical synchrony in cognitive tasks, by showing respective response time benefits and costs of synchronous versus asynchronous tACS to frontal and parietal regions during a working memory task (Polania et al., 2012). This led me to investigate the effects of interregional synchrony in the artificial numeral learning task from the previous chapter.

The current experiment

Frontal and parietal regions have both been repeatedly implicated in numerical tasks (Cohen Kadosh et al., 2008; Kaufmann et al., 2011; Menon, 2014). Furthermore, tES to both frontal (Snowball et al., 2013) and parietal (Cappelletti et al., 2013; Cohen Kadosh et al., 2010) regions have resulted in improvements during multi-day numerical learning paradigms. Therefore I hypothesised that oscillatory synchrony between these two regions may play a role in their cooperation in executing such complex cognitive tasks. Given previous research that has demonstrated importance of working memory ability to learning novel numerical symbols (Lyons & Beilock, 2009), and given the success of Polania and colleagues in affecting working memory with synchronous theta tACS to left parietal and frontal regions, I adapted their stimulation montage for this experiment. Theta-band frequency tACS has additionally been found to improve performance on tests of fluid intelligence (Pahor & Jausovec, 2014) and working memory storage capacity (Jausovec & Jausovec, 2014; Jausovec et al., 2014), therefore it appeared to be a promising frequency to test for the current experiment. As a control, Polania and colleagues further illustrated the frequency-specific effect of their paradigm by finding null effects when employing gamma-band synchronous and asynchronous tACS; following their paradigm, I employed gamma-band tACS as a control frequency as well. I hypothesised that, in line with the findings of Polania et al. (2012), synchronous theta tACS to prefrontal and parietal regions would improve performance in numerical symbol learning, relative to sham or gamma tACS.

Methods

Participants

All participants were healthy volunteers and were screened each day before participation to rule out any possible contraindications to electrical stimulation, including current or previous neurological conditions, drug or alcohol use, or lack of sleep (for the full list of screening questions, see Appendix). All volunteers were further screened by a simple set of questions to check that they did not have either NSS or GCS. In total, 30 Oxford students took part, a mix of graduate and undergraduate. Of these, two participants were excluded from analysis, due to missing sessions or problems with the stimulation device. The 28 remaining participants were allocated randomly to stimulation groups (sham, gamma, or theta tACS), which were balanced for age, gender, and numerical competence (WIAT mathematics composite standardised score; all *p*s>.21). Although sample sizes of around 10 participants per group are typical of tES studies to date (e.g., Cohen Kadosh et al., 2010; Jausovec & Jausovec, 2014), these small sample sizes place considerable limitations on the statistical power of results, and can accordingly increase the chances of both Type I and Type II error; therefore results must be interpreted cautiously.

Table 1: *Stimulation groups balanced by gender, age, and WIAT mathematics composite score*

			Age (years)		WIAT Maths Composite	
Stimulation	N	Gender (F:M)	*Mean*	*SD*	*Mean*	*SD*
Sham	9	4:5	21.44	3.02	228.44	12.06
Gamma	10	5:5	21.20	1.47	238.20	11.32
Theta	9	4:5	22.00	2.55	235.67	12.65

Design

As in chapter 4, the main part of this experiment was a multi-day symbol learning paradigm. In this experiment, the learning paradigm was spread over 3 sessions on consecutive days. On the first and last day, participants also completed ‘symbol assessment’ tasks after the learning session. These were designed to evaluate numerical knowledge of the symbols outside of the learning task’s format of lateralised magnitude comparison. Before and after this entire process, participants were pre- and post-tested on various control measures. As in chapter 4, these measures served dual purposes: to check whether any cognitive gains after training 1) could be attributed to general, rather than training-specific, cognitive improvements, or 2) were offset by cognitive costs in other functions (e.g., Iuculano & Cohen Kadosh, 2013). Participants completed the pre-test session at least one day prior to the start of the learning paradigm, and completed the post-tests directly after symbol assessments on the last day of the learning paradigm.

Tasks

The tasks in this experiment were largely the same as in the tRNS experiment, chapter 4. The main differences were that the symbol learning was condensed from five into three daily sessions, and the number line task from the tRNS experiment was swapped out for a physical-numerical size congruity (Stroop-like) task. Additionally, the 3D mental rotation task was removed from the pre-test, and the working memory task in pre- and post-test was changed from digit and Corsi block spans to a computerized visuospatial working memory task (Hale et al., in press). The other control tasks (attention network test, WIAT mathematics tests, and 2D rotation) remained identical to chapter 4.

The symbol learning task, as in chapter 4, required participants to learn relative magnitudes of seven artificial abstract symbols, based on trial-and-error with feedback. The stimuli and setup replicated those of the tRNS experiment, except that the overall 86 blocks of trials were split over three days instead of five (day 1: 26 blocks, day 2: 34 blocks, day 3: 26 blocks). All learning trials showed pairs of adjacent-magnitude symbols. As in the tRNS experiment, the last session included a 'distance transfer' test of all possible pairings of symbols, to assess the transfer of magnitude understanding from adjacent pairs to greater numerical distance pairs (Tzelgov et al., 2000).

The symbol assessment tasks included a numerical priming task and a size congruity task ("numerical Stroop task.") The numerical priming task was adapted fromVan Opstal, et al. (2008). It presented a single symbol on the screen (any value except 4) and asked participants to judge whether its magnitude was greater or smaller than that of the middle-magnitude symbol (value 4). Participants indicated their answer by pressing P or Q on a QWERTY keyboard. All participants in all sessions began by pressing P if the presented symbol was larger magnitude than 4, and Q if it was smaller, and this response key assignment was reversed halfway through the task. Each trial began with a 500msec fixation, then prior to seeing the stimulus, participants were primed with an 83-msec presentation of another symbol (any value except 4), flanked by a 200-msec visual mask both before and after the prime (see Fig. 1). Primes were categorised as either being identical to the stimulus (e.g., 5 priming 5), congruent key-press (e.g. 6 priming 5; both are larger than 4, so would elicit the same key-press), or incongruent key-press (e.g. 2 priming 5; 2 is smaller than 4 so would elicit a different key-press than 5). Each possible pairing of target and prime (36) was presented twice, except for identical-prime trials, which were presented 4 times each in order to provide enough trials for analysis. This totaled 84 trials, comprised of 24 identical, 24 congruent, and 36 incongruent trials.

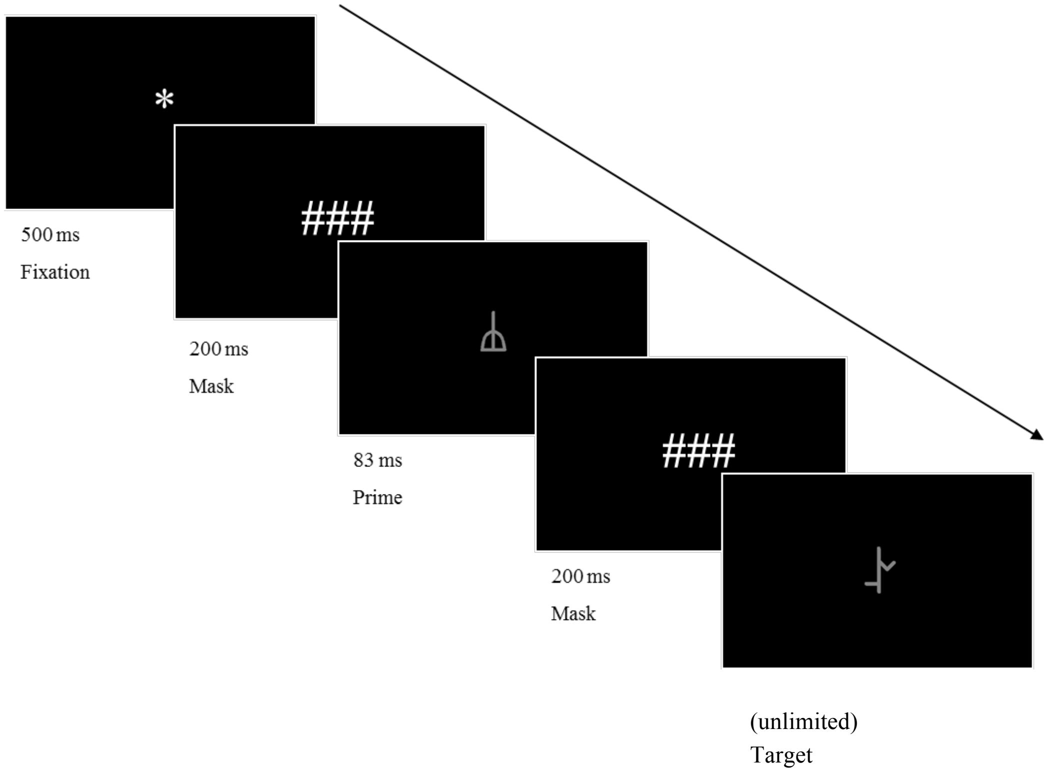

Figure 1: The order of slide presentation in the priming task

The numerical Stroop task asked participants to choose between two symbols presented laterally on a screen, based solely on the physical size of the font whilst ignoring their learnt magnitude values (modeled after: Henik & Tzelgov, 1982; Tzelgov et al., 2000). The task measured automaticity of the learnt magnitudes by systematically manipulating the congruity between the physical size judgment and the numerical magnitude judgment. That is, it compared: congruent pairs, in which the physically larger symbol also had the larger numerical value (e.g. with Arabic numerals, 3 7); incongruent pairs, in which the physically larger symbol had the *smaller* numerical value (e.g., 3 7); and neutral pairs, in which both symbols had the same numerical value (e.g., 3 3).

Stimuli in the numerical Stroop task were manipulated such that the larger symbol was 20% taller and 20% wider than the smaller symbol. All pairs were presented an equal number of times with the physically larger symbol on the left versus on the right. Neutral stimuli included pairs of each symbol, representing values 1-7, differing only in size. Each neutral pair was seen 8 times, for a total of 56 neutral trials. Non-neutral pairs were chosen carefully from the pool of possible unique pairs of symbols. To ensure that the numerical Stroop task did not simply reflect rote learning of symbol pairs from the learning task adjacent-value pairs (e.g. 1&2) were not included. To further ensure that exposure in this task to non-adjacent pairs would not taint the results of the distance transfer test at the end of the training, I used only a small subset of the remaining possible pairs, as done by Tzelgov, et al. (2000). These comprised the symbol pairs corresponding to the numbers: 3&5, 4&6, 1&4, 2&7. Each pair was seen 16 times in each congruency condition, resulting in 64 incongruent trials and 64 congruent trials. Trials began with a 200ms fixation cross, followed by a 300ms blank screen, then the stimulus (user terminated up to 5000ms), and finally a 200ms blank interval before the next trial.

The working memory task (Hale et al., in press) measured visual and spatial working memory. It required participants to remember either the colour or the spatial orientation of 1 to 4 semicircles (low to high cognitive load) presented for 2000ms in the centre of the screen. Participants responded to a single semicircle presented after a 2000ms blank screen delay, indicating with a key press (‘M’ or ‘Z’ on a QWERTY keyboard) whether a semicircle of either this colour (visual condition) or this spatial orientation (spatial condition) had been present in the previous array. Participants were randomized as to whether M or Z would represent yes or no responses. Feedback was presented for 2000ms in the form of a fixation cross in green (correct) or red (incorrect) before the start of the next trial. The spatial and visual conditions of the task were presented in two separate blocks of 48 trials each, with 12 trials in each cognitive load condition (i.e. number of semicircles in the initial array). The spatial and visual conditions yielded two separate measures of visual or spatial working memory (Mohr & Linden, 2005).

Missing Data

One participant's data (sham group) was missing from the symbol learning task, one participant's data (sham group) was missing from the priming task, and two participants' data (one each from sham and theta groups) was missing from the numerical Stroop task, all due to accidental overwriting of data. Because these losses of data were unlikely to be related to the factor of interest, i.e., group assignments, these participants were excluded case-wise from the individual task analyses (Schafer & Graham, 2002).

tACS

Stimulation was administered by a battery-powered wireless StarStim transcranial electrical stimulation device (Neuroelectric, Barcelona, Spain), through three circular rubber electrodes measuring 12.56cm^2 each. Electrodes were housed in saline-soaked sponges to reduce impendence, and were kept in place by a neoprene cap. The electrode montage replicated that of Polania, et al. (2012). Two electrodes delivered synchronous stimulation to the left prefrontal and left parietal cortices, corresponding to areas F3 and P3 in the international 10-20 EEG measurement system. The third electrode served as a reference and was placed over the vertex, area Cz. Each day, participants received either 30 minutes (gamma and theta groups) or 30 seconds (sham) of stimulation, with 15 seconds ramp-up and ramp-down. Stimulation was 1 milliamp peak-to-peak with no direct current offset, at a frequency of either 40Hz (gamma) or 6Hz (theta). These specific frequencies were used by Polania et al. (2012) and would therefore allow my results to maximally comparable to theirs. Participants in the sham group were randomized to receive either gamma- or theta-frequency sham stimulation, consistent across all sessions. Allocation of real and sham stimulation was not known to the main experimenter and the participant (double-blind-like); a secondary experimenter was brought in to control and monitor the StarStim device during stimulation, with no contact with the participant, whilst the primary experimenter explained and administered the tasks.

Results

All trials with RTs more than ±2 *SD* from the mean (by participant and session) were excluded from analysis (symbol learning task, 4.64% of trials; distance transfer task, 4.85% of trials; priming task, 4.42% of trials; numerical Stroop task, 4.29% of trials). Incorrect trials were excluded from RT analyses (symbol learning task, 10.04% of trials; distance transfer task, 7.31% of trials; priming task, 7.97% of trials; numerical Stroop task, 4.46% of trials). When Mauchly's test of sphericity was significant, I used Greenhouse-Geisser values.

Symbol learning tasks

To examine the effects of stimulation on symbol learning, I conducted mixed-model ANOVAs on both accuracy and RT of the symbol learning task. The 3×2×3 design included a between-subjects factor of stimulation group (sham, gamma, or theta) and within-subject factors of orientation ('forward,' i.e., larger symbol on the right, versus 'backward,' i.e., larger symbol on the left) and session (day 1, 2, or 3). The accuracy analysis revealed main effects of orientation (forward more accurate than backward, $F(1,24)=39.66$, $p<.001$, $\eta p^2=.62$), and day ($F(2,48)=20.28$, $p<.001$, $\eta p^2=.46$) but no other effects or interactions (all other *p*s>.13). Post hoc tests on the main effect of day demonstrated that accuracy increased between days 1 and 2 ($t(27)=4.82$, $p<.001$, Cohen's $d=0.91$), and between days 1 and 3 ($t(27)=4.60$, $p<.001$, Cohen's $d=0.92$), but did not differ between days 2 and 3 ($p=.75$). The ANOVA on RTs yielded main effects of orientation ($F(1,24)=42.88$, $p<.001$, $\eta p^2=.64$) and day ($F(2,48)=80.45$, $p<.001$, $\eta p^2=.77$), showing the same patterns of performance as in the accuracy analysis. However, the RT analysis also showed a within-subjects interaction of day and orientation ($F(2,48)=3.51$, $p=.038$, $\eta p^2=.13$; see Fig. 2). Post hoc tests determined that responses were slower for backward than for forward orientation on all days, but that this effect was smallest on day 1 (*t*(27)=2.80, *p*=.009, Cohen's *d*=0.53), largest on day 2, (*t*(27)=7.31, *p*<.001, Cohen's *d*=1.38), and regressed back to an intermediate size on day 3, (*t*(27)=5.32, *p*<.001, Cohen's *d*=1.00). No group effects or interactions in the RT analysis reached significance (*p*s>.13).

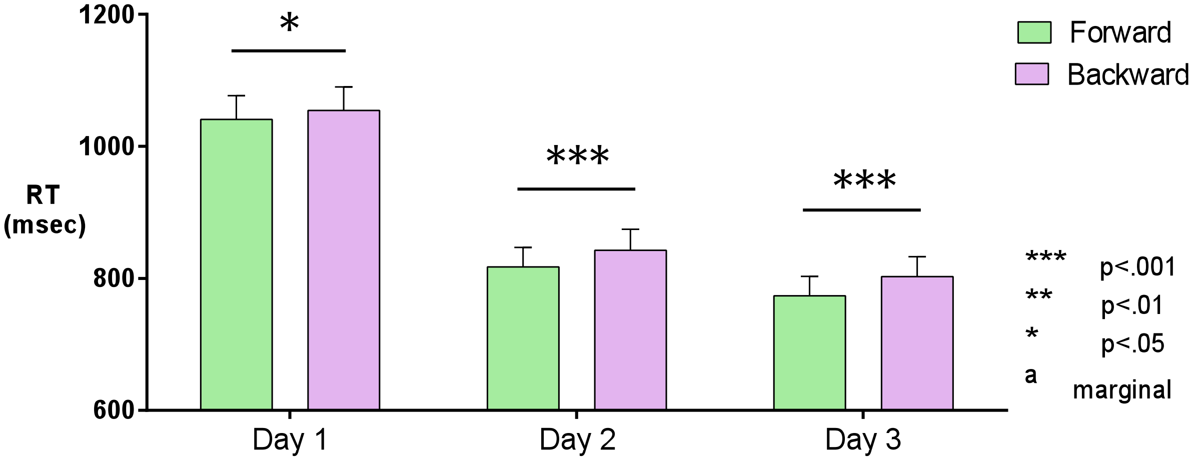

Figure 2: ANOVA of RTs on the main symbol learning task showed an interaction between session and orientation, such that differences between 'forward' (smaller magnitude on left) and 'backward' orientation was larger on later days.

I also modeled individual learning curves based on the same power law function used for the tRNS studies in chapter 4. I used the equation, $RT = \beta * N^{-\alpha}$, where RT is the mean reaction time in a given block, β represents initial performance (reaction time on the initial block), N represents the number of a given block, and α represents the exponential slope of learning trajectory (i.e., the learning rate). This yielded measures of α and β for each participant. I entered these values into univariate ANOVAs with stimulation group as a between-subjects factor; however, neither learning rate (*F*(2,24)=1.56, *p*=.23) nor initial speed (*F*(2,24=2.03, *p*=.15) significantly varied by group. Introducing initial speed as a covariate into the learning rate analysis was similarly ineffective (*F*(2,23)=0.15 *p*=.86).

Distance transfer test

I conducted mixed-model 3×2×5 ANOVA on both RTs and accuracy for the data from the distance transfer test, with stimulation group (sham, gamma, or theta) as the between-subjects factor, and orientation (forward versus backward) and numerical distance (2 through 6) as within-subjects factors. The RT analysis produced a main effect of numerical distance (*F*(2.22,53.24)=19.55, *p*<.001, ηp^2=.45) but no other effects or interactions (*p*s>.24). The accuracy analysis also produced a main effect of numerical distance (*F*(2.98,71.49)=4.42, *p*=.007, ηp^2=.16) as well as a marginal main effect of orientation (*F*(1,24)=3.53, *p*=.072, ηp^2=.13) indicating that answers were slightly more accurate for forward than for backward trials. No other effects were significant (*p*s>.18).

Priming task

For the priming task, I conducted mixed-model 3×2×3 ANOVAs on accuracy and RT, with a between-subjects factor of stimulation group (sham, gamma or theta) and within-subjects factors of session (first or last) and prime-target congruency (incongruent key press, congruent key press but non-identical prime, or identical prime). The ANOVA for accuracy rates yielded almost no significant effects (*p*s>.26) apart from the marginally significant main effect of congruency (*F*(2,48)=2.94, *p*=.062, ηp^2=.11; see Fig. 3A). Post hoc tests indicated that this congruency effect was due to a lower accuracy rate for incongruent trials compared to identical (*t*(26)=2.41, *p*=.023, Cohen's *d*=0.), and, marginally, compared to congruent trials (*t*(26)=1.75, *p*=.092, Cohen's *d*=0.46), whereas congruent and identical trials did not differ in accuracy (*p*=.61). The ANOVA for RT yielded significant main effects of both session (*F*(1,24)=17.28, $p<.001$, $\eta p^2=.42$) and congruency (*F*(2,48)=25.74, $p<.001$, $\eta p^2=.52$; see Fig. 3B), although no other effects or interactions reached significance (*p*s>.18). The main effect of session indicated that, unsurprisingly, RTs were faster in the final versus initial session. The main effect of congruency was similar to the accuracy analysis, in that incongruent trials resulted in worse performance (slower RT) compared to identical trials (*t*(26)=5.25, $p<.001$, Cohen's *d*=1.01). However, unlike in the accuracy analysis, incongruent trials did not differ from congruent trials (*p*=.78), and congruent trials were significantly slower than identical trials (*t*(26)=5.76, $p<.001$, Cohen's *d*=1.11). Taken together, these results suggest that accuracy of response was affected by motor priming (i.e., the congruency of key press between prime and target), whereas speed of response was affected by perceptual priming (i.e., whether the prime was identical to the target).

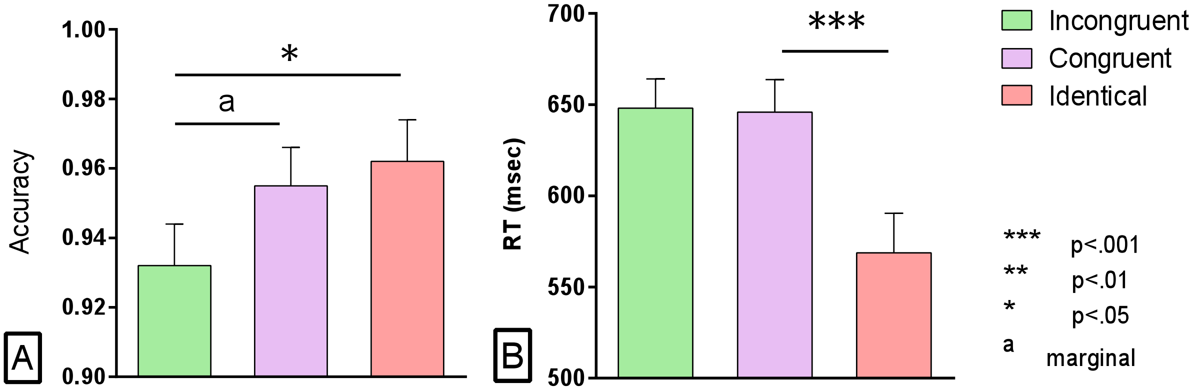

Figure 3: ANOVAs on both accuracy and RT in the priming task found a main effect of congruency across both days. Their different patterns suggest that motor priming surfaced in accuracy rates and perceptual priming surfaced in RTs.

Numerical Stroop task

To investigate the effects of stimulation on automaticity of symbol magnitude associations, I conducted two mixed-model ANOVAs on the size Stroop task data, one each with RT and accuracy as dependent variable. The 2×3×3 design comprised within-subject factors of session (first or last) and congruency (incongruent, neutral, congruent), and a between-subject factor of stimulation condition (sham, gamma, or theta). The RT analysis revealed main effects of session ($F(1,23)=43.90$, $p<.001$, $\eta p^2=.66$) and congruency ($F(2,46)=11.67$, $p<.001$, $\eta p^2=.34$), as well as an interaction between these two factors ($F(2,46)=4.79$, $p=.013$, $\eta p^2=.17$; see Fig. 4). Decomposing the interaction revealed significant simple effects of congruency on both the first session ($F(2,52)=14.99$, $p<.001$, $\eta p^2=.37$) and the last session ($F(1.51,36.52)=5.77$, $p=.013$, $\eta p^2=.18$). Paired-samples t-tests found that in the first session, incongruent trials were slower than both neutral ($t(26)=4.85$, $p<.001$, Cohen's $d=0.93$) and congruent trials ($t(26)=4.32$, $p<.001$, Cohen's $d=0.83$), and neutral and congruent trials did not differ ($p=.98$). However, on the final day, incongruent trials were still significantly slower than both neutral ($t(26)=2.13$, $p=.043$, Cohen's $d=0.41$) and congruent trials ($t(26)=2.73$, $p=.011$, Cohen's $d=0.53$), but congruent trials were marginally faster than neutral ($t(26)=1.96$, $p=.061$, Cohen's $d=0.38$). No other effects or interactions reached significance (ps>.35).

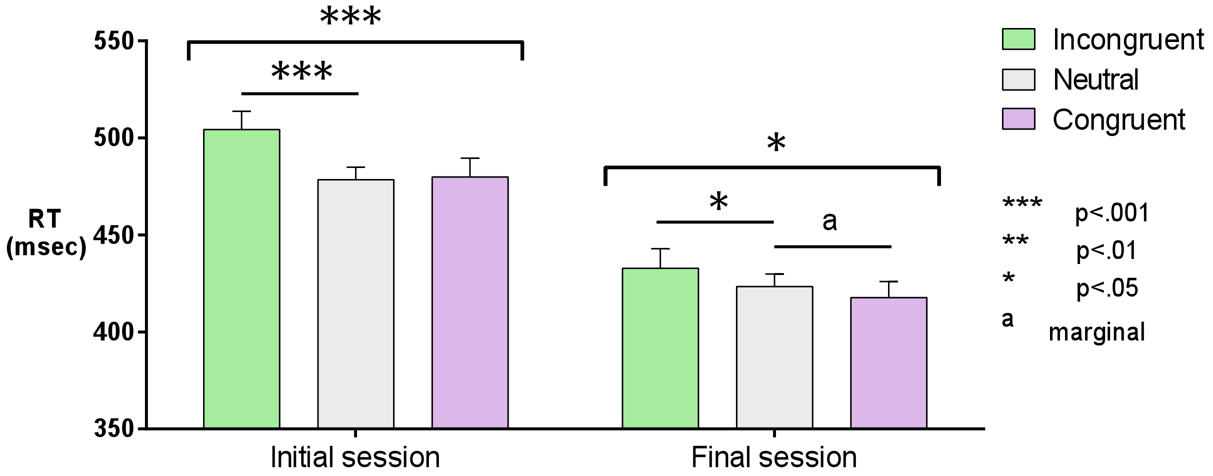

Figure 4: ANOVA of RTs in the numerical Stroop task revealed a within-subjects interaction between session and congruency, due to a marginal facilitation effect of congruent trials on the final but not initial session.

The ANOVA on accuracy rates produced main effects of session ($F(1,23)=15.39$, $p=.001$, $\eta p^2=.40$) and congruency ($F(2,46)=16.98$, $p<.001$, $\eta p^2=.43$), indicating that performance was better in the initial versus the final session and on both neutral ($t(26)=5.65$, $p<.001$, Cohen's $d=1.09$) and congruent trials ($t(26)=4.56$, $p<.001$, Cohen's $d=0.88$) as compared to incongruent (congruent and neutral trials did not differ, $p=.83$). No other effects or interactions reached significance (ps>.20).

Control tasks

None of the measures from control tasks (attention network test, visual working memory, spatial working memory) showed any interaction effects of group and session (ps>.24), indicating that stimulation did not appear to differentially affect these other cognitive abilities.

Discussion

Contrary to the hypothesised frequency-specific effects of tACS, no group differences arose in any of the tasks between those receiving sham, gamma, or theta stimulation when synchronous tACS was applied to left parietal and left prefrontal cortex. However, the tasks did yield certain within-subjects effects that are worthwhile to note. First, the symbol learning task revealed an increase in orientation effects on RT across days, suggesting that the relative presentation frequencies of ‘forward’ and ‘backward’ spatial orientations had an effect on the learning of relative numerical magnitudes. Second, the results of the numerical priming task showed that participants developed a degree of automaticity in their understanding of the numerical magnitudes, illustrated through congruity effects of response choice in accuracy rates. Third, the numerical Stroop task similarly illustrated an automaticity of numerical magnitude processing in the novel numerical symbols. With RT, this automatic magnitude processing increased from simply a performance cost of size incongruity on the first day, to both a cost of incongruity and a benefit from congruity on the final day. This suggests that automaticity of magnitude processing continued to improve after the first day of training. Indeed, the relatively high accuracy rates in all tasks indicate that training was effective and participants learned the magnitude values of the symbols.

However, there was an overwhelming lack of group effects. Although learning did indeed occur, gamma and theta tACS groups did not differ from sham in any of the measures in the symbol learning, priming, or size Stroop tasks. These null effects speak to the difficult logistical nature of brain stimulation paradigms, and especially of the complications introduced by multi-channel stimulation montages.

There are many possible causes for this experiment's null effects. The first and most obvious is the temperamental nature of the brand new equipment I used. To the best of my (and the manufacturer's) knowledge, I was the first to use synchronous tACS in an experimental paradigm, and problems with the software controlling the StarStim system resulted in stimulation frequently shutting itself off due to errors in regulating impedance levels. This occurred between 3 and 15 times per session for at least one session for over half of the participants in the gamma and theta tACS groups. Because tACS relies on entrainment of endogenous large-scale oscillations in neural activity, stopping and re-starting stimulation may in fact interfere with these oscillations, as the stimulation is very unlikely to start back up at the same point in the phase. This consequence of breaks in tACS means that a large portion of participants could have experienced alternating periods of cognitive facilitation and impairment arising from the stimulation, therefore introducing noise into the dataset.

A second possibility is that tACS was not effective at modulating the targeted areas of cortex in some or all participants, due to individual differences. Relatively close placement of reference electrode to stimulation electrodes, depending on the shape of the participant's head, could have caused current shunting across the scalp, reducing effects of stimulation. Even when applied with the best possible theoretical montages, effectiveness of tES has been found to vary greatly across and even within individuals, depending on attributes as diverse as skull thickness and phase of menstrual cycle (B. Krause & Cohen Kadosh, 2014; Lopez-Alonso, Cheeran, Rio-Rodriguez, & Fernandez-Del-Olmo, 2014). Because I did not employ concurrent brain imaging, it is impossible to judge whether tACS indeed had an effect on cortical activity, and the nature of such effect.

TACS also adds a unique complication to the pool of individual variation in tES effectiveness; because tACS works by entraining and boosting endogenous oscillations, recent findings (Schmidt, Iyengar, Foulser, Boyle, & Frohlich, 2014; Zaehle et al., 2010) have demonstrated tACS to be more effective when the frequency is exactly matched to endogenous frequencies, rather than adhering to mean frequencies of typical frequency bands. For instance, Zaehle et al. found a range of endogenous alpha frequencies spanning 9.42 to 11.28 Hz among their participants, and more recent evidence suggests that endogenous alpha may extend well beyond this, from approximately 7 to 14Hz (Haegens, Cousijn, Wallis, Harrison, & Nobre, 2014), meaning that using a standard alpha frequency of 10z could have been mismatched to some participants by over 40%. Even controlling for individual differences in tACS effectiveness and endogenous frequencies, other physiological constraints may have dampened the effectiveness of tACS. Previous studies have shown that tACS only facilitated frequency-specific power when endogenous oscillations were low (Neuling et al., 2013); perhaps, analogously, synchrony between the targeted regions was already high in some or all participants, and stimulation did little to enhance it. This would square with previous accounts that brain stimulation may be able to help those with poor performance more than those with already high performance (Looi, Duta, Huber, Nuerk, & Cohen Kadosh, 2013).

The final possibility is, of course, that synchronous tACS in this montage simply does not benefit the symbol learning process. Polania, et al. (2012) found this setup of theta-band tACS to improve working memory performance, but the working memory demands in this task during training could be argued to be relatively low (there were 6 symbol pairs, or 12 when orientation is taken into account, but each trial in both learning and testing paradigms involved maximum two symbols). Furthermore, learning novel symbols and their associated relative magnitudes is arguably a more complex process than the working memory task employed by Polania et al., which required participants to recall the order of three familiar alphabetic characters. Entrainment of oscillatory synchrony between frontal and parietal regions at theta frequency, whilst helpful in Polania and colleagues' relatively simple task, may have disrupted other important phase couplings of neural populations within the field of stimulation. Indeed, functional segregation through a multiplicity of phase couplings has been found to be instrumental in coordinating the many processes underlying complex cognitive tasks such as numerical manipulation (Dimitriadis et al., 2012).

Chapter 6: The relationship of visuospatial manipulation and processing ability to numerical magnitude learning

Visuospatial mental imagery (VSMI), specifically mental rotation, has been linked to strength of basic numerical representations. Another type of VSMI, number-space synaesthesia (NSS), has been found to confer benefits in learning novel numerical symbols. However, it is unclear to what extent the ability to recognise and visuospatially manipulate number symbols helps to learn their magnitude values. Therefore, this experiment tested mental rotation ability and symbol recognition ability in a group of 79 participants before and after they undertook intensive multi-day training paradigms to learn novel numerical symbols. Learning rate of the symbols was correlated with a pre-test of 3D mental rotation, as well as with symbol recognition ability measured after, but not before, training of the symbols' relative magnitudes. Similarly, numerical distance effect in the symbols was correlated with symbol recognition after, but not before, training. Because the numerical distance effect is a measure that cancels out the contribution of visual processing to performance, these results are interpreted as suggesting that greater visual recognition of symbols is associated with stronger numerical representation when learning novel numerical symbols.

Introduction

Numerical cognition in a numerate and literate population not only involves the conceptual understanding of numbers as precise quantities with systematic relationships, but also requires the processing of numbers' symbolic forms. This chapter is concerned with one of the most common symbolic forms of numbers in highly-developed societies: visually processed numerals.[4] Ubiquitous in everyday life, numerals are typically learned early in development, and in educated populations they tend to be overlearned (Eagleman, 2009; Manuela Piazza, 2010). Numerical cognition inherently contains many visuospatial aspects; for instance, quantity and magnitude have spatial correlates in the real world (e.g., volume, distance), and even the neurological organisation of number representation in cortex is thought to be topographical (Harvey et al., 2013). Numerals make this connection even stronger. Because they are of the visuospatial domain, numerals force people to interact visuospatially with numbers. Namely, beyond the basic demand that numerals require visual decoding, numeral formats require additional overt visuospatial interaction with numbers, e.g., through the place value system in multi-digit numbers or the spatial layout of fractions. Arabic numerals even reflect increasing ordinal and cardinal value from 1 to 3 in the increasing visual complexity of the symbol (although the cognitive and cultural origins of this correspondence may be impossible to verify).

Being in the visuospatial domain allows numerals to be incorporated into other visuospatial contexts, as attested by cultural inventions such as clocks and rulers; in turn, explicitly invoking these visuospatial contexts has been shown to exert spatial effects on number processing (Bachtold et al., 1998). Visuospatial mental imagery of numbers is widespread, as observed by the use of number lines in teaching (Ernest, 1985), prevalence of the SNARC effect (Dehaene et al., 1993), and popularity of cultural aids such as calendars. More explicit examples of visuospatial mental imagery of numbers are found in the atypical and involuntary phenomena of NSS and GCS (Sagiv et al., 2005; Simner et al., 2006).

These non-exhaustive examples indicate that number cognition encompasses visuospatial aspects, including the use of numerals; what is less clear is how visuospatial ability may affect or

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[4] Obviously in most numerate humans, number-learning involves an important auditory symbolic element as well; but for parsimony and elegance of experimental design, this verbal element was not addressed in this study

interact with numerical learning and representation. Therefore, in this chapter I sought to investigate how visuospatial manipulation and processing ability relate to numerical magnitude representation (as measured by ability to learn numerical meaning of novel characters).

The current experiment

In chapter 2, I found that a standard measure of mental rotation ability was related to basic numerical representation. However, there were three aspects of that finding I wished to expand upon. First, the stimuli in the mental rotation measure were drawings of 3D objects. Could better insight be gained from a measure of rotation with 2D objects, in fact the very numerals used to symbolically represent numerical meaning? Second, the basic numerical representations measured in chapter 2 were, for the most part, multi-digit numbers. It is possible that the spatially-based place value system inherent in such numbers could account to some degree for the relationship to visuospatial object manipulation abilities. Therefore, an assessment of single-character numerals would be required in order to rule this out. Third, although the numerical representations measured in chapter 2 were accessed via visual numerals, there was no measure to differentiate the importance of the visual numeral versus the underlying meaning. The current experiment was able to address all three of these issues in one fell swoop, by assessing 2D mental rotation with single-character numerals and taking separate measures of perceptual and representational processing.

In this experiment I sought to investigate how the visuospatial abilities involved in processing numerals are related to ability to learn and access numerical meaning (on an individual basis). The studies in chapters 4 and 5, in which participants learned a set of novel numerical symbols over the course of several days, offered a model of numerical acquisition through which to investigate this question. To measure visuospatial manipulation and processing ability in a manner maximally relevant to the question, I employed a task that can measure both mental rotation and visual recognition of characters. The task utilised stimuli in two categories: both from the set of novel numerical symbols, and as a control, from a set of characters already well-known to the participants (i.e. Roman alphabet, so as to avoid priming the participants with the idea that the novel symbols represented numbers). This was administered before the multi-day symbol learning procedure began, as a pre-test, and again after the procedure, as a post-test, to document changes related to the learning of the novel symbols. The symbol-learning procedure itself offered measures of the learning trajectory (through learning rate, calculated across the sessions) and of eventual strength of numerical representation (through a distance effect calculated from novel pairings of the learnt symbols, after the last learning session). This format of measuring the distance effect (comparing two numerals visually) has been found to be a reliable measure of magnitude processing (Maloney et al., 2010).

Hypotheses

This experimental setup led to several hypotheses related to my research question.

1. Concerning the effects of brain stimulation, I hypothesised that tRNS to the occipital cortex during symbol learning would facilitate visual recognition of these learnt symbols, but not of pre-learnt stimuli (letters).

2. Benefits of brain stimulation are thought to be task-dependent (Cappelletti et al., 2013; Cohen Kadosh et al., 2010), suggesting that even though the parietal cortex is implicated in mental rotation (Carpenter et al., 1999; Gogos et al., 2010), stimulation would not benefit this skill since it was not practiced during stimulation. However, because the after-effects of tRNS can last up

to 90 minutes after stimulation (Terney et al., 2008) and mental rotation ability was post-tested less than an hour after the end of stimulation, I hypothesised that post-tests of 2D mental rotation ability might be improved by parietal, but not sham or occipital, TRNS.

3. Based on findings in chapter 2, i.e., that 3D mental rotation was linked to basic number representation ability, I hypothesised that 3D and 2D mental rotation measures ought to predict numerical representation ability of the learnt symbols as well. If so, this would provide stronger evidence toward the hypothesis that spatial manipulation abilities (or at least a cognitive profile associated with them) aid in learning novel numerical representations.

4. Regarding mental representation of the newly learnt symbol magnitudes, I hypothesised that symbol recognition ability, but not letter recognition ability, would positively correlate with measures of mental representation, i.e. learning rate and symbol distance effect. Furthermore, the mechanisms of how symbol recognition contributed to symbol learning could be illuminated by observing *which* of these mental representation measures related to symbol recognition. If symbol recognition ability helped only to facilitate faster answers in tasks dependent on visual response, then I would expect to observe that symbol recognition would relate to learning rate alone. However, if advantages in visual symbol recognition also help individuals to learn the *value* of symbols, this benefit should be evident even in a measure that captures only representation, e.g. by taking into account the effect of visual processing. Therefore I hypothesised that if the latter model of mechanisms is true, symbol recognition ability ought to correlate positively with the strength of distance effect in the learnt symbols.

Methods

Participants

The participants comprised volunteers (*N*=89) who took part in one of the two symbol learning and brain stimulation experiments previously detailed in chapters 4-5. Ten participants were excluded from this analysis: several participants from chapter 4 (*N*=6) and chapter 5 (*N*=3) did not complete all of the rotation tasks; and one participant from chapter 5 was excluded because accuracy rates on both symbol rotation tasks (43.95% and 45.77%) did not significantly vary from chance level (i.e. 50%; $t(156)=1.52$, $p=.13$; $t(141)=1.01$, $p=.32$).

A table of synaesthesia and stimulation conditions of all participants in this experiment is included below.

Table 1: Numbers of participants in the symbol learning studies who completed pre- and post-tests of a rotation task with letters and symbols

Experiment	**Synaesthesia**	**Stimulation** tRNS Parietal	tRNS Occipital	Sham	Gamma Parietal	Theta Parietal
Ch. 4	Non-synaesthete	8	10	7	n/a	n/a
	NSS	4	5	5	n/a	n/a
	GCS	5	5	5	n/a	n/a
Ch. 5	Non-synaesthete	n/a	n/a	7	10	8

Stimuli

Stimuli were displayed centrally on a computer screen at a distance of approximately 55cm from the participant, and when upright measured a maximal height of 3.4cm. Stimuli comprised the letters R and G in Times New Roman font; and two asymmetric symbols from the week-long symbol learning task (those representing values 5 and 6).

Procedure

Participants were instructed that in each trial they must judge whether a letter (or symbol) on the screen was presented in a forward (normal) or backward (mirror-reversed) orientation. Participants indicated their judgment by pressing keys on the number pad of a typical keyboard with their right hand ('1' for forward, with index finger, or '2' for backward, with middle finger.) The letters or symbols appeared either upright or rotated clockwise at angles of 60, 120, 180, 240 or 300 degrees. Participants saw each stimulus 6 times, except for upright stimuli, which were seen twice as often. This resulted in a total of 168 trials (2 orientations × 6 rotation angles × 2 stimuli × 6 times presented + 24 extra upright trials). Participants completed this in 4 blocks of 42 trials each, separated by a user-terminated break period. Before the main task, participants completed 12 practice trials with feedback: "correct" or "incorrect" was presented on the screen after each trial for 500ms. Each trial began with a fixation cross for 250ms, followed by a blank screen of 250ms, followed by the main stimulus terminated by participant response. A new trial began 200ms after the previous response.

Design

Both the letter rotation and symbol rotation tasks were administered during pre-test and post-test sessions for the symbol learning study. The letter rotation task was always administered first. 54 participants (those in the TRNS studies) completed the 3D Vandenburg & Kuse mental rotation task as well; this was administered at the beginning of the pre-test session.

EZ Diffusion Model

RT and accuracy are relatively easy to capture, but at best they are only proxy measures of underlying mental processes that cognitive psychology seeks to investigate. Therefore, various attempts have been made to distil from them other measures that better represent the actual performance of the brain during cognitive tasks. One such attempt is the EZ diffusion model (Wagenmakers, Van Der Maas, & Grasman, 2007), so named because it is a simplified version of the earlier Ratcliff diffusion model (Ratcliff, 1978), modeling only three variables compared to the previous version's seven. Diffusion models operate on the assumption that patterns of response speed and accuracy on cognitive tasks will vary meaningfully according to several separate internal mental parameters, such as accumulation rate of information ("drift rate"), threshold of certainty required to make a decision ("response conservativeness"), and visuomotor processing speed ("non-decision time"). For a dichotomous forced-decision task, EZ extracts measures for these three parameters from inputs of percentage accuracy, and RT mean and variance. These three parameters are preferable to traditional RT and accuracy measures when, as in this chapter, the investigator wishes to examine mental processing ability (represented by the "drift rate"), regardless of high individual variation in levels of "response conservativeness" (i.e. how much participants prioritise speed versus accuracy).

As any model does, EZ makes several assumptions about the data being modelled, which must be checked before using it for analysis. It first assumes that the data show some degree of right skew; according to both visual checks and to descriptive statistics this was indeed the case (letters: skewness of 1.73, *SE*=.024; symbols: skewness of 2.19, *SE*=.024). Secondly, in simplifying elements of the Ratcliff model, EZ assumes that RT does not differ systematically for correct versus error responses. This was not upheld in both parts of the dataset (letters:

t(76)=1.34, p=.19; symbols: *t*(77)=3.07, p=.003); however, this was likely an artefact of most participants' very low rate of errors overall in the symbols task (mean, 6.44%). Therefore I ameliorated this misspecification by including only RTs of correct trials in the diffusion model analysis, as recommended by Wagenmakers, et al. (2007). Lastly, the model assumes that the two response choices are *a priori* equally attractive; if they are not, then errors will be slower than correct responses for one response choice, and faster for the other. By running a two-way repeated-measures ANOVA on RT for the variables of response choice ("backward" vs. "forward") and response correctness (error vs. correct) I determined that there was no such significant interaction (letters: F(1,45)=2.36, p=.13 ; symbols: F(1,51)=1.99, p=.16). Therefore I determined it was appropriate to apply the EZ model to the task.

Results

All trials with RTs more than 2 SD from the mean were excluded from analysis (letter task: 5.18% of trials; symbol task: 5.50% of trials). Measures of task performance were calculated separately for each version (letter versus symbol) and session (pre versus post) of the task, resulting in four values per measure per participant.

Rotation measures

To calculate a measure of rotation ability, trials were first separated by absolute value of rotation angle from upright (i.e. 0), yielding four rotation categories: 0, 60, 120, and 180 degrees. Because participants varied in the degree to which rotation effects manifested in RT versus accuracy, for each participant I calculated a combined measure of performance ability (i.e. drift rate, from the EZ diffusion model) for each rotation category, from that category's mean RT, variance in RT, and percentage accuracy (for more explanation of drift rate and the EZ model, see the end of the previous section, Methods). Mean ability (drift rate) score was .20 (*SD*=.093). To estimate the extent to which mental rotation demands impaired performance, I then calculated a regression slope for these ability measures in relation to their rotation categories (cf.Viarouge, Hubbard, & McCandliss, 2014). This resulted in a set of slopes significantly lower than 0 (all $t(78)>7.30$, $ps<.001$), with mean slope of -0.56 (*SD*=0.59), representing a 0.033 decrease in ability for each 60 degrees of rotation from upright. This yielded a single measure of mental rotation performance per participant for each version and session of the task; because the slopes are negative, higher values indicate less incremental effect of rotation on performance (shallower slopes), and thus better rotation ability.

Symbol recognition measures

The rotation task relies upon responses to a simple backward/forward judgment. Therefore, if one removes the added manipulation of rotation, the task becomes in essence a visual recognition measure. Because correlations between RT and accuracy showed some evidence of a speed accuracy trade-off (symbol recognition pre-test: $r= -.23$, $p<.05$), I again used the EZ diffusion model to calculate a combined ability measure from mean and variance of RT and percentage accuracy. To ensure that differences in rotation ability did not confound this measure, this was computed from upright trials only. This yielded a single measure of stimulus recognition ability per participant for each version and session of the task; higher scores indicate higher overall stimulus recognition ability.

Distance effect slopes for symbol learning task

To measure participants' distance effect in the symbols, I used the symbol magnitude comparison task completed by participants after all learning trials were completed. This task included all possible pairings of the set of symbols; I used only those that were novel pairs (i.e., those that were not presented during the learning phase). Matching the symbols with their analogous numbers, I calculated mean RT and accuracy for pairs within bins of each possible semantic distance (2-6 "symbol units" apart). Pairs of semantic distance of 1 were excluded as these were the pairs the participants were trained on (as in Tzelgov et al., 2000). For each participant, a distance effect in RT was calculated by subtracting the average of the largest distance pairs (distances 5 and 6) from the average of the smallest distance pairs (distances 2 and 3) and dividing this difference by the larger RT (i.e., smallest distance pairs, distances 2 and 3) to account for differences in overall response time, as done in Holloway and Ansari (2009).

Distance effects for accuracy were calculated in the same way. The distance effects were significantly greater than 0 (RT: $t(78)=15.76$, $p<.001$; $M=.13$, $SD=.07$; accuracy: $t(78)=5.00$, $p<.001$; $M=.02$, $SD=.04$), indicating that the participants did indeed show characteristic distance effects. Note that *smaller* distance effects (i.e., smaller differences between processing large-distance pairs and small-distance pairs) indicate *stronger* numerical representation.

ANOVAs

To investigate the hypotheses that brain stimulation during symbol learning may affect subsequent ability at symbol recognition and mental rotation ability, I conducted mixed-model ANOVAs with stimuli (letters or symbols) and session (pre or post) as within-subjects factors, and stimulation type as a between-subjects factor (separate analyses were conducted for the combined TRNS study: sham, parietal or occipital TRNS; and the TACS study: sham, gamma, or theta tACS). In the TRNS study, which included synaesthetes (both NSS and GCS) as well as controls, synaesthesia type was also included as a between-subjects factor. Separate ANOVAs were conducted with rotation ability or recognition ability as the dependent variable.

Rotation ability

In the ANOVA of rotation measures in the TRNS study, no main effects or interactions with group factors were significant (Fs< 2.12, ps>.13). However, the interaction between stimuli and session reached significance ($F(1,45)=7.92$, $p=.007$, $\eta p^2=.15$). Post hoc tests revealed that in the pre-test, rotation scores were significantly lower (indicating greater effects of rotation) in the letters version of the task compared to the symbols versions of the task ($t(78)=4.69$, $p<.001$, Cohen's d=0.53), whereas no such difference existed between stimuli types in the post-test (p=.54).

In the ANOVA of rotation measures in the TACS study, a within-subjects main effect of stimuli type (F(1,22)=13.44, p=.001 ηp^2=.38), indicated that rotation scores were lower (indicating greater effects of rotation) on the letters than on the symbols versions of the task. No other main effects or interactions reached significance (Fs< 1.21, ps>.28).

Recognition ability

The ANOVA of recognition ability scores in the TRNS study revealed three main effects. The main effect of stimuli (F(1,45)=25.69, p<.001, ηp^2=.36) revealed that scores were higher for the letters version than the symbols version of the task. The main effect of session (F(1,45)= 95.11, p<.001, ηp^2=.68) indicated higher scores for post-tests versus pre-tests. Lastly, the main effect of synaesthesia type was only marginally significant (F(2,45)=2.59, p=.086, ηp^2=.10). Post hoc tests revealed that non-synaesthete control group participants performed worse overall compared to NSS group participants (t(37)=2.19, p=.035, Cohen's d=0.73), whereas no other pairwise comparisons reached significance (ps>.20; Sham, M=.184; NSS, M=.214; GCS, M=.200). No other effects in this ANOVA reached significance (Fs<2.20, ps>.14).

The ANOVA of recognition ability scores in the TACS study revealed main effects of stimuli (F(1,22)=24.79, p<.001, ηp^2=.53) and of session (F(1,22)=22.56, p<.001, ηp^2=.51), as well as an interaction between those two variables (F(1,22)=16.33, p=.001, ηp^2=.43). These effects were explained by a higher-order, three-way interaction effect of stimuli type, session, and stimulation group (F(2,22)=3.26, p=.058, ηp^2=.23). Decomposing this interaction revealed no simple two-way interaction for the sham stimulation group (p=.64), but only the simple main effects of stimuli (*F*(1,6)=12.41, *p*=.012, ηp^2=.67) and session (*F*(1,6)=15.33, *p*=.008, ηp^2=.72). A significant simple interaction of stimuli and session in the gamma TACS group, however (*F*(1,9)=15.17, *p*=.004, ηp^2=.63), revealed that performance on the symbol version of the task was significantly lower in this group in the pre-test (*t*(9)=5.71, *p*<.001, Cohen's *d*=1.81) but there was no difference in performance between letter and symbol tasks in the post-test (*p*=.93). The theta TACS group showed a similar pattern, with a significant simple two-way interaction (*F*(1,7)=6.37, *p*=.040, ηp^2=.48) revealing lower performance in the symbols versus letters in the pre-test (*t*(7)=4.93, *p*=.002, Cohen's *d*=1.74) but not in the post-test (*p*=.42).

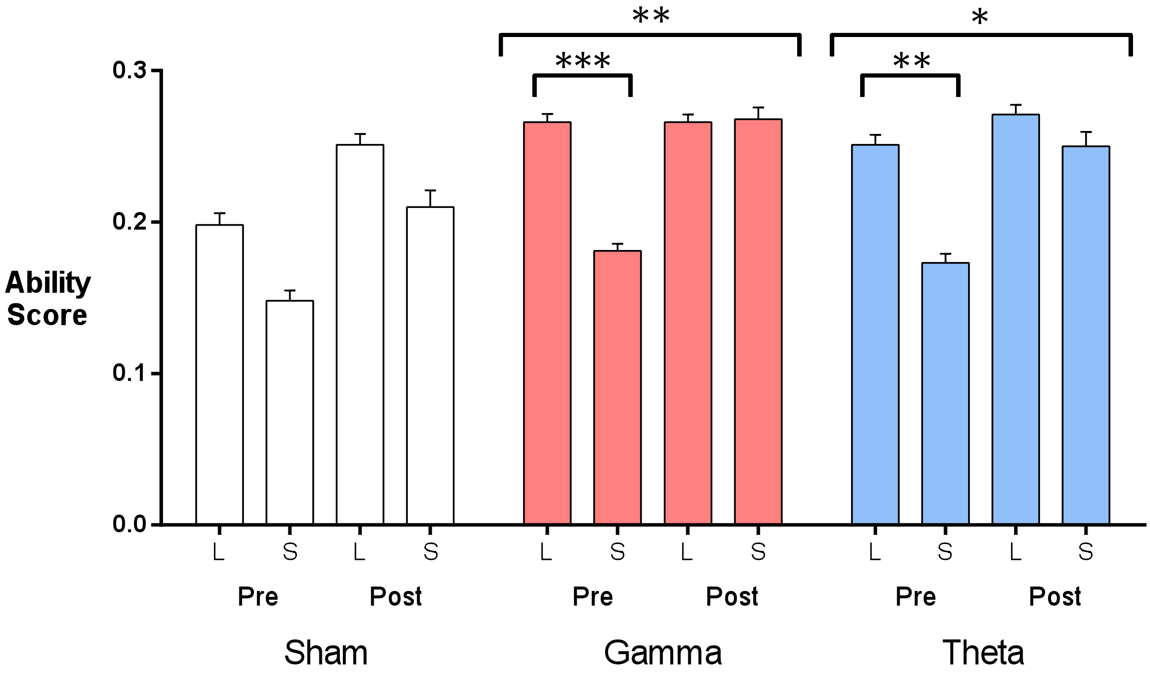

Figure 1: A three-way interaction of stimuli type (letters vs. symbols), session (pre- vs. post-test), and stimulation group (sham, gamma TACS or theta TACS) revealed that Gamma and Theta stimulation groups showed a significant simple two-way interaction between stimuli and session, whereas no such interaction emerged in the Sham group. The two-way interactions were the result of a significantly lower score on symbol versus letter stimuli in the pre-tests but not the post-tests. Error bars represent +1 standard error mean.

Correlation Analyses

To determine whether rotation or symbol recognition ability were related to symbol learning performance, I entered 12 relevant variables in a matrix of bivariate correlations. Overall symbol learning performance was measured by the initial speed (β) and learning rate (α) variables from the power law function analysis of learning rates in Chapter 4, as well as by the symbol distance effect measured from the post-learning symbol comparison. Only symbol distance effect for RT is presented, as the accuracy measure did not correlate with any other measures in the table (*p*s<.11). Mental rotation performance was measured by the four (version × session) performance measure values calculated above, as well as by the 3D task that had been administered to a portion of the participants. Symbol recognition ability was measured by the four (version × session) performance measure values calculated above. See below for a table of all correlations.

Table 2: Values of correlation coefficients from measures of symbol learning, mental rotation, and letter/symbol recognition

		LR (α)	Initial Speed (β)	Symbol Distance Effect	3D Rotation	Rotation				Recognition			
						Letters		Symbols		Letters		Symbols	
						Pre	Post	Pre	Post	Pre	Post	Pre	Post
Learning Rate (α)	r	1	**.783****	-.006	.216	.037	.133	-.140	-.043	-.046	.068	.020	**.308****
	p		**<.001**	.961	.117	.744	.244	.217	.707	.686	.550	.863	**.006**
Initial Speed (β)	r		1	-.187	.009	-.011	.183	-.078	.060	-.189	-.130	-.126	.050
	p			.100	.951	.922	.106	.494	.600	.096	.254	.267	.663
Symbol Distance Effect	r			1	.021	.028	-.051	-.020	-.075	**-.260***	-.172	-.190	**-.265***
	p				.878	.805	.653	.860	.513	**.021**	.129	.094	**.018**
3D Rotation	r				1	**.323***	.007	-.072	-.200	.118	.254	**.281***	**.307***
	p					**.017**	.961	.603	.146	.395	.064	**.040**	**.024**
Rotation: Letters Pre	r					1	**.416****	.206	**.248***	**-.344****	.048	-.033	-.051
	p						**<.001**	.069	**.027**	**.002**	.672	.775	.657
Rotation: Letters Post	r						1	.126	**.302****	-.167	**-.270***	-.125	-.069
	p							.270	**.007**	.141	**.016**	.274	.543
Rotation: Symbols Pre	r							1	**.283***	-.067	-.112	**-.242***	-.086
	p								**.011**	.555	.326	**.031**	.450
Rotation: Symbols Post	r								1	-.017	-.052	-.051	-.077
	p									.882	.647	.656	.502
Recognition: Letters Pre	r									1	**.484****	**.389****	**.317****
	p										**<.001**	**<.001**	**.004**
Recognition: Letters Post	r										1	**.558****	**.495****
	p											**<.001**	**.000**
Recognition: Symbols Pre	r											1	**.620****
	p												**<.001**

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

Of all the rotation and recognition values, learning rate was significantly related only to symbol recognition post-test (*r*=.31, *p*=.006). Notably, it was not significantly correlated with the same measure for the pre-test of symbol recognition, nor for the letter task, suggesting that this relationship of character recognition ability to learning rate pertained specifically to the recognition skill acquired in the symbol learning task, and not simply to prior or broad underlying abilities.

Because initial speed was significantly correlated to learning rate, and pre-test recognition performance was significantly related to post-test recognition performance, I ran the correlation between learning rate and symbol recognition post-test again as a partial correlation, controlling for these two related variables (initial speed and symbol recognition pre-test) to ensure that they did not mitigate the main correlation. Indeed, when partialling these out, the correlation value became stronger (r=.41, p<.001). To check that this effect was indeed unique to the symbols task, I re-ran the partial correlation and found that controlling for the letters post-test performance in addition to (r=.38, p<.001) or instead of (r=.35, p=.002) the symbols pre-test did not affect the result in any noticeable way. This suggests that, although the letters and symbols recognition post-test measures may have reflected a small amount of some common performance aspect also reflected in learning rate (such as motivation), for the most part the observed correlation between stimulus recognition ability and learning rate was particular to the symbols task.

Learning rate was not significantly correlated to the symbol distance effect, contravening what one might expect (that both measures would reflect a common mechanism, namely, more robust learning of mental representation.) However, when controlling for initial speed, the relationship indeed became significant (r=-.29, p=.009), with a multiple regression analysis showing that both learning rate (β= -.47, p=.009) and initial speed (β= .36, p=.043) contributed similarly to predicting symbol distance effect (R^2=.062). Similarly, 3D rotation ability was not correlated with learning rate, but when controlling for initial speed, the correlation became significant (r=.34, p=.014).

Symbol distance effect additionally correlated with pre-test letter recognition and with both pre- and post-test symbol recognition measures (although the correlation with symbol pre-test was only marginally significant). Entering each pair of these variables as predictors of symbol distance effect in three separate multiple regressions revealed that the symbols pre-test could not explain any additional variance when controlling for either of the other variables (ps>.38), whereas those variables remained marginally significant predictors (letters pre-test, $\beta=-.22$, $p=.071$; symbols post-test, $\beta=-.24$, $p=.095$). Letters pre-test and symbols post-test were both still marginally predictive of distance effect when controlling for each other (letters pre-test, $\beta= -.20$, $p=.091$; symbols post-test, $\beta= -.20$, $p=.081$). Together, these analyses suggest that the correlations of letters pre-test and symbols post-test to symbol distance effect were partially due to different factors measured in each test.

To test whether mathematical achievement might be driving the correlations between mental rotation ability, numerical learning, and symbol recognition, I confirmed that controlling for WIAT scores in partial correlations did not mitigate significant effects (ps<.05). Similarly, WIAT scores could not account for any unique variance when entering them as a factor in multiple regression alongside any of the correlated variables as predictors (ps>.22).

Correlations among mental rotation and recognition measures

As might be expected, scores on the four instances of the recognition task all showed positive correlations between each other, with r values ranging from .32 to .62. Similarly, the four instances of the mental rotation task mostly correlated with each other (showing r values ranging from .25 to .42), with the notable exception that the symbols pre-test was not significantly correlated with either of the letters tests (albeit the correlation between the two pre-tests missed significance by only a small amount). This anomaly is actually not surprising, considering that the symbols pre-test suffered from low familiarity with the newly-introduced stimuli, thereby likely introducing a great deal of noise to the measure of rotation ability. In all instances but the symbols post-test, the rotation and recognition measures pertaining to the same test were negatively correlated with each other, meaning that better recognition scores were related to worse rotation ability. This can be attributed to an artefact of the rotation measure, that particularly high ability scores in upright trials can slightly inflate rotation scores (by offering greater room for decrement between upright and rotated trials).

Of the four instances of 2D rotation measures, only the letters pre-test showed a significant correlation (positive) with the 3D rotation task. Because the letters pre-test was the first of the four 2D tasks to be administered, however, it seems likely that this epiphenomenon may be due to practice effects manifesting in the later tests (for instance, through shifts in response strategy to rely less on rotation). This correlation held even when controlling for overall performance in the 2D task (r=.33, p=.017).

3D rotation ability was also correlated positively with both pre- and post-tests of the symbol recognition measures. This may be due to the fact that, like the 3D task, the 2D symbol task requires participants to rotate novel, relatively unfamiliar objects around a vertical axis (i.e. flip them 180 degrees through the horizontal plane between forward and backward). The letter recognition task, on the other hand, may rely more on familiarity and therefore require less manipulation.

As noted above, 3D and 2D rotation measures (letters pre-test) were correlated, but only 3D rotation was correlated to symbol distance effect. Therefore I ran a multiple regression confirming that, indeed, 2D rotation (letters pre-test) and symbol distance effect each predicted distinct parts of the variance in 3D rotation ability (respectively, β=.27, p=.037; β=.27, p=.044, overall model R^2=.15).

Discussion

In summary, this experiment investigated individual differences in visuospatial manipulation and processing of novel numerical symbols, as measured by mental rotation ability and symbol recognition ability. Analysis found that group factors of stimulation type and synaesthesia did little to explain differences in visual recognition and mental rotation, but that individual differences in visual recognition ability contributed to predicting numerical learning. I will now revisit the initial hypotheses of this chapter in light of the results.

Hypothesis 1a: TRNS to the occipital cortex during symbol learning should facilitate visual recognition of these learnt symbols, but not of pre-learnt stimuli (letters).
Hypothesis 1b: Because mental rotation ability was post-tested less than an hour after the end of stimulation, post-tests of 2D mental rotation ability might be improved by TRNS. Benefits would be expected from parietal, but not occipital or sham, stimulation.

Contrary to these hypotheses, stimulation during symbol learning did not appear to exert an effect on either mental rotation or recognition performance. This could be due to any of several possible reasons. Firstly, it is always possible that stimulation did not induce the expected neuroplasticity, either because it did not reach the proper areas, or because its effects were mitigated by individual differences such as skull thickness or hormone or neurotransmitter balance (Krause & Cohen Kadosh, 2014). Second, it is possible that the targeted areas, although crucial to the relevant tasks, are not aided by stimulation, e.g., because of ceiling excitability levels. Mental rotation and symbol learning are complex skills; therefore the mechanisms involved in learning these skills may require an environment of widespread cortical plasticity (i.e., the state of the brain during development). In that case, localised stimulation may not be not sufficient to recreate the needed environment. Lastly, it is possible that stimulation did cause small effects, but the relatively small sample size and large variance in individual ability reduced the chance to detect any stimulation effects.

Regardless of their possible causes, when interpreted alongside the correlations between symbol learning and visuospatial skills, these null stimulation effects suggest that endogenous individual differences may be more important to modulating performance in this case than exogenous differences induced by stimulation.

Hypothesis 2: If spatial manipulation abilities contribute to forming numerical mental representations, then 3D and 2D mental rotation measures ought to predict strength of numerical representation of the learnt symbols.

First of all, I confirmed that performance on the two mental rotation tasks correlated with each other. This correlation replicates the findings of Viarouge, et al. (2014): namely, that better 3D rotation ability coincided with smaller effects of 2D rotation on a letter judgment task. However, Viarouge and colleagues' findings did not stand when controlling for overall performance on the 2D task; mine did. The modest correlation coefficient (explaining only 10% of the variance) is not surprising, considering that the 3D and 2D tasks differ not only in dimensions represented, but also in plane of rotation, stimulus familiarity, response method, scoring, and even test medium (computer versus paper). As Viarouge and colleagues concluded, the two tasks are likely to measure very different sets of visuospatial processes.

3D mental rotation did indeed correlate with both of the measures of numerical mental representations, i.e., symbol distance effect and learning rate (controlling for initial speed.) On the other hand, 2D mental rotation did not, despite the correlation between 2D and 3D mental rotation measures. This pattern of results is curious, considering that written numerical symbols (including the artificial symbols in this study) are 2D in nature and normally are experienced on a 2D plane. Of course, the correlation coefficients of all of these relationships were fairly small, meaning that a great deal of variation was left to be explained by other factors, even across measures attempting to access similar underlying mechanisms. Indeed, 2D rotation and mental representation of numbers were found to explain separate parts of the variance in 3D rotation. Additionally, due to the practical difficulties of measuring this abstract ability, neither measure was likely to be a perfect reflection of mental rotation ability. Ultimately, the relatively easier task of 2D rotation may simply have been more difficult to accurately gauge in the single short task I employed. However, if one can take these results at face value, they suggest that learning of numerical mental representations is aided by some aspect of 3D rotation that is not shared by 2D rotation. This hints at the intriguing possibility that internal mental representation of numbers may indeed be more complex than the unidimensional line often presumed; indeed, future research into this hypothesis would be of great interest.

One must also keep in mind that participants were adults, who already had competence with numerals and underlying numerical representations. Therefore, it is possible (indeed, likely) that their learning of the new system piggybacked off their existing understanding of numbers, although numbers were never explicitly evoked.

Hypothesis 3: Symbol recognition ability, but not letter recognition ability, should positively correlate with measures of mental representation, i.e. learning rate and symbol distance effect. Furthermore, if symbol recognition ability helped only to facilitate faster answers in tasks dependent on visual response, then I would expect to observe that symbol recognition would relate to learning rate alone. However, if advantages in visual symbol recognition also help individuals to learn the value of symbols, this benefit should be evident even in a measure that *captures only representation, e.g. by accounting for the effect of visual processing, as in the symbol distance effect.*

As expected, the post-test of symbol recognition –but not letter recognition—was correlated with learning rate. It is of course impossible to infer causation from correlation, but this relationship at least indicates that faster learning of the symbols' magnitudes went hand in hand with better visuospatial internalization of the characters. Because learning rate was correlated with post-test, rather than pre-test, it suggests that the learning rate advantage was not simply due to *a priori* better visual character recognition skills. Additionally, the fact that the correlation occurred with the post-test of symbols, but not letters, suggests that the correlation is unlikely to be due to mitigating factors affecting overall performance, such as motivation, focus, or motor response[5]. However, could it be an effect of a different shared trait, such as NSS? Learning rate was higher in NSS, and also recognition ability was better in NSS compared to non-synaesthete controls. However, only 14 of the 79 participants were NSS, and indeed when excluding them from analysis, the correlation remained significant (r=.33, p=.007).

Taking a small step back, the impetus behind this experiment was to investigate the role of visual numerals in number cognition. The visual recognition task did this by using a measure that isolates the visual processing of the symbol (recognition of spatial orientation) from its meaning. However, the training task, from which learning rate was calculated, involved visual processing of the symbols as well. Therefore it is impossible to determine from only the correlation of learning rate and symbol recognition, whether visual recognition ability was related to learning the symbols' *meaning*, or simply conferred a speed benefit in the task overall

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[5] Furthermore, the use of drift rate variables as performance measurements aims to minimise such possibilities, as diffusion modelling separates estimates of "non-decision time," including motor response, into a separate variable from drift rate.

due to faster stimulus processing. Therefore, ideally I would compare visual recognition ability to a pure measure of learnt numerical meaning. However, it was difficult to isolate the meaning from the visual aspect of the novel symbols in this experiment, since the participants did not learn any other referent to them (such as names). The solution to this conundrum was to use the symbol distance effect, which extracts a measure of mental representation largely independent of visual processing by comparing trials with similar visual but different semantic content, within each participant. This measure of the symbol distance effect was indeed correlated with post-test symbol recognition ability; it was also correlated to the pre-test of letter recognition and, marginally, the pre-test of symbol recognition, but neither of these could sufficiently explain the correlation with post-test symbol recognition. This suggests that stronger numerical representation (i.e., smaller distance effect) is associated with gains in recognising specific symbols, rather than simply overall visual recognition ability.

Given these results, if the experiment were replicated, it would be helpful to also include a third version of the rotation and recognition task, with novel symbols the participants were trained to recognise, but were not trained to associate with values. This could determine whether lack of effects (i.e. change between pre- to post-test, or correlations with learning rate and distance effect) in the letters task could be due to ceiling effects. Additionally, it could help to explicate whether higher learning rate and stronger numerical representation are linked to competence at recognising specific symbols, or simply overall competence at learning to recognise novel symbols. If the former, this would suggest that the visual aspect of numerals themselves plays a role in numerical representation: namely, that visual learning of numerals can aid in forming stronger numerical representation. This would both implicate visuospatial skills in numerical representation, and also could suggest a host of implications for numerical learning in children.

Lastly, it is also important to note that while visual recognition ability was related to numerical representation ability, the former is certainly not a necessary condition for the latter. Indeed, numerical abilities have been noted in populations with very few symbolic (verbal, written or visual) representations of numbers (Butterworth, Reeve, Reynolds & Lloyd, 2008; Pica, Lemer, Izard & Dehaene, 2004). Therefore, future research in this area might do well to investigate whether visuospatial aspects of representation in particular, or richness of symbolic representation in general, might be more closely related to strength of numerical representation.

Chapter 7: General Discussion

In this dissertation, I sought to answer the question of how visuospatial mental imagery (VSMI), such as mental rotation and number-space synaesthesia (NSS), may influence numerical cognition. Specifically, the first half of my thesis examined how VSMI is linked to numerical representation. The second half of my thesis investigated how VSMI—including its component mental strategies and its neural substrates—affects numerical learning and mental representation in a set of novel numerical symbols. In this final chapter, I first summarise my experimental results by chapter, then discuss how the results fit together and how they inform understanding of VSMI and numerical cognition. Finally, I will discuss potential avenues for future research suggested by my findings.

Summary of results by chapter

Chapter 2 investigated how mental rotation, a form of VSMI, is related to numerical representation ability in a sample of 43 numerate adults. Mental rotation ability, as assessed by a standard 3D mental rotation task, varied widely across the group, replicating previous findings (Vandenberg & Kuse 1978, Peters et al 2007). I assessed numerical representation through a number line mapping task and through a number comparison task that measured the propensity to activate separate numerical representations in two-digit numbers. I found that mental rotation ability showed moderate but significant correlations with both numerical representation measures, but not with a control task (verbally generating random numbers) that measured the executive function of repetition suppression. These results suggest that VSMI may play a role in basic numerical representation.

Using the same battery of tasks, chapter 3 investigated VSMI and number representation in an atypical population with a special form of VSMI, namely, NSS. Compared to both controls with no synaesthesia and controls with a different form of synaesthesia (GCS), the NSS group showed an interference effect on the number line mapping task on trials that overlapped with their mental number forms. Consistent with previous research (Ward et al., 2009), this finding suggests that the explicit number forms inherent to NSS are associated not only with benefits (Brang et al., 2013; Simner et al., 2009) but also costs in some types of numerical tasks. However, mental rotation ability did not differ between NSS and non-NSS groups, nor did the measure of representation in two-digit numbers. These results firstly suggest that NSS may not necessarily recruit the same mechanisms of imagery as mental rotation. Secondly, they reinforce the findings that observable differences in numerical cognition between NSS and non-NSS populations are task-dependent (Price, 2009; Simner et al., 2009).

The latter half of my dissertation sought to alleviate the confounds of familiarity, experience, and culture on numerical ability, by investigating the effects of training adults on a novel numerical system. In chapter 4, I examined how NSS affects the formation of novel numerical representations by comparing a NSS group to GCS and non-synaesthete control groups on 1) this training task, 2) transfer tasks assessing ability with the trained symbols in non-training contexts, and 3) control tasks of attention, working memory, and mathematical achievement. Additionally, I investigated how the neural bases of VSMI and numerical representation can affect this learning process, by manipulating cortical excitability with either sham tRNS, or tRNS to parietal or occipital cortices, orthogonally assigned across synaesthesia groups. Parietal tRNS and NSS both conferred advantages at learning the novel numerical symbols, but although they were broadly similar, they differed in detail. NSS showed an advantage from the first day of training in both number line mapping and in responding to more difficult-to-learn pairs in the middle of the symbol hierarchy. Presumably this is due to the spatial organisation conferred by a newly-minted spatial form for the new symbols. Parietal tRNS also showed advantages in performance on the most difficult, middle symbol pairs in the learning task; however, this advantage appeared at the end of the week, consistent with the hypothesis that it grew from incremental advantages in forming the new number representations, rather than a VSMI aid, as in NSS. Parietal tRNS also demonstrated stronger numerical representation, as measured by a distance effect for the new symbols, but it also was associated with a slight impairment on the most difficult-to-map symbols in the line mapping task.

Following up on findings from chapter 4 that excitatory brain stimulation (tRNS) enhanced learning of novel numerical representations, chapter 5 sought to refine the stimulation effects by testing a specific neural oscillatory frequency. Using a stimulation paradigm previously found to enhance cognitive abilities (working memory, Polania et al., 2012), I applied synchronous tACS to frontal and parietal cortices, either at theta- or gamma-band frequencies, or as a sham control, in non-synaesthetes completing the same novel numerical learning task as in chapter 4. Although participants showed within-subjects effects of learning and automaticity in their processing of the novel symbols, I found no stimulation group effects in either the learning task, transfer tasks, or control tasks. Due to problems with stimulation equipment and possible mismatches of individual endogenous oscillation frequencies, these null results cannot be interpreted as strongly discounting the possibility that theta-band synchrony in frontal and parietal areas does not play a notable role in numerical learning.

In chapter 6, I examined the role that visuospatial abilities play in numerical learning and representation, by relating performance in the previous two symbol learning studies to ability at mental rotation and visual recognition of the numerical symbols. I administered the 3D rotation task (the same task as in chapters 2 and 3) as a pre-test, and a 2D rotation and orientation judgement task, testing both familiar alphabet letters and the novel symbols, both before and after the symbol training paradigm. This repeated test, which assessed baseline and changes in both mental rotation and visual recognition abilities, allowed me to infer the role of each ability in the learning of numerical representation, through the pattern of their correlations to measures of learning rate and strength of numerical representation (symbol distance effect).

I found that 3D rotation ability correlated with learning rate, when controlling for initial speed. 2D rotation ability did not correlate to either measure of numerical learning, but only to 3D rotation (and only in the letters pre-test). Visual recognition ability, however, showed several correlations of note. First, the post-test (but not pre-test) of symbol recognition (but not letter recognition) correlated with the learning rate, with or without controlling for initial speed of the learning task. This indicates that improvement in visual recognition of numerals is related to the trajectory of improvement in learning their values. Second, the post-test of symbol recognition also correlated with the distance effect in the newly-learnt symbols. Because the distance effect is calculated within-subject, it offers a measure that should cancel overall effects of visual processing. Therefore, this correlation could not be merely due to faster symbol recognition in both tasks. Together, these results indicate that better visual learning of novel numerals is related to faster learning of their values and the formation of stronger numerical representation.

Implications for numerical cognition and VSMI

By bringing together the results from various chapters of my thesis, I can begin to answer the larger question that motivated this body of research: how does VSMI interact with numerical representation and learning? Results from chapters 2 and 6 both showed that 3D mental rotation was associated with better numerical representation, but curiously, 2D mental rotation was not. Although I found that one measure of 2D mental rotation correlated with a measure of 3D mental rotation, the fact that 2D mental rotation was not related to any numerical ability measures emphasises the notion that these two measures may capture very different aspects of VSMI (cf. Viarouge et al., 2014). My findings further underline a point of caution in future research on mental rotation, noting that although 2D and 3D rotation measures are often simply classed together as "mental rotation," the findings from one measure do not necessarily transfer to the other. Furthermore, the links I discovered between 3D mental rotation ability and learning rate did not generalise to the measure of distance effect as well. This finding, along with the inconsistency in my results concerning different types of mental rotation, suggests that the link between 3D mental rotation and numerical representation might be mediated by more general cognitive abilities, such visuospatial working memory.

The results from chapters 3 and 6, taken together, illuminate the link between the two types of VSMI I investigated in this dissertation. In neither sample (totalling 31 participants with NSS) did I find a reliable connection between mental rotation ability and NSS. This is surprising, given previous research finding that time-space synaesthetes, closely related to NSS, showed advantages at mental rotation (Brang et al., 2010; Simner et al, 2009). This is surprising at a theoretical level as well, given that mental rotation and NSS share many qualitatively similar aspects, for instance, in the reported ability of many of the NSS participants in this study to spatially manipulate their number forms. One possible explanation for this discrepancy is that NSS, like synaesthesia in general, may be more heterogeneous than researchers like to think. It is already clear that spatial forms vary widely across individuals (e.g., Galton, 1880); could it be that the cognitive mechanisms underlying them vary as well? This would tally with the account that NSS, and synaesthesia in general, may be an extreme end of a spectrum on which all humans fall (Cohen Kadosh & Henik, 2007). Ideally, future research into NSS would target children, as we know the least about NSS in what are potentially its most telling stages, i.e., its early creation. Anecdotal report suggests mental number lines in NSS change with increasing numerical sophistication. If these reflect changes in numerical representation, studying NSS during development could offer a unique window into its maturation.

Chapters 3 and 4 also bring together a surprising combination of results; both show effects of NSS on number line mapping, but the effects appear to be opposite. In chapter 3, NSS showed an RT disadvantage for mapping numbers which fell in the range of their spatial forms, consistent with previous findings showing an interference effect of NSS in incompatible SNARC paradigms (Gertner et al., 2013; Hubbard et al., 2009). In chapter 4, however, NSS showed a mapping advantage versus other groups from the beginning of the week for the newly-learnt symbols, regardless of line orientation or value of symbol. Together, these findings suggest that spatial forms may offer a potential advantage for NSS in early stages of learning symbolic numbers, but that the strategies which offer advantages early on (e.g., idiosyncratic number forms) may become disadvantageous later, by decreasing the flexibility with which individuals with NSS interact with numbers (cf. Ward et al., 2009). Conversely, the unexpected findings that NSS outperformed non-synaesthetes at number mapping also suggest the alternate possibility that environmental traits may influence not just the shape of number forms, but also their flexibility[6].

The issues discussed above are all worthy of investigation in their own right; however, most of the more interesting implications of this dissertation arise from the keystone study,

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[6] Anecdotally, most NSS participants reported visualising spatial forms for the learnt symbols, and one mentioned he could use it to help map both orientations of the line, whereas his number form was not so flexible.

chapter 4. By combining the manipulation of tRNS to modulate neural substrates of cognition, and the inclusion of different types of number-related synaesthesia, the study allowed me to compare the effects of two different types of advantages to learning novel symbols. At a basic level, this answered a simple question of whether a condition such as NSS, which is thought to be characterised by greater structural or functional connectivity between relevant numerical, ordinal, and/or visual regions (Eagleman, 2009; Price, 2009), could be artificially created merely by increasing cortical activity in these implicated regions. This does not seem to be the case. However, the patterns of results between parietal and NSS groups were intriguingly similar; it will take further research, and clever paradigms, to disentangle the possibility that 1) external modulation of cortical excitability perhaps can, to some degree, emulate effects of synaesthesia, from the alternate explanation that 2) the concordance of benefits shown by NSS and tRNS are entirely coincidental.

In combination, the experiments included in this thesis converge on a broadly similar theme in response to the question of how the formation of numerical representation may engage mechanisms of VSMI. They suggest that, to some degree, visuospatial processes do appear to play a role in numerical learning; for instance, the results in chapter 6 suggest that better learning of visual symbolic numbers is associated with forming of stronger numerical representations. Likewise, benefits in VSMI appear to confer specific advantages in numerical learning, although the artificial learning paradigm in adults cannot be compared directly to the organic process of learning numbers during development.

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APPENDIX

tES Screening Form

Project Title: Modulating brain activity in psychological tasks

• Do you currently have any of the following fitted to your body? o Heart pacemaker o Cochlear implant o Medication pump o Surgical clips o Any other metallic object	YES/NO
• Do you have a personal or family history of epileptic fits or seizures? (If YES, then please state your relationship to the affected family member.)	YES/NO
• Do you have a personal history of migraines?	YES/NO
• Have you ever suffered from febrile convulsions in infancy, or had fainting spells?	YES/NO
• Do you have any other medical/psychiatric/neurological disorder?	YES/NO
• Have you ever undergone a neurosurgical procedure (including eye surgery)?	YES/NO
• Could you be pregnant?	YES/NO
• Are you currently taking any prescribed or unprescribed medication (or herbal remedies)?	YES/NO
• Have you drunk more than 3 units of alcohol or used any recreational drugs in the last 24 hours?	YES/NO
• Have you drunk alcohol already today?	YES/NO
• Have you had more than one cup of coffee, or other sources of caffeine, in the last hour?	YES/NO
• When did you have your last proper meal?	
• Have you removed all metallic items (e.g. jewellery, coins, watches) from yourself?	YES/NO
• Have you had a full night's sleep (≥6 hours) the night before the study?	YES/NO
• Have you participated in a TMS study in the last 7 days?	YES/NO
• Have you participated in a tDCS study already today?	YES/NO
• Do you understand that you should not drive for one hour after receiving tDCS/TMS?	YES/NO
• Are you left or right handed?	Left/Right
• Date of Birth	__/__/____

List of abbreviations

ANS: approximate number system

ENS: exact number system

GCS: grapheme-colour synaesthesia

IPS: intra-parietal sulcus

MRS: mental rotation score

NSS: number-space synaesthesia

tACS: transcranial alternating current stimulation

tDCS: transcranial direct current stimulation

tES: transcranial electrical stimulation (a blanket term for tRNS, tDCS, and tACS)

tRNS: transcranial random noise stimulation

VSMI: visuospatial mental imagery