DOCTORAL THESIS

Interactions between knowledge representations: affordances, numbers, and words

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Awarding institution:
Northumbria University

Award date:
2019

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PhD

2017

Abstract

Understanding the world involves complex cognitive processes occurring and interacting within the mind. Traditionally, this has been thought of as analogous to computational processes, with strict rules that encapsulate obligatory and domain specific modules. Current theories of cognition suggest a radically different approach in that sensorimotor simulation forms a necessary basis of abstract and concrete knowledge. These theories suggest that the ability to represent knowledge relies not only on brain-based processing, but also on the embodied experiences of the cognizer in the environment. However, there remains little agreement as to the nature of such embodied representations, particularly at the level of what constrains their properties and their ability to interact with one another. This thesis focuses on how cross-representational interplay is made possible. Through an empirical dataset, a case for a *conceptual interface* is made, suggesting co-activated distinct representations may interact by means of a third-party mediating mechanism (e.g. a joint attentional bias). This is demonstrated across a range of experiments using concepts representing several conceptual knowledge domains from more abstract to more concrete, including concepts denoting numerical magnitude, spatial semantics, emotional valency, and manual affordances.

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Preface

Peer-reviewed publications that have resulted from this thesis:

Myachykov, A., **Chapman, A. J.**, & Fischer, M. H. (2016). Cross-representational interactions: Interface and overlap mechanisms. *Frontiers in psychology*, *7*.

Chapman, A. J., & Myachykov, A. (2015). The interplay between remembered affordances and the perceived numbers: An eye-tracking study. *Cognitive processing, 16*(1), 54

Conference proceedings that have arisen from this thesis:

Chapman, A. J., & Myachykov, A. (2016). *Affordances from words and objects in memory and vision*. Paper presented at International Conference On Memory, Budapest, Hungary.

Chapman, A. J., & Myachykov, A. (2016). *The interplay between remembered affordances and perceived numbers: an eye-tracking study*. Paper presented at Young Researchers Conference in Cognitive Science, Hyderabad, India

Chapman, A. J. (2015). *Understanding how we think: meaning in mind and body*. Paper presented at Career Development Institute: Engaging with young people and adults with SEND, York, UK

Chapman, A. J., & Myachykov, A. (2015). *The interplay between affordances and numbers: an eyetracking study*. Paper presented at International Conference on Spatial Cognition, Rome, Italy.

Chapman, A. J., & Myachykov, A. (2015). *Sensorimotor simulations in lexical and conceptual knowledge*. Paper presented at International Cognitive Linguistic Conference, Newcastle, UK.

Chapman, A. J. (2015). *Understanding cognition: that rug really tied the room together, man*. Paper presented at Northumbria Research Conference, Newcastle, UK.

Chapman, A. J., & Myachykov, A. (2014). *Representations of simulated meaning in perception and action*. Paper presented at Cognitive Control, Communication and Perception: Psychological and Neurobiological Aspects, Moscow, Russia.

Chapman, A. J., & Myachykov, A. (2014). *Verbs as spatial cues: Explicit direction of motion facilitates visual probe detection*. Paper presented at Architectures and Mechanisms of Language Processing, Edinburgh, UK.

Chapman, A. J., & Myachykov, A. (2014). *Verbs as spatial cues: Explicit direction of motion facilitates visual probe detection*. Paper presented at Embodied and Situated Language Processing, Rotterdam, Netherlands.

Dedication

For my parents, that have taught their sons to be curious.

For my grandparents, that have taught their grandchildren to be kind.

For my partner in crime, that has taught me to do the washing up.

Acknowledgements

Thanking everyone that has been helpful over the course of completing this project is an improbable task, but I will endeavour to try. If not here, then in my head. The support of my family, friends, and colleagues was and remains truly invaluable to me.

To my supervisor, Andriy, so long and thanks for all the fish. Vonnegut would be proud.

To Olafur Arnalds, Nils Frahm, David Bowie, and the members of La Dispute, amongst many other musicians, thank you for helping burn the midnight oil.

To John, Greg, Zero, and Umair. Thanks for buying me beer, suckers.

To Adam, Jennifer, Scott and Matt, for a meaningful dialogue on an almost-daily schedule for nearly ten years. May you always carry a towel.

To Jonathan, Adam, Jack and Sophie. Thanks for having ears, the ability to communicate in English, and hold a good belay.

To all of CoCo, for being a persistently loud, pervasive, annoying, and totally perfect place to work in and call home.

To my brothers, that continue to surprise and impress me in everything they do.

To my family, I owe you my existence. Literally. Thank you for making me, shaping me, and always encouraging that I be, well, me.

To Amy, you deserve so much more than this for putting up with me for five years now, these last three especially. Thank you so much.

Author’s Declaration

This work has not been submitted for any other award. The writing of this thesis is the sole work of the author. I confirm that this work has acknowledged opinions, ideas, and contributions from the work of others.

Any ethical clearance for the work presented in this thesis has been approved. Approval has been sought and granted by the Faculty of Health and Life Sciences Ethics Committee.

Word Count: 61926

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Signature:

Date: 28 January 2019

CHAPTER ONE

Introduction

Cognitive science, a pursuit to understand how we acquire, represent, and retrieve knowledge, faces a critical frontier. Having accepted at least some level of sensorimotor representation as necessary in creating cognition (Meteyard, Cuadrado, Bahrami & Vigliocco, 2012; Zwaan, 2014; Borghi et al., 2017), the question now concerns the mechanisms that allow these representations to interact and be constrained by one another.

This thesis offers a theoretical proposal and empirical data set documenting support for interactions between knowledge representations, including manipulation affordances, words denoting spatial semantics, valency, and numerical magnitude. However, before this agenda can be undertaken, the following chapter will begin by introducing the notions of mental representation and abstraction, which are critical for the understanding of how representations of number, affordances, spatial semantics, and valency may share and interact in cognitive domain.

Abstraction

A brief history

Philosophy has been concerned with the machinations of the mind in one way or another since as early as the times of the Ancient Greeks (Kenny, 1997). In Raphael's painting The School of Athens (Figure 1), Plato and Aristotle can be seen arguing. Each philosopher grasps, in their left hand, their magnum opus: for Plato, Timaeus; Aristotle, Nicomachean Ethics. Plato's upward pointing is toward what he would term the realm of forms (Gulley, 1960). These exist beyond what can be seen and are the perfect representations of things around us. For example, a triangle in the real world will never be a *perfect* triangle, as it may never represent the *category* of a triangle, but always a specific representation of

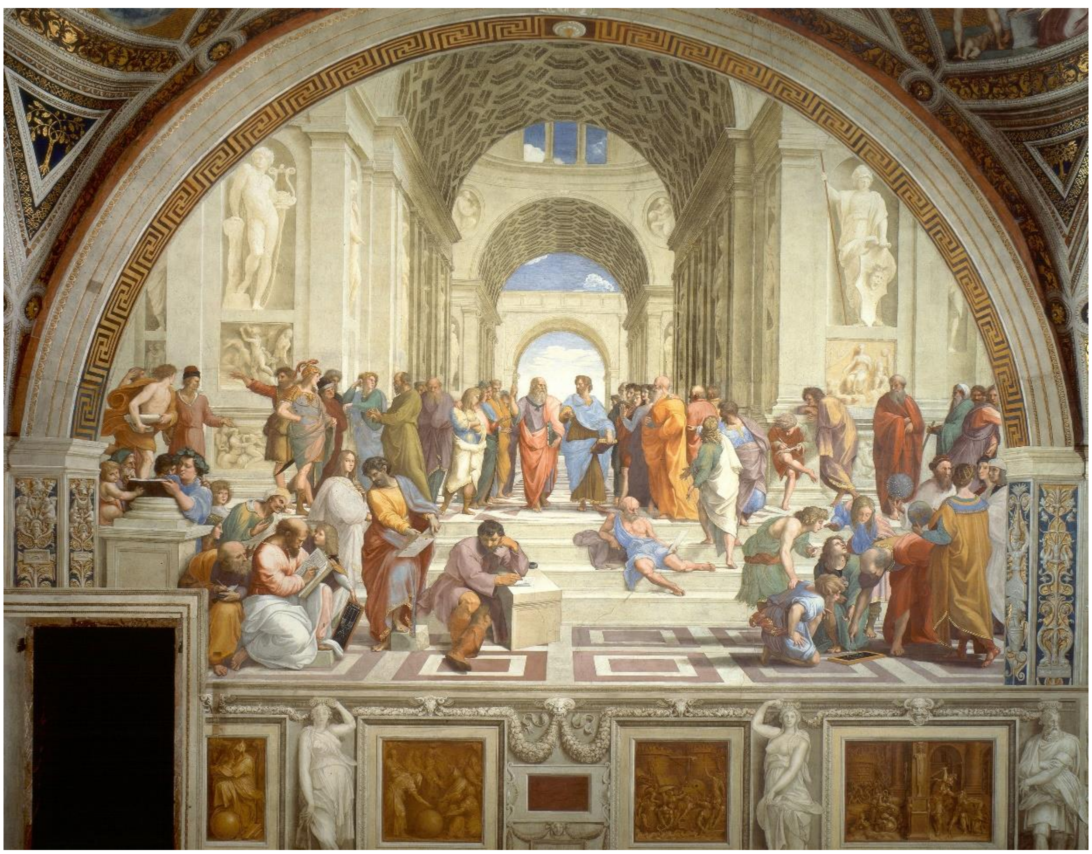

Figure 1. The School of Athens, a fresco painted by Raphael. Note the central figures of Plato and Aristotle, arguing over representation.

one. Aristotle points at the ground, toward what we can physically observe around us. To understand Aristotle's view as a contrast, it is perhaps best to use a quote from Nicomachean Ethics (in Rowe & Broadie, 2002):

> "It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits; it is evidently equally foolish to accept probable reasoning from a mathematician and to demand from a rhetorician scientific proofs". (Book I, p. 1094b)

To Aristotle, seeking perfect forms did not accurately represent the individual or collective experience in which we, as humans, live. Because of this, the forms described by his contemporary cannot exist: an understanding can only come from physical experience.

Plato's ether realm is easily understood today as the realm of propositional and amodal *concepts*, while Aristotle draws focus toward the body and the environment. This division continues throughout the painting, with other philosophers on the leftward side, such as Pythagoras, sharing a similar interest in forms, while on the rightward portion are philosophers concerned with observation, like Euclid. Though the terms have been altered and formalised, the arguments made in the present day are essentially equivocal to the ones conveyed in the painting: how does the mind function? What role, if any, do the body's experiences in the physical and social environments play in cognition? Ultimately, can our thoughts ever be truly abstract and divorced from our experiences?

In answering these general questions, behaviourists eschewed the mind entirely. Following the early ventures of psychoanalysis, Watson (1913) suggested that the only data worthy of study was that which can be measured objectively and directly. To Watson and his ilk, the mind was little more than a black box; an item that received information from the senses and outputted behaviour and bodily action (Mackenzie, 1977). However, with the advent of the computer, this frontier would change drastically (Cooper, 1993). ENIAC, one of the earliest computational devices, was built to give answers to complex problems, however the physical workings of the device were not visible (McCartney, 1999). This served as a powerful metaphor for cognitive science, allowing researchers to unpack the black box of the brain.

So came the boom of cognitive science, with early theories being strongly influenced by the literature of formal computationalism (e.g. Fodor, 1983; Pylyshyn, 1985; Johnson-Laird, 1994). By being able to label cognitive processing as symbolic manipulation, psychological thought could be ordered and categorised according to explicit architectures instead of external stimuli – or in other words, cognition could become abstracted away from the environment (Newell & Simon, 1972). These early views suggested that the brain should operate on amodal symbols, similar in nature to the way binary systems in computers are able to represent information. These symbols, through various processes of transcoding perceptual inputs, are acquired, stored, and retrieved to allow for rich cognitive understanding.

However, problems developed with this view quickly, as can be best illustrated by Searle's (1980) contention using the Chinese Room. This was a thought experiment that had a non-Chinese speaker located in a room. Inside this room were two hatches, a set of rules and nothing else. The person would receive Chinese letters (symbols) from one of the hatches, manipulate them according to the strict set of rules and then send the resulting output through another hatch. Just as the individual performing the manipulations will never know what is being communicated in each message, simple symbolic manipulation cannot lead to the creation of meaning. An alternative approach considers the mechanisms of cognition as having evolved for action (rather, interaction) between the body and the environment it exists within. As a result, the organisation of the brain's sensorimotor processes associated with embodied experience in the world should be reflected, somehow, in the nature and organisation of acquired, stored (offline), and retrieved (online) knowledge representations. Broadly, this relatively simple premise forms the basis for embodied cognition (Wilson, 2002).

The word *broadly* is used with purpose: unlike formalised accounts of symbolic cognition, no clear model of embodied cognition has been accepted by the scientific community at large, with critics referring to it as a theoretical toolkit rather than a full-fledged theory of cognition (see Mahon & Caramazza, 2008; Mahon, 2015; Goldinger, Papesh & Barnhart, 2016). Because of this, it should not be surprising that embodied approaches run the gamut of perspectives, being in the most extreme cases entirely anti-representational like enactivist programme (e.g. Varela, Thompson & Rosch 2017; Gallese & Lakoff, 2005; Lakoff & Johnson, 1980; Pecher & Zwaan, 2005) or so far removed from sensorimotor systems that any activation thereof occurs by means of indirect, or secondary, priming (e.g. Patterson, Nestor & Rogers, 2007; Collins & Quillian, 1969; Levelt, 1992; Binder, Desai, Graves & Conant, 2009). Generally, when the term embodiment (also: groundedness) is used, it is making the claim that conceptual knowledge is *somehow* integrated within *modal* systems (see Barsalou, 1999; Myachykov, Scheepers, Fischer & Kessler, 2014; Pulvermüller, 1999).

Formal semantics as a study of meaning can be seen as a modern-day incarnation of Plato's *forms* (Gulley, 1960), categories that refer to certain items without being a specific representation (e.g. a triangle can be considered a category that includes right angled, equilateral, scalene, equiangular, acute, obtuse and isosceles representations). Thus, a semantic category can refer to things that are present (the cup of coffee I'm drinking; lizards), absent, imaginary (a second cup of coffee not yet made; dragons), or even totally abstract (addiction; love). Undoubtedly, meanings of individual concepts and categories are real things, not only intuitively but also as we seem to understand each other most of the time when referring to things, both concrete and abstract. As a consequence, any proposed cognitive architecture has to have the capacity to represent what is present, not present, and also *that which has never been directly experienced*. So, for embodiment to hold as an account of cognition, sensorimotor systems should be traceable in both *online* and *offline* processes (Myachykov, et al., 2014). This is made possible through a radical shift in how thought is conceptualised: instead of cognition, and by extent the cognising individual, as a separate from the environment, consider that the world is constructed by sensorimotor processes, within the mind of the individual. In other words, the agent, the agent's body, and the environment this body is placed within, are one (e.g. Jackendoff, 2003; McRae, De Sa & Seidenberg, 1997; Ocelák, 2016).

In the literature, there has been a shift away from entirely symbolic and amodal theories; at the same time, radically embodied theories have failed to gain traction as well. While it is generally agreed that sensorimotor information is accessed when semantic representations are activated, the mandatory/optional role of this sensorimotor information remains debated (Meteyard, Cuadrado, Bahrami & Vigliocco, 2012): Does it amount to little more than epiphenomenal effects reflecting access to extraneous and confounding information, or is it a necessary step in mental processing? This thesis refers to cognition-as-simulation, understood as "the re-enactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind" (Barsalou, 2009, p.1281). By adopting this view, the specific hypotheses of each tested area can be advanced. The domains discussed in what follows include *affordances, spatial semantics,* and *valency*, all in relation to *numerical magnitude*. A more detailed discussion of each domain will follow; however, it needs to be noted that these domains differ in their degree of *abstractness.* The most concrete (and, therefore, least abstract) of these domains is affordances, referring directly to objects that are manipulable in the world, and so this domain should have the strongest sensorimotor trace (Tucker & Ellis, 2004). The domain of spatial semantics is relatively more abstract than affordances, but still directly refers to the experienced environment (e.g., "push", "pull", "retreat", and "advance"; Kuipers, 2000). Finally, emotional valency (thereafter, valency) is the most abstract domain amongst the ones studied here. It has little concreteness as emotional states like pride and depression are intangible and internal emotional states rather than direct experiences of the world around (Niedenthal, 2007). These three domains are discussed with relation to the domain of numerical magnitude, which spans levels of abstraction depending upon the type of presentation made (Dehaene, 1992). As noted above, a more detailed description of these domains appears later in the thesis.

The adopted theoretical approach is not taken without strong support from the literature. Recent research shows emotional valency (Foroni and Semin, 2009), spatial semantics (Zwaan, 2014; Dudschig, de la Vega & Kaup, 2014), affordance (Osiurak & Badets, 2016), and number (Myachykov, Ellis, Cangelosi & Fischer, 2016) to be linked with sensorimotor experiences acquired during acquisition and subsequent re-use. Several studies have, in support of these claims, demonstrated what we will refer to as *spatial-conceptual mappings*. For example, studies confirmed that numerical (Fischer, 2003; Fischer & Fias, 2005), spatial (Richardson, Spivey, Barsalou, & McRae, 2003; Chapman & Myachykov, 2014), emotional (Meier & Robinson, 2004), and temporal (Núñez & Cooperrider, 2013) concepts all demonstrate sensorimotor biases.

Having established a general case for cognitive simulation, an argument will now be made for cross-representational interaction. This is theoretically made possible by means of a dual-route whereby both top-down and bottom-up processing can cause interaction. Specifically, this interaction is argued to occur in general cognitive systems (such as memory and attention; see Posner & Petersen, 1990) as opposed to specific knowledge domains.

Interplay between concepts

Think back to the forms of Plato (in Gulley, 1960). Today, these would be known as concepts, with each concept being a combination of permanent (core) and transient (online) features (Myachykov, Scheepers, Fischer & Kessler, 2014; see also Wilson, 2002). When two representations are simultaneously activated, they may interact even when they do not have much in common. The driving force for this interaction is a third-party component utilised by both conceptual representations, and subsequently acts as an interface between the two. (e.g. attention). A number of studies demonstrate spatial-conceptual mappings across different knowledge domains (see Cappelletti, Freeman & Cipolotti, 2009; Bonato, Zorzi & Umiltà, 2012; Lachmair, Dudschig, de la Vega, & Kaup, 2014; Winter, Marghetis & Matlock, 2015; Santiago & Lakens, 2015), and a commonality across all of these studies are fast and simultaneous shifts of spatial attention triggered by access to individual concepts. Congruent or ipsilateral shifts typically lead to facilitatory cross-domain priming indicating the establishment of a conceptual interface. Typically, these studies utilize tasks that require processing of concrete spatially arranged stimuli (such as priming and/or visual probe detection tasks) alongside or following word processing tasks (e.g. Richardson, Spivey, Barsalou & McRae, 2003).

Some particularly strong examples come from lexical decision tasks, whereby participants show faster processing of nouns, verbs and numbers that bias attention upward (e.g. sun, rise, 9; see Lachmair, Dudschig, de la Vega & Kaup, 2014; Lachmair, Dudschig, Ruiz Fernández & Kaup, 2014). This observed effect of priming shows interfacing between two representations by means of attention. Essentially, the first stimuli acts as a spatial cue (Posner, 1980), priming a directional response. If the probe stimulus appears in the same location or shares the same directional bias, a speed-up in processing is observed. Further to this, these studies also suggest the role of attention in underlying spatial biases to be relatively general and universal, and that any two representations known to project spatial biases can interact via an attentional interface (see Posner & Fan, 2008; Posner & Rothbart, 2007; Rueda et al., 2004; Myachykov, et al., 2014).

An important feature of cross-representational interface is its online nature; i.e., the notion that spatial biases triggered during accessing a representation are not stored offline as this representation's permanent features. Consider the following example: both *nine* and *lift* are known to bias attention upward while *one* and *drop* are known to bias attention downward. However, neither sets of these concepts rely on attending upward for understanding. In other words, attention has no mandatory role in understanding either of these concepts. However, accessing these concepts will result in a measurable shift of attention. Because of this, and very importantly for the notion of interaction, it is suggested that any interface must only rely on an *online* relationship between two or more concepts that appear in close spatial or temporal proximity. Arguably, spatial biases are amongst the most studied of general cognitive mechanisms, which is why attentional interaction features so prominently. It is not, of course, the only catalyst for interface: another contender is working memory (e.g. Baddeley & Hitch, 1974; Hickok, Buchsbaum, Humphries & Muftuler, 2003; see also Barsalou, 2008).

Traditionally, working memory proposes distinct mechanisms for visuospatial and verbal content (Baddeley, 2000). However, a case is made in more recent work for long-term knowledge representations as crucial components of the system (Cowan et al., 2005; Cowan, 2010) suggesting the existence of a much more holistic mental process. Additionally, links have been forged between visual working memory and visual attention (e.g. Olivers, 2008), with arguments relying on the overlap in brain regions and task demands forming the cornerstone of arguments (Olivers, Peters, Houtkamp & Roelfsema, 2011; van Moorselaar et al., 2017).

If indeed working memory is an integrated system, it should be capable of acting as an interface between the knowledge representations that, when accessed, share the same working memory space. For example, in the literature of number-space interaction, sequential ordering of number in memorised sequences has led to spatial biases (Huber, Klein, Moeller & Willmes, 2016; for a review, see Abrahamse, van Dijck & Fias, 2016) suggesting that two complex concepts that shared memorial configuration may interact via this interfacing mechanism.

So, it is hypothesised that co-activated concepts known to carry similar spatial mappings regularly interface via a shared attentional system. This forms the basis of the theoretical proposal for a distinct system of interaction by *interface*. The remainder of the chapter serves to introduce the domains tested later in the thesis, by means of affordance, spatial semantics, valency, and number. These domains are delineated by the associated relative degree of abstraction

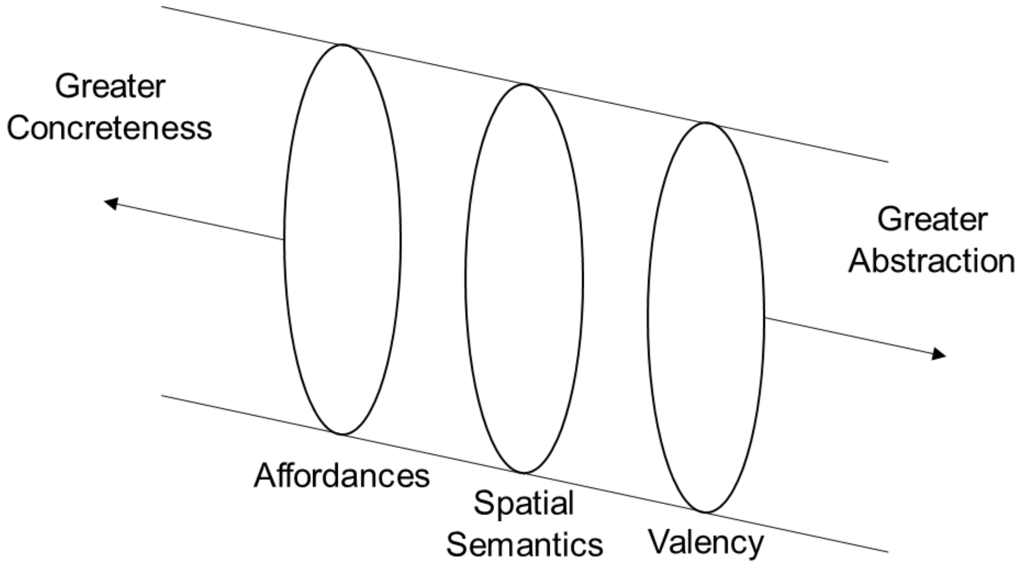

Figure 2. The abstraction pipeline. A reference image used to indicate how concrete, in comparison to the other topics of the thesis, a given section is. Note number is not indicated, as it is used as a tool across all experiments.

(Figure 2), which acts as a tool to display where the present subject matter is in the context of the thesis.

Number

The core concept explored in this thesis is the concept of numerical magnitude, referred to simply as number from this point onward. It is the rug that joins together each of the seemingly separate representations of affordance, spatial semantics, and valency.

Mathematics has been traditionally thought of as a relatively abstract domain of knowledge (see Adámek, Herrlich & Strecker, 2004). At the same time, space-related associations have always been helpful as a tool to aid the understanding of numbers and arithmetic. Cartesian coordinates offer a good example, where a reference system specifies a given location in space relative to an origin point using two fixed coordinates (see Descartes, 2001). To formally define this concept would require a relatively complex mathematical apparatus;

to explain to a layman it is relatively straightforward if space is utilised in understanding. It is easy for one to remark they left a house and travelled i miles in one direction before travelling j miles in another, then show how these points are but coordinates on a map where i and j correspond with an X and Y axis.

But association between numbers and space goes deeper than this. At the level of psychological experimentation, the association between space and number has been shown across a great many behavioural tasks. For example, when a participant is asked to judge the location of a centre point in either a broken or unbroken straight line during a line bisection task, they are fairly accurate despite displaying a slight bias depending on handedness (for a review, Jewell & McCourt, 2000). However, when this line is made of the numbers 2 or 9, or of words that represent them, a participant's judgement of centre is skewed toward the left or right respectively (Doricchi, Guariglia, Gasparini & Tomaiuolo, 2005). This suggests that it is the knowledge of number-space associations that causes the bias in judgements, as if the left-to-right oriented number line had numbers plotted atop of them: 2 would be associated with leftward space and 9 with rightward. A similar effect is observed in vertical space, to a lesser extent, with bisection tasks using larger numbers causing a bias upward, and smaller numbers biasing bisection downward in space (Cappelletti, Freeman & Cipolotti, 2007). There are other factors at work (e.g. see differences in visual vs tactile line bisection; Shelton, Bowers & Heilman, 1990) but the effect of number is consistent across task design.

The spatial biases induced by numbers can also be registered by means of an attention displacement effect (Longo & Lourenco, 2007). In a visual cueing paradigm, participants were presented with a number before having to respond to a target in one of two visual locations on the screen. Presenting small numbers (1 and 2) facilitated faster leftward target detection responses, while presenting larger numbers (8 and 9) facilitated rightward target detection responses (Göbel, Calabria, Farne & Rossetti, 2006; Loftus, Nicholls, Mattingley & Bradshaw, 2008; see also Fischer & Brugger, 2011). It is important to note that the digit itself gave no indication as to the outcome of the task, being entirely uninformative. Later work shows that this effect could be underpinned by an automatic ocular drift that accompanies the attentional shift and occurs independently, preceding an overt saccadic response. Myachykov, Ellis, Cangelosi and Fischer (2016) had participants maintain gaze on a central fixation point or perform left-to-right-to-left saccades following the auditory presentation of a number. In both tasks, spontaneous eye movement in the horizontal dimension confirmed ocular drift along the mental number line: leftward following small numbers, rightward following large numbers.

The Spatial-Numerical Association of Response Codes (SNARC) is another effect confirming the existence of spatial-numerical mappings in horizontal space. It emerges when participants are required to make parity judgements about a perceived number (e.g. "press the left key if the number is odd, press the right key if the number is even"; see Dehaene, Bossini & Giraux, 1993; Fias, 1996). This differs to the previous two effects described, as here the effect is less automatic in a sense that the content of a number representation is being necessarily accessed. The SNARC effect shows that left lateral responses are made faster following small numbers, while right lateral responses are

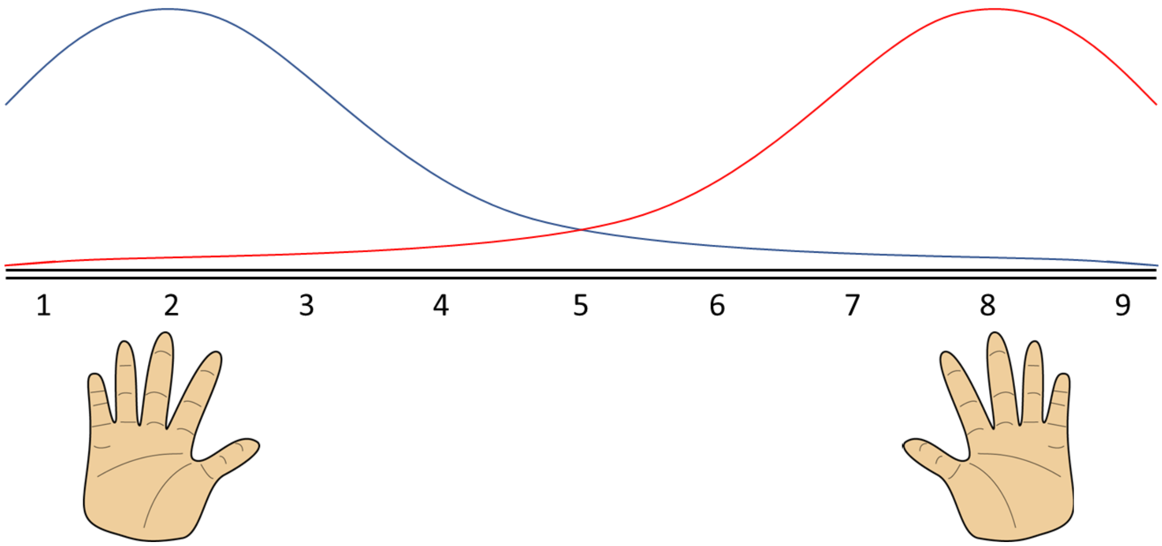

Figure 3. A visualisation of the SNARC effect, whereby the blue line indicates an advantage for smaller numbers and left hand responses, while the red line indicates an advantage for larger numbers and right hand responses.

associated with larger numbers *despite the task not requiring any magnitude estimation* (Figure 3; Fischer, Castel, Dodd & Pratt, 2003; Viarouge, Hubbard & McCandliss, 2014; Ninaus et al., 2017). The SNARC effect has been found both in horizontal and vertical space, though it is weaker in the latter dimension (Hesse & Bremmer, 2017).

Importantly, the SNARC effect has been shown to be relatively rapidly emerging. In Fias, Lauwereyns and Lammertyn (2001), participants were required to view shapes or lines that were superimposed onto numbers. The task then required the judgement of orientation using either the left or the right hand to respond, which resulted in the emergence of a SNARC effect and no observed effects of shape or colour processing. In later work, it was suggested that this can be credited to the overlap in neural regions for number, orientation, and space in the parietal cortex (Lammertyn, Fias & Lauwereyns, 2002), and the lack of overlap for other factors like colour and shape. However, later research has shown this to be a much more complex process suggesting a greater role for the parietal cortex (Evans, Edwards, Taylor & Ietswaart, 2016; Colizoli, Murre, Scholte & Rouw, 2017; Mercier, Schwartz, Spinelli, Michel & Blanke, 2017).

The unifying concept behind the effects discussed so far is the notion of a *mental number line* (Dehaene, 2003), later revised towards a *mental number space* that includes two (Chen & Verguts, 2010) or three (Winter, et al., 2016) mapping dimensions. This construct stems from work on the distance effect, whereby number pairs with greater numerical values of separation are more easily distinguished than number pairs with less numerical distance, at least in numbers less than ten due to a logarithmic compression of the Euclidean distance between the digits (Moyer & Bayer, 1976; Dehaene, Dupoux & Mehler, 1990). The mental number line, and by extension mental number space, is exactly as it sounds: the conceptualisation of number, or magnitude, in top-down, left-right and near-far space.

By incorporating an extra dimension, mental number space evokes cultural effects (among other things) as an explanation of why effects observed in the horizontal domain are much stronger than those seen in the vertical, a suggestion supported by both embodied (e.g. Barsalou, 1999 Myachykov, Scheepers, Fischer & Kessler, 2014) and associative numerical cognition theories (Beller & Bender, 2008; Leibovich, Katzin, Harel & Henik, 2017). Although this thesis does not specifically address this, the effect of culture has been the subject of intense recent research. One study examined a sample of Russian-Hebrew bilingual participants to show SNARC effects when reading left-to-right (Cyrillic) but also when reading from right-to-left (Hebrew), which suggests reading habits contribute to the observed effects (Shaki, Fischer & Petrusic, 2009). Later research examined Iranian participants, which presents a novel set of circumstances: Farsi is read from right-to-left, but the number system used is read left-to-right. While a line bisection task still discovered a conventional number-based priming shift, no such effect was found in a random number generation task. This suggests that the horizontal mapping may be sensitive to the situation experienced (Rashidi-Ranjbar, Goudarzvand, Jahangiri, Brugger & Loetscher, 2014).

So far, the SNARC has been shown to emerge relatively automatically, in other words regardless of individual intention to access the magnitude information (i.e. the task requires no processing of magnitude). Also, it is distinct from accessing other types of perceptual information about the stimuli as it doesn't emerge when participants are asked to identify shapes. It is sensitive to reading direction as it can be modulated by this, and may be extinguished if the system of number and reading habit are in conflict. The question now concerns where SNARC originates. Specific proprioceptive coordinate systems can be ruled out, as studies have demonstrated SNARC effects to emerge when participants point toward targets (Fischer, 2003), cross their hands (Dehaene, Bossini & Giraux, 1993), and even when participants make eye-movement responses over the traditional hand or leg-based triggering (Schwarz & Keus, 2004). In addition to this, the SNARC effect has been seen to emerge in response to grasp aperture, with participants adopting closed-hand and open-hand grasp postures and responding faster to small and large numbers respectively (Andres, Davare, Pesenti, Olivier & Seron, 2004). This will be further discussed later in the chapter as it is crucial for the understanding of overlap-based interactions between simulated representations.

Another method of triggering spatially congruent responses is to use tactile stimulation (Spence, Pavani & Driver, 2000). For example, affecting the left hand of a participant results in faster left-space responses (the equivalent being true for right hand stimulation). Interestingly, even when hands were crossed this effect still occurred (i.e. stimulation delivered to the left hand while it is in right-side space caused faster rightward response). This is starkly similar to work discussed earlier (Dehaene, Bossini & Giraux, 1993), and serves to suggest a similar mapping between the perception of space and the mental representation of number via spatial-conceptual mapping. Indeed, in neuroimaging studies examining visuo-spatial cueing, activation of the parietal lobe is consistently found (Eimer, van Velzen & Driver, 2002; Behrmann, Geng & Shomstein, 2004; Wu, Li, Li, Sun, Guo & Wu, 2014).

When the literature discussed so far is taken collectively, interactions between magnitude and space appear to be relatively consistent. Evidence furthermore shows these findings to be relatively effector-independent, and in line with the theoretical basis for interplay between concepts discussed earlier: due, in part, to shifts in attention linked to spatial, eye, and hand representations. Importantly, it has been suggested that non-human species keep track of numerosity (see Dehaene, 2011) through neurons that are magnitude-selective (Thompson, Mayers, Robertson & Patterson, 1970; Sawamura, Shima & Tanji, 2002; Nieder, Freedman & Miller, 2002). Through training, this behaviour can also be extended to the manipulation of symbols used to represent numbers (e.g.

Matsuzawa, 1985; Whalen, Gallistel & Gelman, 1999; Verguts & Fias, 2004). Similarly, infants (Xu & Spelke, 2000; Coubart, Izard, Spelke, Marie & Streri, 2014) and adults (Barth, Kanwisher & Spelke, 2003) track numerosity also, suggesting that counting or tracking behaviours in the environment might have been a successful evolutionary adaptation.

In A Theory Of Magnitude (ATOM; Walsh, 2003), the interactions observed between number and space, as well as between time and number, and time and space, are exactly that: an evolutionary adaptation which serves to lessen the load on, and aid, cognition when it comes to concepts that all have a magnitude-like meaning. ATOM highlights a classic argument in psychology where Piaget and Binet (in Fraisse, 1963) suggest children are unable to discriminate between temporal and spatial order, because *perhaps the child is right*. That, through experience within the body and environment a cognising infant is born into, the ability to discriminate between time, number and space develops. After all, as far as the architecture of the brain is concerned, it would be inefficient to have several similar systems distributed slapdash across the cortex (Collins & Loftus, 1975; also van den Heuvel, Stam, Kahn & Pol, 2009). The main support for ATOM is that it satisfies these criteria, the need to efficiently process external (magnitude-related) information for action, providing a directly-accountable system for processing that is based in the parietal cortex.

The main competitor of ATOM is the generalised effigy of attention, often evoked in one of many guises as a post-hoc explanation of effects. This may sound like a strong statement to make, but the literature is clear: attention-general is *the* processor of time (Casini & Macar, 1997), *the* system for maintaining number (Burle & Casini, 2001), *the* gatekeeper between time and number processes (Zakay & Block, 1995), and even *the* store containing for any or all of the above (Tracy, Faro, Mohamed, Pinsk & Pinus, 2000). Further, there is no widely accepted region of the brain responsible for attention-general, with the visual cortex (Ghose & Maunsell, 2002), cingulate cortex (Heinze et al., 1994), and parietal cortex (Posner, Walker, Friedrich & Rafal, 1984) being the brain regions1 responsible for attentional mechanisms of number, time and quantity depending upon the level of processing. The ability of attention-general to be used as a catch-all case means any prediction, within reason, can be formulated and find support in the literature. By means of ATOM, a more scientific attentional system allows only for specific hypotheses to be created, developed and tested.

Interim Summary: Numbers and Space

Number and space have been shown across a variety of studies to be intrinsically linked due to an underlying magnitude component or representation. Across numerous modalities and tasks, spatial representations have been seen to affect the processing and judgement of participants in top-down and bottom-up contexts. While this has been mediated by the embodied context and situated demands of a task, such as culture and cognition, the association between spatial and numerical response codes is robust. Further, by means of ATOM (Walsh, 2003), a framework has been presented that links domains beyond empiricism. The parietal cortex is suggested as the seat of sensorimotor manipulations involving space, quantity (number) and time, which allows for the present theory of conceptual interplay to be tested using domains that rely upon spatial components: affordances, spatial semantics and valency.

Affordances

Studies on monkeys have shown two varieties of neurons to exist when processing visual and motor information, these are mirror and canonical neurons (Sakata, Taira, Murata & Mine, 1995; Rizzolatti & Arbib, 1998; Gallese & Freedberg, 2007; Gallese & Goldman, 1998). In the macaque, both neurons are activated when carrying out specific actions, such as grasping. Canonical neurons, however, fire when simply looking at an object, providing support for the notion of affordance (Gibson, 1966; Gibson, 1977; Norman, 1999).

Affordances are the motor programmes associated with potential interactions with an object perceived by an agent within an environment, that become automatically activated; i.e., even without an intention to act (Gibson, 1966). The concept of affordances follows the general proposal for vison-for-action (e.g. Gallese, Craighero, Fadiga & Fogassi, 1999) making visual perception more than a passive input processing system, and allowing for *direct perception* – an understanding without having to recruit more complex higher order cognition. This means that the processing of object features like colour and shape happens at the same time and in close coordination with the processing of what an observer can physically do with the object. To Gibson (1977), an affordance was an *objective* action possibility that exists in the environment independent of the individual's ability to perceive it. It can be inferred, because of this, that objects have a set number of potential affordances, which are universal across agents despite a desire to use or ignore them (McGrenere & Ho, 2000). A door, for example, would afford the ability to be opened even if the handle or the door itself were camouflaged; a switch would afford being triggered, even if it were too high for the agent to reach.

To Norman (1999), this did not follow. How can the locus of an affordance be within an object, when the individual cannot possibly perform them all? Instead, the idea of *individually* perceived affordances is put forward. Under this account, it is not just the physical capabilities and limitations of an object and agent, but also the agent's goals, beliefs and experiences that affect the possible interactions afforded to the observer. For example, in Figure 4 a rock is being observed by three separate agents. In the Gibsonian sense of the term, all agents are equally capable of throwing, tool use, toe stubbing, hiding, climbing, and finding prey. The notion of perceived affordances captures the likelihood of different interactions occurring when the subjects are of different body, goal, and capability (see also Gibson, 2014; Fayard & Weeks, 2014).

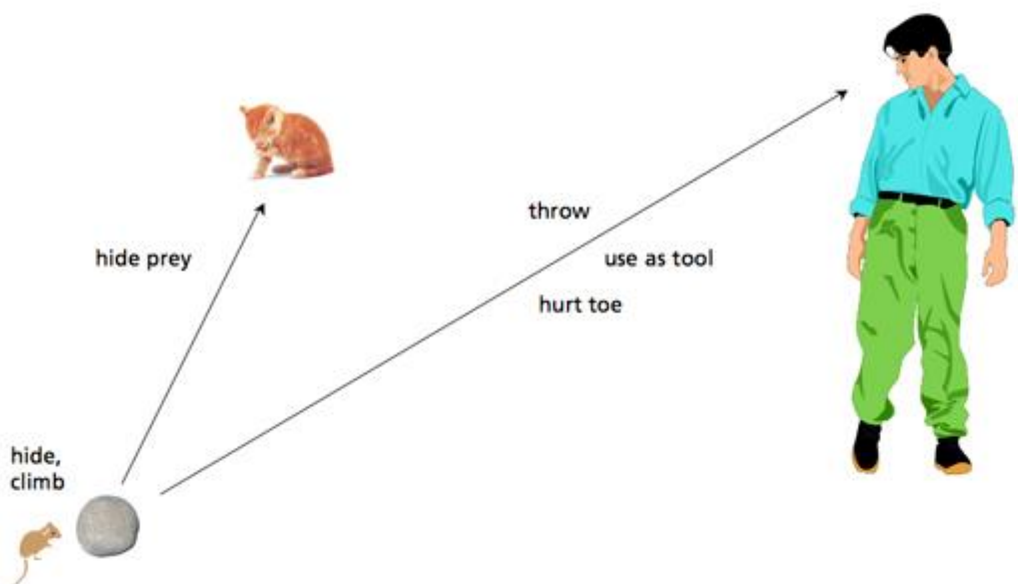

Figure 4. Object interactions as they are afforded to three different agents.

The notion of affordances can be subcategorized further into micro-affordances, whereby specific components of action delineate different profiles of interaction (Ellis & Tucker, 2000; Myachykov, Ellis, Cangelosi & Fischer, 2013). Here, the size and orientation of an object an agent intends to interact with potentiates different profiles of grasping (e.g. power/precision grips; Tucker & Ellis, 2004) or orientation (e.g. pronation and supination of the wrist and hand; Symes, Ellis & Tucker, 2007). As affordances are perceived manipulations, the situation of an interacting agent alters the ability of affordances to emerge (Wagman, Caputo & Stoffregen, 2016). Perhaps the strongest example of affordance variability can be seen in tool use, as here not only grasping affordances are activated but also functional affordances (Creem-Regehr & Lee, 2005). As a means of addressing this, manipulation affordances can *further* be distinguished into volumetric and functional affordances (Bub, Masson & Cree, 2008; Pellicano, Iani, Borghi, Rubichi & Nicoletti, 2010). A functional affordance is one associated with use (e.g. using a claw hammer to pry a nail from a wall) while volumetric affordances are used for grasping (related to the aperture of the hand when picking items up).

Recent research shows that manipulating volumetric and grasping affordances impacts upon the time taken to process subsequent stimuli. Borghi, Flumini, Natraj and Wheaton (2012) had participants observe objects that were related either by functional use (knife and jam), spatial use (knife and mug), or objects that were unrelated (jam and mug). Additionally, a hand was presented near the stimuli, grasping an object functionally, grasping an object with a manipulation grip, or not displayed at all. The reaction time of a participant to the task was fastest when objects were functionally, over spatially, related, but was affected by context. Manipulative conditions made functional trials slower, and functional conditions were slower in spatial trials. This is understood as being likely due to motor simulation. Myachykov, Ellis and Cangelosi (2013) found further support for this, in a task that shown graspable object parts to play a role in the process of affording. For example, in viewing a saw (Figure 5) it is possible to afford many different grasps. However, as use is frequently associated with the handle region, it is more likely to prime: 1) power grips, and; 2) right-hand specific response (c.f. Cho & Proctor, 2010).

Vainio, Ellis and Tucker (2007) make a case for the relative degree of stability in micro-affordances, suggesting that there are *stable* and *variable* featural components of object representations. The stable features of an item exist across objects such as using a precision grip to interact with a pen: despite the variety of different shapes and sizes, a competent adult will tend to grasp a pen

Figure 5. A hand saw. Note that this hand saw is more readily able to prime power grip responses (because of the handle) than precision grip responses (to picking up via the blade).

with the fingertips and thumb pressing against one another. Variable affordances are instead dependent upon situation and exist only when certain circumstances are met (i.e. transporting a pen in the palm of the hand could be done by means of a power manipulation). In a meta-analysis of studies examining brain region activation during viewing of stable and variable affordances, greater activation was found in the dorso-dorsal pathway for variable, and ventro-dorsal pathway for stable, affordances (Sakreida et al., 2013; see also Rizzolatti & Matelli, 2003). Binkofski and Buxbaum (2012) related this difference to use and grasp, driving a connection between the stability of an affordance and functional/spatial item use.

It has been established so far that affordances are *agent-perceived motor programmes supporting interactions with an object* that may be relatively *stable* across use or *variable* depending upon situation and whether the intended use is *functional* or *volumetric*. Given such radical differences in affordance profiles *within the same item*, how can this area be studied free from interference and confounding affordance profiles? Simon effect-like findings (see Simon, 1990; Simon & Berbaum, 1990) when viewing objects provides a plausible explanation. The work of early *stimulus-response compatibility effect* experiments has participants classifying objects into categories, and that the objects tended to be either large or small, affording power or precision grips respectively (e.g. Tucker & Ellis, 2001; Grèzes, Tucker, Armony, Ellis & Passingham, 2003). Although the object size had little to do with successful completion of the task, the congruency between size and affordance type facilitated task response (Thill, Caligiore, Borghi, Ziemke & Baldassarre, 2013). So, by providing a context to the task, it may be possible to reliably trigger activation of certain affordance profiles. Recent research shows cognitive processing of context to rely upon processing in the ventral stream (see Goodale & Milner, 1992), which allows goal-directed behaviour to influence processing occurring in the dorsal stream (vision for action; Mahon et al., 2007).

The focus of the current thesis is on manipulation of stable affordances. As already alluded to above by a review of studies documenting size-congruency effects in power and precision grip items, when assuming a power grip, there is a *larger* grasp aperture than when assuming a precision grip (Castiello, 2005). This difference in volumetric affordances' size has been related to the fact that magnitude-related information may be available in many more domains than is typically appreciated, including in affording action to item (Walsh, 2003; Rossetti et al., 2004; Göbel, & Rushworth, 2004). In Dehaene, Molko, Cohen and Wilson (2004), the argument is made that this is due to an *overlap* in the brain regions responsible for the representation of magnitude information and motor tasks, the intraparietal sulcus. The intraparietal sulcus is a part of one of the visual pathways involved in the encoding of spatial information, the dorsal system (Culham et al., 2003; see also Rizzolatti & Matelli, 2003; Milner & Goodale, 2008).

Generalizing from these and similar findings, ATOM (Walsh, 2003) purports the existence of a relatively universal magnitude system that underlies access to the magnitude information across knowledge domains. Many studies support the notion of an interaction between affordance and number by means of such magnitude system, both directly and indirectly. Firstly, the latter: words that represent objects of relative size have been shown to affect the activation of grasp affordances (Glover, Rosenbaum, Graham & Dixon, 2004). In Glover, Rosenbaum, Graham and Dixon, this effect was shown to diminish as participants interacted with stimuli which suggested an online correction, something only possible without significant delay if the same system is being utilised. Though seemingly convincing, it would not be reasonable to generalise these findings from semantic knowledge to numerical cognition. The understanding of magnitude has been shown across many studies to be an ability reliant on abstract representations of size and quantity (Brannon, 2006; Dehaene, Bossini & Giraux, 1993; Dehaene, Dehaene-Lambertz, & Cohen, 1998).

Secondly, evidence that more directly shows the coupling of spatial representation with magnitude can be seen through the co-location of magnitude and spatial information in the brain. Walsh (2003) suggested the parietal cortex to be the location of the magnitude system. Many studies confirm the link between this region and numerical processing (Dehaene, Piazza, Pinel, & Cohen, 2003; Bueti, & Walsh, 2009), while others show this region to play a role in visual gesturing (Desmurget, Epstein, Turner, Prablanc, Alexander, & Grafton, 1999; Connolly, Andersen & Goodale, 2003) interaction and grasping (Rathelot, Dum & Strick, 2017; Konen, Mruczek, Montoya & Kastner, 2013), and object manipulation (Binkofski et al., 1999; Buccino et al., 2001). Using reversible inactivation, animal research even shows an inability to pre-shape the hand to grasp when there is damage to the parietal cortex (Gallese, Murata, Kaseda, Niki & Sakata, 1994). In a seminal study, the parietal cortex was linked to all the above, incorporating reaching, grasping, object, and tool use (Vingerhoets, 2014). Further, the parietal cortex contains the dorsal stream, one of two visual pathways

(Goodale & Milner, 1992). This pathway is widely accepted as being responsible for guiding actions in space. In Chao and Martin (2000), fMRI and single unit recording was used to show a similar response in parietal cortices when exposed to manipulable objects, suggesting that the understanding of tools relies on specific sites in the dorsal pathway.

Of all the domains examined in this thesis, manipulation affordances are rendered as the most concrete. This is because of the clear link between the physical environment (i.e. the object to interact with) and the associated representation encoding agent's concrete experience. Numerous work has shown that merely perceiving an object is enough to potentiate the stable affordances associated with items (Helbig, Graf & Kiefer, 2006; Ellis & Tucker, 2000; Metta & Fitzpatrick, 2003), and so here a paradigm is suggested whereby participants are first primed with specific object affordances. This priming should later facilitate large/small number responses (cue dependent) in a parity judgement task, and affect recall during a verification task. Thus, the specific hypothesis for these studies is that grasp size and object representations, stored in memory, will lead to the establishment of attentional SNARC effects during auditory number processing, as revealed by saccade parameters.

Interim Summary: Manipulation Affordances

This section reviewed and summarised research pertinent to the area of affordances, with a greater focus on the aspects important to the thesis. In other words, it has been highlighted that mechanisms for manipulation and numerical processing overlap. One such way that this happens is through the dorsal visual pathway, known commonly as the vision for action stream of processing. While affording to items in space is a continuous process, a distinction has been made in that affordances are agent-perceived. Because of this, goal-directed action is fundamental in processing the affordances available to an individual at any one moment – however, it has also noted that the mere perception of an object is enough to activate the affordances associated with it. In order to not be overwhelmed by the number of affordances available at one possible moment, affordance selection relies also on the ventral (vision for understanding) stream of processing.

Spatial Semantics

It is common parlance to *look up* to a respected person or *look down* on a person that is pitied. A proud speaker might describe themselves as *standing tall*, while a person in counselling might remark they're *down in the dumps*. Tall and short people aren't intrinsically worthy of more or less respect, nor does a person's height grow or shrink depending upon their mood. However, these examples serve to highlight the spatial component of language and a very controversial area of research (see Talmy, 1983; Lakoff, 2008; Boroditsky, 2001).

An agent will always be contained within a body, and that body will always be present in an environment. To a varying extent, that environment will be able to be navigated and interacted with. The language used by this agent will, at least in part, reflect both the concrete and the abstract aspects of the situation being experienced and described. Because of this, it is not surprising that language with a spatial frame of reference is fairly frequently used and encountered. The hypotheses of linguistic relativity (Whorf & Chase, 1956; see also Casasanto, 2016) and mediation (Vygotsky, 1978; Levinson, 2003; Slobin,

2003) find support from the use of space in language, and in turn provide strong explanations as to why space is so omnipresent. Both of these perspectives, to varying degrees, suggest language to effect and be affected by the cognitive processes of the speaker. Where these differ is in the degree to which thought is determined by language, with the former taking a relatively hard-line stance that language is thought and the latter being more flexible.

Space is not, within itself, an easy category to delineate within language. In fact, understanding spatial frames of reference is anything but straightforward! Despite a large literature suggesting the opposite – from the space grammar of Langacker (1982), to the conceptual spaces of Gärdenfors (2004), to the mental spaces of Fauconnier (1994), it appears spatial semantics has boldly gone… everywhere. At the same time, not all semantics is spatial. Thus, it is important to have an operational definition of the topic being studied as to avoid sweeping statements and amorphous categorisation.

Probably the easiest way of understanding space is to utilise classes (e.g. Landau & Jackendoff, 1993; Regier, 1996; Tyler & Evans, 2003). While this provides a quick way to make categorical judgements, it is not *universal* and a lot of information becomes lost (e.g. Brown, 1994). A way of circumventing this issue is to turn focus toward *communicative* function. Here, spatial semantics is concerned with being able to, during conversation, determine a location of a referent (Pederson et al., 1998). This view would require being able to answer questions of where, but also who, what, and when. However, this would prove controversial to some (e.g. Troyer, Curley, Miller, Saygin & Bergen, 2014;

Gallese & Lakoff, 2005; Boroditsky, 2000) that would instead have spatial semantics limited to the literal.

Here, spatial semantics is taken to mean *expressions that indicate a location, or a change in location, of an entity in space*. By adopting such a definition, the major controversies of the above are circumvented, and a non-arbitrary position reached whereby language can clearly be labelled as spatial. For example, "lift", "drop", "retreat" and "advance" would be spatial language lexemes; conversely, "love" and "hate", though triggering *spatial biases* (see the section on valency below), would not belong to *spatial language*. In part, the definition is motivated by the notion that cultural influence and embodied understanding of the world is a key component of language (Gibbs, Lima & Francozo, 2004). Another reason for this choice is to allow for a parallel to be drawn between *concrete* and *abstract* aspects of meaning, which will be elucidated further in the sections that follow.

As with most effects in cognitive science, the initial demonstrations of a spatial bias in the perception of imagery extends as far back as the beginnings of psychology (Scripture, 1896). This effect was later rediscovered, following the demise of behaviourism, and extended to visual priming induced by words (LaBerge, 1983). Later work documented the relationship between mental representations of space and spatial linguistic terms (Tversky, 1993; Schober, 1995; Carlson-Radvansky, Covey & Lattanzi, 1999). While these early studies reported some stable and consistent findings (e.g. Hayward & Tarr, 1995), the methods used were confounded by linguistic common ground (Schober), attributes of objects being described (Carlson-Radvansky et al.), and visual context (Spivey-Knowlton, Tanenhaus, Eberhard & Sedivy, 1998). This is expected, as language is used in an open system, and so not free from the confounding effects of the environment (Rizzolatti & Arbib, 1998; Larsen-Freeman, 2002; Larsen-Freeman & Cameron, 2008). A seminal study by Pulvermüller (2001) detailed neurological evidence in support of this, showing words like *kick, lick,* and *pick* to activate areas of the motor cortex involved in the acts of kicking, licking and picking. Spurred on by this, later work also found words to activate the sensory systems that are associated with motion processing, for example the words *rise* and *fall* (Meteyard, Zokaei, Bahrami & Vigliocco, 2008).

There is a large body of research at the behavioural level to support these claims. Arguably one of the most important studies in this area was conducted by Richardson, Spivey, Edelman and Naples (2001). Here, ratings for 30 different action-verbs were gathered, normed, and stratified into functional categories across 2d space: the horizontal and vertical axes (e.g. push, pull; sink float), with the verb-ratings of participants being affirmed in two tasks. Later, Richardson, Spivey, Barsalou and McRae (2003) used these verbs to make a case for image-schema interacting with perceptual processes. Across two tasks, the comprehension of verbs was shown to affect spatial processing, which furthers the claim that linguistic representation and perceptual mechanisms are closely intertwined. However, in these tasks sentences were used and so it is not clear whether the findings were motivated by the spatial representation of a given verb, or by the simulation of a whole sentential content. This is in line with accounts of sentence processing that are based on mental models (cf. Bower & Morrow, 1990). Kaschak et al. (2005), for example, found a similar effect in the comprehension of sentences: when asked to read a sentence and examine an image, participants were faster when the motion described in the sentence was in the opposite direction to the image viewed. This effect was later extended from visual to auditory processing (Kaschak, Zwaan, Aveyard & Yaxley, 2006), and shown to be negated by using single-pulse transcranial magnetic stimulation (TMS; Glenberg et al., 2007), which supports common coding accounts of cognition (e.g. Prinz, 1990). However, even if support is taken to exist for both accounts – that is, processing of both within-word spatial content and within-sentence – it can still be maintained that spatial representation, at least at some level, is recruited by language to aid understanding. Indeed, it would appear the effects finding lexical meaning to be captured by spatial representation are both robust and reliant (see also: Bergen, Lindsay, Matlock, & Narayanan, 2007; Meteyard, Bahrami & Vigliocco, 2007; Meteyard, Zokaei, Bahrami & Vigliocco, 2008). This can be taken as support for embodied and grounded theories of cognition, which would expect spatial representations to interact with cognitive processing during subsequent reactivation (e.g. Barsalou, 1999).

In this thesis single verbs with spatial semantics, instead of nouns or full sentences, are used. Using verbs allows for the focus of an experimental task to be on the mechanism that links perception and action through language. An experimenter is not having to rely upon the correct motor program to activate when participants are shown a ball, but instead directly evoke them through linguistic labelling, e.g. kicking. Further, by presenting only the verb to participants, the possible confounding effects of sentence simulation are avoided.

Experiments have been able to show that the mere perception of words alone activates image schema that either facilitates memory or interferes with attention (Richardson, Spivey, Barsalou & McRae, 2003). Bergen, Lindsay, Matlock, and Narayanan (2007) suggest that the effect emerges dependent upon the image schema implied by the sentence (e.g. concrete vs abstract movement; see Estes, Verges & Barsalou, 2008) where referential framing has been shown to have an ability to bias attention in the spatial semantics of words (Zwarts, 2017).

Additionally, a role for magnitude has been found in the processing of language. One study found an effect whereby language with greater frequency evoked faster left-hand responses (Hutchinson & Louwerse, 2014). Bundt, Bardi, Abrahamse, Brass and Notebaert (2015) provide neurological support through showing greater motor evoked potentials for the right index finger following visual presentation of the word right and for the left index finger following the word left. The common denominator across the reported studies is magnitude-related spatial responses indicating the existence of a mental number space. Additionally, there is ample evidence showing concrete and abstract words and sentences from other domains to also be grounded in sensorimotor experience (Hauk, Johnsrude & Pulvermüller, 2004), showing location information to interact with spatial semantic categories (Luo & Proctor, 2013), and showing numerical information to bias spatial understanding (Shaki & Fischer, 2017). It's important to note that most evidence supporting the mental number line relies upon *manipulating* rather than merely perceiving numbers. For example, it has been shown in healthy adults that, when asked to bisect a line, that 4+2 is estimated as further rightward than 8-2 (Pinhas, Shaki & Fischer, 2014; Pinhas, Shaki & Fischer, 2015). This suggests further research is required to examine whether representational pairs (spatial semantics and numerical cognition) interact. The associated SNARC effect has already been shown to be modulated by reading direction (e.g. Shaki, Fischer & Petrusic, 2009) and so an assumption that meaning will affect processing is grounded. Theoretically, this is made possible through association. Pulvermüller (2013) asserts that neurons make meaning by Hebbian learning mechanisms, and so by means of continued activation both spatial and numerical systems interplay. Mental number space develops through usage, as does the association between linguistic label and space (e.g. Gärling & Evans, 1991; Varela, Thompson & Rosch, 2017).

In comparison to affordances, spatial semantics is more abstract. This is because it relies upon language, and not just on items present in the environment. As previous work has provided a case for the ability of spatial semantics to bias attention (e.g. Richardson, Spivey, Barsalou & McRae, 2003), here a paradigm is suggested whereby participants are first primed with words denoting specific spatial semantics. This priming should later facilitate large/small number responses (cue dependent) in a parity judgement task, and affect recall during a verification task. Thus, the specific hypothesis for these studies is that spatial semantics, stored in memory, will lead to the establishment of attentional SNARC effects during auditory number processing, as revealed by saccade parameters.

Interim Summary: Space in Semantics

This section reviewed and summarized research pertinent to the area of spatial semantics, with a greater focus on the areas important to the thesis.

Numerous studies suggest spatial knowledge to be reliant upon sensorimotor simulations associated with linguistic labels and objects (see Vigliocco, Vinson, Lewis & Garrett, 2004). Indeed, the understanding of action and spatial language has been previously linked to grounded experiences (Richardson, Spivey, Barsalou & McRae, 2003; Meteyard, Bahrami, Vigliocco, 2007). Referential framing, important to the ability of spatial semantics to lead attention (e.g. Landau & Jackendoff, 1993; Pederson et al., 1998; Zlatev, 2007), provides accountability for this system that relies on an individual situated in an environment (à la Gallese, 2007). Because of the similarities in empirical tasks examining visual attentional biases observed in SNARC and spatial semantics, as well as theoretical accounts of cognitive embodiment (Barsalou, 1999; Pulvermüller, 1999; Myachykov, Scheepers, Fischer & Kessler, 2014), motivation can be found for the proposed interactions. Though necessarily more abstract than affordances due to the obligatory linguistic coding, an interplay between representational components is still hypothesised.

Valency

When valency is referred to in this thesis, what is really being discussed is emotion. Specifically, a continuum between positive and negative emotional connotations as expressed by language. So, the language describing a situation that evokes happiness is said to be positively valenced. Likewise, should a situation evoke sadness, it can be said to evoke a negative valency (Frijda, 1986). As argued by embodied literature (e.g. Barsalou, 1999) the processing and understanding of valenced words comes through an interaction between the world, the body, and the mind. For example, it has been known that observing either a smile or frown leads to activation in the very same facial muscles used to produce either expression (Dimberg & Petterson, 2000; Moody, McIntosh, Mann & Weisser, 2007).

It has been argued that this mirroring (e.g. mirror neurons; Rizzolatti & Craighero, 2004) is what allows an agent to comprehend the emotions and actions of other people (Gallese, 2006) as well as their own (Niedenthal, 2007). Here, the thesis is concerned with language, not just emotion, and so a necessary question is whether language that utilises valency necessarily causes *motor resonance* (Zwaan & Taylor, 2006; Taylor & Zwaan, 2008). Motor resonance refers to the hypothesis that descriptions of an action (e.g. "frown") will activate the same motor resources used in performing the action itself, similar to the effects that are observed through visual perception. Foroni and Semin (2009) detailed two tasks that required participants to process verbal stimuli, presented either overtly or covertly, finding smile-related muscle activation to emerge so long as the potential for motor resonance exists (i.e. is not inhibited by task demands). These findings fit with accounts of cognition described previously, whereby language maps onto areas of the brain that are associated with perception and action (Pulvermüller, 2013).

Importantly, when the results of Foroni and Semin (2009) are understood in light of the TMS research by Buccino, Riggio, Melli, Binkofski, Gallese and Rizzolatti (2005), these articles together provide compelling evidence against criticisms of simulation for action (Spaulding, 2011): here, it can be taken that simulation of action co-occurs alongside language understanding, and not as a consequence of it. This is also paramount for the hypothesis of conceptual interplay, which relies upon simulations that occur when two representations are simultaneously activated.

Supporting findings are found in Glenberg and Robertson (2000) who assert that language comprehension relies on proximity between event and linguistic label. This so-called *the indexical hypothesis* follows the idea that the perceptual symbols described in Barsalou (1999) are parasitised by language in order to create meaning (see also Glenberg & Robertson, 1999; Kaschak & Glenberg, 2000; Glenberg, 2002). The *action-sentence compatibility effect* (Glenberg & Kaschak, 2002) – an experimental associate of motor resonance – emerges from this, a result which shows how a conflicting sentence (e.g. push the box) can interfere with subsequent action (e.g. pull the door). In a study bearing similarities to the original Simon effect study (Simon & Berbaum, 1990), participants were tasked with pressing a button that was either closer to, or further from, their body after reading a sentence that implied either an action associated with movement away from (e.g., *push*), or towards (e.g. *pull*), the body (e.g. Borreggine & Kaschak, 2006; Secora & Emmorey, 2015; Vinson, Perniss, Fox & Vigliocco 2017). Due to the necessity of sensorimotor simulation, a bottlenecking when processing conflicting information is observed (Prinz, 2013). This finding is taken to further support an embodied account of accessing meaning (Barsalou, 2009).

It has been shown that affective language can also cause motor resonance, making stronger the case for grounding cognition in sensorimotor experience and creating the avenue of research this thesis is to explore further. Conceptually, valency differs from spatial semantics by means of a greater abstraction. For the purposes of this thesis, a parallel was drawn between *spatial semantics* and *spatial meaning*, which is to say the former relies upon markers of the environment: an agent can *push* or *pull* an object, and by doing so will move through space. Likewise, *advancing* or *retreating* implies movement. At the level of valency, though I can *love* climbing and *hate* football, though this thesis has drove me to both *pride* and *despair*, there is no physical movement associated with any of these emotions.

The *conceptual metaphor theory* as purported by Lakoff and Johnson (1980), suggests that understanding abstract concepts occurs via a metaphoric mapping between the world of concrete experiences (source domains) and the world of abstract concepts (target domain). Space is one such source domain, and already has much support from the literature as far as understanding time (Boroditsky, 2000) and emotional concepts (Richardson, Spivey, Barsalou & McRae, 2003). Similarly, Zacks and Tversky (2001) make a compelling argument for the understanding of events by means of temporal and spatial structure.

The present thesis is concerned with the understanding of valency and how this cognitive architecture can bias spatial processing. Typically, language is used to describe emotional states by means of space. At least in Western cultures, this is implemented in left-right and bottom-up polarities, which is to suggest the horizontal axis advances as it moves left to right and the vertical grows from the bottom upward. Most studies demonstrate that negative valency is associated with downward and leftward space, while upward and rightward space is associated with positive valency (Crawford, Margolies, Drake & Murphy, 2006).

While it is obvious that, in some cultures, the direction of the horizontal or vertical axis may reverse, it is unclear as to actually why this occurs. The Tropic, Embodied, and Situated Theory of Cognition (Myachykov, Scheepers, Fischer & Kessler, 2013) provides an explanation as to why this may be the case, as it taxonomizes grounding representations in experience. Here, embodied and situated representations are equivocal below tropic constraints of the environment.

Regardless of culture, many languages use spatially orientated terms in order to delineate positive and negative valency. It is important not to mistake an experience of valency as spatial representation, however, and understand them as being two distinct systems that are interfaced via a regular mapping mechanism: Gibbs (2005) suggests that there are conceptual similarities between the source and target domains which allows for the description (i.e. concrete) to be used to understand representation (i.e. abstract; see also Gentner, Holyoak & Kokinov, 2001; Gentner, Bowdle, Wolff & Boronat, 2001; Gentner & Hoyos, 2017). Thus, it is possible to describe valency by means of space, but valency will still have a non-spatial representation at its core (e.g. Lebois, Wilson-Mendenhall & Barsalou, 2015). If valency is to be represented in a similar manner to spatial semantics, then there should be markers present in language *and* behaviour. But, there is a tendency to study behaviour through language alone, which may very well be problematic as not all cognition is language.

Through spatial representation, valency utilises a powerful shortcut for the representation of information via a reference to a matching experience (Gattis, 2003). Memory and reasoning has been aided by the inclusion of spatial information (Hintzman, O'Dell & Arndt, 1981; Fellner et al., 2016; Perrault, Lecolinet, Bourse, Zhao & Guiard, 2015), but to date no research has investigated how this interferes cross-modally. As numerical cognition has been shown to incorporate a spatial aspect, it is not illogical to hypothesise about potential interplay between concepts, especially as the understanding of space is made possible through magnitude (Walsh, 2003).

A final note needs to be made: valency is the most abstract of all the domains covered in this thesis. The use of emotional language is almost entirely abstract as it is language based, and reflects feelings not directly traceable in the environment, indirectly traceable in the body, and not entirely understood in the mind (Altarriba & Bauer, 2004; Kousta, Vigliocco, Vinson, Andrews & Del Campo, 2011; Vigliocco et al., 2013). Here, a paradigm is suggested whereby participants are first primed with words differing in terms of valency. This priming should later facilitate large/small number responses (cue dependent) in a parity judgement task, and affect recall during a verification task.

Thus, the specific hypothesis for these studies is that the valency associated with a specific word, stored in memory, will lead to the establishment of attentional SNARC effects during auditory number processing, as revealed by saccade parameters.

Interim Summary: Emotions in Space

This section presents research important to the area of valency, with a greater focus on the areas important to the thesis. Highlighted have been mechanisms by which affect, or valency, utilises the spatial domain in order to be more readily processed cognitively. Additionally, due to utilisation of space, a case has been made for magnitude in the form of a potential conceptual interface between number and valency.

Chapter Summary

Here a theoretical case has been made for the domains of affordances, spatial semantics, and valency interacting with the representation of magnitude by means of a third-party interface. It is suggested that the activation and representation of conceptual domains utilises mechanisms of sensorimotor simulation, in line with embodied theories of cognition. The interplay discussed is made possible by co-activated (i.e. either in close spatial or temporal proximity), distinct knowledge representations being processed in a third-party, general mechanism (such as attention or working memory).

By combining the emerging research, it is possible to generate tentative hypotheses that can be exploited through further academic study. Though discussed in more detail later in the thesis, these can be seen broadly to concern the nature of how the third-party interface processes information when dealing with congruent and incongruent representations. Exploratory by design, these hypotheses suggest that when representations are congruent by means of domain (i.e. between the parameters discussed throughout this chapter) there will be facilitation in response time and greater accuracy in recall.

In the chapters that follow, six experiments are to provide an empirical case for conceptual interface. These six experiments follow a similar methodology, which is described at a broad level in the General Methods (Chapter 2). Two of the studies then explore microaffordances and numerical magnitude interactions in Chapter 3, before another two explore interactions between spatial semantics and numerical magnitude in Chapter 4. Valency and numerical magnitude is explored in Chapter 5 before, finally, Chapter 6 provides the general discussion and conclusions of the thesis. Chapters 7 and 8 comprise the reference list and appendix respectively.

CHAPTER TWO

General Method

The following chapter aims to describe methodological elements of the project that are common across all studies. By describing these features now, more focus can be given to the findings and implications later. As such, this section of the thesis serves as a reference for future chapters, providing an overview of the hardware deployed, general features of participants, basic procedure, and data pruning methods. The experiment-specific chapters cover the precise details of participants, materials, and procedure.

Hardware Used

An Eyelink 1000 system recorded participant's eye movements. The setup consisted of different components, categorized into three domains for simplicity: the Eye Tracking Device, Host PC and Display PC. There is overlap in terms of how the devices act (e.g. the eye tracking device records the eye, the Host PC detects and categorises movements, the display PC coordinates the efforts), however, the groupings are for the sake of simplicity and understanding instead of functionally distinct categorisation.

Eye Tracking Device

The Eyelink 1000 is an ultra-high resolution device, deployed within the laboratory as desktop mounted with the illuminator on the left (SR Research, 2017). Eye detection was performed with centroid fitting, and tracking achieved using the Pupil with Corneal Reflection principle (Duchowski, 2007). Eyes were tracked with a monocular sampling rate of 1000Hz, capable of measuring one data point every millisecond. Such a frequency is important in maintaining a high standard of spatial resolution (measured at .01°), and accuracy (typically between .25° to .5°). At this tracking frequency, the blink recovery time was 1ms and the end-to-end sample delay on average less than 1.8msec.

The camera-to-eye distance of the tracker was approximately 60cm and, with the 35mm lens installed, this provided a gaze tracking range of 32° horizontally and 25° vertically – acceptable for the size of the monitor used to present stimuli and the distance from the monitor to the eye. Movement of the head was restricted using an SR Research head support with both chin and forehead rests attached. By doing so, any movement was contained within allowable parameters (25mm x 25mm x 10mm; horizontal x vertical x depth). The eyetracker produced an infrared wavelength of 940nm, gaining the categorization as a Class 1 LED Device. This is not harmful to participants when used as per standard operating procedures.

Host PC

The Eyelink 1000 was connected to a Dell Precision 390 via a parallel port cable, enabling the two devices to communicate multiple bits of data simultaneously. As the detection and categorization of eye-motion into saccade and fixation events is performed online, the requirements of the host PC are necessarily stringent. The Dell Precision 390 comprised an Intel Core 2 6400 CPU with two cores clocked at 2.13GHz, 1GB RAM and an NVIDIA Quadro NVS 285 with 128mb of memory. When eye-tracking, the Host PC ran a ROM-DOS Real-Time operating system to avoid buffering delays during data processing.

The experimenter could interact with the Host PC using a standard QWERTY keyboard and mouse in order to calibrate, validate, and monitor participant's performance. Participants were required to respond during the task using a Microsoft Sidewinder gamepad connected to the Host PC via a USB port. USB traffic polling introduces a variable input lag of up to 8ms due to the CPU of the Host PC polling devices at 125Hz (see Plant, Hammond & Whitehouse, 2003). However, low-level drivers produced by SR Research address this problem and the variable delay is benchmarked instead at less than 1ms. Following a successful session, data were transferred to the Display PC using a 100 BASE-T Ethernet cable

Display PC

The display PC served the procedures of calibrating the eye tracker, coordinating data collection, presenting stimuli during the experiment and collating data following completion. Here, the Eyelink Programming API was deployed as part of the experimental paradigm. Thus, the Display PC utilised SR Research's Experiment Builder (SR Research, 2017) to configure and control the Eye Tracking Device through the Host PC. As it was the responsibility of the Host PC to acquire and collect data, millisecond reaction timing was made possible despite the use of a non-real-time operating system on the Display PC (see Garaizar, Vadillo, López-de-Ipiña & Matute, 2014). The Display PC was a custom-built device, comprising an Intel i7-6700k, with 8 CPUs clocked at 4GHz, 16GB of RAM, and an NVIDIA GTX 980 with 4GB of memory. A 64bit image of Windows 7 was installed on the device, and sound played via Realtek Drivers through Kye Systems Corp' Genius Stereo Speakers.

Importantly for reaction timing, stimulus presentation occurred on a 19” ViewSonic Graphic Series G90fB CRT monitor connected to the Display PC via VGA cable. The monitor had a 1280 x 1024 resolution and 85Hz refresh rate. At this rate, the monitor refreshed every 11.764ms.

Software Used

The experiments were designed using Experiment Builder v1.10, software built by the company SR Research to allow for high levels of precision in the recording of data (SR Research, 2017). To aid design, Python v2.7 was utilised to increase the flexibility of Experiment Builder.

Collected data were parsed through Data Viewer v2.6 (SR Research, 2017). The output was then manipulated and analysed using Microsoft Excel 2016, IBM SPSS 24, and RStudio v1.0.136 (RS Team, 2017; via a backend of R v3.3.3, R Core Team, 2017). In using R, several additional statistical packages were required; these were psych (v1.7.3.21), ggplot2 (v2.2.1), plyr (v1.8.4), dplyr (v0.5.0), and extrafont (v0.17).

Participants

Participants were recruited via opportunity sampling of the Northumbria University SONA System, a participation management system. In return for contributing, participants were awarded course credits that could be used in recruiting for under- or post-graduate dissertation projects. It was required that all participants be over the age of 18, native speakers of English, have normal or corrected-to-normal vision, not have any language impairments, and not wear any eye makeup during testing. Due to the potential effects of body specificity (Casasanto, 2011) all participants were additionally required to be right handed, which was assessed with the help of the short form Edinburgh Handedness Inventory (EHI; Ransil & Schachter, 1994; http://www.brainmapping.org/shared/Edinburgh.php). Participants had to have an EHI score over 80 in order for their data to be included into the experimental sample.

Procedure

Experiments 1-6 followed a similar procedure, which gained approval for testing from Northumbria University's Board of Ethics. Before testing, participants were first fully briefed about the study, including use of the eye-tracking apparatus, by means of standardised instructions, and provided written informed consent (for an example, Appendix A). Any participants wearing excessive eye makeup (e.g. eyeliner, mascara, eyeshadow) were asked to remove it for testing.

Participants were seated at a desk in the eye-tracking laboratory with their chin and forehead firmly rested onto a support that was 60cm from the CRT monitor. The setup was adjusted to make participants comfortable, before equipment adjustment and calibration of the eyetracker took place. Calibration comprised a nine-point task that matched eye movement to screen location. This task had participants first fixate on a dot in the centre of the screen before directing gaze toward a series of fixation dots appearing at random across nine locations. A further nine-point validation task confirmed the error of recorded visual angle to be less than 1°.

Experimental trial contents are to be discussed at greater detail in each chapter, but the general structure of a trial remained generally the same across all experiments. Participants were presented first with a fixation dot (20px) for 500ms, before being presented with a priming image for 1000ms. Another fixation dot was then presented for 500ms. Following fixation offset, participants were presented with two square-shaped targets, 150x150px in size, either in horizontal or vertical space (upward: 512,192; downward: 512,576; leftward: 320,384; rightward: 704,384), and heard a female voice saying one of four numbers (one, two, eight, nine; for experimental materials, Appendix B). The use of a female voice recording was important, as previous research has found SNARC to be gender (Bull & Benson, 2006; Bull, Cleland, & Mitchell, 2013) and pitch (Campbell & Scheepers, 2015) sensitive. By controlling for vocal pitch, the extra dimensions of spatial representation that may become activated are prevented from interfering with the study.

Participants were tasked with responding to these numbers by means of a parity rule that was presented at the start of a block of trials, for example *"look left if the number you heard was odd; look right if the number you heard was even"* (cf. Fischer, et al., 2004). The parity rule was manipulated such that all directions were accounted for equally (left and right, up and down). After making the target directed saccade, participants were asked a question that verified the prime as being maintained in memory. This question presented either the same image or word participants were shown, or a different image or word, and to respond participants pressed one of two trigger buttons on a gamepad that corresponded to yes or no. A buffer period of 1000ms existed between the offset of one trial and the beginning of the next. See Figure 6 for an example trial

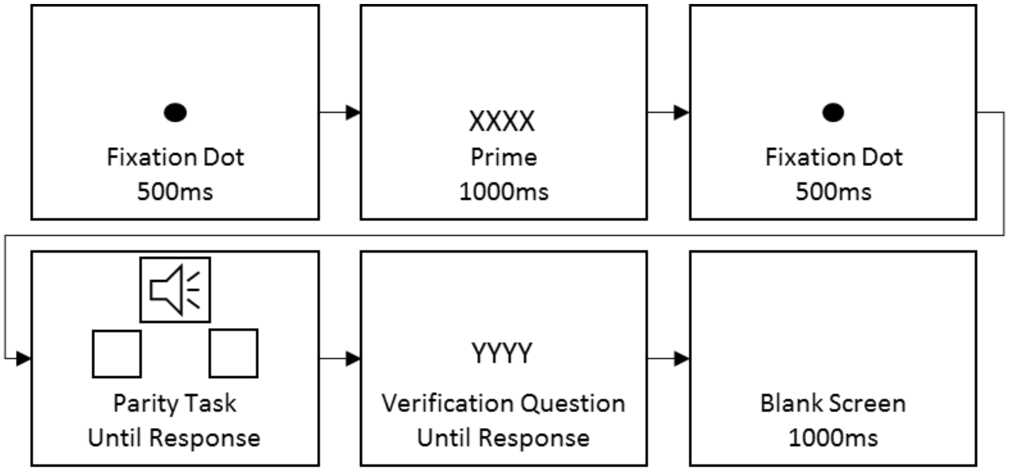

Figure 6. An example trial sequence in which the verification question is a word and incongruent with the prime.

sequence. After completion of the experimental session, participants were debriefed and thanked for their participation.

Data Filtering and Analysis

Filtering

The experimental output was first time-locked to the chronometric periods of interest (POI) that were deemed important for analysis. These POIs were: 1) probe onset to probe offset, 2) probe onset to verification question offset, 3) verification question onset to participant button response. POI 1 was used in the analysis of probe reaction time and measures related to saccadic eye-movement. POI 2 allowed for the analysis of total gaze durations. The reason for the longer duration is that participants may continue to fixate for a period following probe offset, which would be data lost if analysis was conducted under POI 1. Finally, POI 3 allowed for the analysis of measures related to the verification task. Measures of probe and verification accuracy did not require a time locked period, as these were generated automatically by means of custom python scripting.

Time-locked data were subject to filtering to remove any extreme values: for measures of probe and verification reaction times, this was between 150ms and 2000ms; total gaze durations, 10ms and 2000ms; first fixation durations, 10ms and 2000ms; saccade onset, 100ms and 2000ms; saccade duration, 20ms and 600ms. These parameters were based on the typical values found in the literature and they were used to trim the data with regard to anticipatory and severely delayed responses. Resulting data underwent a $\log_{10}$ transformation to account for the right skewness inherent in reaction time-based data and to assume a distribution much more representative of Gaussian-normal. Finally, any participants with too few remaining values were excluded from the analysis. This removed one participant from each task.

Analysis

Data were analysed by means of 2x2x2 within-subjects ANOVAs with further investigations of any interaction effects. The advantage of this type of analysis is that it protects against overclaiming *and* underclaiming the number of significant differences between groups. Furthermore, measures of effect size were provided via the partial eta squared statistic.

CHAPTER THREE

Volumetric Affordances And Numerical Magnitude

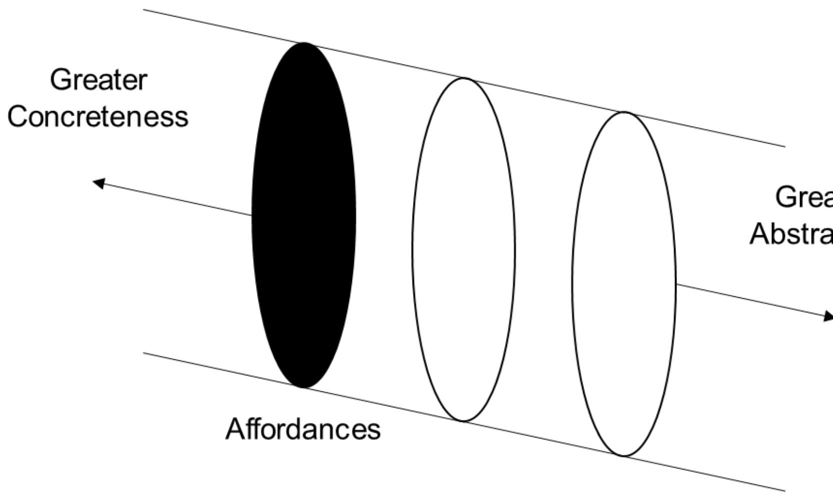

Figure 7. The Abstraction Pipeline. A pictorial example of how far removed the current chapter's subject matter is from concrete representation.

The following chapter comprises two experiments that required participants to maintain in memory the identities of objects of varying grasp volume, listen to numbers of varying number, and then direct eye movement toward one of two targets located on a screen in horizontal (experiment 1) and vertical (experiment 2) space. As discussed in the Introduction, there is growing empirical evidence for the assumption that object representations stored in memory and those formed online during perceptual apprehension rely on sensorimotor simulation (van Moorselaar et al., 2014) and that perceptual and semantic properties of these representations share an interactive processing space (Oliviers, Meijer, Theeuwes, 2006; De Groot, Huettig, & Olivers, 2016). Other studies show a similar case for the processing of numerical magnitude, such as SNARC (Fischer & Fias, 2005) and distance (Lendinez, Pelegrina & Lechuga, 2011) effects. Even more studies relate representations of number to sensorimotor simulations, such as volumetric grasp affordances (Badets, Andres, Di Luca & Pesenti, 2007) and time (Sell & Kaschak, 2011). These studies provide support for the ATOM theory of number (Walsh, 2003) suggesting interplay between number-related knowledge domains, which include perception and memory (Myachykov, Chapman, & Fischer, 2017). Here, it is hypothesized that the grasp size of object representations stored in memory will lead to the establishment of attentional SNARC effects during auditory number processing, as revealed by saccade parameters. Specifically, objects that involve assuming power grasps will prime responses in rightward and upward domains whilst precision grasps will prime responses in leftward and downward domains. Error rates are expected to mirror this, with greater accuracy being observed in wholly congruent trials.

Experiment 1

Horizontal Space

Methodology

Design

The task comprised a within-participants, 2x2x2 design with the following independent variables: Affordance (power/precision), Number (small/large) and Probe (left/right). Two parity rules (even-left; even-right) were used to balance for any effects of number line congruency and auditory number presentation. Trials were replicated to produce 96 instances per participant. Several dependent variables were recorded, including: reaction times in the parity-ruled saccade task and verification question, accuracy rates in the saccade and verification tasks, and both saccadic and fixation measures of eye movement. All participants responded to all trials, which were grouped by parity rule and counterbalanced across presentation. Numbers were presented randomly within blocks of testing.

Participants

The experimental sample consisted of 26 participants (13 males), with an average age of 22 (range: 18-50, SD = 7.593). All participants were native speakers of English, had normal or corrected-to-normal eyesight, and they were all right handed as per the inclusion criteria outlined above. All participants were recruited from the undergraduate population of Northumbria University, and they received course credits in remuneration for their participation.

Materials

In addition to the auditory number files used across all studies reported in this Thesis, objects' pictures were taken from Salmon, McMullen and Filliter's (2010) stimuli database, with the respective affordance norms provided by Lagacé, Downing-Doucet and Guérard (2013). These norms allowed for the creation of objective power and precision object trials, consisting of the most representative objects from each category. Fixation dots and target squares were created in Experiment Builder.

Procedure

All data were collected in a room with minimal lighting. Before testing, participants were briefed about the nature of the experiment (see Appendix A for the standardised brief) and asked to complete informed consent documentation (Appendix A) before answering a demographics questionnaire (Appendix C) and the Short Form Edinburgh Handedness Index (Appendix D; Ransil & Schachter, 1994). After consenting, the participant was then seated on a chair with the backrest tilted to a 110° 60cm from the screen with their head placed on an SR-

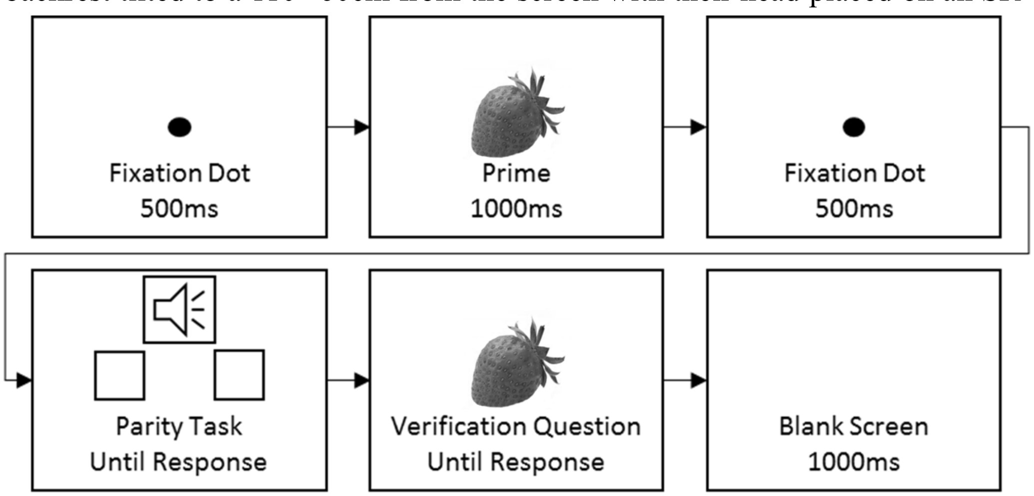

Figure 8. An example trial sequence in which the verification question is an object congruent with the prime. Note that presentation is not to scale but is used to aid clarification.

Research chin-rest, before being calibrated, tested, and debriefed. Figure 8 portrays a typical experimental trial. Each experimental trial started with a fixation cross presentation for 500ms followed by a centrally presented object for 1000ms, followed by another fixation cross (500ms). After that, an auditory number was played alongside two lateral visual targets, located as identified in horizontal space within the General Methods (chapter 2). In accordance with the parity rule, participants made a saccade toward one of the targets. The landing of a saccade triggered the offset of the saccade task and the onset of a verification task, which required participants to view an object and decide whether it is the same or different to the object seen at the start of the trial. This secondary task ensured that participants maintained the object's identity in memory when the auditory number was played hence allowing for the analysis of the potential interactions between the two co-activated representations (Myachykov, Chapman, & Fischer, 2017). Participants pressed a key on the game pad to respond to this task, either the left (corresponding to yes) or right (corresponding to no) trigger. Depress of the button signalled the end of a trial and a 1000ms buffer period before the start of the next. Participants were given accuracy feedback immediately after saccade and verification tasking. Individual experimental session lasted approximately 60 minutes.

Results

The strategy discussed in the general methods section was utilised in filtering and analysing the data provided by participants. This involved, post filtering and transformation, a series of 2x2x2 ANOVAs to understand fixation, saccadic, and manual response parameters of the data.

Responses to the parity and verification task were measured using reaction time and error rates for all participants. Eyetracking data was analysed only for the saccade task, which can be further divided into fixation and saccadic metrics. A standard criterion of α was used and set to .05. Data from one participant was excluded due to not completing the experimental paradigm, and all tests were conducted on the remaining 25 participants. For the raw data, see Appendix E.

Saccade Task

Error Rate Analysis

On average, correct responses in the saccade task were high (85.95%). More accurate responses were given in trials showing precision grip (86.82%) stimuli than those showing power grip (85.07%). The audial presentation of large (87.02%) numbers resulted in greater accuracy than the presentation of small numbers (84.88%). Finally, rightward (86.21%) trials were responded to more correctly than leftward (85.69%) trials. For conditional means, see the breakdown in Table 1.

Table 1. Mean rate of accuracy (%) in response to the saccade task.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	84.54	85.71	87.20	90.66	87.02
	Small	86.51	86.01	82.07	84.93	84.88
Total		85.52	85.86	84.63	87.78	85.95

In a closer analysis, no significant main effect of probe (Wilks' $\lambda = .997$, $f(1,24) = .067$, $p = .797$, $\eta p^2 = .003$), number (Wilks' $\lambda = .964$, $f(1,24) = .888$, $p = .356$, $\eta p^2 = .036$), or affordance (Wilks' $\lambda = .900$, $f(1,24) = 2.657$, $p = .116$, $\eta p^2 = .100$) was found. Additionally, no significant interaction was observed between probe and number (Wilks' $\lambda = .873$, $f(1,24) = 3.495$, $p = .074$, $\eta p^2 = .127$), probe and affordance (Wilks' $\lambda = .926$, $f(1,24) = 1.908$, $p = .180$, $\eta p^2 = .074$), or number and affordance (Wilks' $\lambda = .994$, $f(1,24) = .140$, $p = .712$, $\eta p^2 = .006$), nor was any interaction observed between all three factors (Wilks' $\lambda = .999$, $f(1,24) = .034$, $p = .856$, $\eta p^2 = .001$).

Response Time Analysis

Mean RT in the saccade task was 729.36ms. Responses were fastest when hearing large (721.22ms) over small (737.76ms) numbers. Leftward (735.29ms) conditions were slower than rightward (723.41ms) conditions. Finally, power grip (728.29ms) objects evoked a faster response than precision grip (730.41ms) items. The means for individual conditions can be seen in Table 2.

Table 2. Mean (and standard deviations) for response times in milliseconds to the saccade task.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	738.20 (303.39)	724.18 (278.11)	699.52 (288.03)	723.30 (302.20)	721.22 (292.93)
	Small	720.41 (304.21)	759.03 (346.32)	756.99 (340.78)	715.64 (282.42)	737.76 (311.45)
Total		729.19 (303.61)	741.31 (297.70)	727.38 (315.67)	719.57 (292.46)	729.36 (302.23)

A closer analysis revealed no significant main effect of probe (Wilks' λ = .946, f (1,24) = 1.363, p = .254, ηp^2 = .054), number (Wilks' λ = .992, f (1,24) = .202, p = .657, ηp^2 = .008), or affordance (Wilks' λ = .976, f (1,24) = .597, p = .447, ηp^2 = .024). Additionally, no significant two-way interactions were found between probe and number (Wilks' λ = .991, f (1,24) = .214, p = .647, ηp^2 = .009), probe and affordance (Wilks' λ = .997, f (1,24) = .079, p = .781, ηp^2 = .003), and number and affordance (Wilks' λ = 1, f (1,24) = .012, p = .915, $\eta p^2 < .001$). However, a significant three-way interaction was found between all three factors (Wilks' λ = .808, f (1,24) = 5.705, p = .025, ηp^2 = .192), prompting further investigation. See Figure 9 and 10 for a representation of the interaction. The interaction revealed no further significant differences when trials were grouped by power grip (leftward: large x small magnitude, p = .198; rightward: large x small magnitude, p = .164) or precision grip (leftward: large x small magnitude, p = .382; rightward: large x small magnitude, p = .330) conditions.

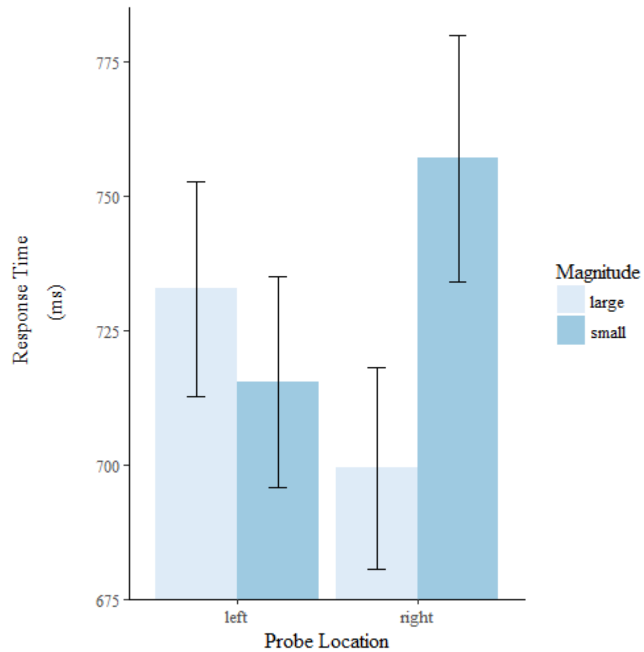

Figure 9. Depicted is one aspect of the three-way interaction for Probe Response Time. Responses to power grip trials are shown across probe location and magnitude, and reaction time is displayed in milliseconds.

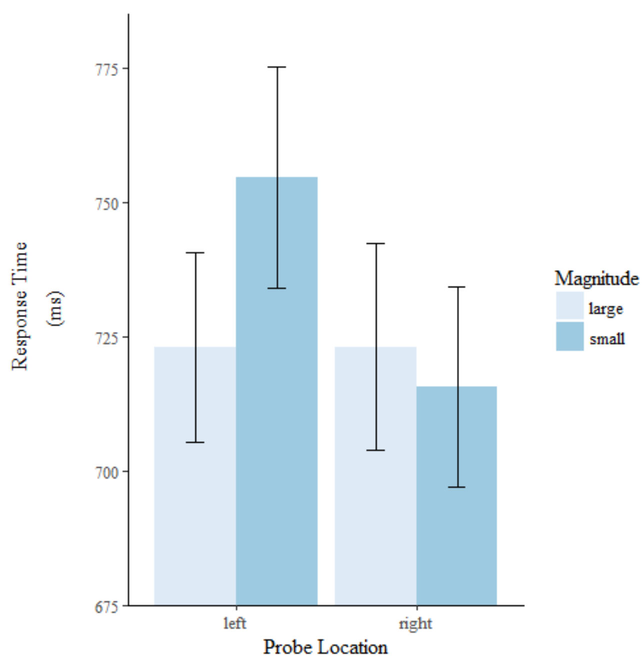

Figure 10. Depicted is one aspect of the three-way interaction for Probe Response Time. Responses to precision grip trials are shown across probe location and magnitude, and reaction time is displayed in milliseconds.

Eye Movement Analysis

Fixation data.

On average, participants' first fixations durations were 359.69ms. Large numbers (359.86ms) primed longer first fixation durations than small numbers (359.51ms), with the same being true for precision grip (365.63ms) over power grip (353.70ms), objects. Finally, leftward saccades (346.54ms) preceded shorter first fixation durations than rightward saccades (372.97ms). In Table 3, first fixation durations are shown on a condition-by-condition basis.

Table 3. Means (and standard deviations) for participant's first fixation durations presented in milliseconds during the saccade task.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	342.95 (188.71)	355.53 (202.35)	353.09 (188.22)	386.92 (219.07)	359.86 (200.54)
	Small	348.48 (191.70)	338.77 (209.09)	371.17 (225.94)	380.14 (277.70)	359.51 (228.36)
Total		345.78 (190.06)	347.32 (205.62)	361.95 (207.51)	383.59 (249.34)	359.69 (214.72)

Inferential analysis revealed no significant main effects of probe (Wilks' $\lambda = .997$, $f(1,24) = .058$, $p = .812$, $\eta p^2 = .003$), number (Wilks' $\lambda = .905$, $f(1,24) = 2.421$, $p = .133$, $\eta p^2 = .095$), nor affordance (Wilks' $\lambda = .959$, $f(1,24) = .983$, $p = .332$, $\eta p^2 = .041$). Additionally, no two-way interactions were observed between probe and number (Wilks' $\lambda = 1.000$, $f(1,24) = .011$, $p = .918$, $\eta p^2 < .001$), probe and affordance (Wilks' $\lambda = .940$, $f(1,24) = 1.473$, $p = .237$, $\eta p^2 = .060$), nor number and affordance (Wilks' $\lambda = .901$, $f(1,24) = 2.530$, $p = .125$, $\eta p^2 = .099$). Finally, no three-way interaction was observed (Wilks' $\lambda = .978$, $f(1,24) = .517$, $p = .479$, $\eta p^2 = .022$).

The amount of time on average spent by participants dwelling on a target during the saccade task was 448.74ms. Dwell time was longer for large (454.66ms) over small (442.71ms) numbers, for precision (454.64ms) over power (442.80ms) grip objects, and for rightward (450.15ms) over leftward (447.36ms) targets. Table 4 details total gaze durations on a condition-by-condition basis.

Table 4. Means (and standard deviations) for participant's total gaze duration presented in milliseconds during the saccade task.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	438.46 (234.67)	467.54 (241.85)	449.90 (243.68)	462.18 (233.75)	454.66 (238.38)
	Small	447.08 (253.11)	435.64 (243.72)	435.21 (232.97)	452.20 (277.08)	442.71 (252.20)
Total		442.88 (244.06)	451.95 (243.02)	442.72 (238.35)	457.28 (255.72)	448.74 (245.32)

Similarly, no significant main effects were found for probe (Wilks' λ = .995, f (1,24) = .114, p = .738, ηp^2 = .005), number (Wilks' λ = .909, f (1,24) = .2.307, p = .142, ηp^2 = .091), or affordance (Wilks' λ = .873, f (1,24) = .3.355, p = .080, ηp^2 = .127). No significant two-way interactions were discovered between probe and number (Wilks' λ = .990, f (1,24) = .226, p = .639, ηp^2 = .010), probe and affordance (Wilks' λ = .998, f (1,24) = .035, p = .852, ηp^2 = .002), or number and affordance (Wilks' λ = .996, f (1,24) = .084, p = .774, ηp^2 = .004). Additionally, no three-way interaction could be observed (Wilks' λ = .914, f (1,24) = 2.159, p = .155, ηp^2 = .086).

Saccade data.

Over the course of every saccade task, the average onset of a saccade was 695.37ms with the reference to the onset of an auditory number as the start of this RT period. Saccades performed in response to large numbers (689.34ms) were faster than saccades performed in response to small numbers (701.59ms). When participants were exposed to a power grip (694.33ms) item, saccades were onset faster than when exposed to precision grip (696.38ms) items. Leftward saccades (701.20) were slower to onset than rightward saccades (689.49ms). Table 5 provides a closer breakdown of saccade onsets by condition.

Table 5. Mean (and standard deviation) values for the onset of saccades, presented in milliseconds, as performed by participants during the saccade task.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	707.43 (315.31)	688.81 (275.82)	670.40 (301.68)	691.05 (313.32)	689.34 (301.69)
	Small	682.69 (306.20)	726.55 (324.73)	718.67 (340.80)	679.52 (297.79)	701.59 (317.68)
Total		694.95 (310.66)	707.40 (301.17)	693.69 (321.70)	685.43 (305.58)	695.37 (309.63)

Analysis of these findings revealed no significant main effects (probe: Wilks' λ = .940, f (1,24) = 1.542, p = .226, $\eta p^2 = .060$; number: Wilks' λ = .1.000, f (1,24) = .002, p = .963, $\eta p^2 < .001$; affordance: Wilks' λ = .970, f (1,24) = .738, p = .399, $\eta p^2 = .030$). Further, a two-way interaction was not observed between probe and number (Wilks' λ = .994, f (1,24) = .156, p = .697, $\eta p^2 = .006$), probe and affordance (Wilks' λ = .980, f (1,24) = .491, p = .490, $\eta p^2 = .020$), or number and affordance (Wilks' λ = .1.000, f (1,24) = .003, p = .954, $\eta p^2 < .001$). However, a significant three-way interaction was revealed (Wilks' λ = .965, f (1,24) = 7.384, p = .012, ηp^2 = .235). This interaction is represented in Figure 11 and Figure 12. Upon closer inspection, the reaction revealed no further effects when grouped by either power (leftward: large x small, p = .087; rightward: large x small, p = .224) or precision grip (leftward: large x small, p = .343; rightward: large x small, p = 177) levels.

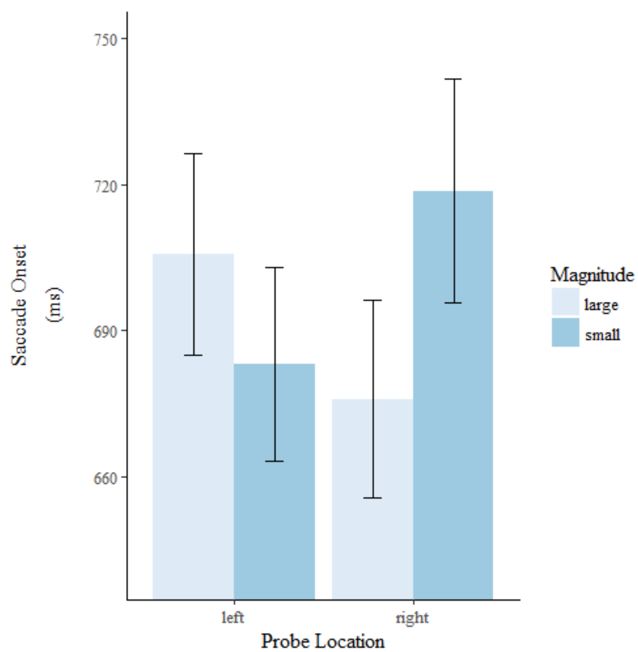

Figure 11. Depicted is one aspect of the three-way interaction for Saccade Onset. Responses to power grip trials are shown across probe location and magnitude, and saccade onset is presented in milliseconds.

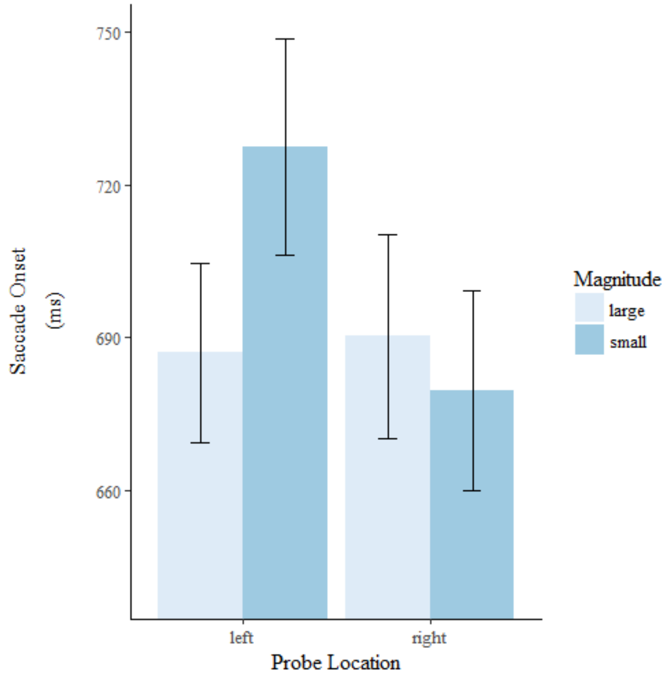

Figure 12. Depicted is one aspect of the three-way interaction for Saccade Onset. Responses to precision grip trials are shown across probe location and magnitude, and saccade onset is presented in milliseconds.

The average saccade duration was 45.03ms. Saccades lasted longer following small numbers (46.04ms) and faster when hearing large numbers (44.05ms). After power grip object (45.75ms) exposure, the duration of saccades was greater than after precision grip object (44.32ms) exposure. Finally, when performing a saccade to the left (45.17ms), the duration was greater than those performed to the right (44.89ms). Table 6 shows a breakdown of the conditional means in greater detail.

Table 6. Means (and standard deviations) for the duration of saccades that were performed by participants during the saccade task, presented in milliseconds.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	48.02 (40.25)	41.87 (15.72)	42.39 (21.23)	43.98 (22.69)	44.05 (26.57)
	Small	44.81 (29.18)	46.11 (31.04)	47.95 (38.72)	45.44 (29.80)	46.04 (32.28)
Total		46.38 (35.05)	43.95 (24.53)	45.09 (31.08)	44.69 (26.36)	45.03 (29.53)

Inferential analysis of saccade durations shows no significant main effects for probe (Wilks' λ = .993, f (1,24) = .169, p = .684, ηp^2 = .007), number (Wilks' λ = .908, f (1,24) = 2.432, p = .132, ηp^2 = .092) or affordance (Wilks' λ = .986, f (1,24) = .347, p = .561, ηp^2 = .014). Additionally, no two-way interactions were observed between probe and number (Wilks' λ = .955, f (1,24) = 1.135, p = .297, ηp^2 = .045), probe and affordance (Wilks' λ = .974, f (1,24) = .644, p = .430, ηp^2 = .026) or number and affordance (Wilks' λ = .960, f (1,24) = 1.009, p = .325, ηp^2 = .040). From the data, however, a significant three-way interaction can be observed (Wilks' λ = .830, f (1,24) = 4.923, p = .036, ηp^2 = .170). This interaction was motivated by a difference in precision grip trials with a leftward probe, with longer saccade durations when the magnitude experienced was small (46.11ms) over large (41.87ms; p = .037), with the other precision grip comparison (rightward: large x small, p = .308) and power grip comparisons (leftward: large x small, p = .333; rightward: large x small, p = .118) providing non-significant results. See Figure 13 and Figure 14 for a depiction of the interaction.

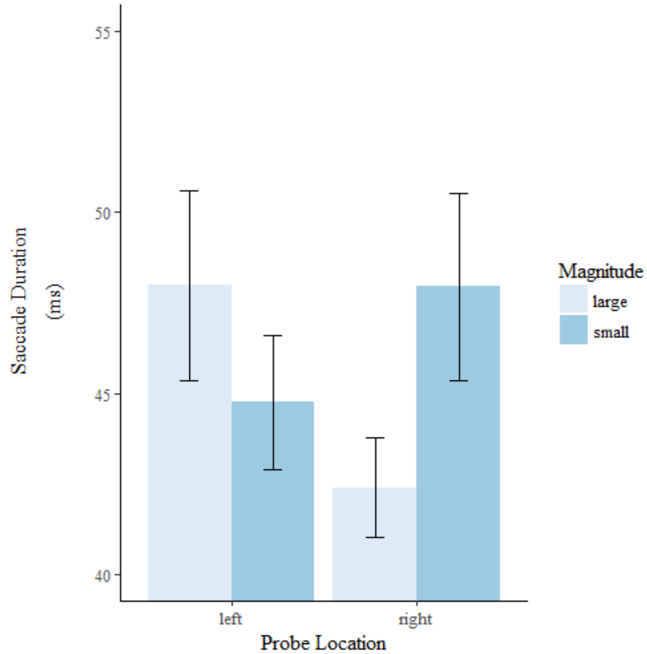

Figure 14. Depicted is one aspect of the three-way interaction for Saccade Duration. Responses to power grip trials are shown across probe location and magnitude, and saccade duration is presented in milliseconds.

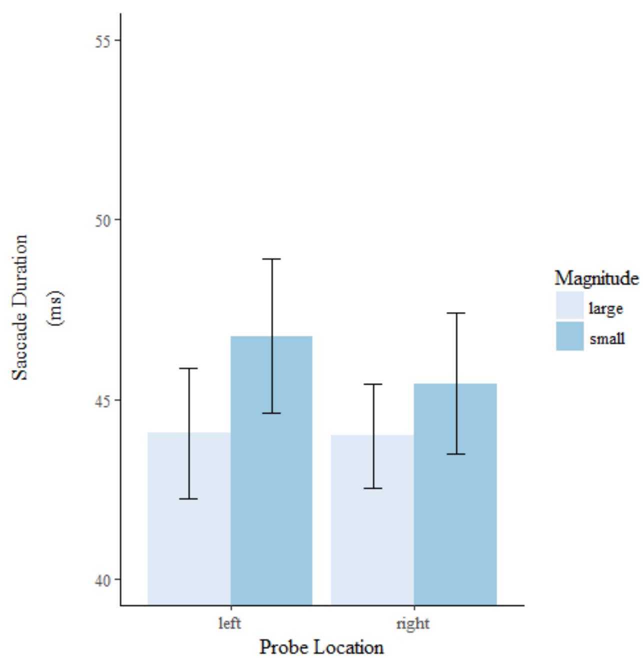

Figure 13. Depicted is one aspect of the three-way interaction for Saccade Duration. Responses to precision grip trials are shown across probe location and magnitude, and saccade duration is presented in milliseconds.

Verification Task

Error Rate Analysis

The average accuracy of participant response to the verification question was high (93.51%). When maintaining large numbers (93.59%) in memory, participants responded more accurately than when maintaining small numbers (93.43%), the same being true for when participants are required to recall power grip (94.12%) objects over precision grip (92.90%) items. Finally, after performing a leftward saccade (93.68%) participants subsequently answered more accurately than when a rightward saccade (93.34%) had been performed. See Table 7 for a more detailed breakdown of conditional means.

There were no significant main effects observed for error rates at the level of probe (Wilks' $\lambda = .979$, $f(1,24) = .505$, $p = .484$, $\eta p^2 = .021$), number (Wilks' $\lambda = .951$, $f(1,24) = 1.231$, $p = .278$, $\eta p^2 = .049$), and affordance (Wilks' $\lambda = .917$, $f(1,24) = 2.184$, $p = .152$, $\eta p^2 = .083$). Further, no significant interactions were found at either the two-way level, between probe and number (Wilks' $\lambda = .999$, $f(1,24) = .020$, $p = .889$, $\eta p^2 = .001$), probe and affordance (Wilks' $\lambda = .999$, $f(1,24) = .018$, $p = .895$, $\eta p^2 = .001$), and number and affordance (Wilks' $\lambda = .992$, $f(1,24) = .183$, $p = .672$, $\eta p^2 = .008$), nor at the three-way level (Wilks' $\lambda = .918$, $f(1,24) = 2.145$, $p = .156$, $\eta p^2 = .082$).

Table 7. Mean levels of accuracy (%) in response to the task verification question.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	93.21	94.08	94.46	92.58	93.59
	Small	95.44	91.99	93.33	92.96	93.43
Total		94.34	93.03	93.90	92.77	93.51

Response Time Analysis

For participant reaction times to the verification task, on average the question was answered in 689.68ms. In trials where large numbers (683.42ms) were experienced, responses to the task were faster than in trials where small numbers were experienced (696.15ms). Questions asking about power grip items (689.81ms) were answered slower than questions asking about precision grip objects (689.55ms). Finally, in trials were leftward (682.87ms) saccades were performed, responses were faster than in trials that required rightward responses (696.46ms). Table 8 shows, by condition, participant response times

Table 8. Mean (and standard deviation) response times by participants to the accuracy verification task, presented in milliseconds.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	655.66 (296.65)	679.63 (343.93)	711.73 (308.10)	685.00 (332.69)	683.42 (321.32)
	Small	683.83 (352.53)	712.23 (362.64)	707.20 (343.32)	682.05 (307.42)	696.15 (341.92)
Total		670.08 (326.41)	695.58 (353.21)	709.55 (325.20)	683.57 (320.34)	689.68 (331.59)

At an inferential level, no significant main effects of probe (Wilks' λ = .963, f (1,24) = 929, p = .345, ηp^2 = .037), number (Wilks' λ = .963, f (1,24) = .934, p = .343, ηp^2 = .037) or affordance (Wilks' λ = .1.000, f (1,24) = .002, p = .965, ηp^2 < .001) were revealed. However, a significant interaction (Figure 15)

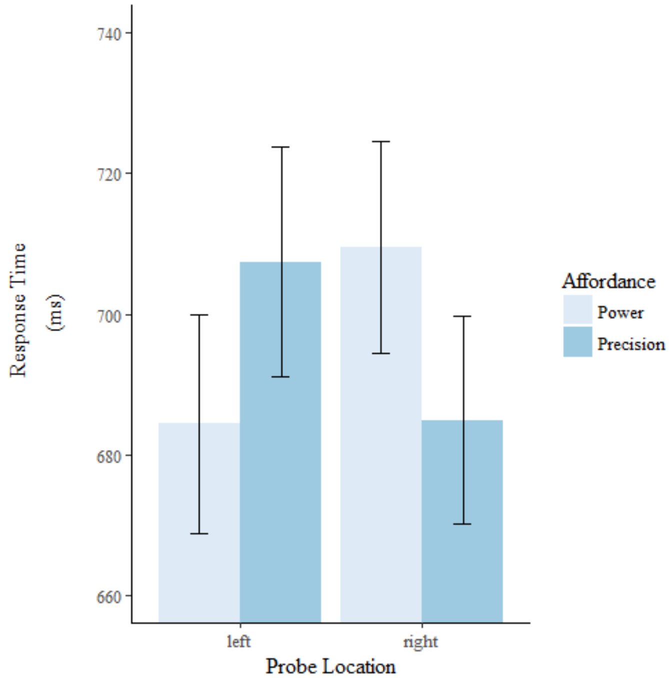

Figure 15. Depicted is the two-way interaction for verification response times. Responses to different affordance types are shown across probe locations, with response time presented in milliseconds

between probe and affordance was found (Wilks' λ = .821, f (1,24) = 5.218, p = .031, ηp^2 = .179). This interaction was shown to be driven by slower responses when maintaining a power object in memory and having performed a rightward (709.55ms) over leftward (670.08ms) saccade (p = .003). No difference in verification response time was observed when participants maintained in memory precision objects (p = .346).

No further significant interactions were found for probe and number (Wilks' λ = .920, f (1,24) = 2.083, p = .162, ηp^2 = .080) number and affordance (Wilks' λ = .971, f (1,24) = .707, p = .409, ηp^2 = .029), or at the three-way level of analysis (Wilks' λ = .978, f (1,24) = .541, p = .469, ηp^2 = .022).

Discussion

The present study investigated the interplay between magnitude-related features of objects with varying volumetric affordances maintained in working memory and concurrently apprehended numbers of varying numerical magnitude with regard to the potentially shared spatial-numerical mappings in horizontal space. Analysis found four interactions, one involving probe and affordance during processing of the verification task, and three, three-way interactions found during the saccade task for response time, saccade onset and saccade duration.

At the level of the two-way interaction, it was found that power grasp-rightward probe conditions resulted in slower responses than power grasp-leftward probe conditions. At the level of three-way interaction, for saccade duration it was found that precision grasp-leftward probe-large magnitude conditions resulted in a longer duration than precision grasp-leftward probe-small magnitude conditions. The remaining three-way interactions revealed little upon further decomposition.

No main effects of affordance, number, or probe were registered, while existing research shows these factors to bias lateral responses. At a physiological level, participants, especially those that are right handed, have been shown to saccade (Hutton & Palet, 1986) and manually respond (Goodin, et al., 1996; Hommel, 1995) faster toward rightward, over leftward, targets.

A similar case is true for numbers. Research supports the notion of a mental number line (Rugani, Vallortigara, Priftis & Regolin, 2015, Chen & Verguts, 2010; Schwarz & Keus, 2004). Typically, faster responses are given in rightward space when presented with large numbers and faster responses in leftward space when presented with smaller numbers (Fischer, Castel, Dodd & Pratt, 2003, Wood, Willmes, Nuerk & Fischer, 2008, Viarouge, Hubbard & McCandliss, 2014). Equally, for affordances, many studies have shown participants to respond faster after being primed with a manipulable object when the location of response is congruent with their dominant hand (Constantini, Ambrosini, Tieri, Sinigaglia & Committeri, 2010, Borghi, Flumini, Natraj & Wheaton, 2012, Lameira, Pereira, Conde & Gawryszewski, 2015). If there is no conceptual interplay between representations, it would be expected that at least one of these documented effects would be replicated, however, the current task fails to reproduce any. The findings of null effects suggest more complex processing may be taking place.

The direction of the interaction between affordance and probe during the verification task, and of the three-way interaction for duration, was unexpected. In line with ATOM (Walsh, 2003) and other previous literature (Namdar & Ganel, 2017, Ranzini et al., 2011) facilitation was expected, but instead interference was found. This is in line with a common coding account of cognition (Prinz, 1990), that because of the activation of both power affordance and large magnitude (for saccade duration) or power objects and rightward probes (for verification response time), there is a bottleneck effect in response time. Similar effects are observed in research by Badets, Andres, Luca and Pesenti (2007), whereby participants, after seeing a large or small number, estimate grasp size required to interact with a rod. After large number exposure, participants underestimated their grasp, and overestimated after small number exposure. As such, data provide further support for the notion of conceptual interplay between co-activated representations. For this to be a truly compelling argument the interaction observed for verification response time would also incorporate number. One possibility is that numerical information is not maintained in memory beyond the main task so this information is unavailable to interfere with the maintained affordance at the point of saccade execution.

Experiment 2

Vertical Space

Methodology

Design

A similar design to the one utilised in Experiment 1 was adopted for Experiment 2, with saccade task changing to vertical space. Hence, the independent factors were: Affordance (power/precision), Number (small/large) and Probe (up/down). The same two parity rules (even-left; even-right) were used to balance effects of number line congruency and the audible presentation of number. In total, there were 96 trials per participant. The same dependent variables were recorded (simple reaction time, error rates, saccade onset and duration, fixation duration and total gaze durations). Every trial required a response from participants. All trial conditions were counterbalanced across presentation, with numbers presented at random within testing blocks.

Participants

The same participants who completed Experiment 1 took part in Experiment 2.

Materials

The same materials were used as in Experiment 1, with the exception of the vertically arranged visual probe.

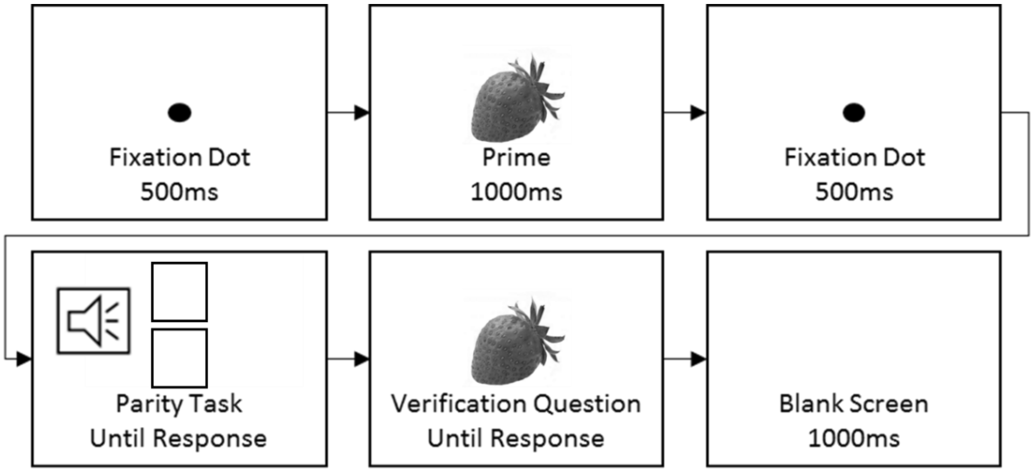

Figure 16.. An example trial sequence in which the verification question is an object congruent with the prime. Note that probe occupied vertical space, not horizontal, and stimuli presentation is not to scale, instead used to aid clarification.

Procedure

The experimental procedure was the same as in Experiment 1 except that this time participants had to saccade to one of the two visual probes presented vertically as per the coordinates specified in General Method (chapter 2; see Figure 16).

Results

The strategy discussed in the general methods section was utilised in filtering and analysing the data provided by participants. This involved, post filtering and transformation, a series of 2x2x2 ANOVAs performed on fixations, saccades, and manual responses.

Responses to the saccade and verification task were measured using reaction time and error rates for all participants. Eye tracking data was analysed only for the saccade task, which can be further divided into fixation and saccadic metrics. Data from one participant was excluded due to not completing the experimental paradigm, and all tests were conducted on the remaining 25 participants. For the raw data, see Appendix E.

Saccade Task

Error Rate Analysis

Participants made correct responses in 84.79% of the trials. Rates of accuracy were greater for small numbers (85.06%) over large numbers (84.52%). Accuracy was observed to be greater after exposure to precision grip objects (85.37%) over power grip (84.21%), and when the saccade task required upward (87.53%) responses over downward (82.04%). Table 9 shows these findings at a condition-by-condition level.

Table 9. Mean rates of accuracy (%) for participants when responding to the saccade task.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	83.28	80.00	84.88	90.00	84.52
	Small	80.28	84.67	88.36	86.90	85.06
Total		81.79	82.30	86.62	88.45	84.79

An inferential analysis of error rate shows a significant main effect of probe (Wilks' λ = .839, f (1,24) = .4.604, p = .042, ηp^2 = .161). This main effect shows upward (87.53%) responses to be significantly more accurate than downward (82.04%) responses. No further main effects of number (Wilks' λ = .999, f (1,24) = .033, p = .856, ηp^2 = .001) or affordance (Wilks' λ = .943, f (1,24) = .1.448, p = .241, ηp^2 = .057) were found to be significant.

No combination of interaction terms were deemed to be significant at either the two-way (probe by number: Wilks' λ = .998, f (1,24) = .046, p = .832, ηp^2 = .002; probe by affordance: Wilks' λ = .987, f (1,24) = .308, p = .584, ηp^2 = .013; number by affordance: Wilks' λ = .989, f (1,24) = .263, p = .613, ηp^2 = .011) or three-way (Wilks' λ = .913, f (1,24) = 2.298, p = .143, ηp^2 = .087) level.

Response Time Analysis

The average time taken by a participant to respond was 724.61ms. Faster responses were gathered for small number (723.15ms) trials over large number (726.05) trials, for power grip (718.42ms) items over precision grip (730.70ms), and for upward (697.55ms) over downward (753.50ms) probes. In Table 10, a conditional breakdown of means and standard deviations can be observed.

Table 10. Mean (and standard deviation) values for participants response time to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	757.11 (311.17)	777.07 (322.47)	688.14 (294.80)	686.64 (287.03)	726.05 (305.91)
	Small	737.44 (298.19)	742.00 (283.28)	693.22 (272.15)	722.22 (309.85)	723.15 (291.31)
Total		747.67 (304.83)	759.30 (303.42)	690.71 (283.29)	704.21 (298.75)	724.61 (298.67)

A significant main effect of probe was revealed (Wilks' $\lambda = .560$, $f(1,24) = 18.829$, $p < .001$, $\eta p^2 = .440$), with downward responses (753.50ms) being slower than upward responses (697.55ms). There were no further statistically significant main effects of either number (Wilks' $\lambda = .999$, $f(1,24) = .027$, $p = .871$, $\eta p^2 = .001$) or affordance (Wilks' $\lambda = .950$, $f(1,24) = 1.254$, $p = .274$, $\eta p^2 = .050$).

At the two-way level, an interaction was found between probe and number (Wilks' $\lambda = .838$, $f(1,24) = 4.639$, $p = .042$, $\eta p^2 = .162$). This interaction was further analysed and found to reflect a difference in response time when the number was large, with upward (687.37ms) responses being significantly faster than downward (766.85ms) responses ($p < .001$). When the number heard was small, there was no difference between probes upward or downward ($p = .076$; see Figure 17).

There were no further interactions at either the two-way level, for probe by affordance (Wilks' $\lambda = .994$, $f(1,24) = .140$, $p = .712$, $\eta p^2 = .006$), and number by affordance (Wilks' $\lambda = .999$, $f(1,24) = .025$, $p = .875$, $\eta p^2 = .001$), or at the three-way level (Wilks' $\lambda = .997$, $f(1,24) = .077$, $p = .783$, $\eta p^2 = .003$).

Eye Movement Analysis

Fixation data.

On average, the duration of the first fixation within a target area was 342.56ms. Fixations were seen to be shorter when hearing large numbers (337.98) over small numbers (347.14ms). When maintaining power grip (339.76ms) items in memory, the first fixation duration was shorter than trials where precision grip objects were maintained (345.27ms). Finally, trials with

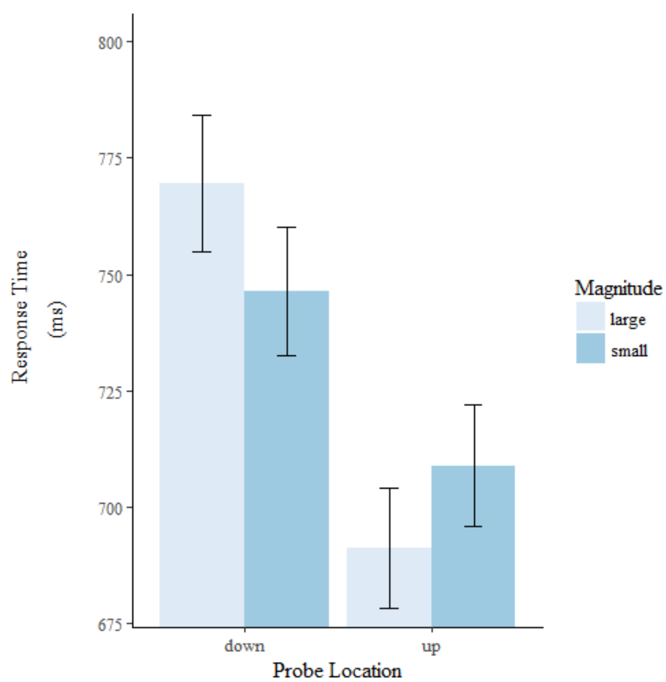

Figure 17. Depicted is the two-way interaction for probe response times. Responses to different magnitudes are shown across probe locations, where response time is presented in milliseconds

response upward (355.02ms) provoked longer durations of the first fixation than trials requiring downward responses (329.30ms). Table 11 provides a closer examination of mean and standard deviation first fixation durations made by participants.

Table 11. Mean (and standard deviation) durations of the first fixation participants made in response to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	320.43 (157.06)	331.95 (212.59)	350.28 (226.61)	347.97 (205.17)	337.98 (202.28)
	Small	328.12 (216.65)	336.59 (205.94)	358.99 (208.00)	362.83 (217.74)	347.14 (212.31)
Total		324.19 (188.44)	334.32 (209.00)	354.62 (217.35)	355.40 (211.46)	342.56 (207.35)

Inferential analyses revealed no significant main effects of probe (Wilks' $\lambda = .957$, $f(1,24) = 1.079$, $p = .309$, $\eta p^2 = .043$), number (Wilks' $\lambda = .991$, $f(1,24) = .214$, $p = .648$, $\eta p^2 = .009$) or affordance (Wilks' $\lambda = .974$, $f(1,24) = .637$, $p = .433$, $\eta p^2 = .026$). Nor were any significant two-way interactions found between probe and number (Wilks' $\lambda = .936$, $f(1,24) = 1.639$, $p = .213$, $\eta p^2 = .064$), probe and affordance (Wilks' $\lambda = .999$, $f(1,24) = .022$, $p = .884$, $\eta p^2 = .001$), or number and affordance (Wilks' $\lambda = .955$, $f(1,24) = 1.122$, $p = .300$, $\eta p^2 = .045$). Finally, no significant three-way interaction was uncovered either (Wilks' $\lambda = .956$, $f(1,24) = 1.101$, $p = .304$, $\eta p^2 = .044$).

Across the study, the total gaze duration of participants in the target area was, on average, 425.47ms. Longer periods of dwelling were observed in trials where participants heard small numbers (430.90ms) than in trials where participants heard large numbers (420.05ms). Trials that displayed precision grip

(432.86ms) items to participants produced longer total gaze durations than trials showing participants power grip (417.76) items. Finally, greater dwell periods were observed after upward saccade response (430.55ms) than in trials requiring downward saccades (420.12ms). For a condition-by-condition rendition of the probe total gaze durations, see Table 12.

Table 12. Mean (and standard deviation) total gaze durations for participant responses to the saccade task, presented in milliseconds.

Probe		Left		Right		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	420.47 (243.57)	428.88 (273.36)	412.04 (272.61)	419.20 (241.62)	420.05 (257.56)
	Small	396.55 (216.53)	433.41 (250.76)	441.03 (295.02)	449.56 (317.94)	430.90 (274.55)
Total		408.81 (230.83)	431.20 (261.77)	426.44 (284.02)	434.41 (282.57)	425.47 (266.16)

No significant main effects of total gaze duration were uncovered for probe (Wilks' λ = .999, f (1,24) = .035, p = .852, ηp^2 = .001), number (Wilks' λ = .944, f (1,24) = 1.421, p = .245, ηp^2 = .056), or affordance (Wilks' λ = .986, f (1,24) = 351, p = .559, ηp^2 = .014). No interactions at either the two-way level for probe by number (Wilks' λ = .925, f (1,24) = 1.952, p = .175, ηp^2 = .075), probe by affordance (Wilks' λ = .999, f (1,24) = 032, p = .859, ηp^2 = .001) or number by affordance (Wilks' λ = .974, f (1,24) = .629, p = ..435, ηp^2 = .026), or three-way level (Wilks' λ = .951, f (1,24) = 1.233, p = .278, ηp^2 = .049) were found.

Saccade data.

On average, participants programmed and launched saccades in 685.95ms following the auditory number onset. Saccades were launched slower in trials where participants heard a large number (687.64ms) over a small number (684.24ms). Likewise, participants were slower after exposure to precision grip (694.67ms) items over power grip (677.13ms) objects. Finally, upward saccades (657.38ms) were initiated faster than downward saccades (716.21ms). For a condition-level showing of saccade onset timings, see Table 13.

Table 13. Mean (and standard deviation) onset times for saccades performed in response to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	717.91 (310.76)	742.03 (338.69)	646.47 (287.00)	648.05 (288.12)	687.64 (308.70)
	Small	695.32 (294.85)	708.99 (288.63)	650.25 (264.06)	684.45 (319.63)	684.24 (292.92)
Total		707.04 (303.08)	725.44 (314.63)	648.37 (275.41)	666.14 (304.42)	685.95 (300.90)

A significant main effect of probe was revealed (Wilks' $\lambda = .499$, $f(1,24) = 24.067$, $p < .001$, $\eta p^2 = .501$). A saccade was launched faster when the probe was directed upwards (657.38ms) than when it was directed downward (716.21ms). No further significant main effects were found for number (Wilks' $\lambda = .988$, $f(1,24) = .280$, $p = .602$, $\eta p^2 = .012$) or affordance (Wilks' $\lambda = .976$, $f(1,24) = .582$, $p = .453$, $\eta p^2 = .024$). In addition to this, no significant interactions were found at the two-way level, for probe and number (Wilks' $\lambda = .908$, $f(1,24) = .2.445$, $p = .131$, $\eta p^2 = .092$), probe and affordance (Wilks' $\lambda = .988$, $f(1,24) = .279$, $p = .602$, $\eta p^2 = .012$), and for number by affordance (Wilks' $\lambda = .998$, $f(1,24) = .045$, $p = .833$, $\eta p^2 = .002$), nor were any interactions found at the three-way level (Wilks' $\lambda = .999$, $f(1,24) = .014$, $p = .908$, $\eta p^2 = .001$).

The average duration of a saccade performed by a participant was 50.23ms. Greater was the saccade duration after hearing large numbers (51.40ms) than when hearing small numbers (49.03ms). The maintenance of power grip (50.17ms) items in memory produced shorter saccade durations than the maintenance of precision grip (50.30ms) objects. Finally, a saccade performed downward (51.27ms) had a greater duration than a saccade performed upward (49.25ms). In Table 14, the duration of saccades can be seen at the condition level.

Table 14. Mean (and standard deviation) saccade durations of participants during the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	52.82 (44.89)	52.14 (47.42)	52.84 (51.87)	48.07 (39.33)	51.40 (46.09)
	Small	50.43 (48.51)	49.64 (38.84)	44.46 (21.86)	51.55 (56.07)	49.03 (43.38)
Total		51.67 (46.63)	50.87 (43.23)	48.70 (40.16)	49.78 (48.51)	50.23 (44.78)

For saccade durations, no significant main effects were found for probe (Wilks' $\lambda = .891$, $f(1,24) = 2.808$, $p = .107$, $\eta p^2 = .109$), number (Wilks' $\lambda = .918$, $f(1,24) = 2.064$, $p = .164$, $\eta p^2 = .082$), or affordance (Wilks' $\lambda = .995$, $f(1,24) = .108$, $p = .745$, $\eta p^2 = .005$). No interactions were found at either the two-way level, for probe by number (Wilks' $\lambda = .995$, $f(1,24) = .109$, $p = .744$, $\eta p^2 = .005$), probe by affordance (Wilks' $\lambda = .995$, $f(1,24) = .121$, $p = .731$, $\eta p^2 = .005$), or number by affordance (Wilks' $\lambda = .897$, $f(1,24) = .2.638$, $p = .118$, $\eta p^2 = .103$), nor at the three-way level (Wilks' $\lambda = .998$, $f(1,24) = .045$, $p = .833$, $\eta p^2 = .002$).

Verification Task

Error Rate Analysis

The rate of correct responses to the verification task was, on average, high (94.61%). Average accuracy was higher in trials were participants had heard large numbers (94.66%) than in trials were participants heard small numbers (94.56%). When participants maintained a precision grip (95.25%) object in memory they were, on average, more accurate than when maintaining a power grip (93.97%) item. Finally, greater levels of accuracy were observed after participants had performed upward (95.11%) over downward (94.11%) saccades. Table 15 details the condition-level rates of accuracy for the verification task.

Table 15. Average rates of accuracy (%) in response to the verification question.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	94.70	94.41	94.14	95.41	94.66
	Small	92.98	94.35	94.06	96.85	94.56
Total		93.84	94.38	94.10	96.13	94.61

For verification accuracy, no significant main effects were found for probe (Wilks' λ = .942, f (1,24) = 1.467, p = .238, ηp^2 = .058), number (Wilks' λ = .989, f (1,24) = .273, p = .606, ηp^2 = .011), and affordance (Wilks' λ = .980, f (1,24) = .490, p = .491, ηp^2 = .020). No significant two-way interactions were found for probe by number (Wilks' λ = .947, f (1,24) = 1.352, p = .256, ηp^2 = .053), probe by affordance (Wilks' λ = .923, f (1,24) = 2.000, p = .170, ηp^2 = .077), or at the three-way level (Wilks' λ = .998, f (1,24) = .051, p = .824, ηp^2 = .002).

Response Time Analysis

The average time taken to respond to an accuracy verification question was 667.47ms. When participants had heard a large number (666.58ms), the time taken to respond to the verification question was shorter than when having heard a small number (668.37ms). When participants were maintaining a power grip (669.97ms) item in memory, the response time was greater than when maintaining a precision grip (665.01ms) object. Finally, time taken for the verification task was greater after having performed a downward saccade (673.31ms) than after a participant had performed an upward saccade (662.00ms). In Table 16, the average response time can be seen at a conditional level.

Table 16. Mean (and standard deviation) reaction times in response to the verification task, presented in milliseconds.

Probe		Down		Up		Total
Affordance		Power	Precision	Power	Precision	
Number	Large	666.64 (329.01)	690.56 (377.20)	668.75 (322.86)	642.89 (308.66)	666.58 (334.32)
	Small	660.64 (318.70)	675.61 (314.52)	683.19 (345.90)	654.15 (327.29)	668.37 (326.71)
Total		663.70 (323.67)	682.93 (346.34)	675.94 (334.25)	648.48 (317.78)	667.47 (330.47)

An inferential analysis revealed no significant main effects for either probe (Wilks' $\lambda = .921$, $f\,(1,24) = 1.969$, $p = .174$, $\eta p^2 = .079$), number (Wilks' $\lambda = .993$, $f\,(1,24) = .166$, $p = .687$, $\eta p^2 = .007$), or affordance (Wilks' $\lambda = .1.000$, $f\,(1,24) < .001$, $p = .998$, $\eta p^2 < .001$). No significant two-way (probe by number: Wilks' $\lambda = .970$, $f\,(1,24) = .717$, $p = .406$, $\eta p^2 = .030$; probe by affordance: Wilks' $\lambda = .880$, $f\,(1,24) = 3.132$, $p = .090$, $\eta p^2 = .120$; number by affordance: Wilks' λ

= .977, f (1,24) = .549, p = .466, ηp^2 = .023) nor three-way (Wilks' λ = .999, f (1,24) = .023, p = .880, ηp^2 = .001) interactions were discovered.

Discussion

The present study investigated the interplay between magnitude-related features of the objects with varying volumetric affordances maintained in working memory and the concurrently apprehended numbers of varying numerical magnitude with regard to the potentially shared spatial-numerical mappings in vertical space. Main effects of probe were found for probe task response time, accuracy and saccade onset. For probe time, participants were faster when performing an upward response over downward – a finding mirrored by the main effect of saccade onset. Participants were also more accurate in making upward, over downward, probe responses. This appears to be in line with polarity accounts of processing (e.g. Lynott & Coventry, 2014, Lakens, 2012, Santiago, Ouellet, Román, Valenzuela, 2012). That is, concepts are categorised faster when at a positive polar endpoint, such as upward over downward.

A two-way interaction was found between probe and number for probe response time. This interaction shows a faster processing of large numbers in upward trials over downward trials. This replicates the findings of many previous studies (Viarouge, Hubbard & Dehaene, 2014, Ito & Hatta, 2004, Gevers, Lammertyn, Notebaert, Verguts & Fias, 2006). It is interesting that no similar effect was found in the downward domain with small numbers, as would be expected and predicted by SNARC and mental number space accounts (Kadosh & Dowker, 2015). More interestingly, this pattern is the opposite of what was observed in horizontal space, in which interference was seen suggesting partially different spatial-numerical mapping mechanisms along these two dimensions.

No main effects or interactions involving affordances were discovered. There are several reasons why this may be the case. Of course, it would be simplistic to rely upon – but stupid to ignore – notions of sample size and task complexity. After all, the claim that 25 participants is too few is not one that the literature agrees with, as both visual research handbooks (e.g. Margolis & Pauwels, 2011) and research in similar domains (Chapman & Myachykov, 2015; Makris, Hadar & Yarrow, 2013; Bulf, Cassia & de Hevia, 2014) suggests or uses similar amounts of participants. Another possible explanation regards the co-occurrence of vertical and radial visual profiles. Typically, vertical eye movement reflects a shift from near-to-far (bottom-to-top) distances. The automatic activation of affordance profiles have been shown to occur depending upon proximity (Constantini, Ambrosini, Scorolli & Borghi, 2011). So, it is possible that a vertical shift of eye movement – especially in a controlled, experimental context – unpacks affordance content. This would require further research to understand.

A much more plausible explanation is the one inferring the situated aspects of manipulation affordance (see Myachykov, Scheepers, Fischer & Kesller, 2014). It is rare that the principle context of an affordance is vertical. Indeed, most effects of affordance are found, when the vertical and horizontal axis is disentangled, in horizontal space (Osiurak, Rossetti & Badets, 2017). So, the case for an interplay between representations may be weakened due affordances not necessarily becoming activated in vertical space.

Chapter Summary

This chapter investigated the interplay between magnitude-related features of objects with varying volumetric affordances maintained in working memory and the concurrently apprehended numbers of varying numerical magnitude with regard to the potentially shared spatial-numerical mappings in horizontal and vertical space. Across two experiments, a case for interaction between numbers and affordances has been diagnosed. Results from the horizontal experiment provide the strongest support for the notion of a conceptual interface between representations, while the study of vertical space provides little affirmation but, importantly, replicates previous findings and poses interesting questions.

In the horizontal tasks, interference between probe location, number, and affordance was observed. One potential reason for this stems from the concreteness of representations. On the continuum between concreteness and abstraction, affordances are at the extreme concreteness pole, requiring very little removal from sensorimotor simulation to be processed and understood. Numerical magnitude can be processed either as concrete or abstract, depending upon circumstance. Typically, numbers below ten are found to rely stronger on concreteness (Dehaene & Cohen, 1995, Pecher & Boot, 2011). Due to the richness of concrete simulations, instead of observing a facilitation of processing, the two concepts attentional bottleneck. This effect would explain the slowing of processing observed, in line with common coding theories (Prinz, 1990, Barsalou, 2008). This is a novel finding; as such, it warrants further investigation. One question for future research this poses is whether or not *another* representational interface would be able to utilise the same two components to find, instead, a facilitating effect.

In the vertical domain, the data revealed little support for any interplay between the co-activated representations. An important aspect to be aware of is that the effects that were observed in the vertical domain (probe location effects and an interaction in line with SNARC) suggest that the contents of an affordance were not, here, being processed automatically. Both suggested explanations require future research to elucidate the actual effects of affordance processing and conceptual interplay in vertical space, as while they are both *compelling* explanations, neither are, right now, *convincing* explanations. To understand this in greater detail, the following chapter deals with a factor that is closer toward abstraction, spatial semantics.

CHAPTER FOUR

Spatial Semantics And Numerical Magnitude

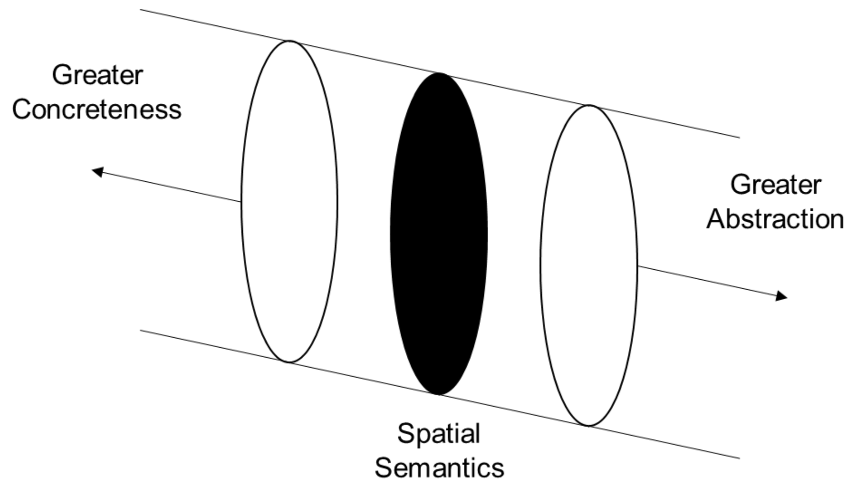

Figure 18. The Abstraction Pipeline. A representation of how far removed the current chapter's subject matter is from concrete representation in comparison to other studies.

Spatial words are used regularly in language to provide a frame of reference for cognizing the world around us. Space is a fundamental aspect of our environment, and its use in language involves helping to understand location, path, size, shape, and orientation (Zwarts, 2017). Crucially, spatial semantics serve to lead the attention of another through referential framing (Landau & Jackendoff, 1993; Pederson, et al., 1998; Zlatev, 2007). If sensorimotor simulation is accepted as forming at least some basis for our understanding of abstract and concrete knowledge (Meteyard & Vigliocco, 2008), then spatial language should form a necessary component of knowledge. Previous research has already shown that understanding spatial (Richardson, Spivey, Barsalou & McRae, 2003) and action-related (Meteyard, Bahrami & Vigliocco, 2007) language involves the simulation of sensorimotor experience. Due to its obligatory linguistic coding, the domain of spatial semantics is less concrete than affordances where no obligatory reference to language is necessary (c.f. Glover, Rosenbaum, Graham & Dixon, 2004; Gibson & Sztybel, 2014), and so the conceptual interplay between cognitive components may manifest differently. Here, two studies examine the ability of spatial language to displace visual attention in the different dimensions of space. Specifically, it is expected that language with either a rightward or upward spatial bias will prime a response for large numerical magnitudes while leftward and downward biasing language will prime responses for small numerical magnitudes. Error rates are hypothesised to mirror this, with greater accuracy observed in wholly congruent trials. In a similar manner to the previous chapter, the first study examines the horizontal domain while the second concerns the vertical.

Experiment 3

Horizontal Space

Methodology

Design

As before, the task comprised a within-participants, 2x2x2 design. Here, the spatial semantics of a word bias (leftward/rightward), number (small/large) and probe (left/right) comprised the independent variables. Two parity rules (even-left; even-right) were used to balance for any effects of number line congruency and audible number presentation. In total, 192 trials were presented to each participant. Recorded were several dependent variables. Non-eye-tracking metrics included simple reaction time and accuracy rates to the saccade and verification tasks. Eye tracking metrics were only recorded for the saccade task, and included saccade measures of onset and duration, as well as fixation measures of total gaze duration and the duration of the first fixation. All participants were required to give a response to every trial, which were grouped by parity rule and counterbalanced across presentation. Numbers were presented at random within blocks of testing.

Participants

There were 27 participants (14 male) recruited from the undergraduate population of Northumbria University, whose participation came in exchange for course credits. The average age of a subject was 22 (range = 18-50, SD = 7.486); all participants were of UK birth, native speakers of English, with normal or corrected-to-normal eyesight. All participants self-identified as right handed, which was confirmed by the Short Form Edinburgh Handedness Inventory (Ransil & Schachter, 1994; average = .979).

Materials

The same recording of the numbers '1', '2', '8' and '9' used previously were, again, deployed here. Words were chosen from a normed database that catered for the spatial semantics of a verb (Meteyard & Vigliocco, 2009). The norms of the database allowed for the creation of leftward and rightward-biasing conditions, which consisted of the most representative verbs from each category. Words were initially presented in lower case for the saccade task, but in the verification task presented in uppercase. This ensured processing of the content of the word itself, and not just the maintenance of stimuli in visual working memory. Both fixation dots and target squares were created in Experiment Builder.

Procedure

The following procedure gained approval from the Northumbria University Board of Ethics. All data were collected in a room with minimal lighting. Before testing, participants were briefed about the nature of the experiment (see Appendix A for the standardised brief) and asked to complete informed consent documentation (Appendix A) before answering a demographics questionnaire (Appendix C) and the Short Form Edinburgh Handedness Index (Appendix D; Ransil & Schachter, 1994). After consenting, the participant was then seated on a chair with the backrest tilted to a 110° 60cm from the screen with their head placed on an SR-Research chinrest, before being calibrated, tested, and debriefed.

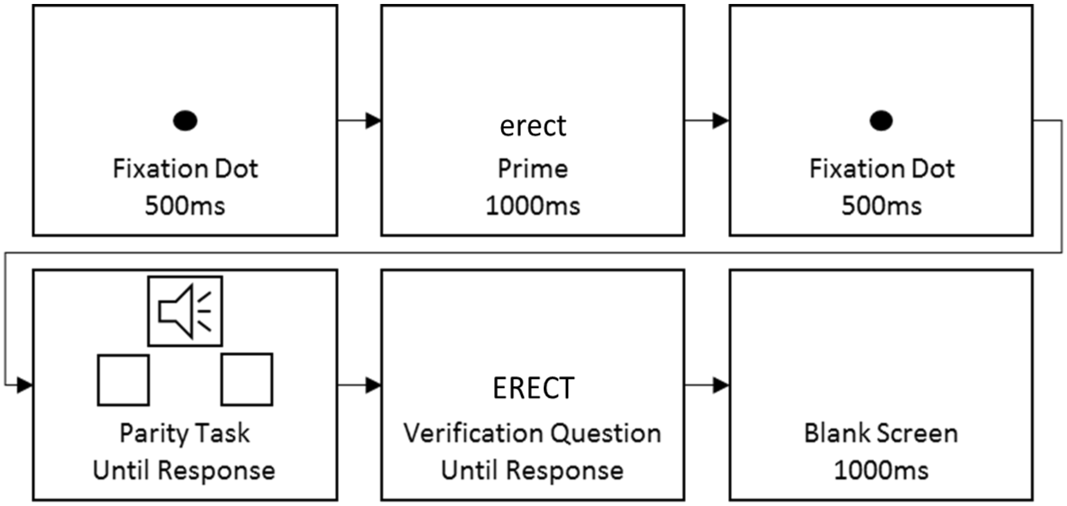

Figure 19. An example trial sequence in which the verification question is a word congruent with the prime. Note that presentation is not to scale but is used to aid clarification.

Testing consisted of a fixation cross presentation for 500ms followed by the visual presentation of a word for 1000ms. After the word another fixation cross (500ms) was presented and the probe task followed. This consisted of a number, audibly presented, and the visual presentation of two targets. In accordance with the parity rule, participants made a saccade toward one of the targets, located as identified in horizontal space within the General Methods (chapter 2). The landing of a saccade triggered the offset of the saccade task and the onset of a verification task, which required participants to view a word and decide whether it is the same or different to the object seen at the start of the trial. Participants pressed a button to respond to this task, either the left (corresponding to yes) or right (corresponding to no) trigger. Depress of the button signalled the end of a trial and a 1000ms buffer period before the start of the next. Participants were given accuracy feedback immediately after saccade and verification tasking. Total testing took approximately 60 minutes. See Figure 19 for an example trial sequence

Results

The strategy discussed in the general methods section was utilised in filtering and analysing the data provided by participants. This involved, post filtering and transformation, a series of 2x2x2 ANOVAs to understand fixation, saccadic, and manual response parameters of the data.

Responses to the parity and verification task were measured using reaction time and error rates for all participants. Eyetracking data was analysed only for the saccade task, which can be further divided into fixation and saccadic metrics. A standard criterion of α was used and set to .05. Data from one participant was excluded due to not completing the experimental paradigm, and all tests were conducted on the remaining 25 participants. For the raw data, see Appendix E.

Saccade task

Error Rate Analysis

In general, task accuracy was high (88.74%). Accuracy was greater in response to rightward words (88.94%) over leftward (88.53%) words, large numbers (90.33%) over small numbers (87.15%), and for leftward probes (89.31%) over rightward probes (88.17%). For a breakdown by condition for rates of accuracy, see Table 17.

Table 17. Mean rate of accuracy (%) in response to the saccade task.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	89.05	89.57	92.99	89.72	90.33
	Small	88.81	89.80	83.33	86.70	87.15
Total		88.94	89.68	88.13	88.20	88.74

A closer analysis revealed no significant main effects for probe (Wilks' $\lambda = .978$, $f(1,25) = .573$, $p = .456$, $\eta p^2 = .022$), number (Wilks' $\lambda = .926$, $f(1,25) = 1.994$, $p = .170$, $\eta p^2 = .074$), or word bias (Wilks' $\lambda = .998$, $f(1,25) = .052$, $p = .456$, $\eta p^2 = .022$). A significant interaction was discovered between probe and number (Wilks' $\lambda = .830$, $f(1,25) = 5.138$, $p = .032$, $\eta p^2 = .170$), which can be seen in Figure 20. This interaction was motivated by a difference at the level of small number ($p = .048$), with rightward (85.02%) responses being less accurate than leftward (89.31%). At the level of large number, no significant difference was found ($p = .281$).

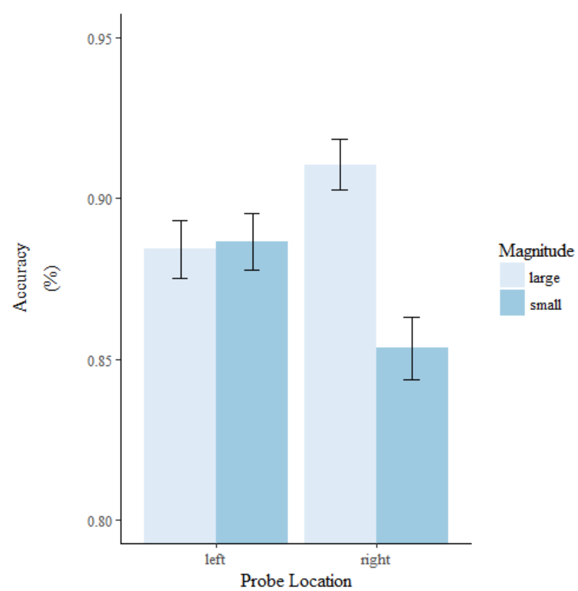

Figure 20. Depicted is the two-way interaction for probe accuracy. Responses to different magnitudes are shown across probe locations, with accuracy displayed as a percentage of correct responses.

No further interactions were observed, either at the two-way level between probe and word bias (Wilks' λ = .1.000, f (1,25) = .002, p = .968, ηp^2 < .001) or number and word bias (Wilks' λ = .889, f (1,25) = 3.108, p = .090, ηp^2 = .111), nor at the three-way level (Wilks' λ = .933, f (1,25) = 1.805, p = .191, ηp^2 = .067).

Response Time Analysis

The average time taken to respond to the saccade task was 750.80ms. Participants were faster when the priming word biased attention toward the left (743.19ms) than to the right (758.24ms). Large numbers (749.10ms) made for faster responses than small numbers (752.51ms), and when the probe necessitated leftward (749.52ms) over rightward (752.09) saccades. See Table 18 for a breakdown of response times by condition.

Table 18. Mean (and standard deviations) for participant response times to a saccade task, presented in milliseconds.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	769.21 (327.28)	757.75 (298.65)	729.26 (295.46)	741.25 (293.69)	749.10 (301.50)
	Small	723.06 (292.98)	748.82 (327.65)	753.08 (305.37)	785.91 (338.05)	752.51 (317.15)
Total		745.65 (310.95)	753.26 (313.45)	740.73 (295.30)	763.34 (317.04)	750.80 (309.35)

No main effects were found for probe (Wilks' λ = 998., f (1,25) = .042, p = .840, ηp^2 = .002), for number (Wilks' λ = .995, f (1,25) = .124, p = .727, ηp^2 = .005), or for word bias (Wilks' λ = .876, f (1,25) = 3.550, p = .071, ηp^2 = .124). At the two-way level, an interaction was found between probe and number (Wilks' λ = .721, f (1,25) = .9.698, p = .005, ηp^2 = .279). This interaction can be seen visually in Figure 21 but reveals only a trend toward significance at large ($p = .055$) and small ($p = .074$) levels of comparison.

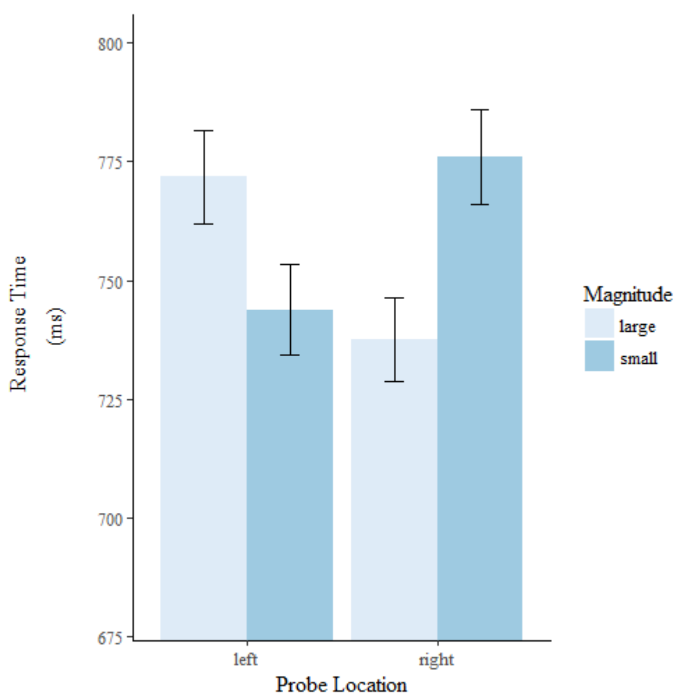

Figure 21. Depicted is the two-way interaction for probe response time. Responses to different magnitudes are shown across probe locations, where response time is displayed in milliseconds.

Eye Movement Analysis

Fixation data.

On average, participants maintained the first fixation for 349.65ms. Fixations lasted for a longer duration after rightward biasing words (351.83ms) over leftward (347.44ms), for small (351.30ms) numbers over large (348.01ms), and for rightward (363.75ms) probes over leftward (336.22ms). Table 19 displays conditional means and standard deviations for first fixation durations.

Analysis by means of ANOVA revealed a significant main effect of probe (Wilks' $\lambda = .840$, $f\,(1,25) = 4.748$, $p = .039$, $\eta p^2 = .160$), with longer first fixations after rightward (363.75ms) probes over leftward (336.22ms). No further main effects were found for number (Wilks' $\lambda = .998$, $f\,(1,25) = .048$, $p = .829$, $\eta p^2 = .002$) or word bias (Wilks' $\lambda = .904$, $f\,(1,25) = 2.662$, $p = .115$, $\eta p^2 = .096$).

Table 19. Means (and standard deviations) for participant's first fixation durations during the saccade task, presented in milliseconds.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	334.14 (182.49)	337.23 (182.43)	358.54 (176.41)	362.19 (177.02)	348.01 (178.91)
	Small	329.86 (182.49)	343.56 (183.78)	369.22 (202.06)	365.47 (177.04)	351.30 (186.89)
Total		331.94 (182.41)	340.44 (183.05)	363.71 (189.24)	363.80 (176.95)	349.65 (183.41)

No interactions were found at either the two-way, between probe and number (Wilks' $\lambda = .984$, $f\,(1,25) = .396$, $p = .535$, $\eta p^2 = .016$), probe and word bias (Wilks' $\lambda = .995$, $f\,(1,25) = .120$, $p = .732$, $\eta p^2 = .005$) or number and word bias (Wilks' $\lambda = .949$, $f\,(1,25) = 1.345$, $p = .257$, $\eta p^2 = .051$), or three-way level (Wilks' $\lambda = .991$, $f\,(1,25) = .231$, $p = .635$, $\eta p^2 = .009$).

For total gaze durations, the average series of fixations lasted for 435.60ms. Leftward (434.91ms) biasing words resulted in shorter total gaze durations than rightward (436.28ms). The number heard resulted in longer total gaze durations when small (431.47ms) over large (439.73), as did probes to the left (455.23) over right (414.78). Table 20 shows, by condition, means and standard deviations for participant total gaze durations.

Table 20. Means (and standard deviations) for participant's fixation total gaze durations during the saccade task, presented in milliseconds.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	464.33 (266.52)	464.95 (257.66)	415.63 (200.78)	412.97 (193.26)	493.73 (233.36)
	Small	435.97 (242.86)	456.29 (265.87)	422.94 (221.66)	407.75 (205.08)	431.47 (236.46)
Total		449.80 (254.94)	460.57 (261.75)	419.19 (211.12)	410.40 (199.08)	435.60 (234.92)

Following analysis, no main effects emerged at the level of probe (Wilks' $\lambda = .933$, $f(1,25) = 1.787$, $p = .193$, $\eta p^2 = .067$), number (Wilks' $\lambda = .934$, $f(1,25) = 1.775$, $p = .195$, $\eta p^2 = .066$), or word bias (Wilks' $\lambda = .998$, $f(1,25) = .046$, $p = .831$, $\eta p^2 = .002$). Nor were any two-way interactions observed between probe and number (Wilks' $\lambda = .942$, $f(1,25) = 1.542$, $p = .226$, $\eta p^2 = .058$), probe and word bias (Wilks' $\lambda = .900$, $f(1,25) = 2.763$, $p = .109$, $\eta p^2 = .100$), or number and word bias (Wilks' $\lambda = .980$, $f(1,25) = .507$, $p = .483$, $\eta p^2 = .020$). An interaction was not observed at the three-way level (Wilks' $\lambda = .987$, $f(1,25) = .317$, $p = .579$, $\eta p^2 = .013$).

Saccade data.

The average time taken until the onset of a saccade was 709.02ms. Participants initiated eye movement faster when the word was leftward (702.79ms) than rightward (715.13ms). Large numbers (709.21ms) made for slower responses than small numbers (708.83ms). Probes rightward (706.63ms) were faster than probes to the left (711.39ms). See Table 21 for a breakdown of means and standard deviations by condition.

Table 21. Mean (and standard deviation) values for the onset of saccades as performed by participants during the saccade task, presented in milliseconds.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	729.99 (325.92)	717.15 (300.83)	690.09 (284.41)	700.96 (291.81)	709.21 (300.91)
	Small	682.50 (294.58)	716.60 (332.83)	710.54 (307.51)	726.07 (321.49)	708.83 (314.78)
Total		705.69 (311.03)	716.87 (317.22)	699.92 (295.76)	713.33 (306.89)	709.02 (307.85)

An analysis of saccade onset revealed no significant main effects of probe (Wilks' λ = .991, f (1,25) = .232, p = .634, ηp^2 = .009), number (Wilks' λ = .970, f (1,25) = .779, p = .386, ηp^2 = .030), or word bias (Wilks' λ = .902, f (1,25) = 2.724, p = .111, ηp^2 = .098). At the level of two-way interaction, a significant result, which can be seen in Figure 22, was observed for probe and number (Wilks' λ = .805, f (1,25) = 6.061, p = .021, ηp^2 = .195). This interaction was motivated by a difference at large levels of magnitude (p = .036), in which rightward (695.47ms) responses were made faster than leftward (723.40ms). No difference was observed at the level of small magnitudes (p = .331).

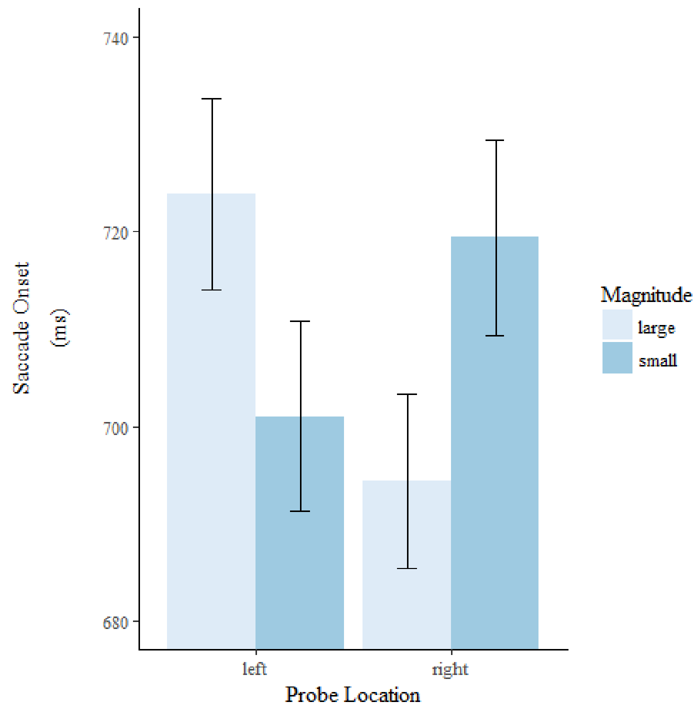

Figure 22. Depicted is the two-way interaction for saccade onset. Responses to different magnitudes are shown across probe locations, where saccade onset is displayed in milliseconds

No further interactions were found at either the two-way, for probe and word bias (Wilks' λ = .973, $f(1,25) = .682$, $p = .417$, $\eta p^2 = .027$) or number and word bias (Wilks' λ = .869, $f(1,25) = 3.778$, $p = .063$, $\eta p^2 = .131$), or three-way level (Wilks' λ = .957, $f(1,25) = 1.114$, $p = .301$, $\eta p^2 = .043$).

The average duration of a saccade was 42.67ms. For words that bias attention to the left (42.40ms), average saccade durations were shorter than when words biased attention to the right (42.94ms). Small numbers (42.56ms) resulted in saccades with shorter durations than large numbers (42.78ms). Finally, leftward probes (42.44ms) were faster than rightward probes (42.90ms). See Table 22 for a breakdown by condition of means and standard deviations for the duration of saccades made by participants.

Table 22. Means (and standard deviations) for the duration of saccades that were performed by participants during the saccade task, presented in milliseconds.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	41.15 (24.58)	42.83 (32.01)	43.98 (26.64)	43.09 (29.62)	42.78 (28.39)
	Small	41.78 (31.40)	43.93 (34.04)	42.64 (33.27)	41.84 (29.89)	42.56 (32.19)
Total		41.48 (28.29)	43.39 (33.04)	43.34 (29.99)	42.48 (29.75)	42.67 (30.34)

An analysis of saccade duration revealed no significant main effects for probe (Wilks' λ = .962, f (1,25) = 1.000, p = .327, $\eta p^2 = .038$), number (Wilks' λ = .960, f (1,25) = .1.041, p = .317, $\eta p^2 = .040$), or word bias (Wilks' λ = .973, f (1,25) = .689, p = .414, $\eta p^2 = .027$). A two-way interaction was found between probe and word bias (Wilks' λ = .841, f (1,25) = 4.724, p = .039, $\eta p^2 = .159$; see Figure 23). Further analysis found both leftward (p = .091) and rightward (p. = 917) word biases to provide nonsignificant results. No further interactions appeared at the two-way level between probe and number (Wilks' λ = .939, f (1,25) = .1.617, p = .215, $\eta p^2 = .061$) or number and word bias (Wilks' λ = .927, f (1,25) = 1.981, p = .172, $\eta p^2 = .073$). No interaction was seen at the three-way level (Wilks' λ = .319, f (1,25) = .319, p = .577, $\eta p^2 = .013$).

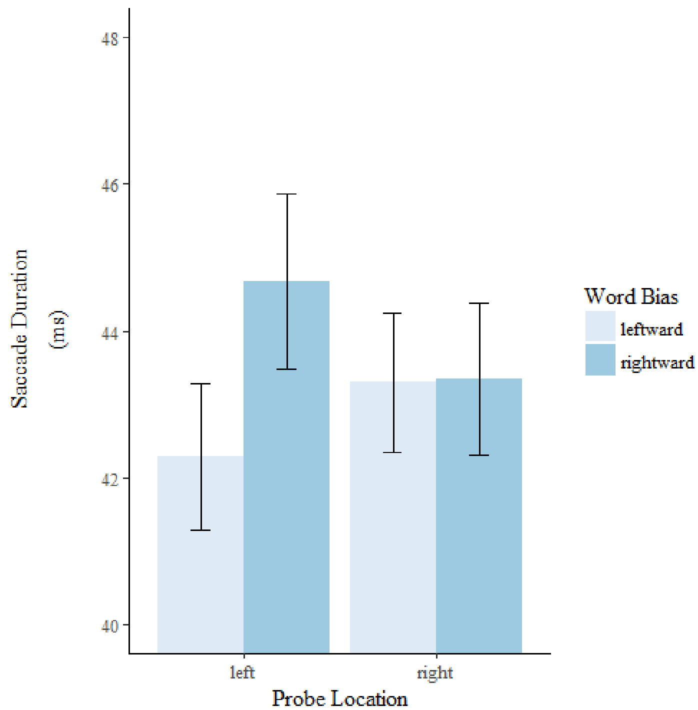

Figure 23. Depicted is the two-way interaction for saccade duration. Responses to different word biases are shown across probe locations, where saccade duration is displayed in milliseconds.

Verification Task

Error Rate Analysis

The accuracy of response to the verification question, on average, was high (94.81%). Participants were more accurate when the question regarded rightward (95.37%) biasing words over leftward (94.24%). Participants were more accurate for the verification task after exposure to small (95.71%) over large (93.91%) numbers. Finally, greater rates of accuracy were seen after leftward (95.03%) probes than rightward (94.59%). For a breakdown of error rate means by condition, see Table 23.

Table 23. Mean levels of accuracy (%) in response to the task verification question.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	92.70	95.08	92.78	95.05	93.91
	Small	96.21	96.11	95.29	95.23	95.71
Total		94.46	95.59	94.03	95.14	94.81

An analysis into rates of accuracy found significant main effects of number (Wilks' λ = .634, f (1,25) = 14.460, p = .001, ηp^2 = .366) and word bias (Wilks' λ = .696, f (1,25) = 10.923, p = .003, ηp^2 = .304). No significant main effect of probe was found (Wilks' λ = .964, f (1,25) = 946, p = .340, ηp^2 = .036). For number, after hearing small (95.71%) numbers participants were more accurate than large numbers (93.91%) confirming some findings demonstrating the so-called "small number advantage" (Cai & Li, 2015; Di Bono & Zorzi, 2013; Towse, Loetscher, & Brugger, 2014; Trick & Pylyshyn, 1994). For word bias, significantly greater rates of accuracy were seen for rightward (95.37%) words over leftward (94.24%).

Further analysis at the two-way level of interaction revealed an interaction between number and word bias (Wilks' λ = .789, f (1,25) = 6.704, p = .016, ηp^2 = .211), which can be seen visually in Figure 24. When words biased attention leftward, a greater accuracy rate was observed for small (95.82%) numbers over large (92.96%; $p < .001$). When the word biased attention to the right, no difference was observed between large and small numbers (p = .464). No further two-way, for probe and number (Wilks' λ = .973, f (1,25) = .698, p = .411, ηp^2 = .027) or probe and word bias (Wilks' λ = 1.000, f (1,25) = .006, p

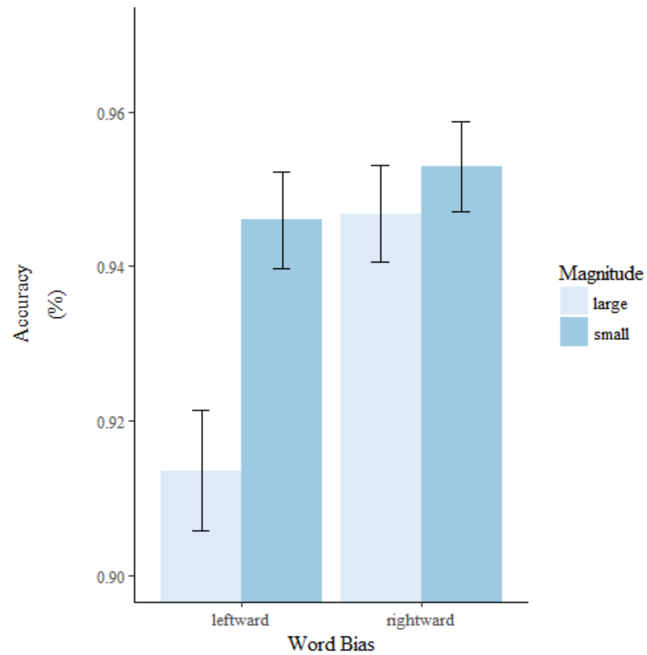

Figure 24. Depicted is the two-way interaction for verification accuracy. Responses to different magnitudes are shown across word biases, with accuracy displayed as a percentage of correct responses.

= .939, $\eta p^2 < .001$), or three-way (Wilks' $\lambda = .995$, $f(1,25) = .137$, $p = .714$, $\eta p^2 = .005$) interactions were observed.

Response Time Analysis

The average time taken to respond to the verification task was 683.84ms. Participants were faster when the word remembered was leftward (683.10ms) biasing over rightward (684.57ms). After large (683.35ms) number exposure, participants were faster than after small (684.34ms) number exposure. Finally, after having made a right (682.36ms) probe, participants were faster than after having made a left (685.36ms) probe. See Table 24 for a view of means and standard deviations by condition.

Table 24. Mean (and standard deviation) response times by participants to the accuracy verification task, presented in milliseconds.

Probe		Left		Right		Total
Word Bias		Left	Right	Left	Right	
Number	Large	686.95 (326.75)	689.29 (317.64)	694.69 (359.29)	662.59 (307.73)	683.35 (328.46)
	Small	677.58 (342.78)	687.64 (350.03)	672.55 (344.16)	699.07 (348.99)	684.34 (346.44)
Total		682.16 (334.90)	688.46 (334.24)	684.04 (352.09)	680.58 (329.06)	683.84 (337.48)

Analysis by means of ANOVA revealed no significant main effects for probe (Wilks' λ = .972, f (1,25) = .708, p = .408, ηp^2 = .028), number (Wilks' λ = .987, f (1,25) = .332, p = .570, ηp^2 = .013), or word bias (Wilks' λ = .997, f (1,25) = .081, p = .779, ηp^2 = .003). No interactions were observed at the two-way level for probe and number (Wilks' λ = .946, f (1,25) = 1.430, p = .243, ηp^2 = .054), probe and word bias (Wilks' λ = .995, f (1,25) = .129, p = .723, ηp^2 = .005), or number and word bias (Wilks' λ = .914, f (1,25) = 2.361, p = .137, ηp^2 = .086). Finally, no significant three-way interaction was found (Wilks' λ = .912, f (1,25) = 2.421, p = .132, ηp^2 = .088).

Discussion

The present study investigated the interplay between words with varying spatial semantics maintained in working memory, and concurrently apprehended numbers of varying numerical magnitude, with regard to potentially shared spatial-conceptual mappings in horizontal space. The findings from this study found, in total, three main effects and five two-way interactions. The two-way interactions for probe response time and saccade duration found trends toward significance. The remaining interactions were for probe accuracy (magnitude x probe location), saccade onset (magnitude x probe location), and verification accuracy (word bias x probe location).

The main effect of probe found in the parity judgement task shows that rightward probes caused longer first fixation durations than leftward probes. This is not a surprising finding, being in line with previous research (e.g. Salthouse & Ellis, 1980).

The present study also partially replicated the SNARC effect by showing that, primed with large magnitudes, participants are faster to launch a saccade rightward and, when primed with small magnitudes, participants more accurately perform leftward parity judgements. This makes for an interesting contrast: it would be expected that small number and leftward response, and large number and rightward response, would have an advantage over their counterparts. Here, it is shown that larger magnitudes instigate a faster response, potentially at the expense of greater accuracy while smaller magnitudes cause more accurate responses at the expense of speed, when the response required is in the typically expected direction. In the context of research published at present, this is a novel finding. Mental number space is a well-documented phenomenon that shows a mapping of number to space (Ranzini, Lisi & Zorzi, 2016). When asked to categorise numbers in space, participants have been shown to be more accurate when the spatial location is congruent with the number's position on the mental number line (Hoffmann, Hornung, Martin & Schiltz, 2013). Equally, the spatial semantics in words has been consistently shown to influence attention in participants (Richardson, Spivey, Barsalou & McRae, 2003; Chaterjee, Southwood & Basilico, 1999; Bedny, Caramazza, Pascual-Leone & Saxe, 2011).

The remaining results were found in the verification task accuracy. Main effects were found for number and word bias. Participants were more accurate for small over large numbers, and for rightward biasing words over leftward biasing words. An interaction was found between word bias and magnitude showing participants to be more accurate when the question regarded a leftward biasing word after hearing a small magnitude number. It could be argued that this supports the polarity account of processing (Lakens, 2012). In this instance, the positive pole for small number is leftward, ergo increased accuracy is observed when the probe location and number coincide. This finding is similar in nature to the one found for probe accuracy. The argument made could be much stronger, were an interaction also to be found for verification response time like that found for saccade onset, however this is not the case. A potential reason for this is that probe response is a passive component of the verification question. There is no active requirement to look left or right at this stage of testing, and so the directionality aspect is maintained in memory only by temporal proximity. It would be interesting for future research to incorporate this aspect to see how the results would be affected.

Altogether, findings from horizontal space suggest the effects being observed are more complex than initially hypothesised. The SNARC effect has been partially supported, as well as the mapping from conceptual metaphor to numerical number space. No clear-cut effects of representational interplay were observed here, though a case can be made for its existence by means of inhibition. Were no interaction between conceptual representations occurring, it would be expected that previous research would replicate fully.

Experiment 4

Vertical Space

Methodology

Design

As in experiment 3, the task comprised a within-participants, 2x2x2 design. Here, the spatial semantics of a word (leftward/rightward), intrinsic number (small/large) and probe (upward/downward) comprised the independent variables. Two parity rules (even-left; even-right) were used to balance for any effects of number line congruency and audible number presentation. In total, 192 trials were presented to participants. Recorded were several dependent variables. Non-eye-tracking metrics included simple reaction time and accuracy rates to the parity and verification tasks. Eyetracking metrics were only recorded for the saccade task, and included saccade measures of onset and duration, as well as fixation measures of total gaze duration and the duration of the first fixation. All participants were required to give a response to every trial, which were grouped by parity rule and counterbalanced across presentation. Numbers were presented at random within blocks of testing.

Participants

The same participants used in Experiment 3 took part in Experiment 4

Materials

The same recording of the numbers ‘1’, ‘2’, ‘8’ and ‘9’ used previously were, again, deployed here. Words were chosen from a normed database that catered for the spatial semantics of a verb (Meteyard & Vigliocco, 2009). The norms of the database allowed for the creation of upward and downward-biasing conditions, which consisted of the most representative verbs from each category. Words were initially presented in lower case for the saccade task, but in the verification task presented in uppercase. This insured processing of the content of the word itself, and not just the maintenance of stimuli in visual working memory. Both fixation dots and target squares were created in Experiment Builder.

Procedure

The same procedure used in Experiment 3 was used again for Experiment 4. However, here the probe array was arranged vertically, in line with the coordinates provided in the General Methods (chapter 2; see Figure 25)

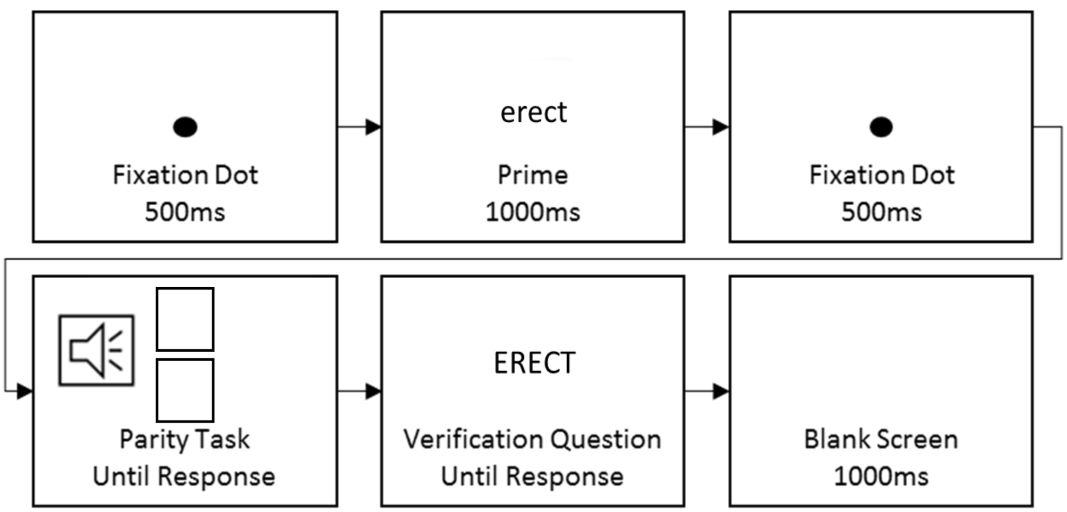

Figure 25. An example trial sequence in which the verification question is a word congruent with the prime. Note that presentation is not to scale, but is used to aid clarification.

Results

The strategy discussed in the general methods section was utilised in filtering and analysing the data provided by participants. This involved, post filtering and transformation, a series of 2x2x2 ANOVAs to understand fixation, saccadic, and manual response parameters of the data.

Responses to the parity and verification task were measured using reaction time and error rates for all participants. Eyetracking data was analysed only for the saccade task, which can be further divided into fixation and saccadic metrics. A standard criterion of α was used and set to .05. Data from one participant was excluded due to non-completion of the experimental paradigm, and all tests were conducted on the remaining 25 participants. For the raw data, see Appendix E.

Saccade task

Error Rate Analysis

The average rate of accuracy by participants was 86.12%. Participants were more accurate when maintaining downward (86.66%) words in memory than upward (85.57%). More correct answers were received after experiencing large (86.84%) numbers than small (85.39%). Finally, greater rates of accuracy were seen when upward (87.79%) probes were made over downward (84.43%). Table 25 shows a breakdown of accuracy rates by condition.

Table 25. Mean rates of accuracy (%) for participants when responding to the saccade task.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	86.95	84.15	87.81	88.44	86.84
	Small	83.47	83.16	88.39	86.51	85.39
Total		85.20	83.66	88.10	87.48	86.12

No significant main effects were found for probe (Wilks' $\lambda = .876$, $f(1,25) = 3.532$, $p = .072$, $\eta p^2 = .124$), number (Wilks' $\lambda = .973$, $f(1,25) = .690$, $p = .414$, $\eta p^2 = .027$), or word bias (Wilks' $\lambda = .920$, $f(1,25) = 2.170$ $p = .153$, $\eta p^2 = .080$). No two-way interactions were revealed between probe and number (Wilks' $\lambda = .981$, $f(1,25) = .491$, $p = .490$, $\eta p^2 = .019$), probe and word bias (Wilks' $\lambda = .992$, $f(1,25) = .214$, $p = .647$, $\eta p^2 = .008$), or number and word bias (Wilks' $\lambda = 1.000$, $f(1,25) = .001$, $p = .973$, $\eta p^2 < .001$). Further, no three-way interaction existed (Wilks' $\lambda = .921$, $f(1,25) = 2.158$, $p = .154$, $\eta p^2 = .079$).

Response Time Analysis

The average time taken to respond to a trial, regardless of condition, was 741.70ms. Participants were faster than this after experiencing an upward (738.20ms) biasing word, and slower after a downward (745.10ms) biasing word. Participants were faster after small (741.16ms) number exposure over large number exposure (742.12ms). When the probe was made upwards (722.25ms), participants were faster at responding than when the saccade task required a downward (761.94ms) response. Table 26 shows a breakdown of conditions by mean and standard deviation.

Table 26. Mean (and standard deviation) values for participants response time to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	769.58 (315.26)	746.58 (287.69)	731.17 (321.31)	721.76 (297.42)	742.12 (306.22)
	Small	765.02 (305.09)	766.58 (295.51)	716.07 (292.86)	719.82 (299.93)	741.26 (299.08)
Total		767.34 (310.14)	756.39 (291.57)	723.66 (307.42)	720.80 (298.51)	741.70 (302.68)

Analysis revealed a significant main effect of probe (Wilks' λ = .628, f (1,25) = 14.800, p = .001, ηp^2 = .372), and no further main effects for either number (Wilks' λ = .982, f (1,25) = .467, p = .501, ηp^2 = .018) or word bias (Wilks' λ = .999, f (1,25) = .017, p = .896, ηp^2 = .001). The main effect of probe shows upward (722.25ms) responses to be faster than downward (761.94ms).

No interactions were found at either two way, for probe and number (Wilks' λ = .964, f (1,25) = .924, p = .346, ηp^2 = .036), probe and word bias (Wilks' λ = .989, f (1,25) = .287, p = .597, ηp^2 = .011), and magnitube and word bias (Wilks' λ = .963, f (1,25) = .961, p = .336, ηp^2 = .037), or three-way level (Wilks' λ = .963, f (1,25) = .954, p = .338, ηp^2 = .037).

Eye Movement Analysis

Fixation data.

On average, the duration of a participant's first fixation in response to the saccade task was 346.67ms. The spatial semantics of a word made little difference to fixation duration, with upward (346.53ms) words resulting in a slightly shorter duration of the first fixation than downward (346.81ms). The processing of small (345.57ms) numbers resulted in a shorter first fixation than large (347.74ms) numbers. See Table 27 for a breakdown of first fixation durations by condition.

Table 27. Mean (and standard deviation) durations of the first fixation participants made in response to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	330.73 (166.41)	327.55 (145.87)	358.30 (170.67)	372.68 (190.32)	347.74 (170.33)
	Small	338.38 (173.96)	330.73 (153.59)	358.64 (179.58)	352.56 (177.62)	345.57 (172.10)
Total		334.47 (170.09)	329.11 (149.62)	358.47 (175.10)	362.74 (184.33)	346.67 (171.18)

An analysis revealed no main effects for probe (Wilks' $\lambda = .896$, $f(1,25) = 2.913$, $p = .100$, $\eta p^2 = .104$), number (Wilks' $\lambda = .997$, $f(1,25) = .080$, $p = .780$, $\eta p^2 = .003$), and word bias (Wilks' $\lambda = .983$, $f(1,25) = .428$, $p = .519$, $\eta p^2 = .017$). A two-way interaction was found between number and word bias (Wilks' $\lambda = .782$, $f(1,25) = 6.982$, $p = .014$, $\eta p^2 = .218$; Figure 26). Further testing shows no statistically significant differences between first fixation durations to large and small numbers after hearing a downward biasing word ($p = .266$) or upward biasing word ($p = .266$). No further two-way interactions were found either for probe and number (Wilks' $\lambda = .904$, $f(1,25) = 2.647$, $p = .116$, $\eta p^2 = .096$) or probe and word bias (Wilks' $\lambda = 1.000$, $f(1,25) = .012$, $p = .913$, $\eta p^2 < .001$).

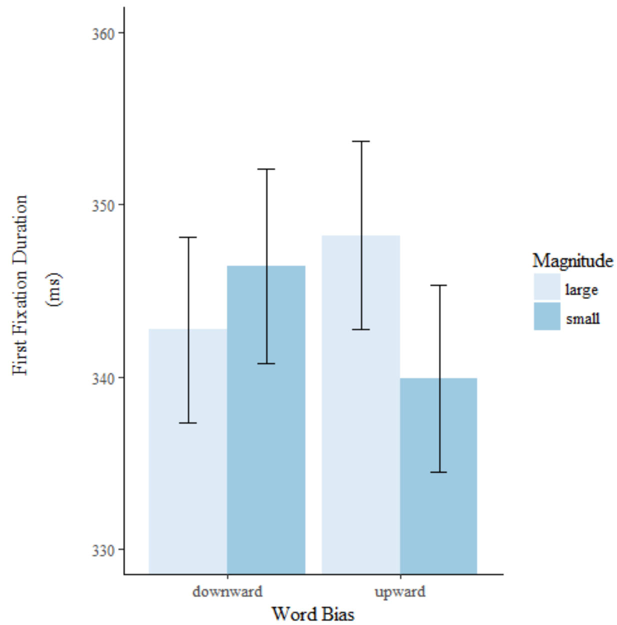

Figure 26. Depicted is the two-way interaction for first fixation duration. Responses to different magnitudes are shown across word biases, where fixation duration is presented in milliseconds.

Additionally, no three-way interaction was observed (Wilks' λ = .980, f (1,25) = .515, p = .480, ηp^2 = .020).

For total gaze durations, participants on average remained for 415.00ms. This was shorter for upward (414.51ms) biasing words, and slower for downward (415.48ms). Small numbers resulted in shorter total gaze durations (410.08ms) than long numbers (419.79ms). When responding to the saccade task downwards (401.05ms), participants would remain for a shorter duration than responding upwards (428.36ms). Table 28 shows the mean and standard deviations for total gaze duration by condition.

Table 28. Mean (and standard deviation) total gaze durations for participant responses to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	404.87 (197.58)	404.41 (189.42)	432.58 (215.24)	436.58 (226.67)	419.79 (208.32)
	Small	397.00 (199.89)	397.56 (191.67)	426.34 (223.78)	417.72 (214.44)	410.08 (208.49)
Total		401.03 (198.64)	401.07 (190.45)	429.46 (219.47)	427.25 (220.79)	415.00 (208.43)

Following analysis, no significant main effects were found for probe (Wilks' $\lambda = .884$, $f(1,25) = 3.296$, $p = .081$, $\eta p^2 = .116$), number (Wilks' $\lambda = .982$, $f(1,25) = 465$, $p = .502$, $\eta p^2 = .018$) or word bias (Wilks' $\lambda = .996$, $f(1,25) = .109$, $p = .744$, $\eta p^2 = .004$). No two-way interactions could be found for probe and number (Wilks' $\lambda = .999$, $f(1,25) = 0.14$, $p = .907$, $\eta p^2 = .001$), probe and word bias (Wilks' $\lambda = 1.000$, $f(1,25) = .004$, $p = .947$, $\eta p^2 < .001$) or number and word bias (Wilks' $\lambda = .901$, $f(1,25) = 2.739$, $p = .110$, $\eta p^2 = .099$). Finally, no three-way interaction was found either (Wilks' $\lambda = .986$, $f(1,25) = .363$, $p = .552$, $\eta p^2 = .014$).

Saccade data.

An average saccade was onset in 704.36ms. Faster was the onset when upward (700.62ms) over downward (708.00ms) words were maintained in memory. For numbers, onset was quicker after small (702.59ms) numbers over large (706.09ms), and probes upward (684.68ms) were faster than downward (724.85ms). Table 29 shows the average onset times for saccades in the saccade task by condition.

Table 29. Mean (and standard deviation) onset times for saccades performed in response to the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	733.57 (319.45)	709.64 (285.05)	699.28 (330.89)	682.13 (293.30)	706.09 (308.38)
	Small	724.52 (300.27)	731.59 (300.42)	675.86 (293.41)	681.18 (300.05)	702.59 (299.29)
Total		729.14 (310.08)	720.42 (292.75)	687.62 (312.85)	681.66 (296.52)	704.36 (303.90)

Following an inferential analysis, a significant main effect of probe was found (Wilks' $\lambda = .593$, $f(1,25) = 17.183$, $p < .001$, $\eta p^2 = .407$), indicating a significantly faster onset of saccades upward (684.68ms) than downward (724.85ms). No further main effects were found for number (Wilks' $\lambda = .966$, $f(1,25) = .883$, $p = .356$, $\eta p^2 = .034$), or word bias (Wilks' $\lambda = 1.000$, $f(1,25) = .003$, $p = .956$, $\eta p^2 < .001$). No two-way interactions were found for probe and number (Wilks' $\lambda = .965$, $f(1,25) = .920$, $p = .347$, $\eta p^2 = .035$), probe and word bias (Wilks' $\lambda = .997$, $f(1,25) = .082$, $p = .776$, $\eta p^2 = .003$), or number and word bias (Wilks' $\lambda = .932$, $f(1,25) = 1.815$, $p = .190$, $\eta p^2 = .068$). At the level of three-way interactions, no significant result was found (Wilks' $\lambda = .979$, $f(1,25) = .540$, $p = .469$, $\eta p^2 = .021$).

An average saccade in response to the saccade task lasted for 44.46ms. This was consistent across downward (44.38ms) and upward (44.55ms) word biases, with the former being marginally faster than the latter. Large (43.71ms) numbers resulted in saccades with shorter durations than small (45.23ms) numbers, while probes downward (47.77ms) had longer durations than those made upward (41.30ms). Table 30 represents the means and standard deviations broken down by condition.

Table 30. Mean (and standard deviation) saccade durations of participants during the saccade task, presented in milliseconds.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	46.89 (34.49)	45.47 (31.26)	41.09 (12.26)	41.49 (15.89)	43.71 (25.36)
	Small	49.76 (40.21)	49.06 (38.03)	40.19 (11.34)	42.49 (26.72)	45.23 (31.17)
Total		48.29 (37.40)	47.23 (34.77)	40.64 (11.81)	41.99 (21.96)	44.46 (28.39)

After analysing this by means of ANOVA, no significant main effects were found for probe (Wilks' $\lambda = .873$, $f(1,25) = 3.651$, $p = .068$, $\eta p^2 = .127$), number (Wilks' $\lambda = .914$, $f(1,25) = 2.343$, $p = .138$, $\eta p^2 = .086$), or word bias (Wilks' $\lambda = .1.000$, $f(1,25) = .004$, $p = .950$, $\eta p^2 < .001$). A significant two-way interaction was revealed between probe and number (Wilks' $\lambda = .828$, $f(1,25) = 5.189$, $p = .032$, $\eta p^2 = .172$) which can be seen in Figure 27. Further analysis shows no significant results. No significant differences were found following large number exposure between downward and upward targets ($p = .166$) or following small number exposure ($p = .070$). No further interactions were found at either two-way, between probe and word bias (Wilks' $\lambda = .967$, $f(1,25) = .851$, $p = .365$, $\eta p^2 = .033$) or number and word bias (Wilks' $\lambda = .981$, $f(1,25) = .489$, $p = .491$, $\eta p^2 = .019$), or at the three-way level (Wilks' $\lambda = .989$, $f(1,25) = .266$, $p = .610$, $\eta p^2 = .011$).

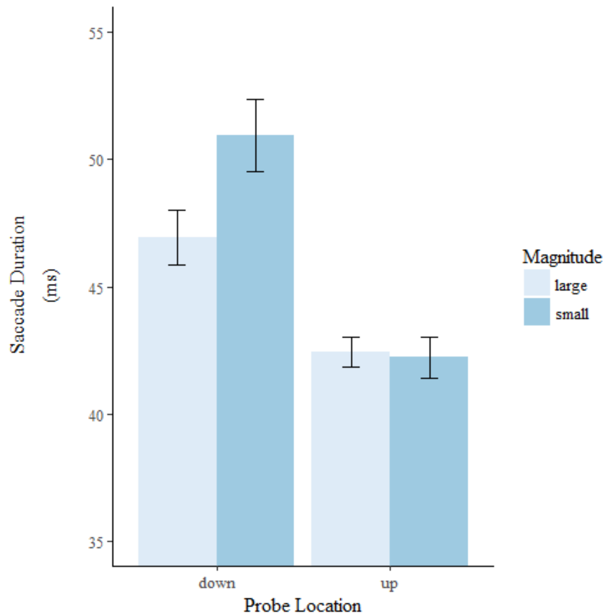

Figure 27. Depicted is the two-way interaction for saccade durations. Responses to different magnitudes are shown across probe locations, where saccade duration is presented in milliseconds.

Verification Task

Error Rate Analysis

Average accuracy for the verification task was high (95.38%). More accurate responses were made after exposure to downward (95.91%) biasing words than upward (94.76%). Large (96.15%) number trials had greater accuracy than trials where participants had experienced small (94.53%) numbers. Participants were slightly more accurate after having made probes upward (95.38%) over downward (95.29%). See Table 31 for a breakdown of accuracy rates by condition.

Table 31. Average rates of accuracy (%) in response to the verification question.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	96.72	96.37	96.91	94.55	96.15
	Small	95.64	92.47	94.36	95.68	94.53
Total		96.19	94.41	95.63	95.12	95.34

Inferential analysis revealed significant main effects of number (Wilks' λ = .830, f (1,25) = 5.132, p = .032, ηp^2 = .170) and word bias (Wilks' λ = .851, f (1,25) = 4.372, p = .047, ηp^2 = .149), but no significant main effect of probe (Wilks' λ = .992, f (1,25) = .208, p = .652, ηp^2 = .008). For number, a significantly greater level of accuracy was seen after exposure to large numbers (96.15%) than small numbers (94.53%). Findings from word bias show significantly higher accuracy in response to downward biasing words (95.91%) over words with an upward bias (94.76%). Though no two-way interactions were observed (probe and number: Wilks' λ = .920, f (1,25) = 2.186, p = .152, ηp^2 = .080; probe and word bias: Wilks' λ = .969, f (1,25) = .806, p = .378, ηp^2 = .031; number and word bias: Wilks' λ = .950, f (1,25) = 1.309, p = .263, ηp^2 = .050), a significant three-way interaction was found (Wilks' λ = .813, f (1,25) = 5.747, p = .024, ηp^2 = .187). This three-way interaction can be seen in Figure 28 and Figure 29. When this is analysed further, the interaction can be seen to be motivated by two contrasts. The first is for downward biasing words, whereby upward biasing probes and small (95.53%) magnitudes resulted in less accurate responses than large (96.16%) magnitudes (p = .044). The second is for upward biasing words, whereby downward biasing probes and small (92.26%) magnitudes resulted in less accurate responses than large (95.45%) magnitudes (p = .031). The remaining two contrasts were non-significant (downward word bias, downward probe bias: large x small number, p = .321; upward word bias, upward probe bias: large x small number, p = .085).

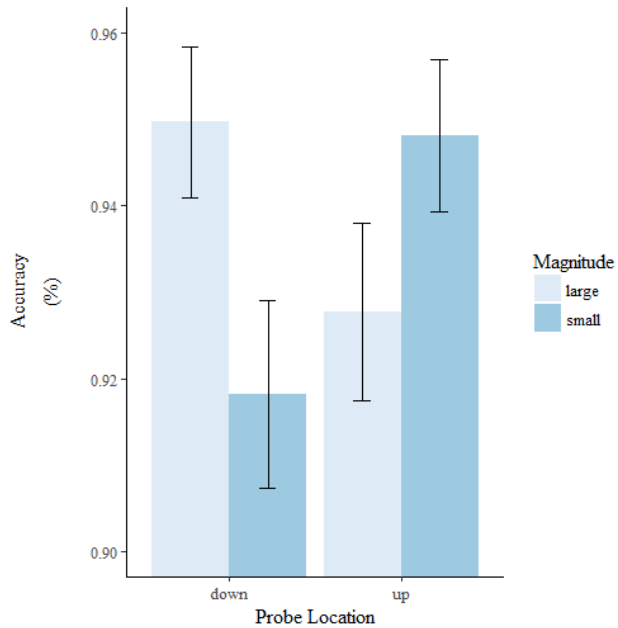

Figure 28. Depicted is one aspect of the three-way interaction for verification accuracy. Responses to upward biasing trials are shown across probe location and magnitude, with accuracy displayed as a percentage of correct responses.

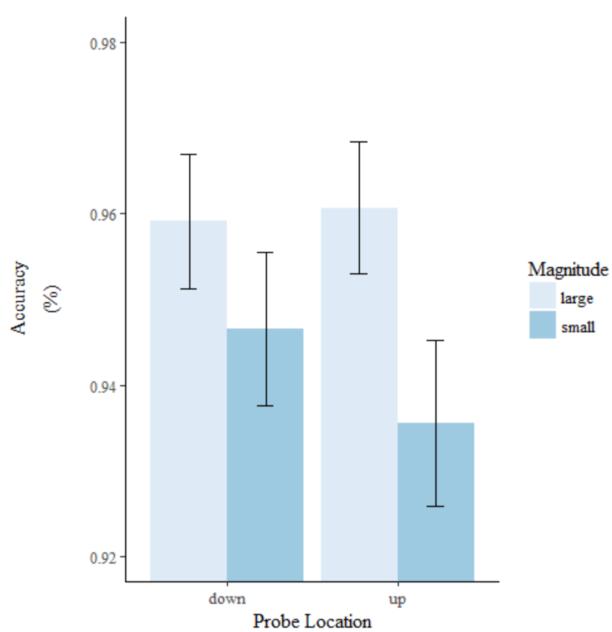

Figure 29. Depicted is one aspect of the three-way interaction for verification accuracy. Responses to downward word biasing trials are shown across probe location and magnitude, with accuracy displayed as a percentage of correct responses.

Response Time Analysis

On average, a participant took 667.67ms to respond to the verification question. This was faster when participants maintained downward (660.88ms) biasing words in memory over upward (673.98ms) and large (661.69ms) numbers over small (673.21ms). There was relatively little variation for response time to the verification task after participants had performed downward (667.11ms) over upward (667.61ms) probes, with the former being slightly faster than the latter. See Table 32 for response time to the verification task by condition.

Table 32. Mean (and standard deviation) reaction times in response to the verification task, presented in milliseconds.

Probe		Down		Up		Total
Word Bias		Down	Up	Down	Up	
Number	Large	644.12 (313.47)	675.30 (323.90)	671.17 (347.81)	656.31 (334.14)	661.69 (330.16)
	Small	665.34 (332.26)	684.90 (347.12)	662.90 (338.86)	680.19 (352.15)	673.21 (342.55)
Total		654.48 (332.78)	680.00 (335.32)	667.07 (343.24)	668.17 (343.23)	667.37 (336.33)

A further analysis shows no significant main effects (probe: Wilks' λ = 1.000, f (1,25) = .010, p = .921, $\eta p^2 < .001$; number: Wilks' λ = .976, f (1,25) = .624, p = .437, $\eta p^2 = .024$; word bias Wilks' λ = .863, f (1,25) = 3.965, p = .057, $\eta p^2 = .137$), two-way interactions (probe and number: Wilks' λ = .999, f (1,25) = .019, p = .890, $\eta p^2 = .001$; probe and word bias: Wilks' λ = .928, f (1,25) = 1.935, p = .176, $\eta p^2 = .072$; number and word bias: Wilks' λ = .999, f (1,25) = .016, p = .901, $\eta p^2 = .001$), or three-way interaction (Wilks' λ = .960, f (1,25) = 1.029, p = .320, $\eta p^2 = .040$).

Discussion

The present study investigated the interplay between magnitude-related features of words with varying spatial semantics maintained in working memory and concurrently apprehended numbers of varying numerical magnitude with regard to potentially shared spatial-numerical mappings in vertical space. This study found several main effects and interactions. In the saccade task, main effects were found for probe response time and saccade onset; interactions were found for first fixation duration and saccade duration. However, both interactions provided nothing of further interest. The main effects found participants to be both faster at launching a saccade and, by extension, responding to the trial when the task required responses in upward over downward domains. In the verification task, main effects were found for number and word bias, as well as a three-way interaction in error rates. Here, the main effects indicated that participants were more accurate at responding to the task when the magnitude was large, and when the word bias was downward. The three-way interaction implies caution with the interpretation of these main effects and provided an interesting finding. When the word bias was downward and the probe appeared in the upper space, participants were more accurate if the magnitude heard was large; when the word bias was upward and the probe was in lower space, participants were more accurate if the magnitude heard was small.

Findings from the saccade task are consistent with previous research, which also finds a vertical asymmetry in saccade latencies (Abegg, Pianezzi & Barton, 2015). Generally, an upward saccade is performed faster than a downward saccade (Oohira, Goto & Ozawa, 1982). It is suggested that this is due the upper and lower visual fields accessing different networks in attention and motor preparation, which then manifests as a behavioural (saccade) asymmetry (Tzelepi, Laskaris, Amditis & Kapoula, 2010). This is supported by ecological theories of cognition (e.g. Barker, 1968; Gärling & Evans, 1991; Rietveld & Kiverstein, 2014; Shaw & Bransford, 2017), which would suggest eye movement in upward space to be parasitised by abstract thinking. In humans, the necessity to understand and process features of the environment in upward space has diminished with evolution, and so actively processing abstract information has expropriated upward saccadic exploration (Previc, Declerck & de Brabander, 2005). As upward space is not as heavily involved in the processing of grounded or embodied stimuli, less common coding confabulation should occur and faster responses are to be expected. By being able to replicate this finding, a stronger case can be made for the question of why other findings do not replicate (e.g. SNARC, conceptual metaphor effects; c.f. Fischer, Castel, Dodd & Pratt, 2003; Lakoff & Johnson, 1980).

In vertical space, the case for spatial semantics is much clearer than number. Previous work has found that, though mental number space incorporates the Y-axis, effects are much stronger across the X-axis (Gevers & Lammertyn, 2005). However, as there are numerous examples of vertical SNARC effects (e.g. Schwarz & Keus, 2004; Jarick, Dixon, Maxwell, Nicholls & Smilek, 2009), it would still be expected that the present study should support the literature if no interplay between representations were occurring. Generally, vertical space finds support in the literature, something the present study is not able to uphold. A number of studies have found interactions between the image schema of words like push and pull and the spatial location of a response (e.g. Schubert, 2005; Paladino, Mazzurega & Bonfiglioli, 2017). This is motivated by the notion that our understanding is grounded in our knowledge of the world around us. For example, standing tall when proud and looking up to others are metaphors entwined in upward space. This is thought to transcend meta-cognitive association (i.e. it is not that words and concepts are merely associated over time) and instead be a fast and automatic process (Richardson, Spivey, Barsalou & McRae, 2003). An alternative account of this relationship suggests that there is a difference in the processing of positive and negative polar endpoints, so that positive (e.g. upward, moral) is processed faster than negative (e.g. downward, immoral; Lakens, 2012), and while this is a potential alternative explanation for the data it still does not account for why no effects of number were observed. It does, however, provide at least some explanation as to why more accurate results were observed after upward biasing words over downward.

Here, then, similar findings to the first two studies are observed, and, once again, a much more complex nature of conceptual interplay is presented than initially hypothesised. Instead, at the bottom-up level of processing, when representations are interacting, competition occurs and there is an interference in response times. At the top-down level, in stark contrast, there is a facilitation effect. This will be discussed in more detail in the Chapter Summary.

Chapter Summary

The present chapter investigated the interplay between words with varying spatial semantics maintained in working memory and concurrently apprehended numbers of varying numerical magnitude with regard to potentially shared spatial-conceptual mappings in horizontal and vertical space. Once again, the strongest support to an interactive simulation hypothesis entertained throughout this Thesis has been provided in the horizontal domain, which, arguably, has a stronger situated mapping mechanism than the vertical space (Myachykov, Scheepers, Fischer & Kessler, 2014). Both studies have, to an extent, replicated findings from the literature: in vertical space, a saccade asymmetry was observed (Abegg, Pianezzi & Barton, 2015). In the horizontal domain more accurate responses were gathered after rightward over leftward words (Lynott & Coventry, 2014) and following small over large numbers in leftward space, while faster onset saccades and longer first fixations were observed in rightward space after large number (e.g. Fischer, 2003).

Further evidence was found for the differences in top down and bottom up cognitive processing. Although originally predicted as a facilitatory mechanism, conceptual interplay appeared to *interfere* with information stored in memory when bottom-up processing was measured. In this chapter, were no conceptual interplay occurring, it would be expected that strong support would be found for SNARC or effects of spatial semantics. This was not the case. Given other effects were replicated, and given the claimed power and wealth of the respective literatures, the absence of what would be considered normal is in itself interesting. At the bottom-up level of processing, conceptual interplay confounds memory in line with common coding accounts (e.g. Prinz, 1990; see also Tye-Murray, Spehar, Myerson, Hale & Sommers, 2013). However, at the level of top-down processing (e.g. the verification question) interplay between representations was shown to *aid* processing, which is more in line with spreading activation accounts of cognition (Collins & Loftus, 1975; Barr, Walker, Gross & Hayne, 2014; Foster et al., 2017).

An interesting contrast is made across verification accuracy. In horizontal space, leftward words and small magnitudes resulted in more accurate responses. In vertical space, downward words, upward probes and large magnitudes were more accurate than small magnitudes, while upward words, downward probes and large magnitudes were also more accurate than small magnitudes. For horizontal space, the effect observed is what would be expected, albeit missing an effect of probe location. For the interaction in vertical space, a different picture entirely is revealed. The driving force was large magnitude, however only when combined with one other facilitatory factor: either upward probes or upward words, but not both. This would suggest a mixed case of support for both common coding (Prinz, 1990) *and* spreading activation (Collins & Loftus, 1975), as facilitation can be seen, but only when there are not *too* many factors at work simultaneously.

Finally, it would be remiss not to pass comment on the inherent flaws of the ANOVA approach to analysis, which provides a very specific answer to a very unspecific question. By averaging across trials and participants, a lot of statistical power is sacrificed, and this is reflected in the findings. Many of the lost findings were interactions that would have supported the number and spatial semantics literature, and in some cases provide a strong support for conceptual interplay. However, it is wrong to massage results in a fashion that supports personal interest, and through understanding these findings two main issues are brought to bear: 1) the analysis strategy must be sufficient to encapsulate all results. Perhaps by adopting a mixed linear modelling approach, some of the findings would be made clearer. This is not to say the overall picture would change, but that the findings would be more understandable due to less power being sacrificed. 2) It is by the incorporation of two related representations that both the findings have become muddled. The interplay between representations has gone to show that the whole is *different* to the sum of its parts, not necessarily *greater*.

The final study chapter to follow increases the level of abstraction further. While there is a clear link to the concrete when dealing with affordances and spatial semantics, the next two studies attempt to understand interplay between number and the relatively abstract representations of valency.

CHAPTER FIVE

Valency and Numerical Magnitude

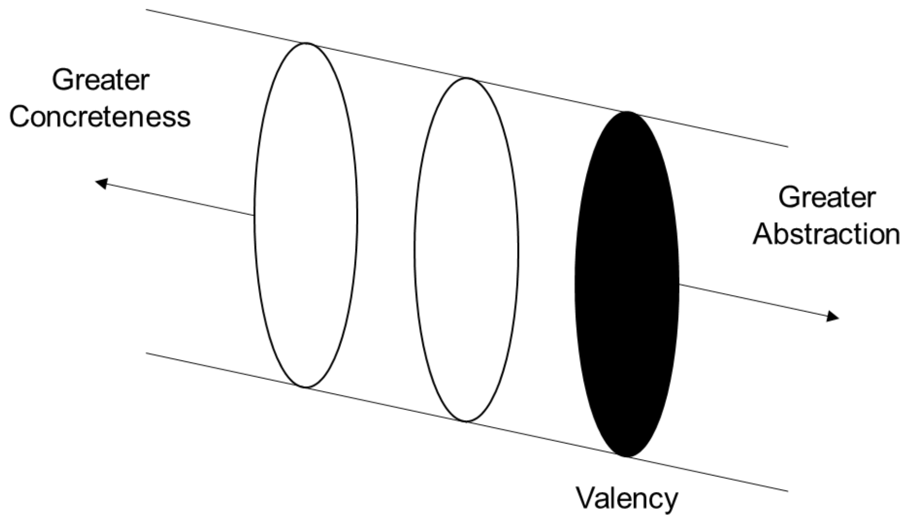

Figure 30. The Abstraction Pipeline. A pictoral example of how far removed the current chapter's subject matter is from concrete representation.

This chapter reports the results of two experiments, similar in nature to the tasks outlined in the preceding chapters. Here, participants maintain in memory a word that carries a certain valency before making a judgement about the parity of an number presented audibly by performing a saccade to one of two onscreen targets, either horizontally (experiment 5) or vertically (experiment 6) distributed. Following this, participants are asked to judge whether a word presented on screen is either the same or different to the one being maintained in memory. Word valency, as it pertains to the psychologist, is typically conceptualised as the attractiveness, or emotions, associated with a term (Kuperman, Estes, Brysbaert & Warriner, 2014). A word that would be considered positively attractive is usually associated with goodness, such as joy, pride, and happiness, while a word with negative attractiveness is associated with badness, like melancholy, depression, and sadness (de la Vega, De Filippis, Lachmair, Dudschig & Kaup, 2012). Word valency has a spatial component (de la Vega, Dudschig, De Filippis, Lachmair & Kaup, 2013). This spatial component utilises sensorimotor simulation (Bastiaansen, Thioux & Keysers, 2009). Because of the nature of spreading activation, the perceptual features of space and semantic properties of word valency have a common locus of activation, and by extension a potential for interaction (e.g. Pulvermüller, Hauk, Nikulin & Ilmoniemi, 2005; Mahon, & Caramazza, 2008; Davey, Cornelissen, Thompson, Sonkusare, Hallam, Smallwood & Jefferies, 2015). As number also shares an activation in space, the current thesis would hypothesise an interaction – interplay – between representations.

Unlike spatial semantics, the content of the previous chapter, word valency is even more abstract and removed from the environment. This is due, in part, to the inability to easily enact valency in the world: with spatial semantics, it is easy to *lift* and *drop* an item. It is not so easy, as is the case with word valency, to force feelings of *love*, *hate*, to feel *aggressive* or *intimate*. These are abstract emotions that are associated with an individual's experiences. Valency is experienced almost entirely without top-down control, and so the nature of the interplay between concepts will be different to what is previously observed for spatial semantics and affordances, whereby due to the concreteness of concepts representation is much richer. Here, two studies examine the ability of language that utilises differing valency to displace visual attention in different dimensions of space. It is hypothesised that words with positive valency will prime attention toward upward and rightward domains while words with negative valency will prime attention in leftward and downward domains. Error rates are expected to mirror this, with greater accuracy being observed in wholly congruent trials. As before, the first of these experiments is to test horizontal space, while the second is to test vertical.

Experiment 5

Horizontal Space

Methodology

Design

As with previous experimental tasks, the present work utilises a within-subjects 2x2x2 design. In addition to the manipulation of number (small/large) and probe (leftward/rightward), there was an additional manipulation of valency (positive/negative). Two parity rules (even-left; even-right) balanced for any effect of number line congruency and audible number presentation. In total, 128 trials were shown to participants. Dependent variables included non-eyetracking metrics (reaction time and accuracy rates to the parity and verification tasks) and eyetracking metrics (saccade onset and duration, first fixation duration and total gaze duration for the parity task). All participants were required to respond to every trial, which were grouped and counterbalanced by parity rule across presentation. Numbers were presented at random within blocks of testing.

Participants

In total, 25 participants (12 male) were recruited from the undergraduate population of Northumbria University, whose participation came in exchange for course credits. The average age of a participant was 23 (range = 18 – 50); all participants were of UK birth, native speakers of English, with normal or corrected-to-normal eyesight. All participants identified as right-handed, which the Short Form Edinburgh Handedness Inventory confirmed (Ransil & Schachter, 1994; average = .977).

Materials

The same recording of the numbers '1', '2', '8' and '9' used previously were, again, deployed here. Words were chosen from a normed database that catered for the spatial semantics of a verb (Meteyard & Vigliocco, 2009). The norms of the database allowed for the creation of leftward and rightward-biasing conditions, which consisted of the most representative verbs from each category. In addition to norms for valency, the database also provided norms for arousal and frequency, which were used to control the groups so that the only differences occurred due to valency. Words were initially presented in lower case for the saccade task, but in the verification task presented in uppercase. This ensured processing of the content of the word itself, and not just the maintenance of stimuli in visual working memory. Both fixation dots and target squares were created in Experiment Builder.

Procedure

All data were collected in a room with minimal lighting. Before testing, participants were briefed about the nature of the experiment (see Appendix A for the standardised brief) and asked to complete informed consent documentation (Appendix A) before answering a demographics questionnaire (Appendix C) and the Short Form Edinburgh Handedness Index (Appendix D; Ransil & Schachter, 1994). After consenting, the participant was then seated on a chair with the backrest tilted to a 110° 60cm from the screen with their head placed on an SR-Research chinrest, before being calibrated, tested and debriefed. See Figure 31 for a standard experimental trial.

All experimental trials consisted of a fixation cross presentation for 500ms followed by the visual presentation of a word for 1000ms. After the word was another fixation cross (500ms) and the probe task followed. This task had an auditory number presented alongside two lateral visual targets, which participants would saccade toward in accordance with the parity rule. The landing of a saccade triggered the offset of the saccade task and the onset of a verification task, which required participants to view a word and decide whether it is the same or different to the word seen at the start of the trial. Participants pressed a button to respond to this task, either the left (corresponding to yes) or right (corresponding to no) trigger. Depress of the button signalled the end of a trial and a 1000ms buffer period before the start of the next. Participants were given accuracy feedback immediately after saccade and verification tasking. Total testing took approximately 60 minutes.

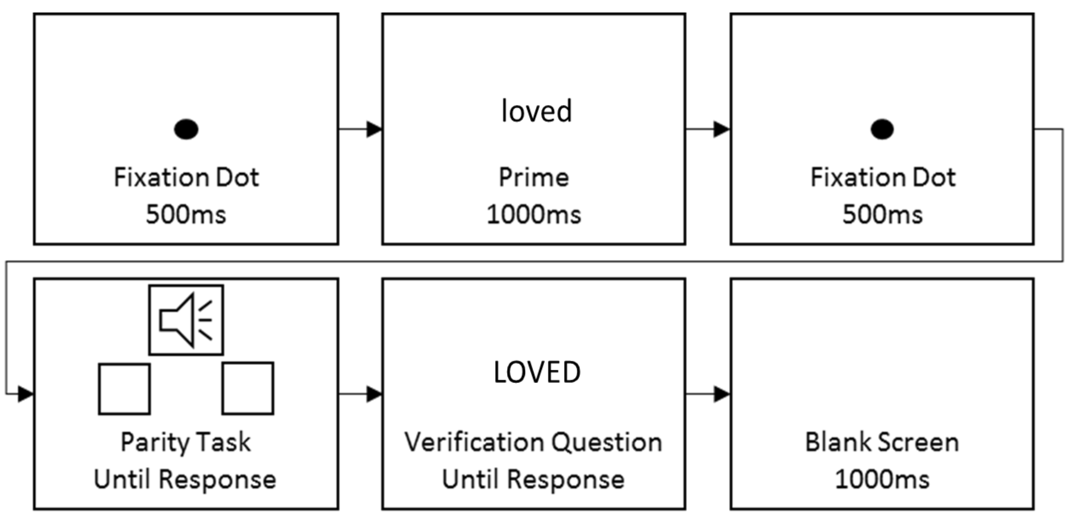

Figure 31. An example trial sequence in which the verification question is a word congruent with the prime. Note that presentation is not to scale but is used to aid clarification.

Results

The strategy discussed in the general methods section was utilised in filtering and analysing the data provided by participants. This involved, post filtering and transformation, a series of 2x2x2 ANOVAs to understand fixation, saccadic, and manual response parameters of the data.

Responses to the parity and verification task were measured using reaction time and error rates for all participants. Eyetracking data was analysed only for the saccade task, which can be further divided into fixation and saccadic metrics. A standard criterion of α was used and set to .05. Data from one participant was excluded due to not completing the experimental paradigm, and all tests were conducted on the remaining 25 participants. For the raw data, see Appendix E.

Saccade Task

Error Rate Analysis

Participants displayed relatively high levels of accuracy across the task (85.41%). Similar levels of accuracy were observed for trials containing positive (85.44%) or negative (85.38%) words, and for trials containing large (85.63%) or small (85.19%) magnitudes. For the probe response, more accurate trials were seen when answering rightward (86.13%) over leftward (84.69%). For a condition-by-condition basis, see Table 33

Table 33. Mean accuracy (%) for responses given to the saccade probe task.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	82.00	84.50	87.25	88.75	85.63
	Small	87.00	85.25	85.25	83.25	85.19
Total		84.50	84.88	86.25	86.00	85.41

Analysis of the results revealed no significant main effect of probe location (Wilks' λ = .987, f (1,24) = .324, p = .575, ηp^2 = .013), magnitude (Wilks' λ = .998, f (1,24) = .041, p = .840, ηp^2 = .002), or valency (Wilks' λ = 1.000, f (1,24) = .004, p = .951, ηp^2 < .001). Considering multiple factors, a two-way interaction was found between probe location and magnitude (see Figure 32; Wilks' λ = 795, f (1,24) = 6.176, p = .020, ηp^2 = .205). However, inferential analysis revealed neither large (p = .153) nor small (p = .450) comparisons to be significant.

No further interactions at the two-way, for probe location and valency (Wilks' λ = .998, f (1,24) = .060, p = .809, ηp^2 = .002) or magnitude and valency

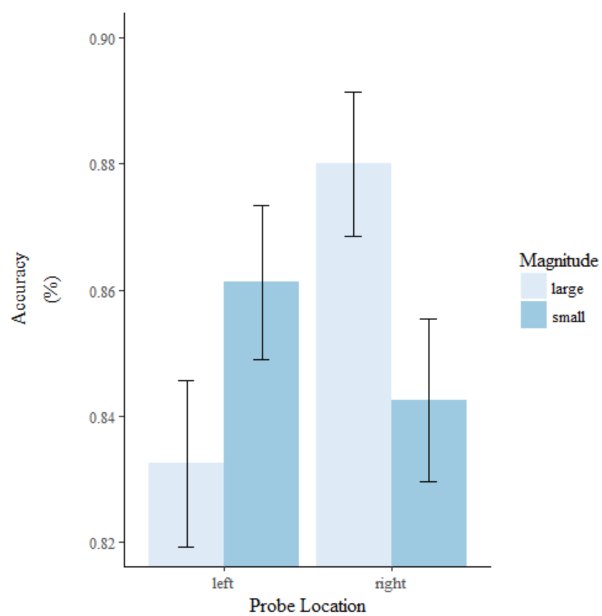

Figure 32. Depicted is the two-way interaction for probe accuracy. Here, magnitude is shown across probe location.

(Wilks' λ = .929, f (1,24) = 1.836, p = .188, ηp^2 = .071), or three-way level (Wilks' λ = .999, f (1,24) = .023, p = .881, ηp^2 = .001) were found.

Response Time Analysis

The average trial was responded to in 715.72ms. This was faster when the valency of a word was negative (703.95ms) over positive (727.67), when the magnitude experienced was small (712.60ms) over large (718.87ms), and the direction of response was rightward (715.57ms) over leftward (715.88ms). These can be seen by condition in Table 34.

Table 34. Mean and standard deviations values for the duration participants taken to respond to the saccade task conditions in milliseconds, presented in milliseconds.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	707.31 (302.84)	721.55 (324.64)	700.35 (302.82)	746.04 (348.31)	718.87 (320.43)
	Small	692.21 (319.90)	742.46 (341.22)	716.22 (326.90)	699.15 (285.32)	712.60 (319.58)
Total		699.52 (311.60)	732.16 (333.05)	708.24 (314.87)	723.16 (319.73)	715.72 (319.96)

Inferential analysis revealed a significant main effect of word valency (Wilks' λ = .820, f (1,24) = 5.283, p = .031, ηp^2 = .180), with words of negative (703.95ms) valency being responded to faster than words of positive (727.67ms). No significant main effect was found when investigating parity response (Wilks' λ = 1.000, f (1,24) = .001, p = .982, $\eta p^2 < .001$) or magnitude (Wilks' λ = .966, f (1,24) = .835 p = .370, ηp^2 = .034). At the level of interaction, no significant results were revealed at the two-way level between probe location and magnitude (Wilks' λ = .960, f (1,24) = .987, p = .330, ηp^2 = .040), probe location and valency (Wilks' λ = .986, f (1,24) = .336, p = .567, ηp^2 = .014), or magnitude and valency

(Wilks' λ = 1.000, f (1,24) < .001 p = .996, $\eta p^2 < .001$) or at the three-way level (Wilks' λ = .897, f (1,24) = 2.749 p = .110, $\eta p^2 = .103$).

Eye Movement Analysis

Fixation data.

The average duration of a participant's first fixation was 385.66ms. This was made longer after exposure to negative (383.95ms) over positive (387.39ms) words. Large (392.02ms) magnitude exposure caused longer durations of fixation than small (379.31ms) magnitudes. Finally, a leftward (356.32ms) biasing response made for shorter first fixations than right (414.75ms). Table 35 shows descriptive statistics on a conditional basis.

Table 35. Mean (and standard deviation) values for the first fixations participants made in response to the saccade task, presented in milliseconds.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	353.71 (196.12)	366.60 (205.29)	419.12 (211.99)	425.45 (214.70)	392.02 (209.46)
	Small	359.40 (183.43)	345.38 (168.43)	401.92 (205.59)	412.33 (199.85)	379.31 (191.60)
Total		356.67 (189.48)	355.97 (187.88)	410.53 (208.83)	419.12 (207.59)	385.66 (200.77)

A closer analysis revealed a significant main effect of probe location (Wilks' λ = .693, f (1,23) = 10.175, p = .004, $\eta p^2 = .307$), whereby trials that required a rightward (414.75ms) saccade resulted in longer durations of the first fixation than trials requiring leftward (356.32ms) saccades. There were no main effects of magnitude (Wilks' λ = .997, f (1,23) = .072, p = .790, $\eta p^2 = .003$) or valency (Wilks' λ = .989, f (1,23) = .225 p = .618, $\eta p^2 = .011$), nor were there any significant interactions at the two-way, for parity and magnitude (Wilks' λ = .920, f (1,23) = 2.005, p = .170, ηp^2 = .080), parity and valency (Wilks' λ = 1.000, f (1,23) < .001 p = .989, ηp^2 < .001), or magnitude and valency (Wilks' λ = .966, f (1,23) = .817, p = .376, ηp^2 = .034). At the three-way level of analysis, no significant interaction was revealed (Wilks' λ = .969, f (1,23) = .739, p = .399, ηp^2 = .031).

The total gaze duration of an average participant during the saccade task was 458.56ms. This was made longer by exposure to positive words (461.40ms) over negative (455.76ms). When exposed to large (468.66ms) over small (448.49ms) magnitudes, longer total gaze durations were found. Finally, longer durations were recorded in rightward (466.17ms) over leftward (450.89ms) biasing trials. On a condition-by-condition level, these findings can be seen in Table 36

Table 36. Mean (and standard deviation) values for the total gaze duration of participants in response to the saccade task, presented in milliseconds.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	450.12 (238.85)	469.78 (251.01)	477.81 (223.74)	475.72 (223.88)	468.66 (234.43)
	Small	446.53 (226.77)	437.30 (220.31)	448.28 (216.74)	462.56 (219.50)	448.49 (220.82)
Total		448.25 (232.46)	453.51 (236.50)	463.07 (220.59)	469.37 (221.69)	458.56 (227.89)

Through an inferential analysis, no significant main effects were found of probe location (Wilks' λ = .961, f (1,23) = .927, p = .346, ηp^2 = .039), magnitude (Wilks' λ = .968, f (1,23) = .751, p = .395, ηp^2 = .032), or valency (Wilks' λ = .974, f (1,23) = .615, p = .441, ηp^2 = .026). No two-way interactions were found between probe location and magnitude (Wilks' λ = .908, f (1,23) = 2.340, p = .140,

ηp^2 = .092), probe location and valency (Wilks' λ = .996, f (1,23) = .101, p = .754, ηp^2 = .004), or magnitude and valency (Wilks' λ = .967, f (1,23) = .782, p = .386, ηp^2 = .033). However, at the three-way level of analysis, a significant interaction was found (Wilks' λ = .827, f (1,23) = 4.808, p = .039, ηp^2 = .173). Figures 33 and 34 show visually this interaction. Further examination shows this interaction to rely upon one comparison. When shown a negative bias word and a rightward biasing probe, the total gaze duration of participants was longer when the number heard was large (477.81ms) over small (448.28ms; p = .027). The remaining comparisons were nonsignificant (negative word, leftward probe: large x small magnitude, p = .250; positive word, leftward probe: large x small magnitude: p = .257; positive word, rightward probe: large x small magnitude: p = .496).

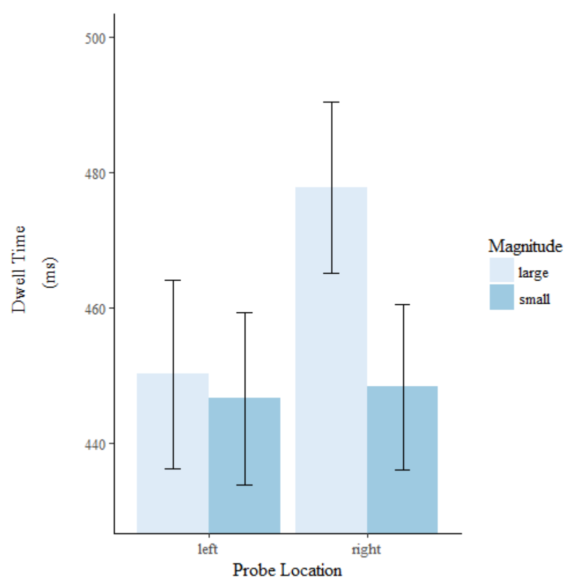

Figure 33. Depicted is one aspect of the three-way interaction for dwell time. Responses to negative word bias trials are shown across probe location and magnitude, where the total gaze duration of participants is displayed in milliseconds

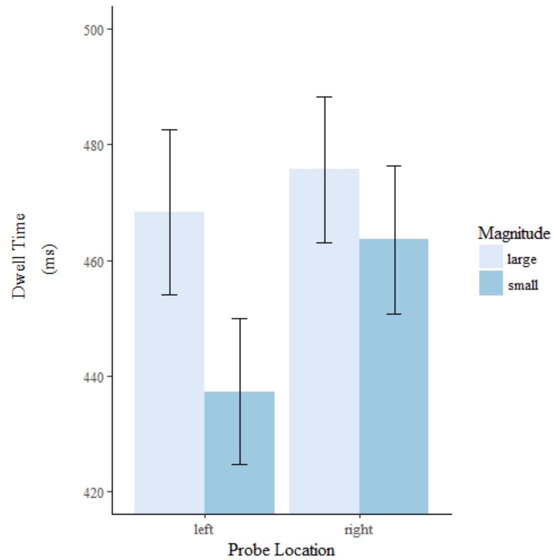

Figure 34. Depicted is one aspect of the three-way interaction for dwell time. Responses to positive word bias trials are shown across probe location and magnitude.

Saccade data.

The average time taken for a participant to onset a saccade was 682.83ms. This was made faster by negative (672.55ms) words and slower by positive (693.26ms). After hearing a large (684.68ms) magnitude, participants saccades were onset faster than after hearing a small (680.99ms) magnitude. Finally, trials requiring a leftward (683.02ms) response had saccades onset slower than those requiring rightward (682.65ms) saccades Table 37 shows these findings on a condition-by-condition basis.

Table 37. Mean (and standard deviation) values for the onset times of target-directed saccades during the saccade task, presented in milliseconds.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	674.63 (310.18)	684.32 (326.47)	663.88 (302.77)	715.47 (361.14)	684.68 (326.29)
	Small	667.77 (341.56)	705.35 (340.66)	684.15 (335.04)	666.30 (296.64)	680.99 (329.42)
Total		671.09 (326.53)	694.93 (333.61)	673.98 (319.18)	691.59 (332.04)	682.83 (327.80)

An analysis of these results shows no significant main effect for probe location (Wilks' λ = 1.000, f (1,24) < .001, p = .998, ηp^2 < .001) or magnitude (Wilks' λ = .849, f (1,24) = .483, p = .494, ηp^2 = .020). For valency, a significant main effect was lost by means of rounding to three decimal places (Wilks' λ = .849, f (1,24) = 4.264, p = .050, ηp^2 = .151). No significant two-way interactions were found for probe location and magnitude (Wilks' λ = .949, f (1,24) = 1.298, p = .266, ηp^2 = .051), probe location and valency (Wilks' λ = .999, f (1,24) = .035, p = .852, ηp^2 = .001), or magnitude and valency (Wilks' λ = .999, f (1,24) = .027, p = .871, ηp^2 = .001). At the three-way level of analysis, no interaction was revealed (Wilks' λ = .913, f (1,24) = 2.279, p = .144, ηp^2 = .087).

The duration of a target-directed saccade on an average trial was 41.73ms. Following exposure to words with a negative (41.18ms) valency, saccades were shorter in duration than following exposure to words with positive (42.28ms) valency. The same was found to be true for small (40.69ms) over large (42.77ms) magnitudes, and when trials required rightward (40.90ms) over leftward (42.57ms) responses. This can be seen at the conditional level in Table 38.

Table 38. Mean (and standard deviation) values for the duration of a participant's target directed saccade during the saccade task, presented in milliseconds.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	43.15 (22.16)	44.99 (32.85)	41.98 (22.01)	41.54 (22.01)	42.77 (25.19)
	Small	40.63 (18.74)	41.58 (19.75)	39.58 (19.76)	40.99 (22.56)	40.69 (21.05)
Total		41.85 (20.48)	43.29 (27.17)	40.54 (20.93)	41.28 (23.78)	41.73 (23.24)

Inferential analysis of saccade durations show no main effects (probe location: Wilks' λ = .965, f (1,24) = 860, p = .363, ηp^2 = .035; magnitude Wilks' λ = .852, f (1,24) = 4.167, p = .052, ηp^2 = .148; valency: (Wilks' λ = .945, f (1,24) = 1.398, p = .249, ηp^2 = .055), no two-way interactions (probe location and magnitude: Wilks' λ = .983, f (1,24) = .424, p = .521, ηp^2 = .017; probe location and valency: Wilks' λ = .993, f (1,24) = .157, p = .695, ηp^2 = .007; magnitude and valency: Wilks' λ = .999, f (1,24) = .024, p = .879, ηp^2 = .001), and no three-way interaction (Wilks' λ = .976, f (1,24) = .589, p = .450, ηp^2 = .024).

Verification Task

Error Rate Analysis

Average accuracy to the verification task was high (95.44%). When the word asked about was negative (95.81%), more accurate responses were given than when positive (95.06%). After experiencing a magnitude that was small (95.69%) more accurate answers were given compared to large (95.19%). Finally, more accurate responses were given when the location of the probe was leftward (96.00%), as compared to rightward (94.88%). A conditional breakdown of means can be seen in Table 39.

Table 39. Mean rates of accuracy (%) in response to the verification question asked to participants.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	96.00	95.50	94.25	95.00	95.19
	Small	96.50	96.00	96.50	93.75	95.69
Total		96.25	95.75	95.38	94.38	95.44

An analysis of error rates revealed no main effects for parity response (Wilks' λ = .897, f (1,24) = 2.752, p = .110, ηp^2 = .103), magnitude (Wilks' λ

= .978, f (1,24) = .532, p = .473, ηp^2 = .022), or valency (Wilks' λ = .948, f (1,24) = 1.326, p = .261, ηp^2 = .052). No two-way interactions were found between probe location and magnitude (Wilks' λ = 1.000, f (1,24) < .001, p > .999, ηp^2 < .001), probe location and valency (Wilks' λ = .995, f (1,24) = .119, p = .733, ηp^2 = .005), or magnitude and valency (Wilks' λ = .940, f (1,24) = 1.540, p = .227, ηp^2 = .060). Finally, and further, no three-way interaction was discovered (Wilks' λ = .938, f (1,24) = 1.592, p = .219, ηp^2 = .062).

Response Time Analysis

An average trial was responded within 652.28ms. This was made to be longer following exposure to positive (654.05ms) over negative (650.55) word valency. Participants were faster after experiencing trials with large (648.27ms) magnitudes over small (656.22ms). Finally, after having performed a leftward (658.71ms) saccade, participants were slower than to respond to the verification question than after having performed rightward (645.81ms) saccades. Table 40 shows this at the conditional level.

Table 40. Mean (and standard deviation) values for the time taken to respond to the accuracy verification question, presented in milliseconds.

Probe		Left		Right		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	637.10 (319.53)	677.41 (348.93)	656.57 (326.23)	621.69 (295.25)	648.27 (323.35)
	Small	649.57 (316.20)	670.66 (334.01)	658.37 (342.19)	646.01 (316.36)	656.22 (327.22)
Total		643.57 (317.62)	674.01 (341.24)	657.47 (334.09)	633.63 (305.79)	652.28 (325.27)

An inferential analysis revealed no significant main effects (probe location: Wilks' λ = .897, f (1,24) = 2.752, p = .110, ηp^2 = .103; magnitude: Wilks'

$\lambda = .982$, $f(1,24) = .432$, $p = .517$, $\eta p^2 = .018$; valency: Wilks' $\lambda = .990$, $f(1,24) = .245$, $p = .625$, $\eta p^2 = .010$), no two-way interactions (probe location and magnitude: Wilks' $\lambda = .984$, $f(1,24) = .388$, $p = .539$, $\eta p^2 = .016$; probe location and valency: Wilks' $\lambda = .854$, $f(1,24) = 4.116$, $p = .054$, $\eta p^2 = .146$; magnitude and valency: Wilks' $\lambda = .997$, $f(1,24) = .066$, $p = .800$, $\eta p^2 = .003$), and no three-way interaction (Wilks' $\lambda = .879$, $f(1,24) = 3.290$, $p = .082$, $\eta p^2 = .121$).

Discussion

The present study investigated the interplay between words with varying valency maintained in working memory and concurrently apprehended numbers of varying numerical magnitude with regard to potentially shared spatial-numerical mappings in horizontal space. In total, two interactions and two main effects were found. Of the interactions, there was one two-way (which warranted no further analysis) and a three-way. The main effects were found for probe response time and first fixation duration.

For probe response time, words with a negative valency were found to be responded to faster than positive. The first fixation duration of a participant was found to be longer in duration when responding to a rightward probe than a leftward. An interaction was found for the total gaze duration of participants following their response to the parity judgement task. This was a three-way interaction, and driven by negative words and rightward probes: when participants heard a large number, the gaze duration was longer than after hearing a small number.

To break down these findings, the result found in fixation durations acts as a strong indicator that the paradigm, and by extension the equipment used, accurately recorded data. Previous studies have found longer first fixations to emerge after rightward over leftward saccades, especially when the processing involves linguistic content (McConkie & Rayner, 1976; Paterson, McGowan, White, Malik, Abedipour & Jordan, 2014). As the task on a whole can find support for physiological results, but not for well-established psychological findings such as mental number space (Hubbard, Piazza, Pinel & Dehaene, 2005) and SNARC effect (Fias, 1996), questions are raised.

The interaction for total gaze duration provides weak support for the spatial-numerical mapping in rightward space, which resulted in longer total durations of gaze. However, interestingly, this occurred in combination with a word of negative valency as opposed to one with positive. Some previous research relates fixation durations to the relative memory load (e.g. Van Orden, Limbert, Makeig & Jung, 2001; Meghanathan, van Leeuwen & Nikolaev, 2014; Brouwer, Hogervorst, Oudejans, Ries & Touryan, 2017) and so one possibility here is that the longer durations in this study reflect similar process. If so, then it would be indicative of a task specificity effect in line with the proposal of conceptual interplay. However, others have linked gaze duration with increased attention (Unema, Pannasch, Joos, Velichkovsky, 2005; Podladchikova, Samarin, Shaposhnikov & Petrushan, 2017); if this is held to be the case, then support would be for number-space models of cognition instead. At either possibility, one comparison driving the interaction is not entirely convincing. Further research would be required to examine this in closer detail.

In terms of the main effect found for valency in probe response time, the faster processing of negative words supports previous findings based on valency-arousal models of word recognition (e.g. Robinson, Storbeck, Meier & Kirkeby 2004; Larsen, Mercer, Balota & Strube, 2008; Estes & Adelman, 2008). In an important paper, Kuperman, Estes, Brysbaert and Warriner (2014) disentangle valency from arousal and show further interactions to occur via word frequency: these manifested stronger in low-frequency words than high-frequency, with negativity predicting speed of response. The present study controlled for arousal and frequency, and so an avenue of future investigation could be found in the reanalysis of the data or rerunning of tasks with this taken into account.

While the results here are not compelling, the bigger picture is made clearer. Having advanced into a domain of greater abstraction, processing is not involving the same level of simulation as other domains, e.g. affordances (Binder & Desai, 2011). As less sensorimotor simulation occurs, there is less capacity for conceptual interplay, and so less interaction between representation. Crucially, the lack of replication effects shows there is still something manifesting, but while the degree of interaction is enough to moot effects of number, it is not strong enough to make a comprehensible or obvious interaction.

Experiment 6

Vertical Space

Methodology

Design

As before, the task comprised a within-participants, 2x2x2 design. Here, the spatial semantics of a word bias (leftward/rightward), number (small/large) and probe (upward/downward) comprised the independent variables. Two parity rules (even-left; even-right) were used to balance for any effects of number line congruency and audible number presentation. In total, 128 trials were presented to participants. Recorded were several dependent variables. Non-eye-tracking metrics included simple reaction time and accuracy rates to the saccade and verification tasks. Eye tracking metrics were only recorded for the saccade task, and included saccade measures of onset and duration, as well as fixation measures of total gaze duration and the duration of the first fixation. All participants were required to give a response to every trial, which were grouped by parity rule and counterbalanced across presentation. Numbers were presented at random within blocks of testing.

Participants

The same participants involved in the completion of Experiment 5 took part in Experiment 6.

Materials

The same materials used in Experiment 5 were used again in Experiment 6.

Procedure

The experimental procedure that was used in Experiment 5 was, again, deployed here. However, in place of a horizontal saccade response to the parity task, participants had to saccade vertical targets (see Figure 35).

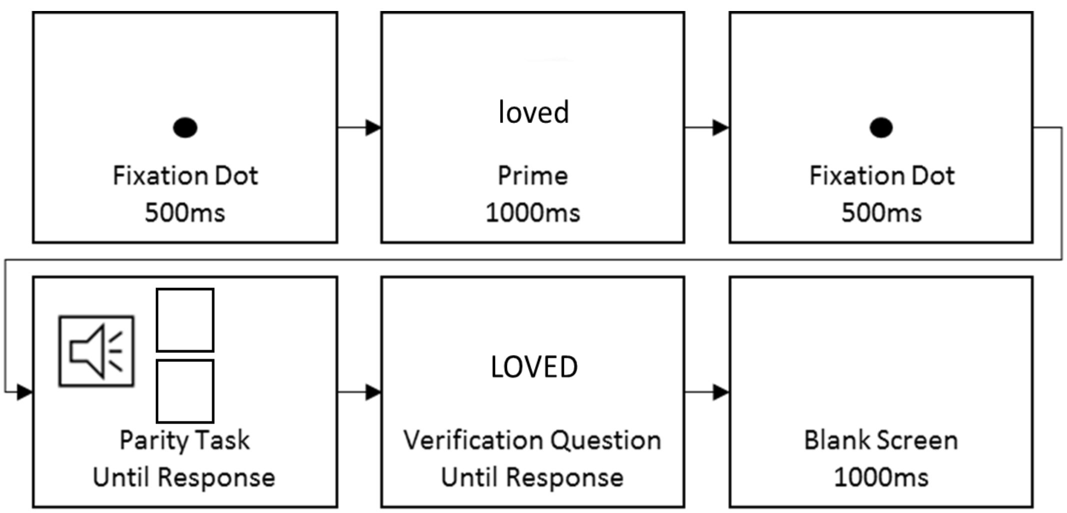

Figure 35. An example trial sequence in which the verification question is a word congruent with the prime. Note that presentation is not to scale but is used to aid clarification.

Results

The strategy discussed in the general methods section was utilised in filtering and analysing the data provided by participants. This involved, post filtering and transformation, a series of 2x2x2 ANOVAs to understand fixation, saccadic, and manual response parameters of the data.

Responses to the parity and verification task were measured using reaction time and error rates for all participants. Eyetracking data was analysed only for the saccade task, which can be further divided into fixation and saccadic metrics. A standard criterion of α was used and set to .05. Data from one participant was excluded due to not completing the experimental paradigm, and all tests were conducted on the remaining 25 participants. For the raw data, see Appendix E.

Saccade Task

Error Rate Analysis

The average rate of accuracy in the saccade task was 82.94%. Greater accuracy was observed for positive (83.81%) valency over negative (82.06). Small (83.13%) magnitudes were responded to with greater accuracy than large (82.75%). Finally, accuracy was higher in trials requiring downward (83.00%) over upward (82.88%) saccades. At a conditional level, accuracy rates can be seen in Table 41.

Table 41. Mean rates of accuracy (%) of participants in response to the saccade task.

Probe		Down		Up		Total
Valency		Negative	Positive	Negative	Positive	
Number	Large	82.25	82.75	81.25	84.75	82.75
	Small	83.25	83.75	81.50	84.00	83.13
Total		82.75	83.25	81.38	84.38	82.94

An inferential analysis revealed no significant results at main effect (probe location: Wilks' $\lambda = 1.000$, $f(1,24) = .004$, $p = .953$, $\eta p^2 < .001$; magnitude: Wilks' $\lambda = .999$, $f(1,24) = .025$, $p = .876$, $\eta p^2 = .001$; valency: Wilks' $\lambda = .870$, $f(1,24) = 3.573$, $p = .071$, $\eta p^2 = .130$), two-way (probe location and magnitude: Wilks' $\lambda = .994$, $f(1,24) = .147$, $p = .705$, $\eta p^2 = .006$; probe location and valency: Wilks' $\lambda = .942$, $f(1,24) = 1.488$, $p = .234$, $\eta p^2 = .058$; magnitude and valency: Wilks' $\lambda = .998$, $f(1,24) = .043$, $p = .837$, $\eta p^2 = .002$) or three-way (Wilks' $\lambda = .998$, $f(1,24) = .040$, $p = .843$, $\eta p^2 = .002$) interaction levels of analysis.

Response Time Analysis

On average, a response was made by participants in 717.41ms. When maintaining in memory a word with positive (715.65) valency, the time taken to respond was faster than when maintaining a word with negative valency (719.21ms). Similarly, small (715.15ms) magnitude exposure resulted in faster responses than large (719.67ms) magnitude exposure. When the required response direction was upward (713.08ms), trials were responded to faster than responses downward (721.72ms). This can be seen at a conditional level in Table 42.

Table 42. Mean and standard deviations values for the duration participants taken to respond to the saccade task conditions in milliseconds.

Probe		Down		Up		Total
Valency		Negative	Positive	Negative	Positive	
Number	Large	721.62 (304.49)	709.50 (284.16)	725.66 (354.26)	722.03 (348.00)	719.67 (323.66)
	Small	745.32 (321.07)	710.24 (298.54)	683.48 (293.86)	720.55 (328.42)	715.15 (311.40)
Total		733.53 (312.90)	709.87 (291.19)	704.43 (325.68)	721.30 (338.18)	717.41 (317.53)

A closer analysis of the data revealed no significant main effects of probe location (Wilks' $\lambda = .976$, $f(1,24) = .585$, $p = .452$, $\eta p^2 = .024$), magnitude (Wilks' $\lambda = .990$, $f(1,24) = .246$, $p = .624$, $\eta p^2 = .010$), or valency (Wilks' $\lambda = .997$, $f(1,24) = .074$, $p = .788$, $\eta p^2 = .003$). No two-way interactions were revealed between probe location and magnitude (Wilks' $\lambda = .989$, $f(1,24) = .260$, $p = .615$, $\eta p^2 = .011$), probe location and valency (Wilks' $\lambda = .889$, $f(1,24) = 3.005$, $p = .096$, $\eta p^2 = .111$), or magnitude and valency (Wilks' $\lambda = .998$, $f(1,24) = .057$, $p = .813$, $\eta p^2 = .002$). Furthermore, no three-way interaction was revealed either (Wilks' $\lambda = .923$, $f(1,24) = 1.994$, $p = .171$, $\eta p^2 = .077$).

Eye Movement Analysis

Fixation data.

The duration of an average first fixation following a target-directed saccade was 362.32ms. Positive (364.16ms) word exposure lengthened this, and negative (360.44ms) word exposure shortened it. Similarly, small (358.93ms) magnitudes made for longer first fixation durations over large (365.70ms) magnitudes. Finally, after having performed a saccade upward (388.18ms) the fixation duration was longer than after having performed a downward saccade (336.40ms). This is represented in Table 43 below, at a condition-level.

Table 43. Mean (and standard deviation) values for the first fixations participants made in response to the saccade task, presented in milliseconds.

Probe		Down		Up		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	338.78 (168.82)	335.82 (164.12)	387.91 (189.98)	399.51 (190.56)	365.70 (180.88)
	Small	331.94 (166.97)	339.04 (178.23)	384.17 (188.58)	380.77 (185.17)	358.93 (181.22)
Total		335.36 (167.79)	337.43 (171.19)	386.04 (189.13)	390.23 (187.99)	362.32 (181.04)

Analysis revealed a significant main effect of probe location (Wilks' λ = .678, f (1,23) = 10.929, p = .003, ηp^2 = .322), whereby first fixations in the upward (388.18ms) target area were maintained for longer than first fixations in the downward (336.40ms) target location. No other main effects were revealed by examination of magnitude (Wilks' λ = .886, f (1,23) = 2.950, p = .099, ηp^2 = .114) or valency (Wilks' λ = .988, f (1,23) = .276, p = .604, ηp^2 = .012). At the level of two-way interaction, no significant findings were uncovered for probe location and magnitude (Wilks' λ = .953, f (1,23) = 1.135, p = .298, ηp^2 = .047), probe location and valency (Wilks' λ = .989, f (1,23) = 1.135, p = .298, ηp^2 = .047), or magnitude and valency (Wilks' λ = .995, f (1,23) = .106, p = .747, ηp^2 = .005), nor were any interactions found at the three-way level (Wilks' λ = .902, f (1,23) = 2.504, p = .127, ηp^2 = .098).

The average total gaze duration participants made following a target-directed saccade was 418.81ms. Following a word with positive (422.83ms) valency, the average was greater than a word with negative (414.71ms) valency.

Large (422.19ms) magnitudes had a similar effect over small (415.42ms) magnitudes, with the total duration being lengthened to the former. When the saccade that had been performed was downward (402.80ms), the total gaze duration was shorter than upward (434.77ms). At a conditional level, these results are reflected in Table 44.

Table 44. Mean (and standard deviation) values for the total gaze duration of participants in response to the saccade task, presented in milliseconds.

Probe		Down		Up		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	399.34 (187.81)	402.12 (193.07)	436.55 (217.58)	450.03 (232.15)	422.19 (209.50)
	Small	396.35 (192.35)	413.36 (208.67)	427.24 (211.88)	424.77 (200.63)	415.42 (203.58)
Total		397.85 (189.93)	407.75 (200.95)	431.90 (214.61)	437.53 (217.31)	418.81 (206.56)

Analysis of these results indicated a significant main effect of probe location (Wilks' $\lambda = .831$, $f\ (1,23) = 4.689$, $p = .041$, $\eta p^2 = .169$), with the same pattern for first fixations repeating: longer total gaze durations were given to upward (434.77ms) than downward (402.80ms) targets. No further main effects were found for magnitude (Wilks' $\lambda = .985$, $f\ (1,23) = .347$, $p = .562$, $\eta p^2 = .015$) or valency (Wilks' $\lambda = .989$, $f\ (1,23) = .246$, $p = .625$, $\eta p^2 = .011$). At the interaction level, no two-way interactions were revealed for probe location and magnitude (Wilks' $\lambda = .944$, $f\ (1,23) = 1.377$, $p = .253$, $\eta p^2 = .056$), probe location and valency (Wilks' $\lambda = .987$, $f\ (1,23) = .294$, $p = .593$, $\eta p^2 = .013$), or magnitude and valency (Wilks' $\lambda = .968$, $f\ (1,23) = .752$, $p = .395$, $\eta p^2 = .032$). No three-way interaction was found (Wilks' $\lambda = .891$, $f\ (1,23) = 2.817$, $p = .107$, $\eta p^2 = .109$).

Saccade data.

The onset a participant's target directed saccade occurred, on average, at 678.94ms. Words with a negative (677.69ms) valency caused saccades to onset faster than words with positive valency (680.16ms). The same was found to be true for small magnitudes (675.71ms) over large magnitudes (682.17ms), and for trials that required upward (674.35ms) over downward (683.51ms) saccades. These descriptive statistics can be seen in Table 45 below, at a condition-by-condition level.

Table 45. Mean (and standard deviation) values for the onset times of target-directed saccades during the saccade task, presented in milliseconds.

Probe		Down		Up		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	682.12 (302.61)	679.36 (298.50)	683.06 (348.10)	684.13 (347.63)	682.17 (324.64)
	Small	701.92 (310.64)	670.45 (295.65)	642.83 (293.33)	686.41 (336.41)	675.71 (310.11)
Total		692.09 (306.59)	674.93 (296.88)	662.78 (322.01)	685.26 (341.84)	678.94 (317.41)

Through analysis, no significant main effect (probe location: Wilks' λ = .967, f (1,24) = .808, p = .378, ηp^2 = .033; magnitude: Wilks' λ = .994, f (1,24) = .143, p = .709, ηp^2 = .006; valency: Wilks' λ = .1.000, f (1,24) = .001, p = .978, $\eta p^2 < .001$), two-way (probe location and magnitude: Wilks' λ = .996, f (1,24) = .087, p = .770, ηp^2 = .004; probe location and valency: Wilks' λ = .889, f (1,24) = 2.994, p = .096, ηp^2 = .111; magnitude and valency: Wilks' λ = .998, f (1,24) = .044, p = .835, ηp^2 = .002) or three-way (Wilks' λ = .911, f (1,24) = .2.332, p = .140, ηp^2 = .089) interaction was found.

On average, the duration of target-directed saccades was 44.53ms. Longer durations were found for negative (44.86ms) over positive (44.20ms) word valencies, for small (45.60ms) over large (43.46ms) magnitudes, and for downward (48.35ms) over upward (40.70ms) saccades. This is reflected at the conditional level in Table 46.

Table 46. Mean (and standard deviation) values for the duration of a participant's target directed saccade during the saccade task, presented in milliseconds.

Probe		Down		Up		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	48.24 (42.24)	45.61 (25.31)	40.44 (19.10)	39.57 (17.53)	43.46 (27.95)
	Small	48.16 (35.70)	51.44 (47.10)	42.53 (29.65)	40.30 (20.83)	45.60 (34.88)
Total		48.20 (39.04)	48.50 (37.83)	41.50 (24.99)	39.93 (19.23)	44.53 (31.63)

An examination of saccade durations reveals a significant main effect of probe location (Wilks' λ = .646, f (1,24) = 13.128, p = .001, ηp^2 = .354), with downward (48.35ms) saccades last, on average, longer than upward (40.70ms) saccades. A further main effect was identified for magnitude (Wilks' λ = .841, f (1,24) = 4.535, p = .044, ηp^2 = .159), whereby the duration of a saccade was longer if the magnitude experienced was small (45.60ms) instead of large (43.46ms). No main effect was found in the analysis of word valency (Wilks' λ = .955, f (1,24) = 1.119, p = .301, ηp^2 = .045). At the level of two-way interaction, no significant results emerged for probe location and magnitude (Wilks' λ = .986, f (1,24) = .333, p = .569, ηp^2 = .014), for probe location and valency (Wilks' λ = .941, f (1,24) = 1.504, p = .232, ηp^2 = .059) or for magnitude and valency (Wilks' λ = 1.000, f (1,24) = .011, p = .916, ηp^2 < .001). The same was true at the level of three-way interaction, with no significant result being found (Wilks' $\lambda = .989$, $f(1,24) = .267$, $p = .610$, $\eta p^2 = .011$).

Verification Task

Error Rate Analysis

Participants were accurate in response to the verification task 95% of the time. This was higher following positive word exposure (95.31%) and lower following negative (94.69%). After hearing a large (95.31%) magnitude number, participants responses were more accurate than after hearing a small (94.69%) magnitude number. Finally, participants were more accurate after having performed downward (95.25%) over upward (94.75%) saccades. A breakdown by condition of accuracy rates can be seen in Table 47.

Table 47. Mean rates of accuracy (%) in response to the verification question participants were tasked with answering.

Probe		Down		Up		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	95.00	95.50	94.75	96.00	95.31
	Small	95.50	95.00	93.50	94.75	94.69
Total		95.25	95.25	94.13	95.38	95.00

For the error rates observed during the verification question, no significant results were found at either main effect (probe location: Wilks' $\lambda = .975$, $f(1,24) = .606$, $p = .444$, $\eta p^2 = .025$; magnitude: Wilks' $\lambda = .977$, $f(1,24) = .558$, $p = .462$, $\eta p^2 = .023$; valency: Wilks' $\lambda = .941$, $f(1,24) = 1.500$, $p = .233$, $\eta p^2 = .059$) two-way interaction (probe location and magnitude: Wilks' $\lambda = .980$, $f(1,24) = .480$, $p = .494$, $\eta p^2 = .020$; probe location and valency: Wilks' $\lambda = .975$, $f(1,24) = .615$, $p = .440$, $\eta p^2 = .025$; magnitude and valency: Wilks' $\lambda = .992$, f

(1,24) = .194, p = .664, ηp^2 = .008), or three-way interaction (Wilks' λ = .994, f (1,24) = .133, p = .718, ηp^2 = .006) levels of analysis.

Response Time Analysis

It took a participant, on average, 645.69ms to respond to the verification task. When the task asked about words with a positive (646.07ms) valency, a longer response time was observed in comparison to words with negative (645.30ms) valency. Small (647.55ms) magnitudes were also responded to slower than large magnitudes (643.84ms). Finally, after having performed a downward (637.50ms) saccade, participants were faster in responding to the verification task than after having performed an upward (653.91ms) saccade. This is seen at a condition-by-condition level in Table 48 below.

Table 48. Mean (and standard deviation) values for the time taken to respond to the accuracy verification question, presented in milliseconds.

Probe		Down		Up		*Total*
Valency		Negative	Positive	Negative	Positive	
Number	Large	620.66 (287.53)	642.34 (304.27_	669.45 (319.57)	643.05 (323.17)	643.84 (309.14)
	Small	626.97 (286.21)	660.10 (335.86)	665.30 (332.12)	639.12 (319.31)	647.55 (318.70)
Total		623.85 (286.65)	651.19 (320.26)	667.41 (325.53)	641.08 (320.99)	645.69 (313.89)

Analysis of reaction times to the verification question revealed no significant main effect of probe location (Wilks' λ = .926, f (1,24) = 1.907, p = .180, ηp^2 = .074), of magnitude (Wilks' λ = .967, f (1,24) = .817, p = .375, ηp^2 = .033), and no main effect of valency (Wilks' λ = .999, f (1,24) = .032, p = .859, ηp^2 = .001). At the two-way interaction level of analysis, a significant finding was revealed between probe location and valency (Wilks' λ = .829, f (1,24) =

4.941, p = .036, ηp^2 = .171). This interaction can be seen in Figure 36. This interaction was motivated by the difference between negative words and probe location (p = .017), with downward (623.85ms) probes provoking faster responses than upward (667.41ms) probes. The differences between positive words and probe location did not affect the interaction significantly (p = .512). No further interactions were found between probe location and magnitude (Wilks' λ = .997, f (1,24) = .082, p = .777, ηp^2 = .003) or magnitude and valency (Wilks' λ = .998, f (1,24) = .058, p = .812, ηp^2 = .002), nor was any interaction found at the three-way level of analysis (Wilks' λ = 1.000, f (1,24) = .011, p = .918, ηp^2 < .001).

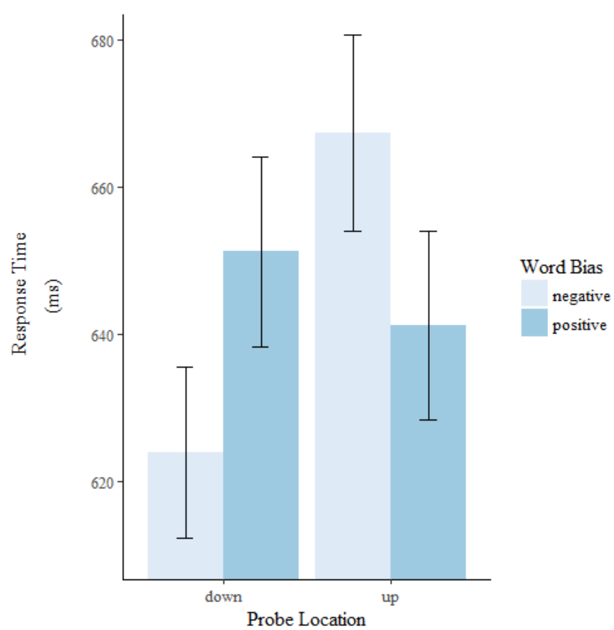

Figure 36. Depicted is the two-way interaction for verification task response time. Here, word bias is displayed across probe location, where response time is displayed in milliseconds.

Discussion

The present study investigated the interplay between words with varying valency maintained in working memory and the concurrently apprehended numbers of varying numerical magnitude with regard to the potentially shared spatial-numerical mappings in vertical space. Analysis revealed a single interaction and four main effects. The interaction was found in verification response times and indicated faster responses when the word was negative and the probe location downward than when the word was negative and the probe location upward; there were no differences in the processing of positive words. The main effects were found in fixation-related measures – first fixation durations and total gaze durations – as well as in the saccade durations. First fixation durations show longer first fixations when the target was upward over downward, which was echoed in the finding for dwell times. The analysis of saccade duration shows effects for probe location and magnitude: When the target participants responded to was downward, saccades lasted longer than when the target was upward. After hearing small magnitudes, saccades lasted longer than after hearing large magnitudes.

The effects of first fixation duration and total gaze duration are complimentary, showing that following an upward target directed saccade participants maintained the first fixation, and the sum of subsequent fixations, in the target region longer than when the target directed saccade was downward. This finding is expected. The vertical asymmetry found in previous studies for saccade latencies shows upward responses to be initiated faster than downward responses (Abegg, Pianezzi & Barton, 2015; Tzelepi, Laskaris, Amditis &

Kapoula, 2010). So, following a saccade upward, participants will take longer to prepare a return saccade to centre as it is a *downward* movement. However, following downward saccades, participants are preparing a return saccade *upward*, which can be programmed and performed faster. Because of the added delay in upward space, longer fixations are observed than in downward space. This is, to a degree, reflected in saccade durations as participants are seen to make movements that are longer in duration when going downward as opposed to going upward.

Interestingly, a main effect of number was also found in saccade durations, though here saccades initiated after hearing small magnitudes lasted *longer* than saccades initiated following large magnitudes. This is unexpected, and further research would be required in order to understand exactly why this result is found. Saccades have been shown to compress time, space and number (Burr, Ross, Binda & Morrone 2010), and so a delay in processing is an indicator of confusion. The question is, then, what is the cause of the confusion. The main effect observed does not fit with current models of mental number space, and any argument that could be made would be much more compelling if probe location and numerical magnitude interacted, which they did not.

The present study failed to replicate some existing findings, with no support being found for the SNARC effect (Fischer, 2003). However, support can be seen for conceptual metaphor accounts of valency processing (Lakoff & Johnson, 1980), insofar as the interaction supports “bad is down” but not “good is up”. To a degree, this is a refutation of accounts of polarity (Lakens, 2012; see also: Lynott & Coventry, 2014) as according to this hypothesis stronger responses should be in polar-positive domains. This interaction occurred in response to the verification question, which is once again a top-down measure of cognition as opposed to a bottom up.

There is perhaps less support seen here than displayed for the horizontal domain in the previous study. Again, this is not necessarily a negative. Every result is informative, and often the lack of a finding is as important as an effect or interaction found. Here, previous research has been supported by the study, though ones pertinent to the hypothesis have not. There are a number of potential explanations for this, though the consistency of results here suggests it is a matter of complexity and not practicality. Abstraction appears to dilute conceptual interplay.

Chapter Summary

The present study investigated the interplay between magnitude-related features of words with varying valency maintained in working memory and concurrently apprehended numbers of varying numerical magnitude with regard to potentially shared spatial-numerical mappings in horizontal and vertical space.

Absence of the normal is presence of the abnormal, and this chapter acts as an exemplar. Here, support for conceptual interplay is of a different nature to the previous two experimental chapters. In total, three interactions, one of which was deemed to be unreliable, were found along with six main effects.

Of the two studies conducted, the least support can be found in the vertical domain. This is not unexpected, as empirical and theoretical evidence suggest this should be the case. Vertical space has been argued as a less embodied and situated domain than horizontal space (Myachykov, Scheepers, Fischer & Kessler, 2014). Being the most abstract of the examined topics, there is a case to be made for interplay in valency being weaker as processing doesn't necessitate as rich and embodied simulations as spatial semantics and affordances do.

All the main effects observed in vertical space act as replications of previous physiological findings, except for a main effect found for magnitude in saccade durations. This is an interesting finding, and not accountable by any theories discussed at present. Stranger still, however, is the lack of strong support for any number-related effect, and only weak support for conceptual metaphor effects. It is strange not to observe an interaction between magnitude and probe location, but perhaps this is due to effects of number being polluted by the presence of valency.

In terms of the horizontal domain, the main effect of valency for probe response time provides an interesting avenue for future research. While words were controlled for frequency and arousal, it is possible that an extraneous component had an effect upon participants. This is not a compelling argument however, as for these studies the same words were used in horizontal and vertical space. For this to be a substantial claim, it would be expected that the same effect would emerge for vertical parity response time, too.

At the three-way level, the studies reported in this chapter provide some ground for interplay between concepts, but the overall pattern is not as consistent as could be expected. Here, large magnitudes were responded to faster than small magnitudes when the response required was rightward and the word maintained in memory was negative. Large magnitude and rightward space is a complimentary domain, and also the only domains important to the parity response task. The argument could be made that the interaction is primarily related to the number-space congruency, but this does not explain why it isn't observed irrespective of wordbias. Additionally, some have argued that longer fixation durations (by extension, total gaze durations) reflect a greater load in working memory (Brouwer, Hogervorst, Oudejans, Ries & Touryan, 2017) and if this standpoint is adopted here then performance is actually hindered. One possibility is that the lack of compatibility between word bias and magnitude heard leads to the confusion and additional load on memory, which is perhaps the most convincing of arguments to be made. This would additionally support the suggestion of interplay between concepts that is presented in this thesis.

Importantly, both studies replicate previous research. In the vertical domain, the interaction seen between valency and probe location partially supports conceptual metaphor accounts of cognition (e.g. Lakoff & Johnson, 1980). In addition to this, both horizontal and vertical domains find asymmetries in fixation durations (for example, McConkie & Rayner, 1976). Were the present tasks not to support anything, then the findings would be suspect. Instead, a strongly supported physiological measure, and a strongly supported psychological measure replicate, which only serves to strengthen the question of *why* other effects, such as the SNARC (Wood, Willmes, Nuerk & Fischer, 2008) and, more broadly, polarity (Lakens, 2012) and other aspects of conceptual metaphor theories (Amin, Jeppsson & Haglund, 2015) do not. One possible explanation is task demands. It may be that interplay occurs, but not to the extent that significant results emerge.

Of course, a possible explanation for the lack of observed effects is the number of trials per participant. However, at this level it is primarily a limitation of the database used as opposed to an experimental issue. The hypothesis tested is novel, and these studies provide a reference point for later work.

Here, then, there is certainly a muted response when compared to the findings from spatial semantics and affordance domains. The framework of the thesis is so that this is the most abstract of all the experiments. Indeed, it is this abstraction that is suggested as being the primary reason for the lack of interplay between concepts in manner as rich as was seen for the other experimental domains.

The following chapter begins the general conclusions of the thesis. It will start with a breakdown and comparison of effects observed across studies before leading into a more general discussion of the overarching implications of the thesis. Reference will be made to the concepts discussed in the introduction, findings in support and not in support of conceptual interplay, and suggestions for moving forward from here, including future research.

CHAPTER SIX

General discussion

The objective of this thesis was to offer a theoretical proposal showing how knowledge representations may interact during co-activation by means of a conceptual interplay. In support of this a set of six empirical studies was offered. These experiments covered concepts that belonged to the domains of number (all studies), manual affordances (1 and 2), spatial semantics (3 and 4), and valency (5 and 6).

Experimental results cover a spectrum of abstraction, providing an overview as to how representations interact at differing levels of abstraction from the environment and body. For Manual Affordances, it was hypothesised that grasp size and object representations, stored in memory, lead to the establishment of attentional SNARC effects during auditory number processing. At the level of spatial semantics, the specific hypothesis was that words with explicitly associated spatial semantics, stored in memory, would lead to the establishment of an attentional SNARC effect during auditory number processing. Finally, the hypothesis for valency was that words with associated emotional biases, stored in memory, would lead to the establishment of attentional SNARC effects during auditory number processing. Strongest support for the conceptual interplay proposal came from the domain of spatial semantics and, to a lesser extent, support was also seen in the domains of manipulation affordance and valency. Figure 37 revisits the abstraction pipeline to detail where, in relation to other areas studied, one domain sits.

The following chapter begins the conclusions of the project and does so by recapitulating the results from each area before discussing the main findings in context of support for and limitations of conceptual interplay. Following this are future directions for research, and finally some closing remarks are presented for overall consideration.

Summary of Results

Here, reviewed briefly are the main findings from the thesis, as well as convenient displays that categorise them in terms of support for conceptual interplay and existing literature. In total, 32 main effects and interactions were found. Of these, seven interactions were deemed to provide nothing of further interest. Of the remaining results, three were three-way interactions, six were two-way interactions, ten were main effects of probe, three were main effects of

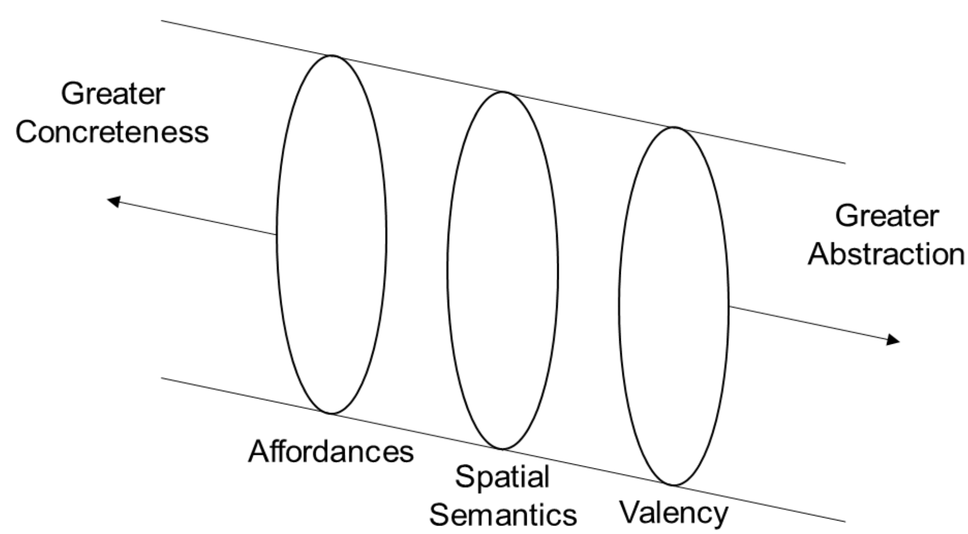

Figure 37. The abstraction pipeline. A reference image used to indicate how concrete, in comparison to the other topics of the thesis, a given section is. Note number is not indicated, as it is used as a tool across all experiments.

magnitude, two were main effects of spatial semantics, and one was a main effect of valency.

Volumetric Affordances and Numerical Magnitude

Participants were required to maintain in memory the identities of objects of varying grasp volume, listen to numbers of varying magnitude, and then direct eye movement toward one of two targets located on a screen in horizontal (experiment 1) and vertical (experiment 2) space. From these experiments eight results emerged: three main effects (vertical), and three interactions of interest (two horizontal, one vertical). Two reactions were deemed to be of no further interest (horizontal).

One interaction was three-way, found in horizontal space, and showed large magnitudes to evoke longer saccade durations than small – but only when participants maintained in memory a precision-grip object and performed a leftward saccade. The remaining interactions were two-way. One was observed in horizontal space the verification response latencies. When participants maintained in memory power-grip objects, and had just performed a rightward saccade, responses were slower than when the saccade performed was leftward. The final interaction was in vertical space for probe response and showed participants to be faster at responding when a large magnitude was presented and the response was upward over downward.

For main effects, all three were observed in vertical space, and were for probe location. Both probe response time and saccade onset, upward targets were responded to faster than downward. In probe accuracy rates, upward targets were responded to more correctly than downward targets. See Table 49 for a representation of findings.

Table 49. Overview of interactions, main effects, and unreliable results found across experiments one and two. Non-significant results are omitted.

Main Effect	Interaction	Unreliable
Vertical – Probe Accuracy	Horizontal – Saccade Duration (Three-Way)	Horizontal – Probe Reaction Time
Vertical – Probe Response Time	Horizontal – Verification Response Time (Two-Way)	Horizontal – Saccade Onset
Vertical – Saccade Onset	Vertical – Probe Response Time (Two-Way)	

All the main effects listed support existing literature. Polarity processing accounts rely upon positive polar endpoints to elicit faster responses than negative polar endpoints (Lakens, 2012; also, Lynott & Coventry, 2014). This is useful, as it shows the equipment utilised works in the manner intended. Given the seriousness of replicability, and the so-called replicability crisis facing cognitive science, this is an important finding (Francis, 2017; Zwaan et al., 2017; Martin & Clarke, 2017). Were no interplay occurring between concepts, replication should be the default finding. After all, given the support for SNARC (Hesse & Bremmer, 2017; Fias, 2006; Fischer, 2003) and affordance (Oztop & Arbib, 2002; Borghi, 2005; Detry et al., 2011) effects, the emergence of similar findings is expected. In vertical space, this is partially true as faster responses were seen in upward space for large magnitudes. However, no bias was found for small magnitudes. This extends the polarity correspondence (Lakens, 2012) hypothesis to the processing of numerical magnitudes.

In horizontal space, the findings tell a different story. Here, an interaction was found in the verification task data that shows interference; that is, slower responses when participants are questioned about power-grasp objects after having just performed a rightward saccade. Another interaction for saccade duration supports this, but also incorporates the processing of number. Here, when participants maintain precision grasp objects and are required to saccade leftward, large magnitudes are faster than small. One possible explanation for the marked interference in response is top-down processing vs bottom-up processing. Previous research showed attention to function in radically different ways dependent on whether it is focussed by volition (e.g. Chapman & Myachykov, 2015; Buschman & Miller, 2007; Connor, Egeth, Yantis, 2004). As both tasks require the conscious maintenance in memory of a parity rule (e.g. "look left if the number is odd; look right if the number is even") and an object concept with a specific affordance profile (power vs precision), it could be argued that the bottlenecking of attention is due to top-down attentional control. This is only a convincing argument for the interaction observed in saccade durations, as all three manipulated factors contribute to the interference, whereas in verification response time it is only object affordance and probe location. As participants are only required to utilise the number during the parity task, one possibility is that it becomes divorced from attention before the verification task, and so only probe location and affordance remain at the bottleneck (see Figure 38). This is certainly the most reasonable of explanations, but research has reported on the flexibility of SNARC and magnitude effects (Alards-Tomalin, Earley, Leboe-McGowan &

Leboe-McGowan, 2013; Fischer, 2012), which means this result needs greater disentangling in order to be fully understood

Both interactions show a slowdown in processing that is not mirrored in vertical space. Because of this, it can be suggested that the processes governing horizontal and vertical dimensions do not fully overlap. What is crucially missing from this domain are any effects or interactions involving affordance. This can be, at least partially, understood by means of domain's nature. When utilising manipulation affordances to control tools, two axes are principally used. The first is horizontal, the second - egocentric. This is not removing entirely the vertical domain but acknowledging that its role is much lesser than that of the distance. Because of this, there may not be enough affordance content activated for bottlenecking to occur. Indeed, research has shown irrelevant features not to cause interference when the contents of visual attention and working memory interact (Olivers, Meijer & Theeuwes, 2006).

TEST suggests a hierarchy of knowledge representations and distinguishes between knowledge that is situated (i.e. based in the context in which it was encoded and retrieved), embodied (i.e. body-based) and tropic (i.e.

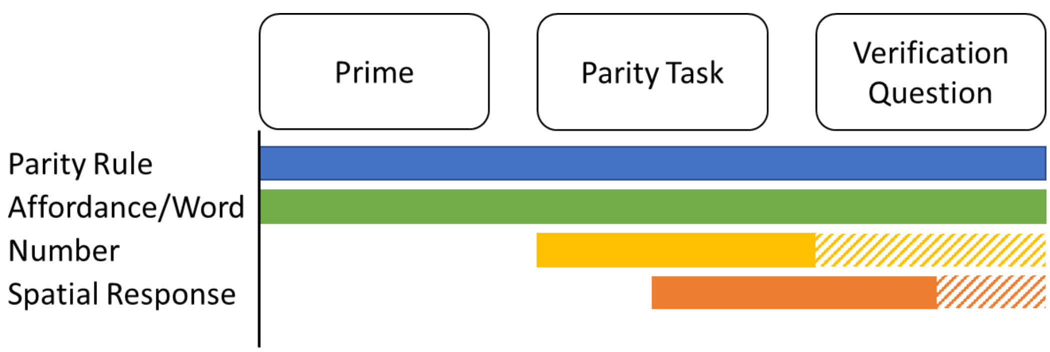

Figure 38. Shown are the components maintained in memory across various timepoints during a trial. The hashed areas for number and spatial response display potential timeperiods in which they may no longer be maintained in memory. Note that fixation dots are purposefully omitted

environment-based). According to this taxonomy, effects of magnitude are tropic in vertical space, which is to say learned from experience within the world. In horizontal space, magnitude is embodied and dependent upon bodily abilities. For affordances, however, if it is considered as a situated representation, then it is not something that will become significantly activated enough to clog up attention.

Spatial Semantics and Numerical Magnitude

Participants were required to maintain in memory the identities of words with varying spatial semantics, listen to numbers of varying magnitude, and then direct eye movement, following a parity rule, toward one of two targets located on a screen in horizontal (experiment 3) and vertical (experiment 4) space. From these experiments 15 results emerged: four interactions providing little upon further decomposition (two horizontal, two vertical), seven main effects (three horizontal, four vertical), and four interactions of note (three horizontal, one vertical).

One of the interactions was three-way, found in vertical space, and motivated by two contrasts. Response accuracy in the verification question performance was greater in both cases when numbers with large magnitudes were manipulated over small. The first contrast found higher accuracy when the probe had required an upward response and the word being questioned about was downward biasing. The second contract found the opposite: when the probe had required a downward response, accuracy was significantly improved when the direction implied by the word was upward. The remaining three interactions were two-way and found in horizontal space. For the participant error rates during the parity task, it was found that participants had greater accuracy when the response required was leftward and magnitude of the number experienced was small. For the onset time of saccades, rightward responses were faster than leftward when large magnitudes were maintained in memory. For the verification task error rates, participants responded more accurately when questioned about words with leftward biases after having heard small magnitudes over large.

Main effects of probe occurred in the horizontal task (once) and the vertical task (twice). In horizontal space, rightward probe locations resulted in longer first fixation durations than leftward. In vertical space, for probe response and saccade onset times, upward targets were reacted to faster than downward. Two effects of magnitude were found, for both task verification error rates. Here, in horizontal space responses to small magnitudes were more accurate than to large magnitudes. In vertical space, responses to large magnitudes were more accurate than to small magnitudes. Finally, two main effects of word's spatial semantics were found, both in verification task error rates. In horizontal space, when the word had a rightward bias, participants were more accurate. In vertical space, words with a downward bias were associated with more accurate responses. See Table 50 for a representation of findings.

Table 50. Overview of interactions, main effects, and unreliable results found across experiments three and four. Non-significant results are omitted.

Main Effect	Interaction	Unreliable
Horizontal – First Fixation Duration	Vertical – Verification Accuracy (Three-Way)	Horizontal – Probe Response Time
Horizontal – Verification Accuracy	Horizontal – Probe Accuracy (Two-Way)	Horizontal – Saccade Duration
Horizontal – Verification Accuracy	Horizontal – Saccade Onset (Two-Way)	Vertical – First Fixation Duration
Vertical – Probe Response Time	Horizontal – Verification Accuracy (Two-Way)	Vertical – Saccade Duration
Vertical – Saccade Onset		
Vertical – Verification Accuracy		
Vertical – Verification Accuracy		

All observed main effects of probe corroborated the polarity correspondence hypothesis (Lakens, 2012), which is to say the main effects for first fixation duration in horizontal space, and in vertical space saccade onset and parity task response time. Interestingly, for magnitude, there were contradictory effects in vertical and horizontal space for verification accuracy questions. It is important to stress that numerical magnitude did not affect performance in the verification task, which asked the participant a question about the word being maintained in memory. In vertical space, large magnitudes produced more accurate responses than small, the reverse being true for the horizontal task. In both vertical and horizontal tasks, an additional effect of word bias was observed, whereby rightward biasing words were more accurate than leftward, and downward biasing words more accurate than upward. Both effects indicate an opposite finding of those found for magnitude, and findings collectively reflect the existence of an interaction. These interactions encourage caution in the interpretation of main effects.

For horizontal space, the driving force behind the interaction was leftward word bias: when coupled with small magnitudes more accurate responses were found than when coupled with large, even though there was no role for magnitude in the verification task. This shows a facilitation effect, at least for small numerical magnitudes, in line with conceptual interplay hypothesis, though it is not expressed as it was predicted as it lacks a spatial component. One reason for this may be the task and the experimental design implemented in the study. At the level of experimental design, there is no need to maintain spatial response in memory, nor does the task require processing beyond the level of launching a saccade. And so, at the task level, there is little space for spatial information to affect responses. Unlike the parity task, which sees all three factors either maintained in memory or processed, the verification task focuses solely upon the word that was maintained in memory and, potentially, the mental trace of number that became activated and processed during the parity task. This provides an interesting avenue for future research, which will be explored further later in the chapter. While it's possible that the number representation may have decayed somewhat before and during completion of the verification task, research shows effects of number to relatively long lived and robust to persist into verification task given the time-course (e.g. Fischer, Mills & Shaki, 2010; Kiesel & Vierck, 2009; Yamamoto, Sasaki & Watanabe, 2016).

However, the interaction in vertical verification error rates *does* involve probe location, which can be taken to echo the need for levels of representation (e.g. TEST; Myachykov, Scheepers, Fischer & Kessler, 2014). While horizontal space shows facilitation, vertical space shows interference. This is a novel and very important finding. For verification error rate, the three-way interaction was shown to rely upon two contrasts. Firstly, when participants were maintaining in memory a downward biasing word, after having heard a large magnitude number and responded to an upward probe, their responses were more accurate than after having heard small magnitudes. Secondly, when maintaining in memory an upward biasing word, and after having heard a large magnitude number and responded to a downward probe, participants' responses were more accurate than after having heard a small magnitude number. It is important to be mindful that the task requirement here is word recall, as participants are asked whether the word maintained in memory is the same as one presented onscreen. One possibility for this effect is that attention may become bottlenecked in wholly magnitude-congruent trials. This means that, by maintaining in memory a word with an upward bias, a large magnitude, and having performed an upward saccade the attentional capacities of a participant become overloaded. Common coding theory (Prinz, 1990) supports existence of such mechanism as similar codes would be queued or shared in attention during processing leading to memory traces that are not as strong (e.g. Navon & Miller, 2002; Marois & Ivanoff, 2005; Sigman & Dehaene, 2006). The interaction is even more interesting as word bias in the first contrast is opposite to the bias of number and probe location; the word in the second contrast is opposite only to probe location. So, the bottleneck, or lack thereof, appears to be non-specific, that the nature of the components in memory do not have to be relevant to the task, only that there are not too many instances of a given magnitude.

With this stated, another, simpler possibility is that experiencing a large magnitude increases awareness. However, other experiments fail to replicate a similar effect. There is, at the same time, literature supporting such a position (Jaśkowskí & Włodarczyk, 2005; 2006; Guoliang & Yan, 2007), and so it would be wrong not to entertain this stance. Response has been shown to be dependent upon the arousal level of participants, which can be modulated by magnitude (e.g. Vierck & Kiesel, 2010). In this instance, if large magnitudes are taken to increase levels of arousal, then greater levels of accuracy can be explained by participants being more vigilant. However, as the design of the current study was fully balanced, this argument does not explain why a general effect of large magnitude was not observed, nor why effects of small magnitudes being more accurate than large have been observed. As such, attentional bottlenecking by means of conceptual interplay is taken to be the most likely mediator of this interaction.

Finally, two interactions at the two-way level show support for SNARC-like effects in horizontal space. In parity task error rates, small number and leftward probes resulted in more accurate responses than small number and rightward probes. For saccade onset latencies, large magnitude and rightward probes were shown to be faster than large magnitude and leftward probes. This shows an *accuracy* advantage for small magnitude, but a *speed* advantage for large magnitude. The speed-accuracy trade-off is a well-documented effect in psychology in which accuracy can be sacrificed for the benefit of a faster response (e.g. Reed, 1973; Wickelgren, 1977; Thura, Huberman & Cisek, 2017). In the literature, studies have failed to find a speed-accuracy trade-off in the SNARC effect (e.g. Shaki & Petrusic, 2005; Bachot, Gevers, Fias & Roeyers, 2005; Patro & Shaki, 2016), which prompts questions as to why one is found in the current task. Traditionally, speed-accuracy trade-off refers to participants consciously sacrificing accuracy for faster responses. In the context of this task, however, it is more likely that this is an implicit biasing as a necessary side effect of processing magnitude. If it is accepted that there is little lag between processing the content of fixations and saccades, then due to the initial auditory processing of magnitude, and because of the novel nature of the response, participant eye movements reflect a unique case of attention-guided response. This interpretation is in line with the eye-mind hypothesis of Just and Carpenter (1980) and suggests the existence of a new type of speed-accuracy trade-off in horizontal space that is material-based as opposed to participant. One mechanism by which this may work is through subitizing small numerosities, which is viewed in the literature as being different to large numerosity processing (e.g. Ansari, Lyons, van Eimeren & Xu, 2007).

Valency and Numerical Magnitude

Participants in this block of studies were required to maintain in memory the identities of words with varying valency, listen to numbers of varying magnitude, and then direct eye movement toward one of two targets located on a screen in horizontal (experiment 5) and vertical (experiment 6) space. From these experiments nine results emerged: one interaction that provided little upon decomposition (vertical), six main effects (two horizontal, four vertical), and two interactions of note (one horizontal, one vertical).

One of the interactions was three-way, found in horizontal space for participant's total gaze durations. In this case, when participants maintained in memory a negative word and had to perform a rightward saccade, large magnitudes resulted in longer total gaze durations than small. Another interaction found was two-way, located in the vertical task, and found for the verification task response times. When participants were questioned about a negative word that was maintained in memory, downward probes were faster than upward.

Four of the main effects found for valency were related to probe location. Of these, three were in vertical space and one was in horizontal. Of the vertical results, for first fixation duration and total gaze durations, upward probes resulted in longer durations than downward. For saccade duration, however, downward probes had longer durations than upward. In horizontal space, for first fixation duration, rightward probes have longer fixation times than leftward. One of the main effects was found in vertical space for magnitude. Participants that had heard small numbers had longer saccade duration. Finally, a main effect was found for word bias in the horizontal task. Words with a negative bias had faster response times to the parity task than words with a positive bias. See Table 51 for a representation of findings.

Table 51. Overview of interactions, main effects, and unreliable results found across experiments five and six. Non-significant results are omitted.

Main Effect	Interaction	Unreliable
Horizontal – Probe Response Time	Horizontal – Total Gaze Duration (Three-Way)	Horizontal – Probe Accuracy
Horizontal – First Fixation Duration	Vertical – Verification Response Time (Two-Way)	
Vertical – First Fixation Duration		
Vertical – Total Gaze Duration		
Vertical – Saccade Duration		
Vertical – Saccade Duration		

These results present an interesting contrast both within and between tasks. Like in previously described experiments, support was found for polarity correspondence (Lakens, 2012) insofar that first fixation durations and total gaze durations in the vertical task, and first fixation durations in the horizontal task, found times increased for polar-positive points (upward; rightward). However, for saccade durations in vertical space the opposite was true, with downward saccades lasting longer than upward saccades. This is interesting, as physiologically upward saccades have been documented as being of longer duration (Collewijn, Erkelens & Steinman, 1988). What makes this effect so difficult to interpret is that it is a main effect of probe. It is a purely-location based response, and so needs to be explored further to understand it fully. An additional main effect observed in vertical saccade duration was for magnitude, with small magnitudes leading to longer saccades than large. However, these did not interact, which would make for a much more understandable interpretation. One follow-up analysis that could help would be the examination of saccade launch and land coordinates as this disentangles further the effects observed.

In the horizontal domain a main effect for word meaning was found: maintaining in memory a negative valency word resulted in faster responses during the parity response task than words with positive valency. This appears to contradict recent work, which shows negative words to elicit slower responses. This is due to what the authors term, *automatic vigilance* (Estes & Adelman, 2008; Adelman & Estes, 2013). In their task, a delay in processing for negative words was independent of factors such as arousal; though both positive and negative words were more accurately recalled than neutral words. Slower response to negative stimuli than to positive stimuli indicated presence of automatic vigilance (see also Pratto & John, 1991; Algom, Chajut & Lev, 2004; Wentura, Rothermund & Bak, 2000). The radical difference between their task and the current project is the orientation of attention: here, participants match a word displayed visually to the one that is already maintained in memory. When the word in memory is negative, and after having made a downward response, automatic vigilance and the associated spatially-congruent bias from downward space combines to facilitate processing.

Interestingly, this interaction was not present in horizontal space, emphasising again a need for distinction between representations that are embodied (vertical) and situated (horizontal; Myachykov, Scheepers, Fischer & Kessler, 2014). Instead, observed here was a three-way interaction for total gaze duration. This interaction is like the observed three-way interactions in other experiments, insofar as it appears motivated by large magnitudes, and the affected conditions avoid any bottlenecking of memory. In this instance, a negative word and rightward probe locations resulted in longer total fixation durations when the magnitude was large over small. This proves for an interesting contrast across studies. For spatial semantics and affordance processing tasks, there was an increase in verification task accuracy and a decrease in parity task saccade durations. These indicate faster processing, whereas longer total fixation durations have been suggested as both indicative of greater attention (Igarashi, Suzuki, Sugita, Kurisu & Kakikura, 2006) and greater confusion (Roy-Charland et al., 2012). If the former is accepted as an explanation, then the result is in line with those found already: that is to say a bottlenecking of attention is avoided by not having to queue representations or share resources (e.g. Navon & Miller, 2002; Tombu & Jolicœur, 2002). However, if the latter is taken to be true then this result is unlike other tasks, as dissimilar magnitudes (negative word, large number) would be causing confusion in the mind of a participant. One possibility for this relies on the abstract nature of valency. As the most abstract of topics studied, there is little concrete about emotional states. In order to be able to understand valence states, it has been suggested that concrete domains, such as magnitude, are recruited to aid, or *scaffold*, learning (Barsalous 1999; 2008; 2009; also Grady & Ascoli, 2017; Kövecses, 2016; Landau, Robinson & Meier, 2014). In this instance, a concrete magnitude is presented that conflicts with the abstract magnitude of valency. Because valency relies upon the concreteness of a source domain in order to be understood (e.g. Shutova & Teufel, 2010), confusion arises when these conflict. Further research is required to disentangle these findings.

Conceptual Interplay, Conceptually

The notion of conceptual interplay was born from necessity. Although cognitive science generally accepts a level of sensory and motor information as necessary in knowledge organization, there has been little agreement as to how the corresponding representations interact. The purpose of this thesis was to propose a case for conceptual interplay between the domains of affordance, spatial semantics, valency and numerical magnitude. This was suggested to be made possible through temporally and spatially co-activated mechanisms that act in line with embodied accounts of cognition (e.g. Barsalou, 1999), which allows for third-party general mechanism to mediate representations.

To this end, across six experimental studies organized around three clusters, general support for this notion was found. Thus, as well as supporting existing literature, the thesis provides a novel contribution to knowledge through a role for conceptual interplay in simultaneously activated knowledge representations. For manipulation affordances, this was found in the horizontal domain via saccade duration. For spatial semantics, the interference presented itself in verification error rates across vertical and horizontal domains. In valency, saccade dwell times during the horizontal task demonstrated the interaction.

The most common way this was presented was as an effect of interference. Interestingly, this stands in opposition to Walsh's (2003) original predictions in ATOM. However, ATOM does not account for between-representation interaction, and instead focuses on within-representation effects. Given this, the original predictions made for facilitation are warranted, but the actual finding of interference is unsurprising. The only facilitation effect in support of conceptual representation found was in spatial semantics; namely, in error rates for the verification task. The old adage *two's company, three's a crowd* may hold some ground here. The incorporation of a third domain that can bias response (i.e. probe location) may be the crucial factor creating an attentional bottleneck. Unique in spatial semantics is the clear direction of effect, as words present either a leftward or rightward bias, an upward or downward bias. In both affordance and valency domains, the effect is less clear, presenting either precision or power responses, or negative or positive. Perhaps the directional effects observed in spatial semantics override probe location, which results in the facilitation seen between this factor and number (in line with Richardson, Spivey, Barsalou & McRae, 2003; Gibbs, 2005). This will be discussed further below, as it has a potentially important impetus for future research.

This research is exploratory, and from this can be derived two strong arguments moving forward. Firstly, and theoretically, the topic of study remains both original and in infancy, thus a lot of what would be comparatively effortless and clear were only one domain to be considered is much more muddied and difficult here. Work concerning itself with conceptual interplay going forward must bear this in mind, as the waters are not necessarily as clear as they may seem; the nature of how an interference effect or priming effect emerges requires further thought and divination.

Secondly, and empirically, the existing wealth of literature that shows support for effects of number, affordance, spatial semantics, and valency, only *partially* replicates. In the context of the current task, were there no role for interplay between representations, it would be expected that, given how robust and strongly supported SNARC effects are (Viarouge, Hubbard & McCandliss, 2014; Myachykov, Ellis, Cangelosi & Fischer, 2016; Ninaus et al., 2017), and due to the experimental design encapsulating the parity task, then replication would be expected were no other effects occurring. Instead, there are mixed cases of *partially* replicating SNARCs, effects of the remembered concept (e.g. valency), and examples of conceptual interplay. Making this argument stronger, the SNARC has been found in other tasks that do not require processing of *numerical* magnitudes. For example, orientation detection (Fias, Lauwereyns & Lammertyn, 2001), monitoring of phonemes (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), pitch detection (Campbell & Scheepers, 2015), and identify judgements (Dehaene & Akhavein, 1995). Yet, it is not always the case that magnitude causes a SNARC. It has been demonstrated that the magnitudes must be *related* in some fashion (Di Luca, Granà, Semenza, Seron & Pesenti, 2006), of which the current thesis has already demonstrated overlapping neural circuitry (chapter 1) and task demands (chapters 3-5). In future research, it remains necessary to adopt very specific experimental paradigms so as to evoke established effects *were conceptual interplay not occurring,* as this provides a further case for interaction between concepts.

When combined, the theoretical and empirical arguments provide a strong grounding for what has been found. Of course, as with all research there are ways to improve upon the adopted design. The limitations of the task will now be discussed, as well as how these may be addressed, and what form future research may take.

Limitations and Future Research

When considering the limitations of a set of experimental studies, there are two types of issues that need to be addressed. These are limitations related to design (i.e. those pertaining to sample size, materials used, task structure, etc.) and limitations related to framework (i.e. theoretical and conceptual limitations). This section will review both types of issue separately, before suggesting future research to improve upon the current research.

Design

In terms of task design, at the core of psychology exists some relatively serious issues when considered from an embodied perspective (e.g. Barsalou, 2008). These issues are that typically research utilises in testing white, middle class, university students from western populations (see Henrich, Heine & Norenzayan, 2010). This has been especially problematic for previous SNARC experiments after the findings that participants from countries that read right-to-left have a reversed horizontal association of numerical codes, and the same down for participants from countries that read top-downward (e.g. Shaki & Fischer, 2008). Unfortunately, this thesis is no different. Participants were predominantly white, middle class university students. However, early on in design this was acknowledged, and so attempts have been made to actually restrict the current sample to this group. By doing so, future research will be able to implement the same restrictions in sampling (as described in Chapter 2) and be able to readily compare findings to this project.

At the level of utilised materials, there is an interesting dichotomy between the implicit effects of microaffordance and valency as is contrasted with the explicit directionality of spatial semantics. While not an issue per se, this does create an unstable platform for contrast. Within the current thesis the different subject areas are compared and contrasted along an abstraction pipeline, though it has become clear that abstraction is not the only level by which these representations differ. Future research should remain wise to task framing and representational choice. For the current project, spatial semantics was the strongest contender for conceptual interplay, which means this issue is one that research should certainly pay attention to moving forward.

A final issue to be raised at the level of design regards task. As one of the first investigations into the interplay between representations, it was decided that the playing field should remain level across tasks – in other words, that each task should be the same. However, this means that if there is an issue with task design in one study, it affects the task design for every study. Luckily, this worry has not came into fruition, however future research may want to consider limiting the number of factors examined. A great many effects of interference were observed across this project, and facilitation seen only in the strongly spatial domain of spatial semantics in the stronger still spatial axis of horizontality.

Concept

There is a conceptual issue regarding the spatial bias mentioned above. Though preliminary research exists to show valency and grasp aperture to work in a similar manner to explicit spatial bias (e.g. Göbel & Rushworth, 2004) and though this research is now supported somewhat by the current tasks, there is no firm evidence. For example, at the level of valency, it is certainly a possibility that arousal, not emotional content, is a candidate for magnitude bias. Indeed, prior investigations demonstrate separate neural processes for valence and arousal, with effects of arousal occurring automatically while effects for valence rely on controlled encoding processes (Kensinger & Corkin, 2004; LeBar & Cabeza, 2006; Tambini, Rimmele, Phelps & Davachi, 2017). In the context of the current task, arousal was controlled for. In terms of research, it would be possible to examine arousal and emotion further and document the conceptual interplay between these representations.

A pragmatic decision was made to avoid examining distance effects (i.e. near-far). However, by doing so some potentially interesting results may have been eschewed. At this level of investigation it is not an issue, but certainly one to be contended with by future research. Near-far effects are perhaps one of the strongest domains in the world around us, and certainly one of the most overlooked in cognitive science. In reality, it is hardly ever the case that the environment can be easily divided into cartesian axes, but at the same time this adds a level of complexity to research that is only just beginning to become addressed (e.g. Myachykov, Ellis, Cangelosi & Fischer, 2013; Thomas, 2017; Thomas & Sunny, 2017; Gronau, Izoutcheev, Nave & Henik, 2017). More abstract domains have yet to begin this line of research. Perhaps, here, this was most notable in the affordance domain of study. It is very rare for a tool to be used in vertical space, and so despite grasp size priming magnitude it is possible to make the argument that by not considering possible distance effects findings were lost.

Future Research

One of the most pressing directions for future research is to address the directional nature of representations. In the context of the current thesis it was assumed that the findings reflected a change in levels of abstraction, though as discussed, another potential contender is the change in explicit and implicit directionality. More representational domains with explicit directionality need to be assessed in order to further examine this proposition. One such hypothesis could be that explicit directionality primes *location* of response instead of *magnitude* and can be investigated further by cross-examining rightward and upward responses, and leftward and downward responses as groups. For example, if location is primed over magnitude, a rightward bias should only prime a response in the rightward domain and not the upward. If magnitude were primed, then a leftward bias would also prime a downward response, as would an upward bias a rightward response.

Naturally, the question of distance is one that, too, should be addressed. Pupillometry has traditionally proved to be difficult to implement in cognitive tasks (e.g. Hartmann & Fischer, 2016) and presently relies on significant pruning of data to remove eyeblinks and other artefacts. However, it is still the strongest candidate at the level of eyetracking for assessing near-far changes. In spatial semantics, near-far ratings already exist, which makes it a strong prospect for examination. Again, an issue of directionality arises in that there is an assumption in implicit spatial bias that power (affordances) and positive (valency) are upward and rightward-biasing – albeit somewhat supported – however this may not be the case for the z-axis. Thus, important and crucial norming studies are also suggested for future research. A tentative hypothesis in this domain would be that objects with power grasp affordances would prime far-distance effects (i.e. large magnitudes) while precision grasp affordances would prime close-distance effects (i.e. small magnitudes). This could be replicated in the domain of valency and spatial semantics, whereby examining rightward and upward biasing words should prime far-distance effects. By doing this, the issue of directionality would further be clarified.

Another possibility is reversing the order of processing. As it has now been established that observable effects occur in the current paradigm, a strategic choice would be to replicate the domains studied at present but swap the ordering of numerical and task-specific stimuli such that participants are first primed with a magnitude before asked a question about an item (in the case of valency, perhaps *look left if the word is negative; look right if the word is positive*) and then the verification question regards the numerical content. By conducting such a task, it would extend the literature on SNARC and conceptual interplay. Here the expectations are the same as are currently hypothesised, but in reverse: large numerical magnitudes prime positive word responses, small numerical magnitudes prime negative word responses – of course, similar predictions are to be made across affordance and spatially semantic domains.

Naturally, the cultural question is one that needs to be addressed, but eventually. An idiom that comes to mind is *do not try to run before being able to walk*. While exciting opportunities exist in examining whether the reversed mental number line in other populations extends also to the domains studied here, it is not presently the most important of future directions. As such, this is offered as a suggestion for future research, but only when other opportunities have been addressed.

Conclusions

This thesis offers a novel contribution to knowledge through the examination of how representations activated in close spatial or temporal proximity may interact with one another through a process termed conceptual interplay. The experiments conducted as a part of this project demonstrated a case for this interplay through demonstrating interference and facilitation effects between the related domains of microaffordance, spatial semantics, valency and numerical magnitude. Though pressing questions have been generated from the analysis of these tasks, support for the overarching hypothesis has been found. An important question in cognitive science regards how representations interact now has a fundamental platform from which a response can be developed, going forward.

Additionally, the present studies have generated novel support for embodied models of cognitive processing, through the demonstration that representations, acquired through sensorimotor processing, play a role in understanding of more abstract domains (e.g. valency) and the understanding of the world. Future research suggestions have been presented which include replication, cultural, representational and pragmatic directions. From the perspective of the author, the most important of these are pragmatic, by which the other recommended tasks naturally follow.

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APPENDIX

APPENDIX A: Participant Documentation

Volumetric Affordances and Numerical Magnitude

Participant Information

PARTICIPANT INFORMATION

NAME OF RESEARCHER Ashley Chapman

PROJECT SUPERVISOR Andriy Myachykov

PROJECT TITLE Priming a SNARC via Object Affordances: The Attentional Interplay Between Numerical and Perceptual Information

1. What is the purpose of the project?

We aim to discover more about the processes that contribute to our general systems of memory and attention. Previous research has shown a bias in object and number processing dependent upon our perceptual senses and representations stored within working memory. In the context of the current study, we aim to establish how offline representations establish a bias in processing.

2. Why have I been selected to take part and what are the exclusion criteria?

You have been selected for the present study because you have given your consent to participate within the experiment and also met the inclusion criteria (over 18 years of age, speak English fluently, have normal or corrected-to-normal vision).

3. What will I have to do?

Testing is to take place within laboratory space in the Northumberland Building at Northumbria University. Before the task commences, you will be asked to complete an informed consent document and provide demographic information. Once this has been completed you will be given information about the task you are to complete via computerised instructions. The duration of the study is not expected to last longer than 45 minutes.

4. Will my participation involve any physical discomfort?

No.

5. Will my participation involve any psychological discomfort or embarrassment?

No discomfort is anticipated, though minor psychological discomfort has been reported by participants undertaking timed tasks in the past. Further, some physiological discomfort in the form of eyestrain is expected. Breaks are allocated throughout the study, though please notify the experimenter if this becomes overbearing.

6. Will I have to provide any bodily samples (i.e. blood, saliva)?

No.

7. How will confidentiality be assured?

You will be given a participant number that shall be kept separately from your consent form. Any information and data gathered during this research study will only be made available to the research team identified in the information sheet. Your results will not be identifiable and any data will only be used for the purposes of this research project, and potentially for publication in scientific journals or presented at conferences.

8. Will I receive any financial rewards / travel expenses for taking part?
No.

9. How can I withdraw from the project?
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Participant Debrief

PARTICIPANT DEBRIEF

PARTICIPANT NUMBER

NAME OF RESEARCHER Ashley Chapman

PROJECT SUPERVISOR Dr Andriy Myachykov

PROJECT TITLE Priming a SNARC via Object Affordances: The Attentional Interplay Between Numerical and Perceptual Information

1. What was the purpose of the project?

Previous research revealed similarities between objects' representations in memory and perceptual representations formed online during tasks suggesting that memory and perception are grounded in sensorimotor experience. This was also shown to be true for numbers: magnitude representations in memory show similar features to perceptual number representations, such as SNARC and distance effects. Other studies show sensorimotor simulations in memory are similar to other representations of magnitude, such as time and grasp affordances. The latter reports provide support to the ATOM theory of magnitude (time, space and quantity processed as part of the same mental system) suggesting an interplay between magnitude-related knowledge both in perception and memory.

We expect to find that grasp size of the object representations stored in memory will lead to the establishment of attentional SNARC effects during auditory number processing revealed by eye movement and magnitude.

2. How will I find out about the results?

You can obtain a summary of the research through indicating your preference on the informed consent document. It must be noted that no interpretation of individual results will occur, and any document will be generalised to the wider sample as opposed to being individualised.

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PARTICIPANT INFORMATION

NAME OF RESEARCHER Ashley Chapman

PROJECT SUPERVISOR Andriy Myachykov

PROJECT TITLE Priming a SNARC via Spatial Semantics: The Attentional Interplay Between Numerical and Perceptual Information

1. What is the purpose of the project?

We aim to discover more about the processes that contribute to our general systems of memory and attention. Previous research has shown a bias in object and number processing dependent upon our perceptual senses and representations stored within working memory. In the context of the current study, we aim to establish how offline representations establish a bias in processing.

2. Why have I been selected to take part and what are the exclusion criteria?

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PARTICIPANT NUMBER

NAME OF RESEARCHER Ashley Chapman

PROJECT SUPERVISOR Dr Andriy Myachykov

PROJECT TITLE Priming a SNARC via Spatial Semantics: The Attentional Interplay Between Numerical and Perceptual Information

1. What was the purpose of the project?

Previous research revealed similarities between word representations in memory and perceptual representations formed online during tasks suggesting that memory and perception are grounded in sensorimotor experience. This was also shown to be true for numbers: magnitude representations in memory show similar features to perceptual number representations, such as SNARC and distance effects. Other studies show sensorimotor simulations in memory are similar to other representations of magnitude, such as time and grasp affordances. The latter reports provide support to the ATOM theory of magnitude (time, space and quantity processed as part of the same mental system) suggesting an interplay between magnitude-related knowledge both in perception and memory.

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Dr Nick Neave
Chair of Department of Psychology Ethics Committee (Postgraduate)
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Informed Consent

INFORMED CONSENT

Project Title:

Priming a SNARC via Word Valency:
The Attentional Interplay Between Numerical and Perceptual Information

Principal Investigator: Ashley Chapman

Participant Number:

	please tick where applicable
I have carefully read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐
I would like to receive feedback on the overall results of the study at the email address given below. Email address……………………………………………………………………	☐

Signature of participant.. Date……………………..

(NAME IN BLOCK LETTERS)..

Signature of researcher.. Date……………………..

(NAME IN BLOCK LETTERS) ASHLEY CHAPMAN

APPENDIX B: Experimental Materials

The materials that have been used in this study can be found in the respective sources, or in the case of materials created purely for the thesis, found online at https://github.com/howisstifflucky/chapmanPhDData

This can be downloaded either directly, via the web, or by using a git client (see documentation here: https://book.git-scm.com/).

APPENDIX C: Demographics Questionnaire

Demographics

1) Your date of birth: -------/--------------/--------------

Day Month Year

2) What sex were you assigned at birth?

Male ☐ Female ☐

3) Which of the following best describes your ethnic background?

White ☐ Pakistani ☐

Black – Caribbean ☐ Bangladeshi ☐

Black – African ☐ Chinese ☐

Black – Other ☐ Asian – Other ☐

Indian ☐ Other– please specify ☐____________________

4) What is your country of birth? __________________________

5) What is your country of residence? ______________________

6) Are you a native English speaker?

Yes ☐ No ☐

7) How would you describe your parents' education and income?

Upper class ☐ Upper-middle class ☐

Middle class ☐ Lower-middle class ☐

Working class ☐ Decline to answer ☐

8) Do you have siblings?

Yes ☐ No ☐

9) What is your birth order?

____

10) Which hand do you use to write?

Left ☐ Right ☐

Ambidextrous ☐

11) How would you describe your vision?

20/20 uncorrected vision ☐ Corrected with contact lenses ☐

Corrected with glasses ☐ Vision problems ☐

12) Do you have any problems with language?

No ☐ Yes (please specify) ☐ ____________________

12) Are you currently: (please tick as many boxes as apply)

In active paid work ☐ Unemployed and seeking work ☐

Retired ☐ Unemployed due to illness or disability ☐

Doing voluntary work ☐ At home doing housework ☐

Full time student ☐ Other (please specify) ☐ ____________________

13) Please complete for present or last paid job (for retired or unemployed)

Job title: ____

APPENDIX D: Short form Edinburgh Handedness Inventory

Participants would be given a sheet with the following questions:

Edinburgh Handedness Inventory - Short Form

Please indicate your preferences in the use of hands in the following activities or objects:

	Always right	Usually right	Both equally	Usually left	Always left
Writing					
Throwing					
Toothbrush					
Spoon					

Responses would then be scored with the following experimenter's sheet:

Scoring:

For each item: Always right = 100; Usually right = 50; Both equally = 0; Usually left = -50; Always
left = -100

To calculate the Laterality Quotient add the scores for the four items in the scale and divide this by four:

Writing score	
Throwing score	
Toothbrush score	
Spoon score	
Total	
Total ÷ 4 (Laterality Quotient)	

Classification:	Laterality Quotient score:
Left handers	-100 to -61
Mixed handers	-60 to 60
Right handers	61 to 100

APPENDIX E: Raw Data

The raw data from experimental studies has been mirrored online at https://github.com/howisstifflucky/chapmanPhDData

This can be downloaded either directly, via the web, or by using a git client (see documentation here: https://book.git-scm.com/).