

Cognitive and Neural Correlates of Processing Spatial Relations by Humans

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Dedication

This thesis is dedicated to my family. Especially to Alfred, who has accompanied me on my writing journey.

Abstract

Human cognition has long been thought to exceed that of other animals; however, what it is that makes humans “so smart” continues to be questioned. Gentner argues that language and relational reasoning together elevate human cognition and she takes a developmental approach to support her theory. This project takes a similar approach to Gentner’s. I examined the relationship between language and relational reasoning in children, specifically as they are learning the relational terms for right and left as compared to relations for terms that they already know (i.e., above/below). What sets this project apart from Gentner’s work is that I also looked at the effect of lateralization on children’s performances as well the neural mechanisms underlying these same relational judgments in adults. Some of the neural mechanisms underlying relational reasoning in humans and monkeys are known. However, it is not known whether one set of relations (i.e., above/below) should be advantaged over the other (i.e., right/left) in both verbal and nonverbal modalities. To answer this question, I have developed a set of tasks to examine the following queries: 1) how verbal and nonverbal knowledge of above/below/right/left develops from 5 years to 10 years of age, 2) whether verbal knowledge aids performance on a nonverbal task that requires judgments of these relations, 3) whether strength of handedness promotes either verbal or nonverbal performance, and 4) what the neural correlates of these judgments are.

The chapters of this thesis are organized to address each question separately. In the first chapter, I give a general overview of the work already done regarding these questions. In Chapter 2, I describe the spatial relational task used to investigate each question. Chapters 3-6 report on the findings from each of my four questions and Chapter 7 provides a general discussion of what this research adds to the current literature.

Overall, my findings suggest that language is not necessary for relational coding to emerge, verbal and nonverbal knowledge of relations follow different developmental trajectories, lateralization (handedness) does not aid in learning relations, and the two sets of spatial relations are represented differently in the brain.

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Chapter 1 General Introduction

The uniqueness of human intelligence has been debated for centuries with various capacities being proposed as distinguishing human intelligence from that of other animals (e.g., Darwin 1871; Descartes 1637/1985; Hume 1739/1978). Gentner (2003; 2010) argues that it is having the capability for language and relational reasoning, both separately and when used together, that promotes human cognition to higher capacities than other animals. She takes a developmental approach to support her theory and I will add to her work by adding two other dimensions to my investigations: 1) effects from lateralization of the body and brain, and 2) the underlying neural mechanisms that support such processes.

Gentner (2003) considers “relational terms” to be any term that references a comparison to another object, where the reference could be relatedness, hierarchical, social communicative, causal, etc. For purposes of this thesis, I use “relation” to refer only to the relative spatial position of one object in comparison to another. Although animals show some evidence of both language and relational reasoning, humans seem to far surpass animal performance. Considering relational knowledge in itself, even humans’ closest living relative, the chimpanzee, shows a limited capacity for relational coding (e.g., Penn et al. 2008). The inability of nonhuman primates (e.g., chimpanzees and capuchins) to combine more than one relation (attend to more than one relation)

illustrates the limitations of their relational reasoning abilities (Fragaszy et al. 2011; la Cour et al. 2014).

In this thesis, I address how humans deal with spatial relational information. I do this by answering a series of questions: 1) how verbal and nonverbal knowledge of *above/below/right/left* develops from 5 years to 10 years of age, 2) whether verbal knowledge aids performance on a nonverbal task that requires judgments of these relations, 3) whether lateralization (as measured by strength of handedness) promotes either verbal or nonverbal performance, and 4) what the neural correlates of these judgments are. Incidentally, I organize this introduction and thesis according to these questions and address each in order. Specifically, in this first chapter, I give a general overview of the work already done regarding these questions, tackling each question in order. In Chapter 2, I describe the spatial relational task used to investigate each question. My task design was based on work by Goodwin et al (2012) and inspired by the work of Hermer and Spelke (1994, 1996), so I will describe these studies in more detail and in separate subsections of this first chapter. Chapters 3-6 report on the findings from each of my four questions, respectively, and Chapter 7 provides a general discussion of what this research adds to the current literature.

My focus on language goes beyond Gentner's thesis and will serve as a crux of my investigation as it has been shown to facilitate the extraction and encoding of relational information (Hayward and Tarr 1995). However, the exact role that language plays remains unclear. While some findings indicate that language plays a critical role in the

development of and ability to make relational judgments (Hermer and Spelke 1996; Hermer-Vazquez et al. 1999; Hermer-Vazquez et al. 2001; Loewenstein and Gentner 2005); other studies suggest a less vital role (Landau and Hoffman 2005; Hupbach et al. 2007; Ratliff and Newcombe 2008). Some researchers have looked to developmental disorders in an attempt to provide evidence for the interdependence of language and spatial cognition (e.g., Williams syndrome: Karmiloff-Smith et al. 1997; Brock 2007), but there is no consensus in this line of work either (Bellugi et al. 1988; Musolino et al. 2010). An additional potential source of insight on the role of language in relational knowledge comes from animal studies, which I will use to supplement the arguments for and against the role of language throughout this thesis.

1.1 What is relational reasoning?

Fluid reasoning ability – the capacity to think logically and solve problems in novel situations – is strongly linked to the development of other cognitive abilities and to academic achievement (reviewed in Wright et al. 2008). Relational reasoning is one aspect of fluid reasoning, where analogical reasoning and spatial relational reasoning are two types of specialized relational reasoning which require similar general comparison skills. The ability to make general relational judgments is thought to be central to human intelligence in that it promotes higher cognition (Gentner 2003; Gentner 2010; Halford et al. 2010) – including math and science skills (National Research Council 2006) – and is a skill set rarely attributed to animals. It appears to be bolstered by language (e.g., Hayward and Tarr 1995; Hermer-Vazquez et al. 2001; Loewenstein and Gentner 2005; however

see Munnich & Landau 2003 for a review of contradictory findings) and is shaped by culture and linguistic specificities (e.g., Hespos and Piccin 2009; Bowerman 1996).

Evidence for human superiority in relational reasoning has been gathered from animal studies. In comparison to other animals, only humans over 5 years of age appear to be able to make relational (transitive) inferences reliably in one trial by integrating multiple premises (e.g., Halford 1984; Halford 1993). In fact, chimpanzees, monkeys, rats and pigeons are capable of learning serial orderings when items are introduced in sequential order (and presumably some overlearning occurs), but the human capacity seems to be of a much greater order, even at an early age. On an evolutionary note, recent studies have suggested that humans begin with the same spatial reference frames as the other great apes, but develop additional reference frames throughout development which reflect their specific language and culture (e.g., Haun et al. 2006a, Haun et al. 2006b; Gentner 2007). Specifically, allocentric frames of reference – where the location of an object is determined by its relation to the environment or other object – appear first, then become progressively more relative (Rigal 1994; Wassman and Dasen 1998; Moraleda et al. 2013). For example, frames of references begin universally with respect to the environment in absolute terms (e.g., cardinal direction), then move to less fixed, more relative terms with respect to other objects (or object parts, like “fronts”), with some cultures coding location in egocentric terms (i.e., in object-to-self terms).

However, the relation between culture (human and animal) and frame of reference is not entirely clear-cut. For example, the scale of the environment being coded has an effect on

the frame of reference selected and applied (e.g., Ratliff and Newcombe 2008). Furthermore, nonhuman primates have difficulty in aligning manipulable objects in allocentric space (Fragaszy et al. 2011) despite this generally being an easy task for (Western) humans (Scott et al. 2006) and despite preferring an absolute (allocentric) frame of reference in a hidden-object-search task (Haun et al 2006a). Further muddying the picture, there is some evidence that the shift from allocentric to egocentric incurs a cost: children who do not make the switch master their linguistic coding system as early as 4 years (Wassman and Dasen 1998; Brown and Levinson 2000), whereas children who switch to a relative-coding system continue to confuse the associated labels into adolescence (Rigal 1994). Thus, although those individuals without access to linguistic representations – such as animals and young children – are often found to not be able to make the same types of complex relational judgments that individuals with linguistic access – such as human adults – can make, they can excel at some types of spatial coding. Nevertheless, language is often pointed to as an accelerant for the development of superior relational reasoning abilities.

1.1.1 Development of relational reasoning in humans

Piaget argued that children cannot perform classical analogy problems until they reach the stage of formal operations (around age 11 years) because they lack the capacity to represent the necessary relations (Inhelder and Piaget 1958). Children seem to fail because they rely on lower-order relations that do not complete the analogy, such as picking a perceptual match over a relational match (Piaget et al. 1977; Sternberg and Downing 1982). Although fluid reasoning develops greatly between ages 5-10 years –

with strong effects on later achievement (Ferrer and McArdle 2004) – the slow development of this type of reasoning may be due to limitations in general knowledge or lack of familiarity with the items to be compared or the relations to be matched (Goswami and Brown 1989). Familiarity with relations can come from experience manipulating objects or from learning the labels associated with the relations. Some researchers have suggested that knowledge of the corresponding labels is tightly linked to nonverbal performance (Hermer-Vasquez, et al. 2001; Shusterman 2006); however, this thesis will address this potential linkage directly.

Relative to other terms, relational language comes into a child's vocabulary slowly and in a specific progression (Brown 1973). For instance, in English, concrete nouns are learned first, then verbs and even later prepositions (Gentner and Boroditsky 2001; Gentner and Bowerman 2009). Many spatial concepts are universal (Bowerman 1989; Talmy 1983), such as containment and support, and the terms which describe these are acquired in a specific order. Thus, the emergence of nonverbal understanding of these spatial concepts appears in the same order; and this occurs similarly across all languages (e.g., Slobin 1973 in Gentner and Bowerman 2009). However, that is not to say that the linguistic label and corresponding concept co-occur or co-emerge: it has yet to be determined whether one always appears before the other.

More specific to the current project, the terms for *right* and *left* are learned around the age of 6 or 7 while *above* and *below* are learned around the age of 3 (Martin and Sera 2006). Initial knowledge of the terms *right* and *left* has been linked to a child's ability to identify

relative positions of objects within their own body-centered coordinates (i.e., egocentric frame of reference), sometimes mapping one of these directions to their dominant hand despite not showing any correlation of strength of handedness to score on a *left-right* discrimination test (Rigal 1974; Rigal 1994). However, although 7-year-olds are able to correctly discriminate their own *left* and *right* body parts, it has been suggested that only about half of 11-year-olds can apply the labels *left* and *right* to other persons' bodies correctly (Dellatolas et al. 1998; Rigal 1994). It may be that the case of applying the correct label to another's body is more of a mental rotation problem, which appears to be inherently more difficult, particularly for women (Voyer et al. 1995). According to Benton (1968) an adult level of *left-right* orientation is normally attained around 12 years. In consideration of these studies, it is evident that some sort of development must take place before these concepts are acquired. What is not clear is whether this development stems from experience or is more physiological and independent of experience (e.g., maturational), particularly in terms of the underlying neural substrates.

In terms of experience, it should be noted that not all cultures code relations egocentrically, but rather they code relative locations according to their absolute cardinal directions (e.g., the cup is *northeast* of the plate; Levinson 2003), an environment-centered frame of reference. In terms of maturation, I will explore the possibility that the slow development of *left-right* knowledge is due to relatively slow development of the associated neural areas in Chapter 6, although indirectly by looking at neural activation in adult brains. Since adult brains are already mature, I will use knowledge about the order of maturation of brain areas to draw conclusions about the role of maturation. For

example, if differential neural activation is indicated in areas of the brain that are known to mature later in life, then such a finding could suggest that maturation is more involved in the emergence of that skill than experience is. I will discuss the development of the human brain as it pertains to relational reasoning in section 1.3.

1.1.2 Reasoning in other animals

Humans are not the only animals with some capacity for relational reasoning (Thompson et al. 1997; Cook and Wasserman 2007; Fagot and Thompson 2011): relational judgments are ecologically relevant for all animals, although the extent to which these judgments are similar to the human ability or are less abstract in nature is hotly contested (Cheng and Newcombe 2005).

1.1.2.1 *Nonhuman primates*. Being our closest living relatives, primates are widely considered the best species for comparison to humans in search of evolution of human intelligence. Relational reasoning, as it is considered critical for development of higher cognition, should be present in some species of primates – especially those most related to us, such as chimpanzees – if this ability evolved independently of language. However, if language truly is responsible for its development, then only individuals with symbolic representation (i.e., experience with symbol use) should illustrate relational reasoning (Premack 1983). Most studies with other primates have used analogical reasoning tests, such as relational-match-to-sample paradigms, particularly ones which test *same-different* relations or matrix reasoning. Some researchers believe analogical thinking (Gentner et al. 2001; Holyoak and Thagard 1997; Sternberg 1977) or perception of *sameness* (French

1995) is uniquely human, while others maintain that there must be some phylogenetic antecedents to such cognitive capacity, even if the capacity is more limited in other animals (Cook and Wasserman 2007). The current literature is thus riddled with contradictory evidence for (Gillan et al. 1981; Boysen and Berntson 1995; Thompson et al. 1997; Premack 1983) and against the necessity of symbolic representation (Fagot and Oden 2011; Wasserman et al. 2001; Goodwin et al 2012; for evidence in birds see Cook and Wasserman 2007) for relational reasoning.

In terms of evidence against the role of language, or symbolic representation more generally, Fagot and Thompson (2011) gave 29 symbol-naïve baboons a *same-different* relational match test. Although, only 6 monkeys reached passing criterion, even without language these 6 animals were able to accomplish “higher-order” relational reasoning. However, in a different study by Thompson and colleagues (1997) a language-trained chimpanzee and three language-naïve, but symbol-trained chimpanzees were given this same task with the result that both groups of chimps performed equally well. The language-trained chimpanzee had been taught at the age of 5 years to combine “words” (tiles with symbols printed on them) to communicate with researchers (Premack 1976), while the symbol-trained chimpanzees had been trained to associate a token (heart-shaped) with the concept *same* and a different token (diagonally-shaped) with the concept *different* and to associate Arabic numerals to numerical arrays (Boysen 1993; Boysen and Bernston 1989). The one chimpanzee who had been taught neither language nor tokens could not perform the task. It appears that symbol-training (functional token) was just as helpful as language-training (propositional string) in enhancing relational ability. So,

even if it isn't necessary to perform relational matching, having access to symbolic representation seems to boost performance.

On the other hand, Goodwin and colleagues (2012) were able to train symbol-naïve monkeys to make spatial relational judgments. In their study, they examined two monkeys' ability to categorize a dot's position as being *above*, *below*, *to the right* or *to the left* of a line. Although they were interested in how a rule would be represented in neural activity, they found evidence that the two monkeys treated *above-below* judgments differently than *left-right* judgments. Not only were these monkeys more accurate at *right* and *left* decisions (or the rule that induced a *right* or *left* decision) than at *above* and *below* decisions (or the rule that induced an *above* or *below* decision), but their neural activity was stronger for *left-right* judgments as well (Figure 1.1). This seems counter-intuitive considering it contradicts findings from human performance comparing these two relational planes. Humans have sometimes been shown to be less accurate in making *left-right* decisions as compared to *above-below* decisions on a nonverbal task (Dessaegn and Landau 2008). One could make the argument that this difference arises within the primates because of locomotive differences – humans are bipedal, monkeys are quadrupedal – and thus the ecological and physiological constraints have resulted in different evolutionary trajectories. However, a different interpretation is the *left-right* advantage could be explained by an order of acquisition effect: these monkeys were trained on *left-right* judgments first, and then were trained on *above-below* judgments. At least linguistically, humans learn *above-below* before *left-right*; although, it is yet to be determined, behaviorally, whether this difference exists nonlinguistically in humans. I

will answer the question concerning human behavior in Chapter 4 and the question regarding human neural activity in Chapter 6.

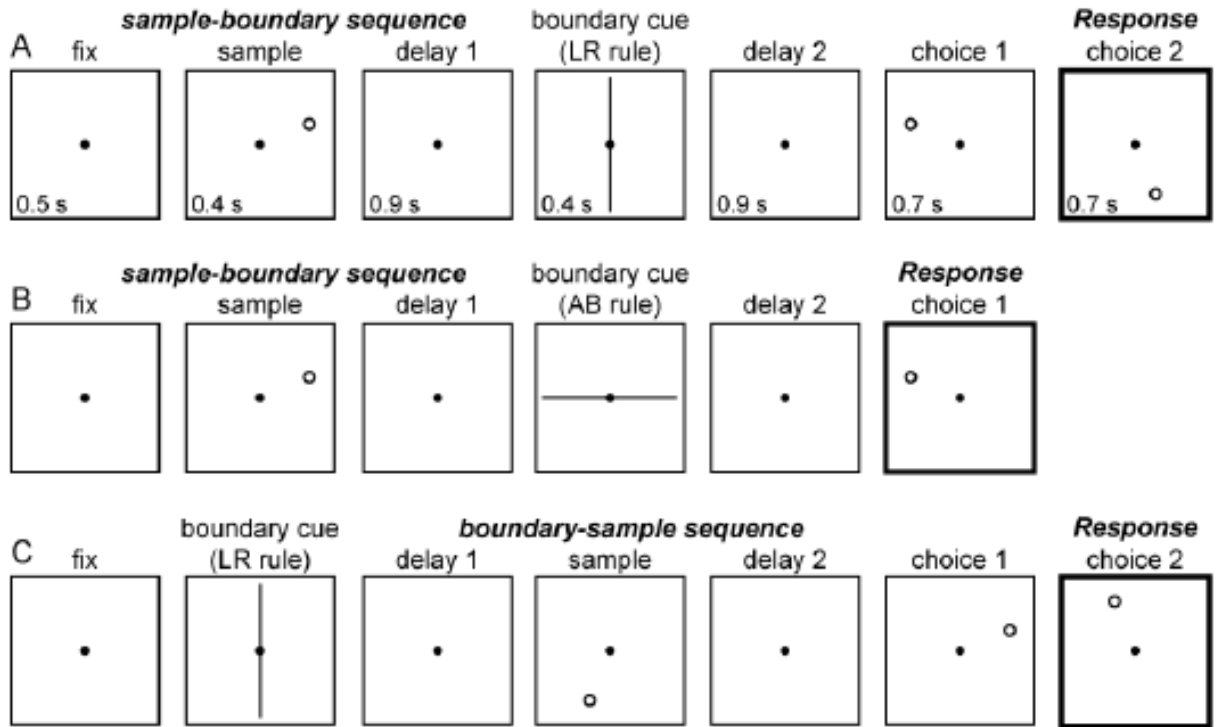


Figure 1.1: Dynamic Spatial Categorization task from Goodwin et al. (2012), adapted from their Figure 1. A) The sample is presented first then the boundary (i.e., *left-right* rule) followed by up to two choice screens. B) The same task except that the boundary changes to a horizontal orientation (i.e., *above-below* rule). C) The same task except now the boundary cue precedes the sample cue. This task served as the basis of my task design.

1.1.2.2 *Rats, humans & the blue wall task.* The search for evidence beyond nonhuman primates has focused on lab animals, such as rats. One popular, yet, controversial task that has been implemented as a test for relational ability is the blue wall task. This task

involves a small rectangular room in which one short wall was painted blue (Figure 1.2; although in some studies the wall was painted a different color). One of the first studies compared performances of young children (18-24 months) and rats (Hermer and Spelke, 1994; Hermer and Spelke 1996) and found their performances to be similar: neither was able to reliably utilize the feature cue – the blue wall – to guide their reorientation to the correct location of a hidden object. Instead, both relied on geometric cues (placing their performance at 50%, or chance), indicating that each group had only the simplest relational ability: that the object was to the left of the short wall without the ability to distinguish between the two short walls. It is unlikely that young children and rats are encoding the relation *left of*, but rather are matching a visual representation (of long wall *left of* short wall) instead of a specific relationship (of long wall *left of* blue short wall) or propositional string.

Adults perform the test quite well; but, only when they have available to them internal speech (Hermer-Vazquez et al. 1999): when researchers placed headphones over the ears of adult participants, adult performance fell to the levels of children and rats. The researchers argued that it was the ability to encode the target as *left of* or *right of* the blue wall (the landmark feature) that led to successful performance, and thus, language was necessary to perform "higher-order" relational reasoning such as that requiring the coding of features. Furthermore, when Hermer and colleagues (2001) tested 5-7-year-olds they found that only those children who could correctly produce the words *left* and *right* could succeed on the task; again, suggesting that language was key to enhanced relational performance.

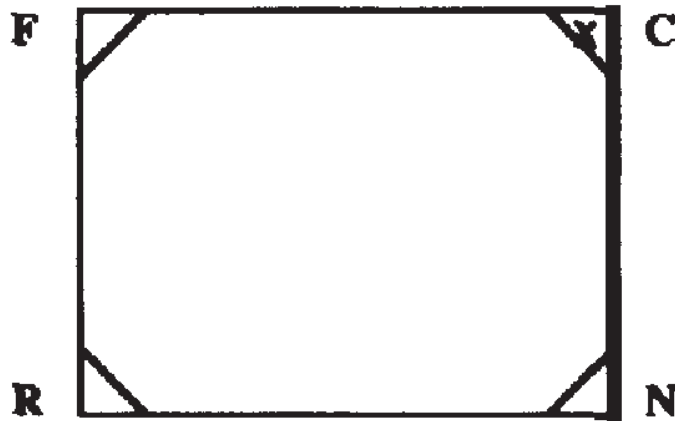


Figure 1.2 The "blue" wall task from Hermer and Spelke (1994, 1996) and Hermer-Vazquez et al. (2001). The dark, thicker line between corners C and N demarcates the blue wall in the room. The "x" in the corner "C" represents the hidden object.

The re-orientation effects reported by Hermer and colleagues (Hermer and Spelke 1996; Hermer-Vazquez et al. 1999; Hermer-Vazquez et al. 2001) have been shown to vary as a function of room size and other variables unrelated to linguistic knowledge, such as when explicit instructions are given (Ratliff and Newcombe 2008). Ratliff and Newcombe (2008) suggest that both geometric and feature cues are utilized by humans, but in different degrees depending on the uncertainty of the information provided by each, as well as their salience. For instance, humans can successfully shift their frame of reference strategy from a relative (e.g., egocentric) to an absolute (e.g., environment-centered) system when appropriate landmarks are available for external reference (Li and Gleitman 2002).

In their study, Li and Gleitman presented English speakers with a table and asked them to reproduce what they saw on a table behind them. The default frame of reference for English speakers was egocentric, so they would arrange the items from left to right; however, by manipulating landmark cues the researchers were able to get these adults to switch to a room-centric (environment-centered) frame of reference based on cardinal direction. They interpreted this flexibility in frame of reference coding as suggesting that language itself may not be the key causal factor in choice of spatial perspective and pointed to prior evidence on rotation problem solution from infants (Acredolo 1979) and from laboratory animals (Restle 1975) to support the interpretation of their findings. Li and Gleitman (2002) concluded that humans and animals approach spatial problems differently depending on the availability and suitability of local cues. This not only suggests that landmarks are only as good as their perceived utility, but also that humans are not bound to one encoding system and rather choose one according to the information available. Furthermore, it suggests that language, when engaged, biases users to a specific frame of reference, but does not bind users to that frame of reference when it is not engaged; an interpretation supported by Talmy (1983) and Haun et al. (2006a).

1.1.3 Relational reasoning in humans who do not have language

It should now be clear that there is mixed evidence on the role of language in human cognition. Similarly, there is mixed evidence on the role of symbolic representation (which includes language) as indicated in the research on animal performance. Studies on infants (section 1.1.3.1) suggest that they can make simple categorical, spatial relational judgments, yet studies on young children suggest that relational reasoning is dependent

on having access to labels to represent relations. Studies on populations that are still developing relational language (section 1.1.3.2), such as Nicaraguan Sign Language users, corroborate studies on young children – another group of people who are learning to match labels to relations. However, this disjointed story of language sometimes being necessary and sometimes not being necessary for spatial relational judgments needs to be explained.

1.1.3.1 *Infants*. Infants are able to discern the positions of objects located in space and can identify spatial relational categories (see Bjorkland 2012, p.234). For instance, Gava, Valenza and Turati (2009) used a habituation-dishabituation visual preference paradigm to test newborns' abilities to differentiate between *left* and *right* spatial relations. Using a static solid vertical bar and a blinking solid square that would appear on one side of the bar, these experimenters habituated newborns to the square being on one side of the bar (either *left* or *right*) and then gave infants the choice of two novel scenes: a square on the same side of the bar but in a new location versus a square on the opposite side of the bar. Newborns preferred to look at the scene which showed the blinking square on the opposite side of the vertical bar, indicating that they had categorized the relative position of the squares to the line and preferred to look at the new category over the habituated category. Gava et al. (2009) were additionally able to show that newborns could discriminate within category stimuli – which is important for drawing conclusions on whether infants can categorize based on exemplars since, for such a conclusion, it must be shown that exemplars are perceived as being different (Quinn 2002) – and that their

preferences were not based solely on distance from the bar. Quinn (2007) has found similar results for *left-right* and *above-below* relational categories across a number of different paradigms.

1.1.3.2 *Developing languages*. Evidence from a developing language suggests that having access to labels is critical for relational reasoning. Pyers et al. (2010) studied three generations of Nicaraguan Sign Language (NSL) users and measured their performance on the *blue wall task* described previously (section 1.1.2.2). These groups of adults represent groups at different stages of language development. The first cohort, the oldest generation, was responsible for the creation of NSL but the language in their form was quite rudimentary. The second cohort, about 10 years younger, added words and rules to the new language, but their use of it was still limited compared to more advanced languages. The third cohort had developed relational language and was much more consistent in their use of it. In comparing reorientation and search performance for these three groups, Pyers and colleagues (2010) found that the third cohort excelled at the task compared to the other two groups, and concluded that it was because they were able to linguistically encode the location of the hidden object as *to the left* of the blue wall.

1.2 How does language enhance reasoning?

Language has been shown to facilitate the extraction and encoding of relational information (Hayward and Tarr 1995). Some researchers even suggest that language

precedes the ability to encode and remember spatial information. There are a number of studies that suggest that language is required for remembering locations for hidden objects (some of which I have already discussed: Hermer-Vasquez et al. 1999; Hermer-Vasquez et al 2001; Pyers et al. 2010). But it doesn't necessarily have to be the case that language *precedes* or is *necessary* before nonverbal judgments can be made, as suggested by the infant studies (Gava et al. 2009; Quinn 2007) and some animal studies (Cook and Wasserman 2007; Fagot and Oden 2011; Goodwin et al. 2012). In this section, I will discuss possible roles of language in nonverbal spatial reasoning.

1.2.1 Labels are necessary for encoding and remembering space?

1.2.1.1 *Infant and children studies.* A number of studies have shown that providing children, or even infants, with a familiar label enhances their ability to perform relational judgments. In a study with 18-month-olds, Casasola (Casasola 2005) found that infants who heard the familiar word *on* while being habituated to a support event in a dishabituation task looked longer at a containment event whereas infants who heard only a generic word, a novel word or silence looked equally long at a new support event and a containment event. These findings led Casasola to conclude that infants who heard the familiar word had formed the abstract category of “support” whereas infants who did not hear the familiar word were not able to form the category. To what extent infants formed the category on the spot versus accessed the pre-existing category (assuming the familiar word had a corresponding pre-formed category) is not clear.

Preschoolers also seem to do better with remembering a spatial category when they are provided with a familiar label at the encoding stage of the task. Loewenstein and Gentner (2005) described where they were hiding an object as they hid it in the view of the child (e.g., I'm putting the cup *on top*). Those children who received a familiar label were better able to remember where they had seen the object hidden and to find the corresponding position on a matching structure than children who heard a generic word (e.g., I'm putting the cup *here*). Again, the necessary category was better accessed when a familiar label was provided, whereas a generic term was not sufficient.

1.2.1.2 *Cross-linguistic studies.* A different method of examining the influence of language on relational judgments is to test individuals from different cultures who speak different languages. Hespos and Piccin (2009) found that 5 month old infants were sensitive to *tight/loose* fit relationships of objects and containers under conditions of covering and occlusion. Hespos and Spelke (2004) similarly found that infants are sensitive to different conditions of support and containment. However, adults from different cultures showed differential sensitivity to these relations according to how their language encodes the relations. For instance, adult English speakers – whose language does not code tightness of fit – were not sensitive to tightness of fit relationships even though infants of the same culture were sensitive to these relationships. Adult Korean speakers – whose language does code tightness of fit – were sensitive to these relations, as were Korean infants. Hespos and Piccin (2009) suggest that language underlies this sensitivity as fit relationships are obligatorily marked in Korean. These results suggest

that language plays a role in how spatial relations are automatically encoded in adults, but that infants are prepared to notice a greater range of spatial relations.

Consistent with findings on the effects of language on cognition, Levinson (1996) showed that whether a language codes spatial information in terms of *north-south* (cardinal) or *left-right* (relational) coordinates affects speakers' representations of object locations (see also, Levinson 2003; Li, Shusterman and McNaughton, under revision). However, it should be noted that the facilitative role of language has not always been found in spatial tasks (Munnich and Landau 2003) and individuals are able to shift from their preferred frame of reference to a different one in order to successfully encode a spatial or relational location (Gentner 2007; Li, Shusterman and McNaughton, under revision). Therefore, although language appears to affect encoding of spatial relations and locations, its primacy has not always been shown, its effects may only be temporary, and it is possible to override its influence (and limitations).

1.2.2 Possible mechanisms by which language affects relational reasoning

Before examining some possible mechanism by which language might promote relational reasoning, it will be useful to explore one proposal for how relational reasoning develops: the “career of similarity” hypothesis. This account is particularly relevant since it seems also to explain some of the animal literature which has suggested that perceptual features are the most salient in matching paradigms: paradigms that are most commonly used in testing relational reasoning. Therefore this account has the potential to offer a common

ground from which animal and human reasoning each begin and where language might enter to promote reasoning.

1.2.2.1 *Career of similarity*. The “career of similarity” hypothesis was first introduced by Quine (1960) then updated by Gentner and Ratterman (1991; see also Gentner, 2003). This hypothesis explains infants’ perception as initially directed by “brute” similarity (i.e., perceptual matching) and later by “theoretical” similarity (i.e., conceptual matching), meaning infants initially fail to recognize similarity in more complex situations than just superficial similarities. Gentner and Ratterman (1991) then “amplified” Quine’s account of developmental shift by more explicitly laying out how the progression from “brute” perceptual similarity to “theoretical” perceptual similarity occurs. They suggest that infants stop responding merely to overall similarity and begin to be more selective in their attention. Then, infants use their selective attention to move beyond simple object similarity and begin to focus on *relational* similarity, which requires a concept formation rather than just perception. One way infants achieve this progression from object to relation as the focus of similarity is by comparing across situations.

Christie and Gentner (2010) suggest that it is only when children have an appropriate point of comparison, such as seeing two or more exemplars or when given a prompt to make a comparison, that relational information comes to the forefront of attention and overshadows mere perceptual similarities. This is where language enters the process.

These researchers (Christie and Gentner 2010; Christie and Gentner 2013) argue that labels trigger the comparison process that leads to new relational abstractions. However, language alone cannot succeed in this process: without an appropriate comparison (two exemplars rather than one) only the objects themselves appear salient and therefore any label provided, which is meant to aid the comparison, is automatically attributed to the objects rather than the relationship between them. On the other hand, only seeing two exemplars and no label is similarly not sufficient to trigger the appropriate comparison process. These accounts suggest that relational judgments are developed early in life, but gradually as children learn their language and culture. As such, language may then be acting to progress relational reasoning to a new level, although exactly *how* it accomplishes this transition remains unclear.

1.2.2.2 *Possible mechanisms by which language helps.* There are several ways in which the results of current studies can be combined and interpreted, each of which leads to a different, although not necessarily mutually exclusive, theory of how language might affect relational reasoning¹. One conception is that language provides a scaffold that potentiates comparison (Christie and Gentner 2013) by binding together relevant elements for comparison (Hermer and Spelke 1994; Hermer-Vazquez et al. 1999; Hermer-Vazquez et al. 2001; Loewenstein and Gentner 2005) and structuring the comparison (particularly when linguistic structure matches the logical or visual structure; Dessalegn and Landau 2008; Franconeri et al. 2012; Roth and Franconeri 2012).

For example, Hermer and colleagues (Hermer-Vazquez et al. 1999) argued that although different aspects of a problem are accessible without access to linguistic encoding (e.g., long wall *left of* short wall, blue short wall), binding of the different aspects is impossible without language. In this way, language is acting as a mediator between the visual system (what one sees) and the cognitive system (how one categorizes what is seen). Also, when linguistic information is provided in a similar structure as the comparison (e.g., showing a square that has a green *left* side and red *right* side, then pointing out that the green is to the *left* versus the red is to the *right*; from Dessalegn and Landau 2008) then binding is likely made easier through this parallel structure. It has been argued that this is because the linguistic information maps directly onto the incoming visual information (Roth and Franconeri 2012), which diminishes the need for additional cognitive manipulation. It follows then, that labels invite comparison, particularly when the information it provides matches the perceptual/relational information at hand. In short, language may be acting to unify information into a single representation whereby the representation can then be manipulated or acted upon more flexibly and subsequently used to make a direct comparison to an existing structure (e.g., to decide whether two structures are the *same* or *different*).

Another possibility is that language provides a mode of thinking about a problem (Slobin 1987) by providing a category into which the problem constituents can be parsed (e.g., Lupyan and Casasanto 2015) which in turn directs attention to the relevant elements (Boutennet and Lupyan 2015). This possible mechanism pushes the effect of language to preceding stimulus experience by directing attention to the relevant stimulus attributes in

a rapid and automatic manner, in addition to affecting later cognitive processing. From this view, language acts to create categories into which stimuli are to be slotted, thereby biasing (or warping) subsequent perception to match the established category, which will vary by a particular language (i.e., culture; reviewed in Lupyan 2012). This process is best described by Lupyan (2012) using an example from the color literature:

In the case of color, this means that after learning that certain colors are called “green,” the perceptual representations activated by a green-colored object become warped by top-down feedback as the verbal label “green” is co-activated. This results in a temporary warping of the perceptual space with greens pushed closer together and/or greens being dragged further from non-greens. Viewing a green object becomes a hybrid visuo-linguistic experience.

As such, this alternative mechanism of language differs from the previously described possible mechanism in three important ways: 1) the effect of language is immediate, occurring simultaneously with perceptual processing rather than in a more sequential order, 2) language has a modifying effect rather than a mediating effect, and 3) its effect is evident at the attention-level of cognition rather than at the deeper, later occurring comparison-level.

A third, more simple possibility is that language does something else (like simply provide a robust memory strategy for maintaining the goal of the task at hand), although this hypothesis is more difficult to test. One commonality between each of these proposals is that language is viewed as separate from the spatial representational system and that these two systems interact. In any case, language might also be considered as either obligatory

or optional. Language-as-obligatory assumes that verbal and nonverbal systems are intertwined such that nonverbal reasoning is dependent upon language acquisition and that language activation is automatic, while language-as-optional considers them as completely separate systems that must be co-engaged such that success in one modality is relatively independent of success in the other. Lupyan (2012) laid out a similar argument for language's rapid and automatic influence on "non-verbal" cognition: language affects online visual/perceptual processing and is not as deep as Whorf's (1956) proposal that language directly alters cognition such that they are equivalent. Although Lupyan thinks that language has an automatic effect on reasoning, he also believes these effects are transient. Landau and colleagues (Landau and Dessalegn 2008; Landau and Lakusta 2009) have reached similar conclusions that language effects are transient, but they take the position that language must be intentionally engaged before its effects can be seen. These potential mechanisms will be further explored in Chapter 4.

1.3 What are the underlying neural mechanisms?

Aside from investigating the role of language in the development and promotion of relational reasoning, it is important to examine the underlying neural mechanisms associated with this type of reasoning. Forthcoming research by Kojori et al. (under review; in Krawczyk 2012) has revealed that areas of the prefrontal cortex (PFC), occipital cortex and parietal cortex are increasingly involved in the processing of relational information as relational complexity increases. Supporting evidence for the role of PFC has been provided by a number of different lab groups (Waltz et al. 1999;

Christoff et al. 2001; Bunge et al. 2005; Wendelken et al. 2012) each pointing to left-lateralization of such processes in PFC. Other researchers have found areas such as basal ganglia (Melrose et al. 2007), inferior parietal lobule (Wendelken et al. 2011), cerebellum and visual cortex (Kalbfleisch et al. 2007) to be co-activated with PFC in certain relational reasoning tasks, indicating that a network of neural areas associated with this type of reasoning is distributed and extends far beyond the borders of PFC. Additional evidence suggests high overlap between visual relational reasoning and semantic analogical reasoning (Ferrer et al. 2009; Krawczyk et al. 2010) with respect to the brain areas engaged.

The dependence of relational reasoning on PFC and the slow development of this brain area have led some researchers to suggest that relational knowledge development follows PFC development (Robin and Holyoak 1995; Halford et al. 2010). Since PFC is evolutionarily late-emerging (Preuss 1995; but see also Fuster 2008), some researchers suggest that relational reasoning is restricted to apes (Thompsen and Oden 2000) or may even be uniquely human (Penn et al. 2008). However, PFC is not the only brain area in which relational processing occurs, therefore, it would be inappropriate to draw a direct link between the two. In the next sections, I will briefly discuss some important aspects of brain development in relation to reasoning abilities and will further explore previous findings linking specific brain areas to relational reasoning in both children and adults.

1.4 Lateralization and handedness

In light of the neural findings described above, it may be tempting to conclude that relational reasoning is left-lateralized in the brain; however, the role of brain lateralization in cognition is still not well understood, even in the non-human research (e.g. Hopkins et al. 2007). Lateralization is common in other animals (Vallortigara 2006) both in terms of hemispheric specialization and handedness, pawedness or eyedness (including visual field biases; see also Fagard 2006 for overview of a special issue of *Developmental Psychobiology*). There are evolutionary benefits to lateralization including more efficient brain use at the individual level and predictive group behavior at the population level (Vallortigara 2006).

Lateralization of behavior has been linked to hemispheric specialization beyond motoric control (with each hemisphere controlling the contralateral side of the body) to emotional processing. For example, Casasanto and colleagues have shown that positive valence is often attributed to the same side as one's dominant hand, both in adults (Casasanto 2009; Casasanto and Jasmin 2010) and in children (Casasanto and Hennez 2012). Similar findings for other apes have been recorded by Quaresmini et al. (2014). Thus, lateralization is important for the *organization* of cognition even if its evolutionary benefit to human cognition is unclear.

Some consider the preponderance of right-handedness in humans to be a consequence of left hemisphere specialization of language (Annett 2002), while others consider these to be relatively independent (Kinsbourne 1997; Witelson 1990). Michel and colleagues (2013) go so far as to argue that the development of handedness contributes to the

development of language in children, as they move through a series of sensorimotor skills (as first suggested by Arbib 2006). Although Michel and colleagues concentrated on strength of handedness, some researchers have suggested that right-handedness alone is the key to language, demonstrating that left-handers have language pathologies or are more susceptible to cognitive pathologies (Smith et al. 1989), such as *left-right* confusion (Hannay et al. 1990, but see Jordan et al. 2006 for null findings). Furthermore, *left-right* confusion has been linked to perception of symmetry (Brandt and Mackavey 1981; although see Sholl and Egeth 1981 for opposing evidence), which the human body displays particularly well. I will explore these potential differences in my study of handedness effects on verbal and nonverbal performance in Chapter 5.

Others argue that, handedness aside, the hemispheres are differentially used for various cognitive tasks. For example, some have suggested that language acquisition begins in the right hemisphere earlier in life but then shifts to the left-hemisphere such that early-learned words continue to be processed later in life predominately by the right hemisphere while later-learned words are processed by the left hemisphere (Bowers et al. 2013). In fact, the right hemisphere has been implicated in certain cases of recovering from aphasia, although only for certain types of lesions (Anglade et al. 2014). Aside from language, a left hemisphere advantage for processing categorical relations (i.e., is a dot *above/below* a line) and a right hemisphere advantage for processing coordinate spatial relations (i.e., is the dot *near/far* from a line) has been suggested by Niebauer (2001) and others (e.g., Kosslyn 1987). Furthermore, there appears to be a right lateralization for spatial working memory and left lateralization for nonspatial working memory (although

not conclusively; D'Esposito et al. 1998). I will examine my findings for supporting evidence of hemispheric specialization in Chapter 6.

1.4.1 What about shifting the frame of reference?

In the task I have designed (see Chapter 2), participants must be able to shift the frame of reference in order to encode the appropriate relation. That is, the location of the stimulus (on the screen) must sometimes be ignored in order to encode the experimentally correct relation. In this way, the relative location of the stimulus (global spatial information) on the screen sometimes mismatches the relation depicted within the stimulus (local spatial information): in these cases, an incongruence is apparent which may distract from the participant's goal to encode only the relation depicted within the circle. Effects of irrelevant location information on judgments have been demonstrated many times in the literature. The typical effects rendered are usually response time measurements, and two domains of studies, those of the Simon effect (see Simon 1969) and the spatial Stroop effect (MacLeod, 1991), have illustrated such effects in both developmental and neural studies. In a Simon task, the relevant stimulus feature is a nonspatial physical feature, such as color or shape, and the irrelevant stimulus feature is the location in which it appears. The Simon effect refers to the fact that responses are faster when the stimulus location corresponds to the location of the assigned response (e.g., the stimulus requires a *left* key-press and appears on the *left* side of the screen) than when it does not (e.g., the stimulus requires a *left* key-press and appears on the *right* side of the screen). The spatial Stroop task provides a similar spatial incongruency as the Simon task, wherein the stimulus location is irrelevant.

In the spatial Stroop task, the relevant stimulus dimension is a word or symbolic feature that conveys spatial information, where a *left* key-press to the word LEFT is faster when the word appears on the *left* side of the screen than when it appears on the *right* side of the screen. These tasks tap similar neural areas such as anterior cingulate, supplementary motor area, visual association areas, inferior temporal cortex, inferior parietal areas, dorsolateral prefrontal cortex, inferior frontal areas, and caudate nucleus (Peterson et al. 2002). One study investigating neural areas activated by the Simon task indicated similar, but adjacent areas: pre-supplementary motor area, superior parietal lobule and cuneus (Wittfoth et al. 2006). Interestingly, within the Simon task, location-based incongruencies additionally activated the left fusiform gyrus (Wittfoth et al. 2006). These studies set up comparisons for my own study, which compares congruency of the stimulus position to the spatial relation it depicts with incongruency of stimulus position and spatial category depicted. This comparison, in my study, can potentially provide answers about response-selection processes and particularly account for shifting attention between spatial relations: processes that some researchers propose are influenced by language (refer back to section 1.2).

1.4.2 **The developing brain**

The human brain develops from center-to-peripheral and backwards then forwards such that the PFC is one of the last cortical areas to develop (see Qiu et al. 2015 for review). Over the first year of life, the total volume of the brain increases by 101%, but only increases by 15% over the second year: these increases are due largely to gray matter

growth and less so to white matter growth (Knickmeyer et al. 2008) which follows a prolonged developmental trajectory, continuing to develop through adolescence (Qiu et al. 2015). Gray matter comprises neurons while white matter comprises the connections between neural areas. It appears that brain development follows a hierarchy such that the most basic, receptive (sensory) areas develop and connect first, and the integrative, higher-level cognitive processing areas develop and connect later in life (Guillery 2005). In this way, the infant brain is characterized by dense, local connections whereas development slowly adds long-distance connections both within and between hemispheres (e.g., Wendelken et al. in press): this likely explains why infants start out as information-processing machines and slowly develop into reasoning beings.

Infants are not born with all their inter-cortical connections, although they are largely born with the spatial distribution of cortical thickness that they will have as an adult. Li et al. (2015) showed that the infant brain is fluctuating in cortical thickness and asymmetry during the first 2 years of life, although they found that overall spatial distribution of thickness was largely consistent across these ages and reflected similar structural differences as is seen in adulthood. They (Li et al. 2015) took MRI scans of infants from 0, 1, and 2 years of age and calculated changes in cortical thickness and asymmetry. They found that over the first year of life infant brains got thicker, particularly in areas that started out thicker such as prefrontal, temporal, and inferior parietal cortices, as well as insula cortex and orbitofrontal cortex: areas, they suggest, largely corresponding to heteromodal association cortices. Areas that showed less growth were those that were classified as thin and were mainly found in the precentral gyrus, postcentral gyrus,

paracentral lobule, superior parietal cortex, and occipital cortex: regions which largely correspond to unimodal cortices. These findings support the conclusions of Guillery (2005) that sensory (unimodal) areas develop first and higher-level cognitive areas and connections (heteromodal) develop later.

Over the second year of life, however, fewer cortical regions got thicker – particularly, the slow-growth areas from year 1 plus posterior portions of cingulate sulcus, occipital pole, and entorhinal cortex – while some got thinner – particularly, bilateral medial superior frontal, bilateral orbitofrontal, bilateral superior temporal cortex, right frontal pole, right inferior frontal gyrus, and right cuneus cortex (Li et al. 2015). It is interesting infants as young as 3 days old are able to categorize spatial relations (Gava et al. 2009) when there is so much growth still happening in neural areas associated with relational reasoning; however, since these infants were performing basic spatial categorization (i.e., the judgments were largely based on perceptual information rather than purely relational information) it is unlikely their PFC was necessary for making these judgments. Since my task, described in Chapter 2, has a basic reasoning component (congruent trials) in addition to a purely relational component (incongruent trials), I would expect to similarly find a lack of PFC control over the basic reasoning judgments, although I may find activation for the pure (incongruent) relational judgments: these findings are discussed in Chapter 6.

The language areas of the brain, on the other hand –the involvement of which in relational reasoning is contested – appear to be developed earlier in life². These language

areas include left inferior frontal gyrus (Broca's area) and extend to left superior temporal lobe (Wernicke's area) for most right-handed individuals, although females tend to be more bilateral in their language areas as are left-handed persons (however, for contradictory evidence see Plante et al. 2006; Sommer et al. 2008). These structures are thought to be generally responsible for verbal production (Broca's Area) and comprehension (Wernicke's Area) and are present at birth, although the pathway which connects the two will continue to develop into toddlerhood (Perani et al. 2011). These structures are present in other primates, as homologues (Petrides and Pandya 2009). However, there is accumulating evidence that these so-called language areas have other functions as well. Recent evidence links the functioning of the language areas with inferior PFC in human adults (Lupyan and Mirman 2013; Lupyan et al. 2012), which suggests the traditional language areas are activated in cognitive controls tasks, such as those involved in categorization. Furthermore, there is evidence of differential neural activation for early-learned words compared to later-learned words in areas outside of these traditional areas: the precuneus shows increased activity for early-learned words while lateral inferior PFC areas show increased activity for later-learned (Fiebach et al. 2003).

1.4.3 Mapping brain development to relational reasoning development

The development of relational reasoning appears to follow the slow maturation of the brain, and particularly the PFC, such that reasoning ability increases with age, presumably as the necessary neural connections are made. Aside from relational reasoning, PFC houses many executive functions including rule switching and working

memory (e.g., Wendelken et al. 2012). Working memory activity is also correlated with age and appears to be housed in the superior frontal sulcus (extending anteriorly to precentral sulcus) and the intraparietal cortex, bilaterally (Klingberg et al. 2002). Both of these areas, plus the inferior parietal cortex, are also correlated to working memory capacity (with respect to working memory activity), but only on the left side. Therefore, as these brain areas continue to develop, working memory skills increase which likely further promote relational reasoning abilities.

Aside from the connections that continue to form from infancy through adolescence, children gradually come to use the same neural areas that adults engage while performing specific tasks. For example, by the age of 6 years children engage the same set of brain regions as adults during analogical reasoning (Wright et al. 2008; Wendelken et al. 2011). However, the process by which these regions are formed into a reasoning network continues to be refined throughout adolescence. Wendelken et al. (2015) provide a sketch of the changing connectivity – both increasing and decreasing connections – between key frontal and parietal areas that are part of a developing reasoning network which appears to stabilize around age 14 years. However, Richland et al. (2006) demonstrated that children between ages 9-11 years can reliably make correct relational matches even in the face of distracting information, so even if the neural connections are still being solidified, children may be capable of successful cognitive reasoning, though likely through alternative neural pathways and cognitive strategies from what they will use as adults. This is an important point to take note of: sometimes behavior appears the same despite the underlying neural correlates being different. Such a distinction is particularly

important to make whenever cross-sectional or cross-species comparisons are made, regardless of whether these comparisons are of behavior or neural correlates.

Three studies by Bunge and colleagues offer a case in point, providing evidence for differential activation in PFC and strategy use between children and adults. Wendelken et al. (2011) provided evidence for increased functional selectivity across ages 6-18 years in rostralateral PFC (RLPFC) and inferior parietal lobule (IPL): at first these two neural areas were activated indiscriminately for first-order and second-order relational judgments, then activation for first-order relations diminished with age whereas activation for second-order relations stayed elevated. These researchers suggested that increased functional selectivity in RLPFC could be partly accounted for by cortical thinning in IPL.

Crone and colleagues (2009) demonstrated a developmental shift of neural activation patterns for adolescents (8-12-year-olds) compared to adults in PFC areas as they performed relational problems, which could indicate that children are solving these problems differently than adults. Behavioral evidence suggests that children initially neglect to consider more than one dimension when searching for possible dimensional changes in a Raven's Progressive Matrices test. Specifically, 8-12 year old children exhibited similar response times to adults on problems with two dimensions to consider, but performed with much less accuracy. Children performed more slowly than adults on problems with no or only a single relation to consider, but were more accurate on these problems than the 2-relation problems, yet still less accurate than adults. These findings

suggest children may not be exploring all the available options in search of the correct one and that children failed to allocate sufficient time to the higher relation problems as compared to adults. Similar results have been obtained for older low-performing individuals (9-14 year olds and adults), which may suggest a deficit in working memory information organization (e.g., monitoring or manipulating the available options).

Lastly, Bunge and colleagues (Wright et al. 2008) demonstrated age-related changes in the recruitment of VLPFC as well as temporal cortex and other cortical regions for processing the retrieval of individual semantic relations in a 4-item analogy task. They further found age-related changes in RLPFC where this region is engaged by children (6-13-year-olds) in analogy trials as it is for adults but, too late to have an effect on behavior. From the results of Bunge and colleague's studies, we expect to find increasing performance with increasing age of participants in our own relational judgment task, which will be discussed in Chapter 4.

It appears that there is differentiation in activity between anterior and posterior regions within PFC generally as well as within specific areas of PFC (Krawczyk et al. 2011; Wendleken et al. 2012; Bunge et al. 2005). For example, Wendelken et al. (2012) discovered a domain-specific gradient along the anterior portion of the middle frontal gyrus (an area of the RLPFC considered to be domain-general for relational integration) where visuo-spatial judgments activated areas dorsal to the areas activated by semantic judgments. In my own neural study, I will check for differential neural activity in anterior and posterior regions of brain areas: these results are discussed in Chapter 6.

1.4.4 Development of attention networks

Additional networks that seem to vary according to ventral and dorsal pathways may also be identified in my study. In particular, my task may involve activation of attention networks since it is dynamic and requires the participant to shift their frame of reference (see Chapter 2). The *dorsal attention network*, which is thought to be responsible for focusing attention on a task via top-down processing, consists of bilateral intraparietal sulcus and frontal eye fields (Farrant and Uddin *in press*) while the *ventral attention network* responds to unexpected events to break ones attention in a bottom-up fashion and includes the neural areas of the temporoparietal junction and ventral frontal cortex, mostly in the right hemisphere.

Other attention networks have been described previously in different terms. For example, others have divided attention networks into three parts: orienting, alerting and executive (Pozuelos et al. 2014). The orienting network comprises the superior parietal cortex, temporoparietal junction and frontal eye fields and is responsible for shifting attention to exogenous cues. The alerting network involves the locus coeruleus and areas of the frontal and parietal cortices: these areas are responsible for sustained attention and response readiness. The executive network comprises the anterior cingulate cortex lateral and ventral PFC and the basal ganglia and is responsible for processing conflict. These described networks develop asymmetrically, each following a separate trajectory, with alerting appearing to mature first and executive attention appearing last. This possibly illustrates what has been measured in cognitive development studies of children moving

from primarily bottom-up attention mechanisms to better top-down attentional capacities (Pozuelos et al. 2014; Farrant and Uddin in press). I should note that the technique used in my neural study primarily records only from cortical areas, therefore the subcortical areas described in these studies – such as basal ganglia and locus coeruleus – will not be investigated in this thesis.

1.4.5 Mapping relational reasoning in the adult brain

Many researchers have attempted to pinpoint areas of the brain that are preferentially activated for a number of processes, including working memory and relational reasoning (see Appendix C). Many studies of relational reasoning have focused on the connections between prefrontal cortex and parietal areas and are especially focused on executive functions such as task switching and rule learning, as evidenced by the previous discussion of studies with children. These fronto-parietal connections are well documented and central to spatial encoding in humans (Wendelken et al. 2008; Amorapanth et al. 2009; Wendelken et al. 2012; Cocchi et al. 2013) and monkeys (Chafee and Goldman-Rakic 2000). Activity in parieto-occipital cortices during spatial relational reasoning is also well documented (Ruff et al. 2003). More recently, the superior temporal lobe has been implicated in spatial awareness as well. In fact, the superior temporal gyrus (STG) subserves spatial awareness and encoding in monkeys (bilaterally), but only the right STG is thought to house this processing in humans, while the left STG has been adapted to language processing (Karnath et al. 2005): yet another link of space and language.

1.4.5.1 *Dichotomies in representation.* I might expect to find differential activity between *above-below* and *left-right* relational planes considering there have been a number of such dichotomies discovered in other arenas of spatial reasoning. Some studies have focused on dichotomizing and dissociating general mechanisms for such spatial processes as navigation (e.g., route vs. survey encoding: Shelton and Gabrieli 2002), perspective taking (e.g., first vs. third person perspective: Vogeley and Fink 2003) and working memory (e.g., spatial vs. nonspatial working memory: D’Esposito et al. 1998). For example, the medial prefrontal and medial parietal cortex are associated with egocentric encoding of space (e.g., route encoding: Shelton and Gabrieli 2002; 1st person perspective: Vogeley and Fink 2003). In terms of visuo-spatial decision making, Zacks and Michelon (2005) did not find areas of the brain that were selectively activated for *left-right* decisions in a frame of reference task, but did find selective activation for determining whether objects were the *same* or *different*, despite their different orientations. In my own project, I will look for differential neural activity between *above-below* judgments and *left-right* judgments (see Chapter 2 for description of task).

1.4.5.2 *Dissociations in representation.* Krawczyk et al. (2008) examined analogical matching abilities of two patient populations: one group had PFC damage and the other had temporal lobe damage. Although both patient groups performed worse than the healthy controls, individuals with damage to the temporal lobes had intact goal maintenance and resistance to distraction, while individuals with damage to PFC were less able to overcome these distractions. In short, patients with frontal lobe damage erred

in making perceptual or semantic matches rather than the correct relational matches on the analogy problems. Additional lesion studies have revealed a double dissociation between relational reasoning and both episodic memory and semantic knowledge: temporal lobe patients show impairment on declarative recognition memory for names while prefrontal patients show impairment on second-order relational reasoning (e.g., Waltz et al. 1999). For example, PFC patients are successful on relational problems where only one relation has to be considered, but fail when two or more relations are required for a comparison (e.g., matching items in an analogy task for both shape and color). However, aphasics are more impaired on low-dimensional categorizations (i.e., objects with few shared features such as “things that are green”) than on high-dimensional categorizations (i.e., objects with many shared features such as “farm animals”; Lupyan and Mirman 2013). This may seem odd since detecting perceptual similarities have been shown to develop first and to take precedence in comparison tasks. Together, these neurological findings provide further evidence that, although language supports cognitive functioning, reasoning and categorization are possible without access to it. Therefore, I may not find neural activation in language-related areas. On the other hand, I may find that language-related areas are differentially activated for the two relational planes.

1.5 Sex differences in spatial ability and neural activity

That males outperform females on spatial tasks is almost expected in spatial research today and in terms of cognitive functioning it appears to be the most predominant sex

difference studied (Kimura 1999). Some suggest these differences do not emerge until age 10 (e.g., Maccoby and Jacklin 1974), but others suggest differences can be seen by preschool (e.g., Levine et al. 1999; Bjorklund 2012). Children are learning to form and use cognitive and real maps to help them navigate and make sense of their surroundings around the preschool and early school years (Bjorklund 2012). During this time of learning, males generally show better performance on spatial-orientation and spatial-visualization tasks while females perform better on memory tasks (Bjorklund 2012). However, these findings should not suggest that males are “naturally” better at spatial tasks. For example, Levine, Vasilyeva, Lourenco, Newcombe and Huttenlocher (2005) found that boys and girls from low socioeconomic status (SES) families did not differ in performance on these tasks; only children from middle and high SES families displayed a male advantage. The source of some of the differences could be related to parent-child interactions during play: children who hear more spatial language from their parents have higher spatial skills and better spatial language skills (Pruden et al. 2011) suggesting that the activities in which children participate (such as block building) can compound or create sex differences.

Finding sex differences at such a young age as preschool has implication for schooling and other educational techniques given that spatial skills have been linked to achievements in the sciences, math and engineering (Ehrlich et al. 2006; Stieff et al. 2013; Uttal et al. 2013a; Uttal et al. 2013b). Furthermore, in light of the findings for SES, there must be an environmental influence that propels boys to be advantaged over girls. If this environmental influence stems from the school system, then measures must be taken

to give girls the same opportunities to practice their spatial skills. Parents could also be a source of differentiation in how they speak to their sons versus their daughters. The most highly robust findings of the male advantage are on mental rotation tasks (e.g., Voyer et al. 1995). Again, some researchers attribute this isolated difference to biological predispositions (e.g., Kimura 1999; Geary 2006), but environmental factors such as child-initiated activities cannot be ignored, especially if these two combine to create even larger differences (Baenninger and Newcombe 1995).

To help answer the nature-nurture question, Baenninger and Newcombe (1989) performed a meta-analysis of spatial training effects and concluded that spatial skills can be enhanced, but more importantly that males and females improve equally, even with brief training (for similar findings see Stieff et al. 2013; Uttal et al. 2013a). Thus, since brief training is equally as effective as sustained practice, then even a few minutes taken for a class lesson can have huge benefits for girls, who may not be getting the same sustained practice that boys get from their play behavior. Due to the mixed findings on sex differences, and the ensuing implications for any differences, I will test for a male-advantage in each of my studies where such comparisons are possible (Chapters 4-6). I will further explore the educational implications and applications in the General Discussion (Chapter 7).

Kessler and Wang (2012) suggest that the difference between the sexes in spatial ability has less to do with general spatial ability, but they suggest it has more to do with individuals' social skills, such as empathy and embodiment. Their argument is that

individuals with high social skills are able to take the place of another easily and automatically, and, therefore, should be very good at mental rotation in perspective taking to see exactly what another sees; whereas, individuals with low social skills should be less able to perform embodied processing in part because they are less empathetic, but should be good at perspective taking when only considering what is in the other person's line of sight (since no embodiment is required in that process). These predictions are in part based on developmental trajectories since perspective-taking in terms of "line of sight" is developed by age 2 and in part because autistic children and most primates can do "line of sight" but not embodied perspective taking; embodied perspective taking does not develop until age 4 or 5 years. When embodiment skill is considered, it becomes evident that those individuals who have higher social skills (i.e., more empathetic) are better at embodiment problems, although slower to compute the solution. This last finding could explain any difference of reaction time between the sexes in my own study, expecting, then, that females will be slower than males but be just as accurate in problem solving.

When looking at *left-right* confusion specifically, there is again an apparent sex difference: women confuse these relations more than men (Jordan et al. 2006; Hirnstein et al. 2009). Although this has been shown time and time again by measures of self-report (Hannay et al. 1990; Jordan et al. 2006; Wolf 1973), it has not always shown in performance (Teng and Lee 1982; Manga and Ballesteros 1987; Snyder 1991). It appears then, at least, that women are more likely than men to report that they are less competent at *left-right* judgments regardless of their actual competence (although Jordan et al.,

2006, found that women's self-assessment were better correlated to their actual abilities than were men's assessments).

In terms of sex differences in neural activity, it has been shown that women are more efficient than men in terms of neural processing in a visuospatial task without concurrent performance differences (Christova et al. 2008). Furthermore men and women appear to differentially activate the two hemispheres in certain tasks, further providing supporting evidence of a difference in strategy use (Georgopoulos et al. 2001). Additionally, it has been shown that sex differences may exist across a number of cognitive tasks despite performance differences, with men showing stronger neural signals and signals in a larger number of areas (Bell et al. 2006; Weiss et al. 2003; Thomsen et al. 2000). With respect to hemispheric differences in language processing, it has not always been shown that men are more lateralized than women (Plante et al. 2006; Sommer et al. 2008). In Chapter 6, I will examine potential sex differences in neural activity, particularly in terms of hemispheric differences.

1.6 Hypotheses and aims

I have developed a set of tasks to examine four questions in a series of four studies: 1) how verbal and nonverbal knowledge of *above/below/left/right* develops from 5 years to 10 years of age, 2) whether verbal knowledge aids performance on a nonverbal task that requires judgments of these relations, 3) whether strength of handedness promotes either verbal or nonverbal performance, and 4) whether the neural correlates of these judgments

differ across relational plane (*above-below* vs. *right-left*) or congruency type (congruent vs. incongruent).

A question that underlies all of these studies concerns the connection between language and spatial cognition. Although we will not attempt to answer whether spatial language is equivalent to spatial cognition, especially in development (e.g., Hendricks et al. 2010), there is ample evidence that language plays a role in higher-level reasoning and problem solving (e.g., Baldo et al. 2010). The question we aim to answer is *how* language (e.g., having the relational term for a relative position) is related to relational reasoning (e.g., identifying relative spatial location of an object). Previous research has indicated that monkeys are able to successfully make relational judgments, even without language to guide their performance (Goodwin et al. 2012); therefore, it is not likely that language is necessary for this processing.

In the first study (Chapter 3) I summarize a study that investigated the order of development of verbal and nonverbal knowledge of the four relations from ages 5 to 10 years. Comparing across age groups, we (Scott et al. 2015a) attempted to capture the change in structure and gain of information in the cognitive system as development progressed. We hypothesized that chunking would lead to a systematic decrease of the entropy in the cognitive organization of relational concepts as an increasing number of different relational tasks were performed more similarly with increasing age. We expected concomitant improvement in performance across multiple relational tasks with

age, culminating with minimum cluster entropy at age 10 years and near adult levels of performance.

In the second study (Chapter 4) I sought to better understand the role of language in making nonverbal dynamic relational judgments. We (Scott, Georgopoulos, Sera, to be submitted) did this in two ways. First, we examined developing knowledge of a broader set of relations than had been studied previously, both verbally and nonverbally. This enabled us to address the hypothesis determining whether language *acquisition* was critical for successful performances. Thus, if language systematically precedes and causes the ability of nonverbal relational judgments to emerge (i.e., that nonverbal performance is language acquisition-dependent), we should find better nonverbal performance along the vertical (*above-below*) relational plane than the horizontal (*right-left*) plane, since knowledge of the words *above* and *below* precedes knowledge of the words *right* and *left*. Second, we manipulated the accessibility of language, which sheds light on whether language *use* is the critical factor, in spite of the available vocabulary. Thus, if having the labels is not enough, then we should find no correlation between verbal and nonverbal performance, but we should see overall improvement in the nonverbal task when children are primed to apply a linguistic strategy (i.e., to *use* labels).

In the third study (Chapter 5) I explored the potential role of handedness in verbal and nonverbal performance. Handedness is often attributed to lateralization of the brain (e.g., Smith et al. 1989; Knecht et al. 2000a; Knecht et al. 2000b) and the evolution of the language areas (Hewes 1973; Hopkins et al. 2007); therefore, degree of handedness may

contribute to *left-right* performance on the nonverbal task. However, knowledge of which hand is which (through one's own handedness), outside of any potential effects from brain lateralization, is an important but relatively unstudied parameter in relational reasoning research. Since the dominance of one hand over the other creates an asymmetry – which could be used as a strategy for telling *left* from *right* – I will explore the development of this knowledge as well as the development of handedness, including how each measure relates to verbal and nonverbal performance. I hypothesized that if handedness was a true measure of left-hemisphere development (and subsequently language development) then I expected to see a positive correlation of performance to degree (or strength) of handedness. I also examined the strength of footedness and degree of eyedness.

In the final study (Chapter 6) I investigated the underlying neural mechanisms of nonverbal performance. Our (Scott, Sera, Leuthold, Georgopoulos, submitted) broad predictions were that the two sets of spatial relations (or relational planes: *above-below* vs. *left-right*) are represented in the brain differently despite a lack of matching differential results in performance (i.e., all adults should perform a simple relational task perfectly). Specifically, we expected to find areas of the brain that are differentially activated for one set of relations compared to the other set. We also expected to find differential neural activity for the two types of congruencies: congruent trials versus incongruent trials. It might be the case that *left-right* reasoning taps into the same neural areas used in reasoning about incongruencies – where the relative position of something does not match its global position; therefore, we compared the activity maps of relational

plane differences and congruency differences to check for shared areas of differential activity. I will also draw comparisons Goodwin et al.'s (2012) findings. Unlike Goodwin and colleagues (2012) - who recorded only from monkeys' frontal and parietal areas, areas associated with spatial relational reasoning (Friedman and Goldman-Rakic 1994; Chafee et al. 2007) – we conducted a whole-brain analysis. Nevertheless, in my analyses we will pay special attention to frontal and parietal activity. Research looking specifically at the evolution of fronto-parietal connections suggests these pathways emerged early in primate evolution and are responsible for mediating ethologically relevant movement patterns (Kaas et al. 2012), so it is likely that I should similarly find differential activity in both frontal and parietal areas, if these two brain areas are equally important in making relational judgments of the sort I examine in this thesis.

Chapter 2 Overview of Methods: Nonverbal Task

2.1 Introduction

The experimental portion of this dissertation is divided into four chapters, each examining nonverbal performance on *above*, *below*, *right* and *left* using the same computerized task. The first experiment (Chapter 3) concentrates on comparing the development of nonverbal knowledge of these relations to developing verbal knowledge of the associated labels. The second experiment section (Chapter 4) focuses on the direct link between verbal and nonverbal performance and includes a discussion of how language may enhance nonverbal reasoning. The third experiment (Chapter 5) considers the possible role of handedness in the development of both verbal and nonverbal knowledge. The fourth experiment (Chapter 6) uses a modified version of the task and is devoted to examining the neural correlates of adult performance on the nonverbal task; specifically, whether *above-below* relations are neurally coded differently than *left-right* relations. Therefore, in this chapter, I will describe the nonverbal task used in these experiments.

My nonverbal task design is based on the work of Goodwin and colleagues (2012) who measured the performance of macaque monkeys. I used this task in order to maintain a comparative component with which I can potentially collate and extrapolate findings from my study and Goodwin's in future work. I kept the design as simple as possible in

order to yield clear results which I could confidently interpret. In designing the task, I kept a number of factors in mind: 1) keep it as similar to Goodwin's so that any comparisons to the monkey data would be appropriate, 2) keep it entertaining enough to hold children's attention, and 3) keep the response basic enough to be implemented in an MEG machine without biasing neural activity. To achieve this, I did two things: 1) in the behavioral study, I made a computer task which used a touch screen so that children could indicate the exact relation they wished to relay to the experimenter, and 2) in the MEG study, I provided adults with a button box which mapped directly to the relations with which they were responding.

2.2 Nonverbal spatial reasoning task

I based the design of my task on Goodwin et al.'s task (Figure 1.1). Similar to their task, my task was dynamic, was presented via a computer, and tested participants' abilities to make correct judgments of *above-below* and *left-right*. However, unlike Goodwin et al., the dot and line were presented simultaneously and there was an added layer of complexity: my task included both congruent and incongruent trials. Incongruent trials were trials in which the object-centered frame of reference (the relation of the dot and line) indicated a spatial relation that differed from the environment-centered frame of reference (the relation of the entire stimulus to the computer screen). Only incongruent trials required relational reasoning for successful judgments, while congruent trials could be successfully judged using perceptual matching. Therefore, in my analyses of this task, I made two comparisons: relational plane (*above-below* vs. *left-right*) and congruency (congruent vs. incongruent).

2.2.1 Materials and design.

This task required the participant to encode and remember on which side of the line a dot had appeared. The dot could appear *above*, *below*, *to the left* or *to the right* of the line (Figure 2.1A). The dot and line were encompassed by a circle and the whole stimulus could appear in 1 of 4 quadrants on the screen (Figure 2.1B), in one of 12 places around the perimeter of the computer screen. The stimuli appeared in each of these locations three times within a trial set for a total of 48 trials, but the order of presentation was randomized for each person. The participant had to remember the dot's relative position for 3 seconds before responding by touching the computer screen on the same relative side of a new line. The circle measured 225 pixels in diameter, the line bisected this circle and the dot was displaced straight out from the center of the line by 56 pixels.

The relative position of the stimulus on the computer screen could either match or contradict the internal relation represented. Therefore, each relation was either congruent or incongruent. Trials where the relative location of the stimulus on the screen matched the relation depicted by the dot and line were congruent (stimulus at top of screen, dot *above* line); trials where these relationships did not match were incongruent (stimulus at top of screen, dot *below* line; see Figure 2.1C for an example). For the congruent trials, children would be correct 100% of the time if they followed a strategy of touching exactly where they saw the stimulus, thereby (perhaps) not encoding the actual relation. For the incongruent trials children could only answer correctly by using flexible relational coding.

In the three studies with children (Chapters 3-5) auditory feedback was provided to the child on each trial: a 3 second clip of applause was played after a correct answer; a 1 second zapping sound was played after an incorrect response. Children started with the same set of 8 training trials before moving on to the test trials. The experimenter never provided verbal relational terms to describe the position of the dot to the line. The only terms used were “here” and “there” to we could avoid providing the child with a verbal strategy for the game.

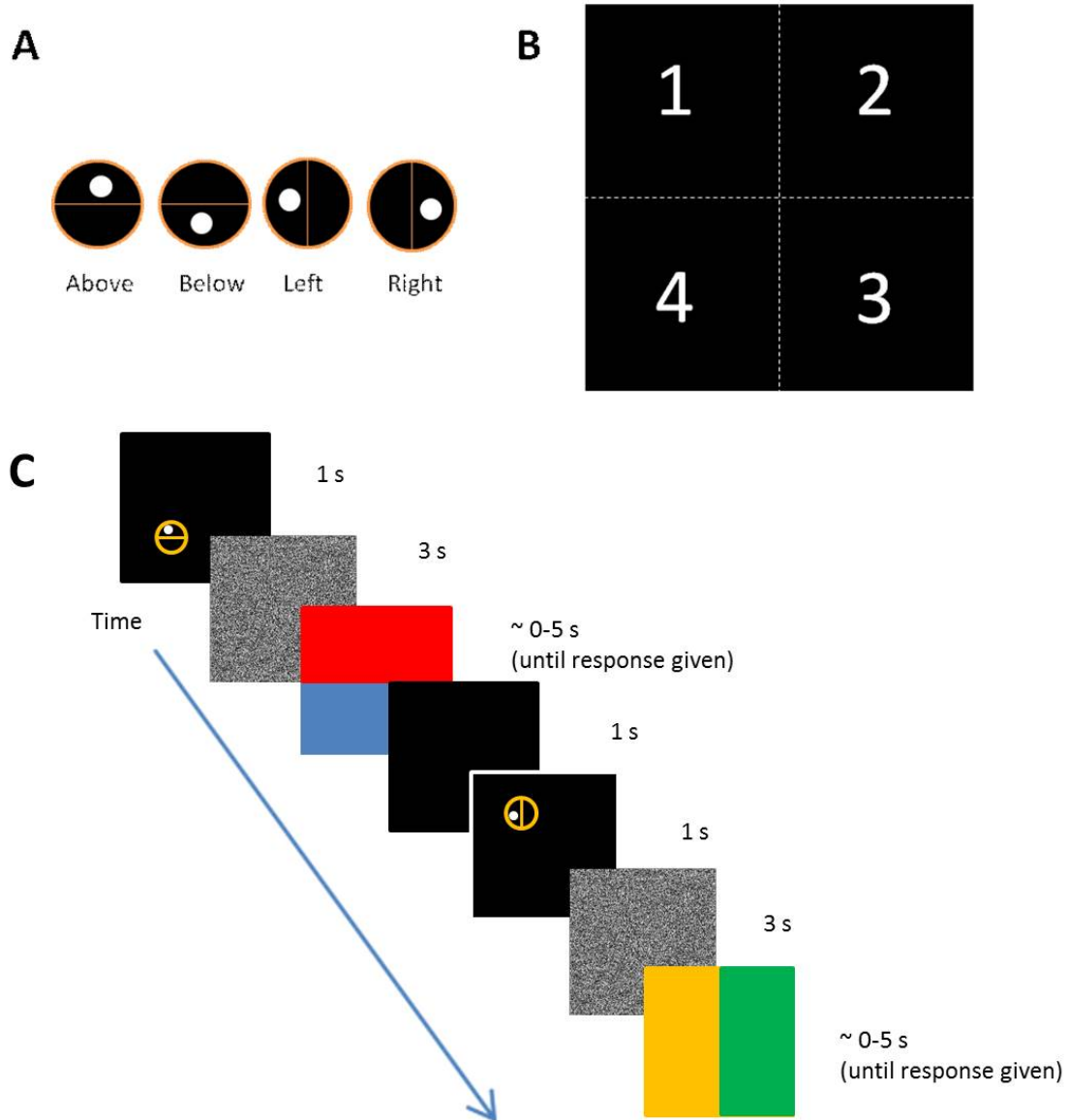


Figure 2.1 Illustration of nonverbal task used for the studies with children. (A) Set of all four stimuli types illustrating spatial relations of *above*, *below*, *right* and *left*. (B) The four quadrants in which the stimuli appeared. Every relation appeared in each quadrant three times. Each quadrant was divided into sub-quadrants for a total of 16 possible locations on the computer screen; however, stimuli only appeared in the 12 locations along the perimeter of the screen so stimuli never appeared near the center of the screen. *Above* trials were congruent when the stimulus appeared in quadrants 1 or 2, but incongruent when they appeared in quadrants 3 or 4. The

opposite was true for *below* trials. Similarly, trials in which the stimulus for *right* were congruent were when they appeared in quadrants 2 or 3, and incongruent when they appeared in quadrants 1 or 4. The opposite was true for *left* trials. (C) Illustration of the screen progression of two trials for the nonverbal task and the amount of time each screen was displayed. The upper-most panel shows the first screen (an example of *above* incongruent trial), the middle panel is the distracter screen (static snow), and the lower-most panel shows the response screen. The second example trial depicts a congruent *left* trial. Figure originally published in Scott et al. (2015a)

2.2.2 Procedure

Instructions provided to each child were as follows: *“I am going to show you how to play this computer game. It is kind of hard to explain so I am going to tell you how to play the game, then we are going to play together, and then I will let you play on your own. In this game there is a circle and it going to appear anywhere on the screen. There is going to be a line that goes through the middle of the circle and there is going to be a dot on one side of this line. You have to remember which side of the line you saw the dot. Then the circle is going to disappear and the screen will do something funny [white noise]. Then the screen will split in half and each side will be a different color. If you can imagine that the line that goes through the middle of the screen is just like the line that went through the middle of the circle then I want you to touch the screen on the side of the line that the dot appeared. Do you understand how to play the game? Are you ready to try a few with me?”*

Then, the experimenter showed the child how to play the game by performing the first three trials of the game correctly then purposely answered incorrectly on the 4th trial to show them what happened when an incorrect answer was provided. This way, the children were also introduced to the feedback sounds: an applause followed correct responses, but a zapping sound followed an incorrect response. When the 8 training trials were finished, the experimenter asked, “Do you think you know how to play the game?” If children said “yes” then the test trials were started and the child was no longer provided with verbal feedback. If a child responded that they did not understand the game, then the 8 training trials were done again. An example of what the child saw is illustrated in Figure 2.2.

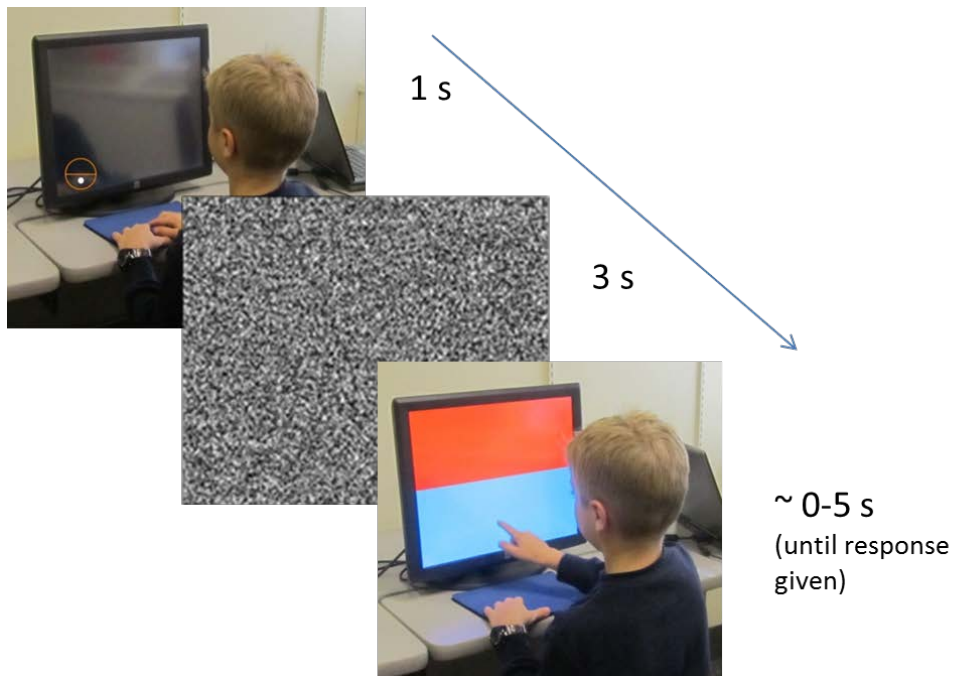


Figure 2.2 Illustration of progression of one trial for the nonverbal task and the amount of time each screen is displayed. The upper-most panel shows the first screen (an example of “below” congruent trial), the middle panel is the distractor screen (static snow), and the lower-most panel shows the response screen and the child making a correct response.

2.3 Pilot study

Thirteen children were recruited to participate in a pilot study. The purpose of the study was to test the experimental methods and decide on the most appropriate parameters for the computerized nonverbal task. Specifically, the parameters that were altered included exposure time to stimulus (0.5 seconds to 2 seconds), length of the white noise delay (1 second to 5 seconds) and time to respond (5 seconds to 10 seconds). Also, the size of the stimuli, location of the stimuli on the screen and the exact appearance of the stimuli (e.g. form and color) were adjusted. The parameters I selected yielded results that differentiated the age groups (e.g., not all participants were performing at ceiling). The data collected from these individuals were not used in any analyses.

2.4 Adult study design

Participants performed a slightly altered version of the same computerized nonverbal task given to children. Again, the dot and line were encapsulated by a circle (Figure 2.3A) that measured 225 pixels in diameter: the line bisected the circle and the dot was displaced straight out from the center of the line by 56 pixels. Also the same, was that the stimuli appeared in one of 12 positions along the perimeter of the screen and were defined by quadrants (Figure 2.3B). Each relation appeared in each position once for a total of 48

unique trials. The position of the stimulus was either congruent or incongruent with their locations on the screen (Figure 2.3B).

A trial progressed as a series of 3 screens, followed by 1 second of empty black screen: (1) the stimulus appeared against a black background for 1 second, (2) replaced by static white noise for 3 seconds, (3) replaced by a response screen that disappeared after a response was given or after 5 seconds had passed. The response screen comprised a single orange line against a black background: the line bisected the entire screen in the same direction as the line that had bisected the circle earlier in the trial. Responses were provided via a button box onto which the relations directly mapped (i.e., right button = *right*, top button = *above*, etc.). No training was provided. Participants received only verbal instructions and received no feedback on any trial to avoid eliciting an experimentally irrelevant neural response. Responses were provided for every trial and we recorded whether participants pressed a button prior to the appearance of the response screen (this occurred only 6 times over 576 trials: 1% of all trials).

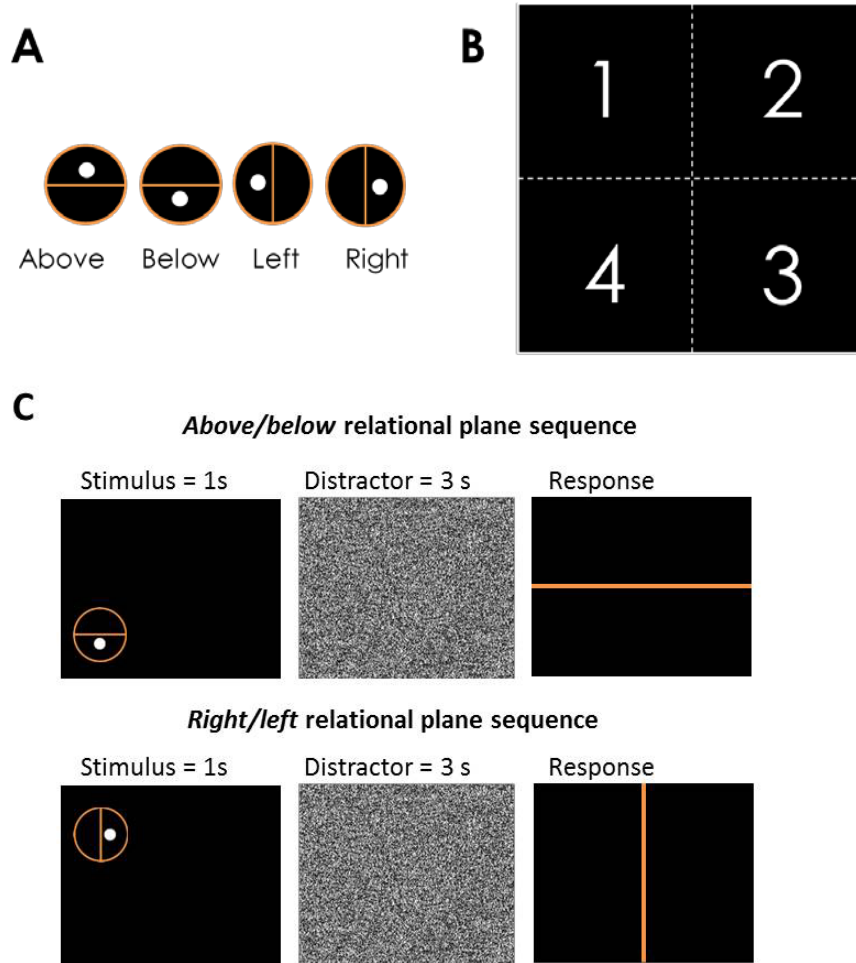


Figure 2.3 Illustration of computer task used in adult study. A) Example of each of four spatial relation stimuli. B) Each stimuli appeared in each subquadrant 3 times. C) Progression of two trials: the upper panel illustrates a below congruent trial, the lower panel illustrate a right incongruent trial (NB: this drawing is not to scale and does not reflect the actual stimulus size with respect to the computer screen).

Chapter 3 Development of verbal and nonverbal knowledge of four relations in 5-10-year-olds as entropy reduction

3.1 Overview

In this chapter, I summarize the results of Scott et al. (2015a): a study which investigated the order of skill acquisition in verbal and nonverbal judgments of *above*, *below*, *left* and *right* relations. In that work, we applied an information theoretic approach to also assess quantitatively the gain of knowledge across various elements of the cognitive domain of spatial, relational knowledge, as a function of development. Specifically, we examined changing spatial relational knowledge from ages 5 to 10 years. Our analyses consisted of a two-step process. First, we performed a hierarchical clustering analysis on children's verbal and nonverbal spatial relational performances to determine which aspects of verbal and nonverbal knowledge were performed similarly by each age group as well as to discover how the verbal and nonverbal performances clustered together. We next used two measures of entropy to capture the gradual emergence of order in the development of relational knowledge. These measures of "cognitive entropy" were defined based on two independent aspects of chunking, namely (1) the number of clusters formed at each age group, and (2) the distribution of verbal and nonverbal performances across the clusters. We found that both measures of entropy decreased with age in a quadratic fashion and were positively and linearly correlated. The decrease in entropy and, therefore, gain of

information during development was accompanied by improved performance. These results document, for the first time, the orderly and progressively structured “chunking” of decisions across the development of spatial relational reasoning and quantify this gain within a formal information-theoretic framework.

3.2 Introduction

Decisions are made across all domains of knowledge, including spatial, perceptual, linguistic, conceptual and social domains. However, these knowledge domains are structured and restructured gradually throughout cognitive development. Piaget was the first to suggest that adaptive mechanisms, such as assimilation and accommodation (Piaget 1964 1977), guide the emergence of different cognitive abilities across domains. He suggested that these mechanisms work through the addition and alteration of knowledge structures and that the subsequent cognitive abilities emerge in a predictable order. However, Piaget was not able to precisely define these mechanisms, yet they remain important for understanding how children eventually come to represent the world. Many researchers have provided evidence in support of Piaget’s (1955) stages (Pascual-Leon, 1970; Flavell 1971; Fischer 1980; Demetriou 2013), but operationalizing the mechanisms that drive cognitive change through restructuring has remained elusive.

Previous attempts to operationalize these mechanisms were grounded in dynamic systems approaches. For example, van Geert (1998) used a dynamic systems approach to model

Piaget's mechanisms of cognitive change, an approach that describes developmental order as being driven by self-organization (e.g., Thelen and Smith 1994; Spencer et al. 2012). Stephen, Dixon and Isenhower (2009) also relied on self-organization as the process driving structural change in their study of cognitive development, and like our approach, they used the construct from information theory known as entropy. Entropy is a powerful approach for studying development, because it provides a method for quantifying how characteristics (e.g., skills, knowledge) are related and change over time.

Information theory was first used to study how information is processed and stored, especially in terms of efficiency (Shannon 1948; Newell et al. 1958). It has often been applied to the study of memory (Miller 1956; Simon 1974; Ericsson et al. 1980; Cowan 2001), but in this paper we apply information theory – and specifically entropy – to quantify the structural change in developing cognition and to discover the developmental order of those constructs. Specifically, we offer a method for applying it to the emergence of spatial relational reasoning in 5-10 year olds: that is, children's ability to recognize the relative position of one object with respect to another as being *above*, *below*, *right*, or *left*.

We chose to investigate spatial relational reasoning because this ability, and spatial thinking more broadly, has been implicated in promoting other cognitive skills (National Research Council 2006; Uttal et al. 2013a; Uttal et al. 2013b). For example, the National Research Council (2006) reported that spatial thinking provided a means of representing a problem abstractly which could then be reasoned about and solved through mental manipulation: a skill that is necessary for problem solving in science and mathematics. In

addition, relational reasoning, broadly defined, has been proposed as a cognitive feat that separates humans from other animals, especially when combined with linguistic abilities (Gentner, 2003; Gentner 2010). There have been many recent attempts to explain how relative spatial positions are categorized (in infants: Quinn 1994; Gava et al. 2009; in healthy and disordered cognition: Hayward and Tarr 1995; Landau and Hoffman 2005; in computational models: Regier and Carlson 2001; Lipinski, et al. 2012) and how the ability to represent relative location interacts with language (Loewenstein and Gentner 2005; Dessalegn and Landau 2008; Ratliff and Newcombe 2008; Shusterman et al. 2011). Because much previous work has centered on the role of human language in relational reasoning, we investigated the development of spatial relational knowledge across the verbal and nonverbal modalities. Furthermore, we chose to compare *above/below* with *right/left* since these represent spatial relational planes (i.e., vertical and horizontal, respectively) which are learned at different ages. That is, 5 year olds have been shown to know the verbal terms *above* and *below*, but it is typically around 6 or 7 years of age that children master the terms *right* and *left* (Clark 1980; Cox and Richardson 1985; Martin and Sera 2006).

Since spatial relational reasoning is poorly understood in terms of which knowledge domains are in place first (e.g., verbal or nonverbal) and how this knowledge is restructured across development, we were interested in identifying the organizing principles that governed the reorganization of children's knowledge structures. There are a number of different ways in which spatial reasoning could be structured. For example, the knowledge structure of different spatial relations could be based on the specific

identity of the relation (e.g., above) such that all instantiations of the relation are performed equally well. On the other hand, the modality in which the relation is experienced (verbal or nonverbal) or the plane to which the relation belongs (e.g., vertical or horizontal) could be major factors in organizing spatial relational knowledge. To investigate the nature of changing conceptual organization over 6 years of development, we focused on the information theoretic process known as “chunking”.

Chunking consists of combining individual items into units (chunks) which can then be processed efficiently given their smaller number (Miller 1956). Miller gave the example of recalling 5 monosyllabic words (e.g., cat, dog, bee, rat, cow) rather than 15 phonemes (or letters: c, a, t, d, o, g, etc.), where words are chunks of 3 phonemes (or letters).

Different types of information (e.g., words, images, etc.) can be chunked differently (e.g., as sentences, scenes, etc.) and within different capacities of memory (remembering lists of letters versus lists of digits; Miller 1956; Simon 1974), and the chunking of information is based largely on the current structure of a cognitive hierarchical organization (e.g., Larkin et al., 1980). For example, experts already have large chunks of like information organized together, making for quick retrieval, whereas novices are still learning how to organize information in the new context (e.g., chess: Chase and Simon 1973). Novices must discover on their own the optimal organization of new information with respect to already held concepts, whether to integrate new concepts with old ones or form new chunks in memory. For example, a chess master “sees” the relationships between pieces on the board (e.g., attack or defend) and combines the position of pieces into meaningful chunks, whereas novices are more likely to remember only the position

of single pieces on the board (Chase and Simon 1973). This suggests that chunking begins on an item-by-item basis with each individual piece of information being processed separately; then, after a set of similar items (or, in the case of chess, positions) have been chunked together, new but similar information can be processed as if it belonged to the previously formed group. Taken together, chunking expedites learning of similar tasks and aids in organizing new knowledge with other knowledge like it. In this sense, chunking makes stored information more accessible and optimizes decision-making. By studying how information is processed and stored over human development, it would be possible to identify which parts of knowledge domains (or specific skills) are acquired first and provide structure to other areas, and at what points in development certain skills are performed similarly and when learning accelerates.

It has been previously demonstrated that infants have some capacity to chunk incoming information according to spatial, perceptual, linguistic, conceptual or social similarities (Feigenson and Halberda 2008; Stahl and Feigenson 2014). For example, Feigenson and colleagues presented 16-month-old infants with arrays of 4-6 same or similar objects (e.g., balls, dolls, cars, or cats) and recorded their looking time as the objects were retrieved, one at a time, after being hidden for a short period. When the objects were spatially or categorically grouped, infants would look longer at the hiding spot for objects that had not yet been retrieved (to come into view), indicating that infants expected at least one more object to be retrieved. Clearly, then, chunking is available to infants; therefore, it is a potentially powerful tool for discovering the order, or progression, of concept development (e.g., in the spatial, perceptual, linguistic, conceptual or social

domains). To our knowledge, however, this approach has not been applied to any domain of conceptual development.

In summary, the main goal of this paper is to offer an example of this new approach to the study of cognitive development. We demonstrate the approach using data from one of our current studies on the development of spatial relational knowledge in 5-10-year-olds. Specifically, we document how knowledge of the spatial relations *above*, *below*, *right* and *left* changes over development and how these concepts are reorganized with increasing age, knowledge and skill. We used hierarchical clustering analyses to identify conceptual “chunks”, and information theoretic methods to quantify the amount of organization in the cognitive system by measuring the amount of entropy at each age group. Specifically, we document how knowledge of the spatial relations *above*, *below*, *right* and *left* becomes more unified across six years of life as different instantiations of these relations gradually become “chunked” together.

We propose that chunking together different instantiations of spatial relational information is at the core of this conceptual change. However, we had no *a priori* expectation of which aspects of spatial relational information would be chunked together at each age group. Thus, we sought to discover the organizing principles through which chunking acted. As mentioned earlier, there were a number of different organizing principles that could direct chunking (see also Methods section below). We also examined the “chunks” with respect to the amount of entropy, or uncertainty, in the system. Fewer chunks indicate well-structured organization in the system and lower

entropy, whereas many chunks indicate little structural organization and higher entropy. Our two measures of entropy were: 1) cluster entropy, which involves the number of clusters at each age, and 2) task entropy, which involves the distribution of the 16 tasks across the clusters at each age group. So, the amount of entropy *in the chunks* (i.e., task entropy) could be used as a measure of how the concepts are structured in the cognitive system (i.e., what organizing principles govern each structure), while the entropy *within an age group* (i.e., cluster entropy) reflects the changing amount of structure in the cognitive system with development. Comparing across age groups, we were able to capture the change in structure and gain of information in the cognitive system as development progressed. We hypothesized that chunking would lead to a systematic decrease of the entropy in the cognitive organization of relational concepts as an increasing number of different relational tasks were performed more similarly with increasing age. We expected concomitant improvement in performance across multiple relational tasks with age, culminating with minimum cluster entropy at age 10 years and near adult levels of performance. Remarkably, until our study, verbal and nonverbal knowledge of these four spatial, relational concepts had not been examined in a single cross-sectional study.

3.3 Methods

3.3.1 Participants

Children between the ages of 5,0 and 10,11 were recruited from the Minneapolis-St. Paul metro area. These children came mostly from middle to high SES Caucasian families. We chose this age range because at the age of 5 years children have been shown to have some

spatial relational knowledge, and at 10 years their relational knowledge should be close to adult levels. Each of 6 age groups (5, 6, 7, 8, 9, and 10) included 10 boys and 10 girls for a total of 120 children. To ensure that the entire range within each age group was represented, both younger and older children at each age group participated so that the mean age was at the midpoint for each group. The children had no known cognitive or language deficits. An additional 19 children were tested but their data were not used: 13 participated in pilot work, while the 6 other children were discovered to have a known cognitive disorder when they came to the lab or were consistently exposed to a language other than English at home. This research complied with University of Minnesota IRB approval and HIPAA protocols.

3.3.2 **Tasks**

Children performed a total of 16 tasks of spatial relational reasoning. Four spatial relations were investigated: *above*, *below*, *right* and *left*. Knowledge of each relation was tested in two conditions within each of two modalities: verbal production, verbal comprehension, nonverbal congruency, and nonverbal incongruency (4 relations x 2 conditions x 2 modalities = 16 tasks; see below for additional task details). Children always performed the nonverbal tasks before the verbal tasks to avoid priming children with a verbal strategy for the nonverbal tasks and always performed the comprehension tasks last in order to avoid giving children the correct label for each relation before they performed the verbal production tasks. Some may argue that each instantiation of a spatial relation should not be considered separate tasks, but we chose this approach because we were interested in trying to capture how decisions across various

instantiations of relational tasks were chunked together as a function of development. Again, we had no a priori expectation of which aspects of spatial relational information (e.g., relation type, relational plane, modality of task, task condition, or no pattern) would be chunked together at each age group and from which we could interpret an underlying cognitive mechanism. However, it should be pointed out that this study was focused only on spatial tasks, and, hence, a possible extension of this approach to other domains will need to be explored in future studies.

3.3.2.1 *Nonverbal conditions* These tasks were described in the General Methods section. For this set of analyses, we treat each relation within each condition of congruency as separate “tasks” and refer to them as such throughout this chapter.

3.3.2.2 *Verbal conditions.* The eight verbal tasks consisted of a tic-tac-toe-like magnetic board with a circle in the middle square (modified from Cox and Richardson 1985). Children were first required to say the location of a magnet on the board with respect to the circle (production), then asked to place a magnet onto the board with respect to the circle (comprehension; see Figure 3.1). The magnet could be placed *above, below, to the right* or *to the left* of the circle.

In the production task, parents were allowed to watch their child’s performance upon request so long as they did not interact with or speak to their child. In these cases, the parent played the role of the confederate; however, the parent did not actually participate in the game beyond sitting behind the other tic-tac-toe board completely out of their child’s view. The instructions provided to the child were as follows:

In this game, I am going to put a magnet on the board and you need to tell [confederate's name or parent] where the magnet is in terms of this circle (experimenter points at the circle). [Confederate's name or parent] cannot see your board so you need to be as specific as possible. If you tell her/him where the magnet is in terms of the circle then s/he will know exactly where to place their magnet so that their board looks just like yours.

For the comprehension condition, the instructions were as follows:

In this game I am going to tell you where to place a magnet on the board in terms of this circle (experimenter points at the circle). You put the magnet where I tell you in terms of the circle.” Then, children were told, “Put the boy (or dog, etc.) above (or below, right, left) the circle.

No feedback was provided to children with respect to correctness of their response. Trials progressed in sets of four wherein each relation was seen only once per set. The order the relations were given within a set was randomized using a Latin square design.

Performance in these tasks, and in the nonverbal tasks, was quantified as percent correct.

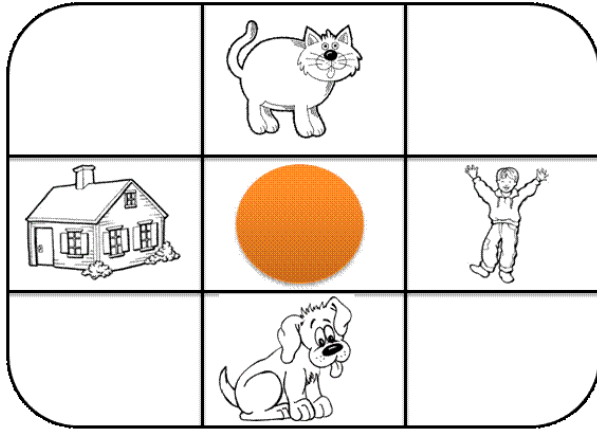


Figure 3.1 Verbal task. Illustration of the apparatus for the verbal task. Each object represents the exact appearance of each magnet. The “cat” is in the *above* position; the “child” is in the *right* position; the “dog” is in the *below* position; and, the “house” is in the *left* position.

A potential caveat in this design is that the house is a potential confound due to its “other” category placement as an inanimate object. However, it is equally unlikely that any of these objects would be seen as naturally appearing above an orange circle (which perhaps could be construed as a sun even though no story line was provided and the only label attributed to the orange circle was “circle”). Nevertheless, subsequent analyses showed the house was not a confound: children were just as likely to incorrectly place/label the position of the house as they were the other three magnets.

The confederate had the order of magnet location already written on their score sheet so they did not actually have to place the magnets on the board, but did so anyway to keep up the premise of the game. In this way the confederate did not have to see the child’s board in order to know if the instruction was correct. Occasionally, there was experimenter error in placing a magnet out of order and these cases were marked on the

score sheet (n=3); however these cases were not removed from analyses. Answers were considered correct if they produced a relative term that was closely related (similar to Cox & Richardson 1985). For instance, the child could produce “on top” for “above”.

3.3.3 Hierarchical tree clustering

We hypothesized that a key mechanism in the development of relational knowledge is the progressive treatment of different tasks as the same (i.e., they become chunked) such that more items should be packed into fewer clusters with increasing age. We tested this hypothesis by conducting a hierarchical tree clustering analysis (Shepard 1980) of performance on the 16 tasks for each of 6 age groups, separately. We then searched for consistent grouping (i.e., chunking) of task performance to find out whether a knowledge structure had been formed that represented particular organizing principles or task characteristics (e.g., modality, condition, relation or plane). If tasks consistently chunked together from one age to the next (e.g., two tasks chunk at age 5 then appear as a chunk at each subsequent age), then it can be argued that each task that joins the chunk later in development (e.g., age 7) has been assimilated with the previously chunked tasks, or that the chunk at 5 years of age has been modified to accommodate the new skills at the later age.

Hierarchical cluster analyses can be used to find the general factors that underlie general performance on a set of tasks as it clusters individual task performances according to their shared factors and organizes the clusters by their similarity (Shepard 1988; Corter 1996). It is a useful analysis for capturing progressive similarity of items. In our study,

clusters were formed based on performance as measured by percentage of correct trials. The tasks that fell into a cluster, then, can be judged to be performed similarly well or similarly poorly consistently across all individuals in the group. In hierarchical tree clustering, clusters are scaled in distance starting an origin that starts at 0 for items that are the most similar and ends at 25 for items that are the most different. Therefore, the further from the origin that a cluster forms, the less similar the items are within the cluster. Furthermore, items that are placed adjacently along the origin (i.e., at the bottom of each panel in Figure 3.2) are more closely related than items placed farther apart. To examine the content of the clusters (i.e., tasks) we cut the tree at scale interval 3 (blue line across tree structures in Figure 3.2) and considered tasks to be chunked only if they formed a cluster by scale interval 2. Below scale interval 3, we considered clustered items (tasks) to be reasonably similar with performance being neither completely equal nor completely different. In this way, items in a cluster could represent tasks performed at 87 and 88% or tasks performed at 45 and 42%, etc. (percentages taken from 5 year olds' dendrogram). Cutting the trees at interval 6 (and counting only clusters formed by scale interval 5) – which makes the items in the clusters less similar to each other – yielded similar results, thus the choice of interval size does not change the results substantially. SPSS for Windows (version 21) was used for this analysis (method: between-group linkage; measure: squared Euclidean distance).

3.3.4 Cognitive entropy measures

Since relational knowledge is less developed at age 5 years than at later years, we hypothesized that relational concepts would be poorly connected (i.e., not chunked

together) at 5 years of age and, therefore, entropy would be highest at that age. We further hypothesized that entropy would decrease with increasing age, and in doing so would capture the structure that is added as knowledge is gained and suggest which different concepts have become connected or unified. Finally, we expected that a decrease in entropy (i.e., reflecting a gain of information) would be accompanied by an improvement in performance.

We identified and measured two sources of entropy. One was *cluster entropy*, S_C , referring to the number of clusters in a tree (i.e., at each age group), with respect to the maximum of 16 possible clusters, whereas the other was *task entropy*, S_T , referring to the distribution of tasks ($T = 16$) across clusters (at each age group). We calculated each entropy measure separately (Shannon, 1948), assessed their change during development, and evaluated their relation to each other, as follows.

The cluster entropy for a given tree is:

$$S_C = \log_2 N \text{ bits}$$

where N is the number of clusters in the tree. For example, for a tree with 16 clusters, $S_C = \log_2 16 = 4$ bits, and, for a tree with 2 clusters, $S_C = \log_2 2 = 1$ bit. With regard to task entropy, it should be noted that chunking cannot dictate by itself how the chunked items (tasks) would be distributed across the chunks (clusters). For example, if the 16 tasks were distributed across two clusters, then in an isotropic distribution each cluster

should contain 8 tasks; however, in any number of different anisotropic distributions the two clusters could contain 10 and 6 tasks or 2 and 14 tasks, etc. Then, to find the task entropy for a given tree (age group) with N clusters, let k_i be the number of items (tasks) in the i^{th} cluster, where $i = 1, N$. Then, the task entropy of the $T = 16$ tasks for this tree (in bits), where p is the probability of finding that distribution, is:

$$S_T = - \sum_{i=1}^N p(k_i) \log_2 p(k_i)$$

where

$$p(k_i) = \frac{k_i}{T}$$

and

$$\max S_T = S_C$$

Since the maximum task entropy is limited by the number of clusters in a tree, we defined the tree-specific (i.e., age-specific) task entropy S'_T as a fraction of $\max S_T$:

$$S'_T = \frac{S_T}{\max S_T} = \frac{S_T}{S_C}$$

Again, it should be noted that S_C and S'_T are independent of each other. In other words, there is no *a priori* reason to assume that task entropy should be anything but isotropic (i.e., $S'_T = 1$). Since S'_T is a fraction, its values range from zero to one.

3.4 Results

First, we discuss the results from the cluster analyses, and the changes that they capture in “chunking” of relational information with development. Then we discuss the changes observed in entropy reduction with development. Within each age group, cluster entropy is discussed first, followed by task entropy.

3.4.1 Hierarchical clustering

Figure 3.1 illustrates the results from the hierarchical cluster analyses, with each panel showing the dendrogram observed for each age group. Five-year-olds’ performance on the 16 tasks grouped into 10 clusters (Figure 3.2A). Each set of relational opposites (*above/below* and *right/left*) clustered according to verbal task condition (production or comprehension), forming 4 separate groups. The nonverbal tasks of congruent and incongruent formed an additional 2 cluster pairs and 4 single, discrete clusters where each relation formed a cluster within the same task condition or held a position adjacent to other relations within the same task condition. For 6-year-olds (Figure 3.2B), again, 10 distinct clusters emerged. These clusters differed from 5 year olds in two ways. Firstly, the *above/below* verbal tasks collapsed into a single cluster and the nonverbal tasks were performed more variably so each relation formed separate, distinct clusters to form the remaining 7 groups. Few changes appeared between 6 and 7 year olds (Figure 3.2C), although nonverbal congruent tasks began to merge with the *above/below* verbal tasks cluster, thus reducing the number of clusters to 9 in the 7 year olds’ cognitive organization. For 8-year-olds (Figure 3.2D), all of the verbal tasks aligned closely together along the tree’s baseline (horizontal) axis indicating that these were performed

more similarly to each other than to the nonverbal tasks, despite still forming 4 separate clusters (i.e., *right/left* comprehension as one cluster and *above/below* verbal tasks as a second cluster) where production of *right* and *left* split off as separate items (or single-item clusters). Similarly, the nonverbal tasks aligned closely along the tree's baseline axis as they began to collapse together, forming an additional 4 clusters (for 8 groups total) according to task condition. For 9 year olds (Figure 3.2E), only 3 distinct clusters emerged: *right/left* comprehension, *right/left* production, and everything else. Ten year olds (Figure 3.2F) had only 2 clusters after comprehending *right/left* collapsed with the other tasks, leaving production of *right/left* as a single cluster.

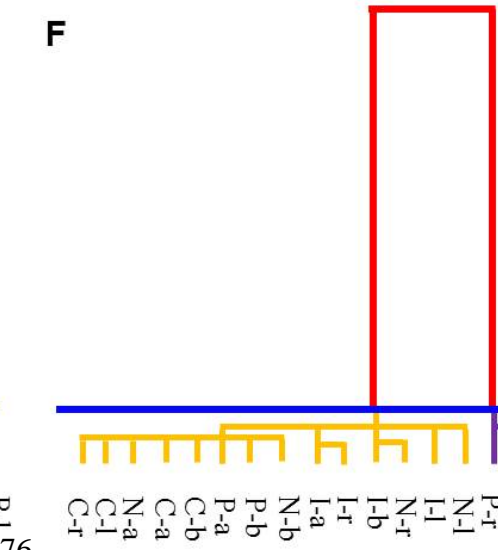
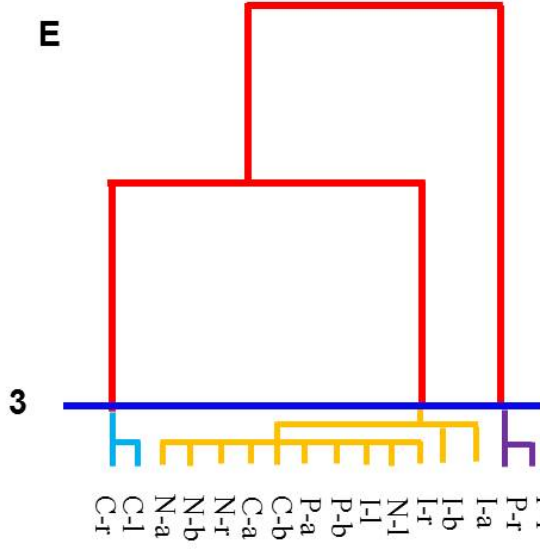
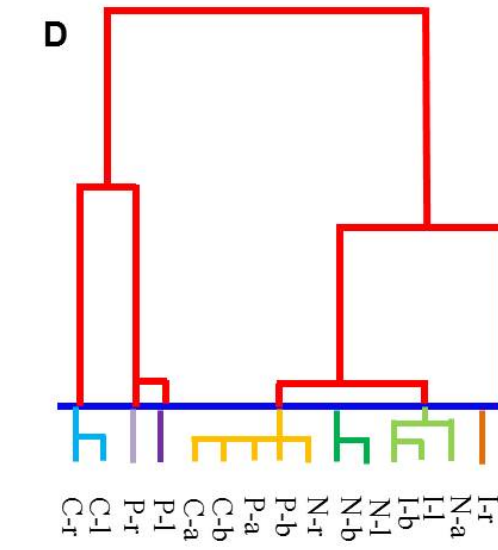
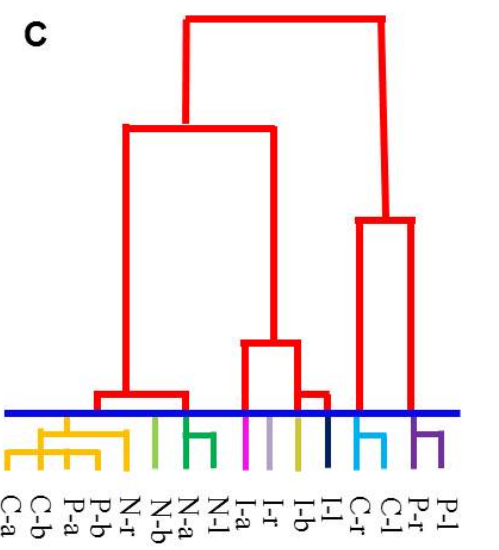
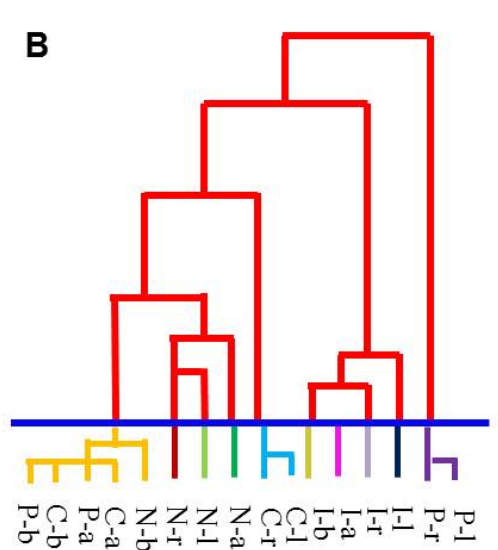
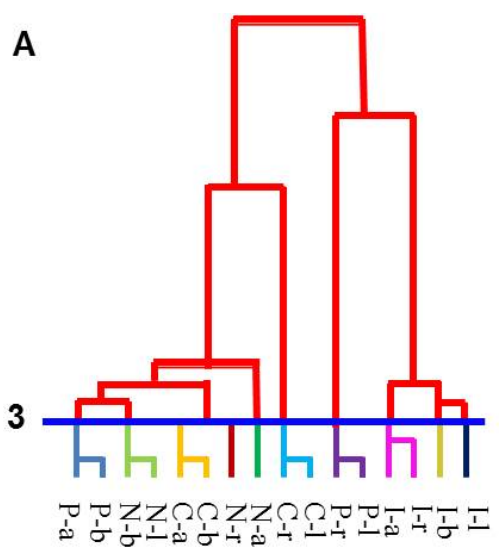


Figure 3.2 Hierarchical tree clustering of performances across the 16 tasks for each age group.

(A) The tree for 5-year-olds. (B) The tree for 6-year-olds. (C) The tree for 7-year-olds. (D) The tree for 8-year-olds. (E) The tree for 9-year-olds. (F) The tree for 10-year-olds. Increasing chunking (i.e., fewer clusters) can be seen as development progresses from age 5 (A) to age 10 (F). Clusters were defined as a group of tasks that formed a group below a scale interval of 3 (blue line). Each color at the bottom of the tree demarcates the distinct clusters. Each task is identified by the condition (capital letter) and relation (lower case letter). Key: P-production tasks; C-comprehension tasks; N-congruent trials; I-incongruent trials; a-above; b-below; r-right; l-left.

Figures 3.3 and 3.4 illustrate the relationship between correct performance, variability, and chunking. As expected, overall performance improved with development, and became much less variable over the 6-year span (Figure 3.3). We also observed that the number of clusters decreased with age (Figure 3.4), thus demonstrating fewer chunks with development. Given the diversity of the tasks, this improvement can be viewed as the outcome of a process in which the children gradually became experts in spatial judgments across relational planes and verbal and nonverbal modalities. A number of organizing principles emerged in the tree structures which underlay chunking which can be used to characterize how development unfolds.

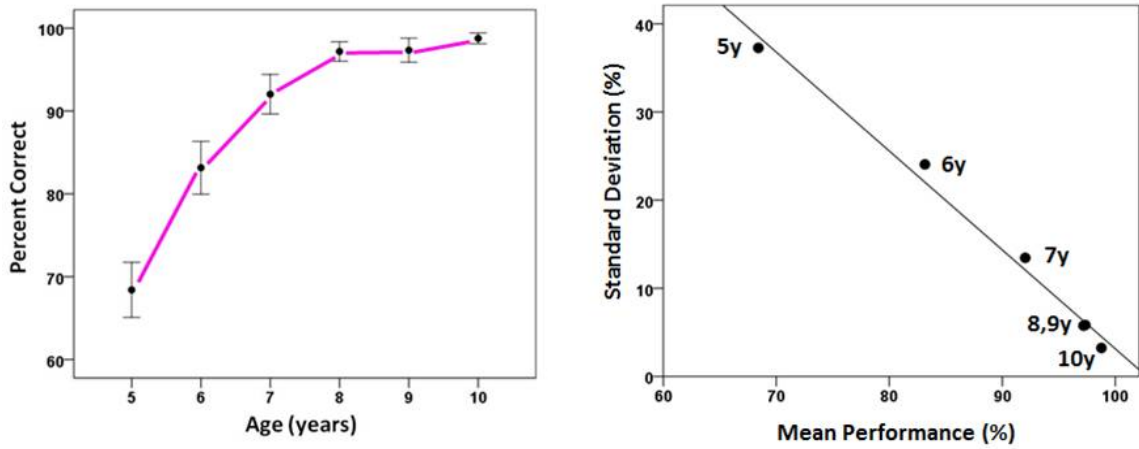


Figure 3.3 Performance as a function of age. Left panel: Correct performance (\pm SEM) increased with age, while variability decreased (error bars). Right panel: Variability in performance decreased with increasing age, and as a linear function of mean correct performance ($r^2 = 0.989$, $P = 0.000044$).

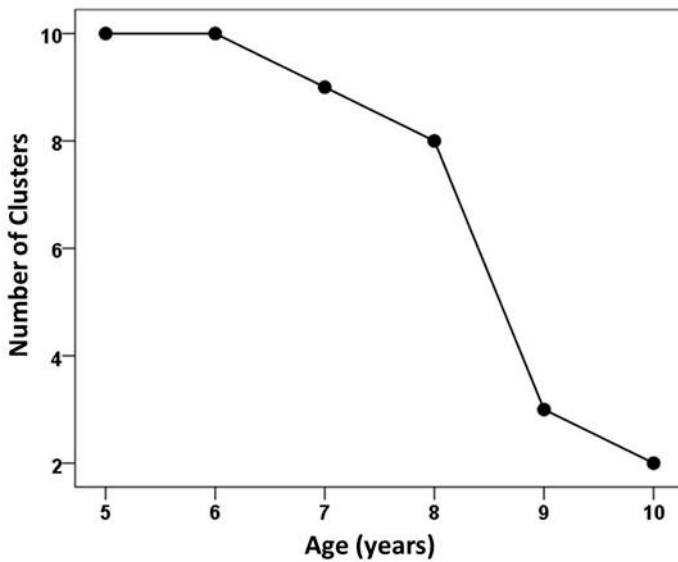


Figure 3.4 Number of clusters plotted as a function of age.

3.4.2 Cognitive entropy

We quantified the incremental chunking process that emerged from our hierarchical clustering analyses using an information-theoretic framework where we measured the entropy in the cognitive organization of each age group. From the trees, we calculated both the cluster entropy within age group, S_C , and the task entropy, S'_T . Both S_C and S'_T decreased as a quadratic function of age (Figure 3.5A and B, respectively) and were positively, strongly and linearly related between themselves (Figure 3.5C). We provide an alternative graphical illustration of changing S_C and S'_T as a function of age in Figure 7, which may be helpful in visualizing the relationship between the two measures of entropy (especially in comparing ages 5 and 6, which have different distributions across the same number of clusters). These data also reveal an inflection point which suggests a relatively large cognitive gain between the ages of 8 and 9 years. Based on our findings, this is a transition to performing nonverbal tasks similarly to each other and similarly to *above/below* verbal tasks. In other words, the nonverbal tasks begin to merge with the verbal tasks.

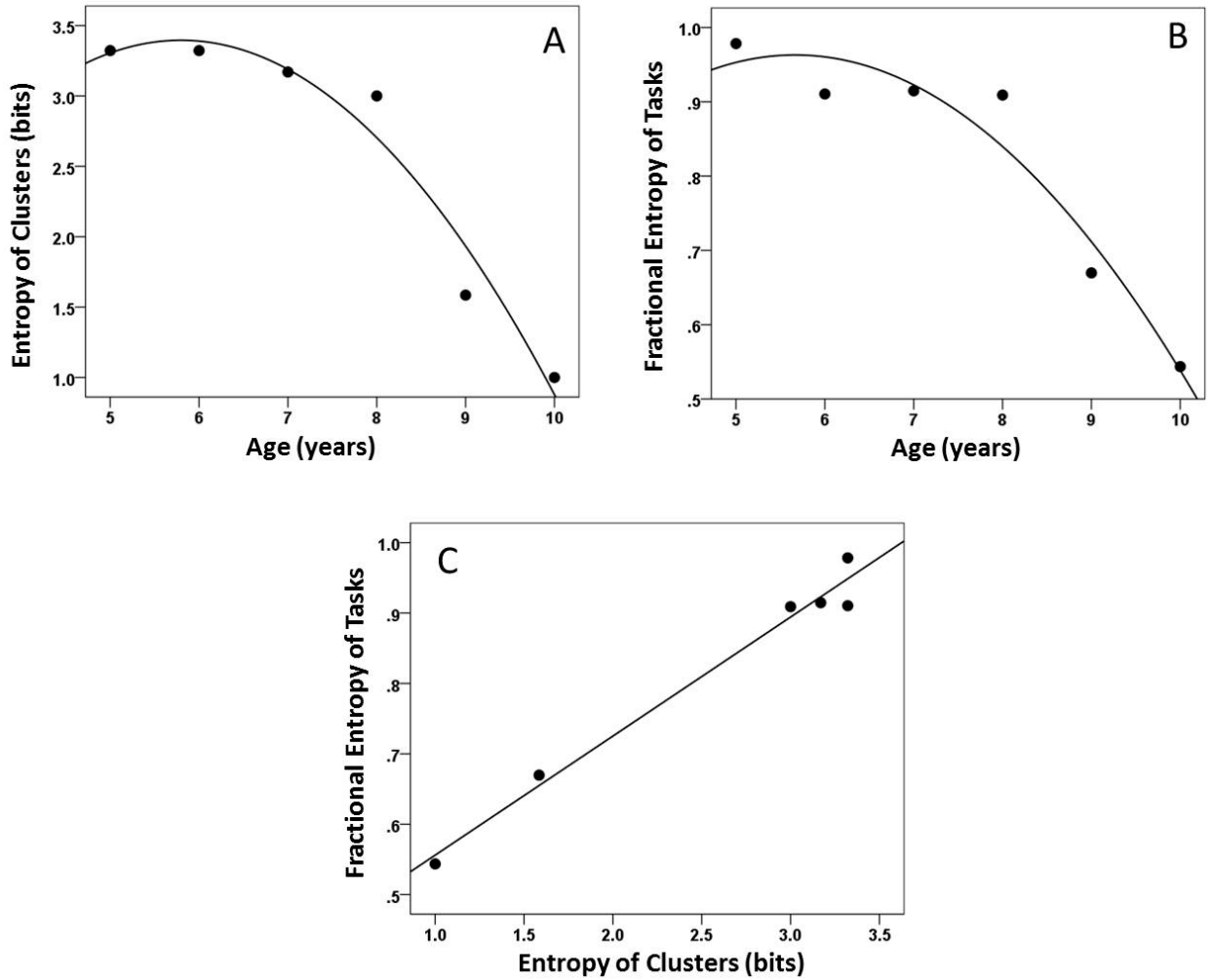


Figure 3.5 Relationship of entropy measures to age and to each other. (A) Entropy of chunking (S_C) decreased with age. (B) Entropy of tasks across clusters (S'_T) also decreased with age. (C) S_C and S'_T were highly correlated ($r = 0.98$).

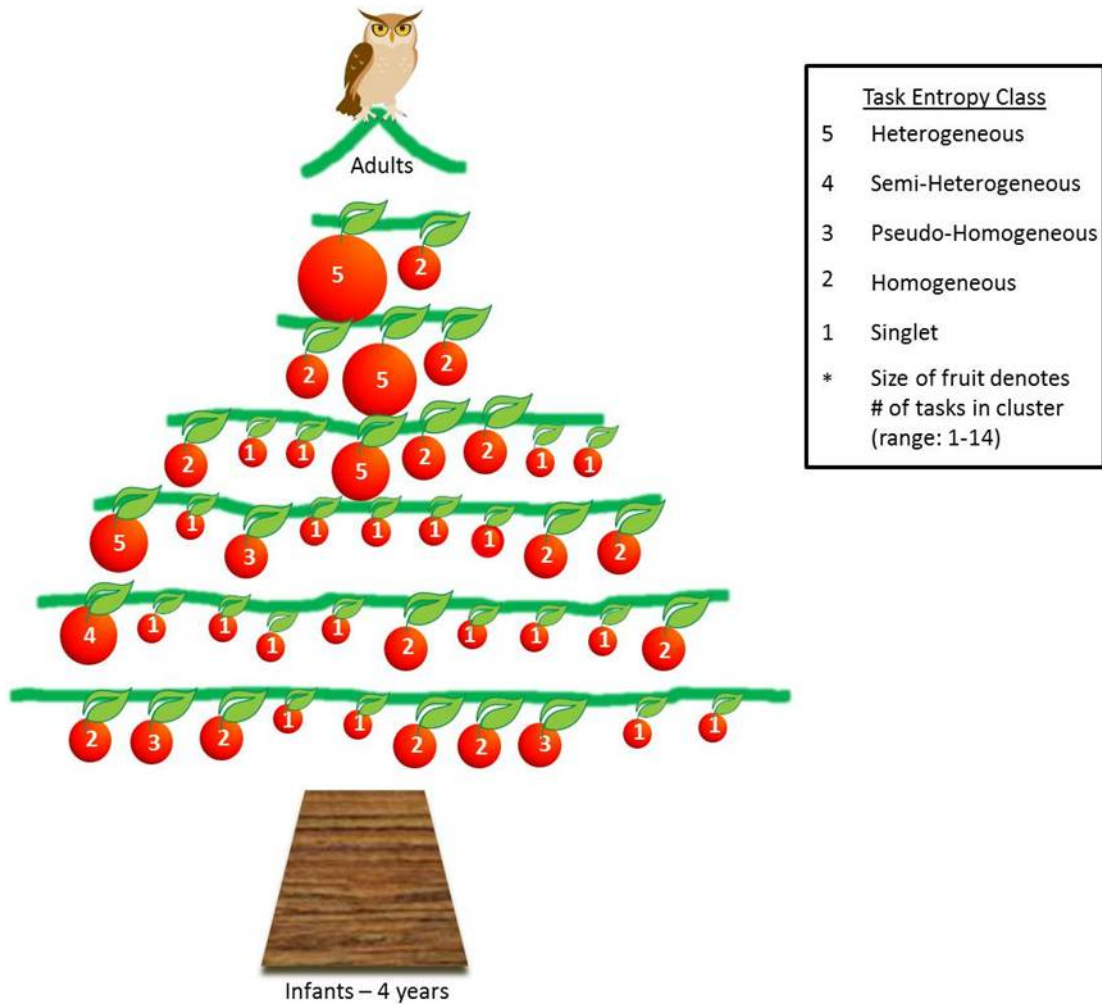


Figure 3.6 Tree representing the development of spatial relational knowledge from 5 to 10 years of age. Each branch represents one year of age, with 5 years as bottom branch and 10 years as topmost branch. Foundational spatial relational knowledge acquired between infancy and 4 years of age is represented as the trunk, although not investigated in this paper. The treetop and owl represent adults and the pinnacle of human spatial relational knowledge. Each fruit represents one cluster, the size of the fruit represents the number of items (tasks) within the cluster, and the quantity of fruit on each branch represents cluster entropy at each age. The number inside each fruit indicates the class of task entropy shown in the legend, which ranges from completely homogeneous (2) to completely heterogeneous (5). A cluster was defined as homogeneous if

tasks within the cluster came from the same relational plane, same task condition and same task modality.

We found an excellent correspondence between the ranked mean percent correct performance and both ranked S_C and S'_T (Figure 3.7, left and right panel, respectively). Although an overall better performance would be expected to be associated with a smaller number of clusters, i.e. a smaller S_C (since the clustering is based on variation in performance), the anisotropic distribution of tasks among clusters, reflected in S'_T , should be independent of the overall performance level. However, ranked performance scores were highly correlated with both S_C and S'_T (Figure 3.7).

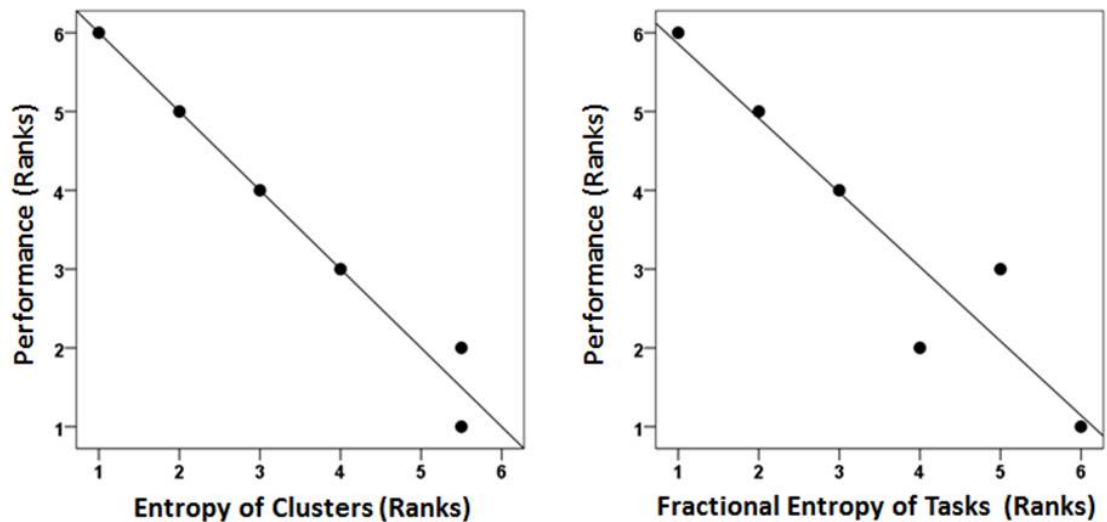


Figure 3.7 Relationship of performance to entropy measures. Ranked correct performance was highly correlated with entropy reduction. Each age group's correct performance was ranked. Its cluster and task entropies were also ranked. These ranks are and plotted against each other. (Spearman's rank correlation coefficient was 0.995 and 0.943 for the left and right panels, respectively).

3.5 Discussion

We believe that our analytic approach offers new insights into the process of cognitive development; namely, the mechanisms of restructuring (Piaget's assimilation and accommodation) that occur as knowledge is added to the cognitive system. In this paper, we have illustrated the application of this new approach using the development of relational knowledge in children. Our cluster analyses revealed the progressive treatment of different tasks as being similar (i.e., chunking) as these tasks became hierarchically organized with cognitive development. Our finding of entropy reduction captures the orderly gain of information on spatial relational judgments, as children gradually became experts in these judgments as indicated by their increasing performance accuracy. It should be remembered that the chunking measured in our cluster entropy cannot, by itself, dictate the outcome of our task entropy although the possible distributions of tasks across the chunks (clusters) is constrained by the number of available chunks. Taken together, our results also point to the operation of a basic "gain-of-knowledge" (i.e., reduction of entropy) process that drives both the chunking (S_C) and the anisotropic distribution of tasks among the chunks (S'_T), as evidenced by the high correlation between these two entropy measures. Such a process has been proposed previously on behavioral and theoretical grounds (Pascual-Leone 1970; Piaget 1977; Fischer 1980). The orderly decrease of the number of clusters with age, their unequal sizes, and the diversity of their item membership all point to the chunking of information as a key mechanism of cognitive development. It is through consideration of which tasks chunked together at each age (i.e., stage of development) from which we can identify the task attributes on which the organizing principles act in organizing relational knowledge.

With this approach, we were able to capture the organization of relational knowledge as it was being built up from poorly connected (isolated pieces of) knowledge at age 5 years to nearly unified treatment of the different tasks at age 10 years, with an acceleration of chunking occurring between ages 8 and 9 years. Unlike previous studies (Miller 1956; Ericsson et al. 1980; Feigenson and Halberda 2008), our results addressed chunking of conceptual knowledge, not working memory. Previous work on memory has concentrated on children's (or adults') abilities to remember given information based on inherently chunking information into meaningful units that require fewer memory resources. For example, after 230 hours of practice recalling a large list of numbers using mnemonic association (e.g., chunking number spans into dates, ages or running times), one man was able to increase his memory span from 7 to 79 items (Ericsson et al. 1980). To the best of our knowledge, our study is the first to apply this type of analysis to any area of conceptual development as a measure of cognitive organization.

Importantly, the diversity of our tasks, along multiple dimensions, provided the requisite variety for investigating how uncertainty in performing relational judgments becomes reduced with development, while the unevenness of children's learning of the basic spatial relational concepts allowed us to compare the development of these concepts across different modalities. If the tasks we chose were less differentiated in performance, especially at 5 years of age, then we would have found more chunks early in development and, thereby, would have less clarity in how concepts became organized and structured together. Crucially, our methods reveal the natural development of cognitive organization

since children's strategies for each task were self-generated and under voluntary control rather than relying on the strategy provided by an adult (e.g., children were not given labels prior to any task, except the verbal comprehension task, which were labels they themselves produced).

Through our illustrated application, we showed how cluster analyses could be used to extract empirically significant information from task performance. Specifically, we used children's performance on 16 tasks to cluster performances and then assessed the clusters to discover under what principles performances were being organized and chunked. Our findings indicated that once a chunk was formed it was robust, meaning that it was likely to appear at each subsequent age and that the chunked items continued to be strongly associated. Therefore, once two tasks were performed similarly within one age group, all subsequent ages continued to show strongly similar performance on those two tasks. This was especially true for the verbal tasks. Furthermore, previous research has shown that a chunk can contain any number of concepts that share strong associations to one another (reviewed in Cowan 2001). This means that a chunk need not form from purely similar concepts (e.g., only verbal tasks or only instances of *above*), but it does suggest that once two items are chunked together then those items should continue to be strongly associated and, therefore, chunked. Additionally, the robustness of specific clusters (i.e., content) across the ages (e.g., production of *above/below*) as revealed by the cluster analyses adds qualitative support to our quantitative findings from the entropy measures (see cluster content in Figure 3). This all points to irreversibility as an important aspect of cognitive organization; that once items group, they rarely ungroup.

Importantly, this method provides new insights into knowledge development by revealing the step-by-step progression of organization across age and illustrating how development progresses in an order that does not appear to be logical. To illustrate, the tasks in this study could have chunked according to any of 4 attributes – namely, modality (verbal/nonverbal), task condition (verbal production/comprehension, nonverbal congruent/incongruent), relational plane (*above/below, right/left*) or relation (*above, below, right, left*). It could be logically assumed that chunks would first form by relation if the concept of *above* is consistent across task conditions and modalities. However, our evidence suggests concepts first got chunked by task condition and relational plane (where opposites formed a single chunk), and later across task conditions but within task modality. For example, chunks at early ages (i.e., 5-7 years) were primarily within task condition and within plane, and at later ages tasks began to chunk within modality (i.e., nonverbal congruent and incongruent tasks began to merge at 8 years). Our finding that the relational planes were important organizing principles for chunking the verbal tasks, but not for chunking the nonverbal tasks, suggests that the division between the horizontal and vertical planes exists only linguistically, and not nonverbally. Consistent with our findings, previous research has suggested that children know that two labels are spatial opposites, before they can accurately marry the labels to the concepts (i.e., label specific poles, Clark 1972). More broadly, our findings suggest that the verbal and nonverbal instantiations of a concept do not follow the same organizing principles, nor does it appear that the *above/below* and *right/left* relational planes follow similar organizing principles as each other. Our findings may suggest that the label plays a role

in restructuring the concept and assimilate them to fit with the label – at least this seems to be true for *above* and *below*.

Producing the terms *right* and *left* remained separate from all other tasks, even for 10-year-olds. This suggests that production of *right* and *left* fails to generalize into a common factor with the other tasks and with the production of the terms *above* and *below*. This may be why adults continue to confuse *right* and *left* (Wolf 1973; Hannay et al. 1990) at times. It is unclear at what age the production of *right* and *left* become chunked with the other tasks or whether these terms ever fully merge with their corresponding nonverbal concepts. The current decision-making models that have been developed to explain spatial relational judgments at the neurobehavioral level (Regier and Carlson 2001; Lipinski et al. 2012) do not account for this differential performance across the two planes.

Globally, our approach offers a way of operationalizing and quantifying developmental processes across all domains of knowledge – spatial, perceptual, linguistic, conceptual and social domains – with broad, practical applications. Examples of broad applications include discovering which concepts are needed for other concepts to be gained or the order in which different elements of cognition (e.g., working memory, self-recognition, language, cognitive control, etc.) come online, while more specific applications include finding how labels are attached to concepts. In short, our methods could reveal additional information on how cognitive abilities are developing and getting honed. By looking at the gradual progression of knowledge and skill learning, results from this approach can

unravel developmental processes which can in turn be used to alter educational models to coincide more naturally to how children are actually acquiring skills and knowledge. This approach can be used to uncover the foundation for all knowledge and this approach should be applied within other cognitive domains and across domains.

Specifically, our findings for spatial relational knowledge have immediate, direct application in education. For example, knowing how relational skills are built informs academic curricula development. Current research suggests that spatial skills are often overlooked in curricula creation and implementation, although training in spatial thinking can improve achievement in certain disciplines, such as mathematics and sciences (Uttal et al. 2013b; Stieff et al. 2014). Specifically, our findings suggest that such training might begin by verbally pairing up polar opposites (e.g., *above/below*, *right/left*), in concordance with previous findings that suggest children learn two words are opposites before they fully map the terms to their relations (Clark 1972). Only after opposites are mastered children might be taught to make nonverbal perceptual matching judgments, like our nonverbal congruent trials. Finally, these congruent judgments should be the basis for teaching how to make the more difficult incongruent relational judgments. In short, our findings suggest how a unified system of knowledge for making relational judgments might be built— by appealing to the natural progression by which these skills develop.

Chapter 4 The relationship of verbal and nonverbal performance: the possible role of language in the development of nonverbal reasoning

4.1 Overview

In this chapter I investigate the relationship between verbal and nonverbal knowledge with respect to the four spatial relations of *above*, *below*, *left* and *right*. I answer four questions in four experiments by measuring the ability of 6- to 7-year-old children to remember the position of a dot that was *above*, *below*, *left* or *right* a line. I also measured children's knowledge of the corresponding words and their abilities to overcome incongruent spatial information. The first question concerns which modality of skill is learned first is answered in Experiment 1. In this first experiment I tested the abilities of 5-10-year-olds to validate my focus on 6-7-year-olds in the subsequent experiments; I also compared verbal production performance to verbal comprehension to argue for my subsequent focus on production. I found that knowledge of the words developed before the ability to make accurate nonverbal judgments along the vertical (*above-below*) plane, but not along the horizontal (*right-left*) plane. In Experiment 2, I answered the question of whether my static verbal task was able to capture true verbal ability compared to a dynamic verbal task: children performed similarly on the two tasks. In Experiment 3, I asked whether children's performance could improve on the nonverbal task after language use was activated in a preceding task and found that it did improve. Lastly, in Experiment 4, I responded to the question of whether improved performance in

Experiment 3 was due to a practice effect rather than language activation and found that a practice effect could not account for the improvement. Overall, my findings suggest that language promotes relational reasoning by helping children encode and process relational information.

4.2 Introduction

The ability to make relational judgments is thought to be central to human intelligence in that it promotes higher cognition (Gentner, 2003, 2010; Halford, Wilson, Philips, 2010). For example, relational knowledge is central to spatial cognition, which in turn is critical for math and science skills (National Research Council, 2006). By some views, knowledge of language plays a critical role in this ability. Yet, despite the evidence that language affects relational reasoning, it remains unclear exactly *how* language is helping. One possibility is that language *acquisition* causes improvement in (i.e., leads) nonverbal reasoning such that once the terms are *available* they are accessed *automatically*, and possibly obligatorily (as seen in some Stroop tasks: see Diamond et al. 2002, for discussion). Another possibility is that language *use* is optional and causes improvement in nonverbal reasoning only when the labels are *accessed*. The goal of this study is to better understand the role of language in making dynamic relational judgments. We do this in two ways. First, we examine developing knowledge of a broader set of relations, verbally and nonverbally, across a broader age span than what has previously been investigated. This enables us to address the possibility that language *acquisition* is critical. Second, we manipulate the accessibility of language, which sheds light on

whether language *use* is the critical factor, in spite of the available vocabulary. This study, then, builds on the current literature in two critical ways and therein fills an important gap in our current understanding of the development of relational knowledge.

4.2.1 **Past evidence on the role of language in relational thought**

In trying to understand the development of relational knowledge, many researchers have turned to language as a causal factor, but the current evidence regarding the role of language in relational knowledge is mixed and controversial.

4.2.1.1 *Evidence in favor.* Some evidence suggests that language, that is, having labels to represent items, consistently precedes the ability to encode and remember relative object locations (e.g., Pyers et al. 2010; Shusterman 2006). For example, Loewenstein and Gentner (2005) showed that using vertical labels of *top/middle/bottom*, words that already existed in preschoolers' vocabularies, improved their judgments in a search task: researchers hid a sticker on a shelf and children who were provided a relational term performed better than children who were instructed with a generic term, like *here*. They argued that labels invited comparison of the two shelves. Hermer-Vasquez, Moffet, and Munkolm (2001) provided similar evidence regarding *right* and *left* in a reorientation and retrieval task. In their study, preschoolers who could correctly produce the terms *right* and *left* on their own were better at retrieving a hidden object that was to the *right of* or *left of* a prominent feature in a room than children who did not know these terms. Previously, Hermer and colleagues (Hermer and Spelke 1994; Hermer and Spelke 1996)

had shown that younger children (18-24 month olds) could not use a feature as a relational guide for their performance and that adults could be made to perform like them when their access to linguistic coding was interrupted (Hermer-Vasquez et al. 1999) which led the experimenters to conclude that labels served to bind together relevant information. Importantly, in both the Hermer and Gentner studies, less specific language did not improve performance. Both these studies suggest that having precise relational terms in their vocabulary was necessary for children to correctly encode and remember the location of hidden objects and that accessibility to linguistic encoding, as evidenced by adult performance, was equally important.

Supporting evidence for the increased cognitive power resulting from symbolic representation can be found in various animal studies and even studies with infants. For example, nonhuman primates show relatively limited capacity for relational coding (Penn et al. 2008; for exception, Fagot and Thompson 2011), including the ability to attend to more than one relation at a time (Fragaszy et al. 2011), except when trained to use symbols (Gillan et al. 1981; see Boysen and Bernston 1995, for similar findings in cognitive control). In terms of infants, Casasola (2005) recently found that providing 18-month-olds with a familiar, precise label (*on*) enabled these infants to categorize instances of support, whereas providing infants with a generic term (*Look!*) or no term at all did not aid infants. Together, these studies of children, infants and animals suggest that having a precise term or symbol to label something is imperative for successful relational reasoning, particularly in categorizing something and for making comparisons.

4.2.1.2 *Language might be doing something, but what?* Even among those that agree that language impacts relational reasoning, its specific role is not clear. Particularly contentious is whether there is a necessity that the label already exist in a child's vocabulary, as the previous studies suggest. For example, Shusterman, Lee, and Spelke (2011) found that language use was helpful for identifying a spatial cue in a reorientation task, but that knowing the precise relational term did not affect preschoolers' performances. This suggests that the precise label is *not necessary*. Additionally, Christie and Gentner (2013) found that 3-year-olds were only able to pass a Relational-Match-To-Sample task when given a label; however, they were similarly successful with familiar (*same-different*) and novel (*truffet*) labels. Interestingly, Christie and Gentner's 2-year-olds who were trained on the familiar relational labels of *same* and *different* did not perform as well as their age-matches who were given a novel label for the item-to-be-matched without training on its correct use. This suggests that familiar labels – that is, labels which already exist in the child's vocabulary – were *not necessary*. This further suggests that providing children with a label describing the *item* to be matched is sometimes more helpful than providing a label describing the precise *relation* to be matched (i.e., *same* or *different*); thereby putting the emphasis on matching percepts rather than matching labels to percepts.

To complicate things more, Son, Smith, Goldstone, & Leslie, (2012) offer complementary evidence for the usefulness of novel labels in their label-matching study with 4-5-year-olds; however, children in their study performed better with familiar labels than with novel labels, even when the novel label mimicked the relational-match in its

structure (e.g., using the label Ko-Li-Ko to designate an ABA relation). Meanwhile, Dessalegn and Landau (2008) – who studied 4-year-olds’ ability to remember a patterned square – did not find any supporting evidence for novel labels. In their match-to-sample study, children saw a square that was divided into a red half and a green half, had to remember the layout, and then were asked to recognize the square from a set of three options. Unlike Christie and Gentner, they found that children had difficulty remembering the specific red-green relation when they were given a novel label to describe the square. Their performance only improved when they were told “the red is on (*the left of*) the green” during the sample presentation – despite the fact that these children could not assign the correct label to the correct relation – which the researchers interpreted as establishing an asymmetrical directional value to the precise relation between the colors. Unlike Son et al. (2012), Dessalegn and Landau found that children performed best when the linguistic structure matched the relation-to-be-matched. Roth and Franconeri (2012) provide supporting evidence from adults for the enhancement effects of matching a linguistically structured phrase to relations depicted in a subsequent visual stimulus. It therefore, remains unclear how important it is that the label is familiar (with or without training) and precise.

Another possible mechanism of language aiding relational judgments is that it invites categorization. Studies from both Casasola (2005) and Lupyan (Lupyan & Casasanto, 2015; Boutennet & Lupyan, 2015) indicate that labels provide a category for creating a concept and organizing constituent parts of the relational problem to be solved.

Casasola’s work supports Gentner’s conclusions that labels invite comparison whereas

Lupyan's work supports Landau's conclusions that linguistic structure guides visual attention. In short, in studies that have found support for the role of language, it is not clear (1) whether knowledge of a specific term is needed, (2) whether that term needs to already be in the child's vocabulary, and (3) how the label directs attention to the relation in question.

4.2.1.3 *Evidence Against.* Yet, other findings suggest that language plays a more limited role in encoding and remembering relational information. For example, Hermer and colleagues' (Hermer and Spelke 1994; Hermer and Spelke 1996; Hermer-Vasquez et al. 2001) conclusions have been challenged by findings that other, nonlinguistic factors also affect reorientation and subsequent object retrieval, such as the size of the room where the object is hidden (Learmonth et al. 2002; Ratliff and Newcombe 2008). There appears to be ample evidence that individuals who do not have access to language or labels can make simple relational judgments. For example, when trained to make spatial relational judgments monkeys can show remarkable accuracy (Goodwin et al. 2012). Even human infants show some limited capacity for encoding simple spatial relations without access to or training on labels (e.g., Gava et al. 2009; Quinn 2007). Thus, simple relational judgments (with respect to spatial position) are possible without language.

4.2.2 **Issues with Previous Findings**

One reason that it is difficult to draw clear inferences from the past studies is because of differences across tasks used, relations tested and age groups tested. For example,

Loewenstein and Gentner (2005) studied knowledge of vertical relations (e.g., *top*, *middle*, *bottom*) in 4-year-olds, and Hermer-Vasques, Moffit and Munkholm (2001) studied knowledge of horizontal relations (e.g., *right* and *left*) in 6- and 7-year-olds. Loewenstein and Gentner also used a task in which children were to remember the place of an object on a bookshelf and match it to an identical bookshelf, while Hermer-Vasques, Moffit and Munkholm's (2001) task required children to navigate inside a room. Our current paper is more comprehensive than past work because it examines verbal and non-verbal knowledge of both vertical and horizontal relations within a single group of children who varied from 5 to 10 years of age. In our study, we expected verbal knowledge of *above* and *below* to be in place for all children but *right* and *left* to be more variable across age groups, with older children having complete knowledge of the terms. If language acquisition is the critical driving factor, we should find better nonverbal performance on the vertical plane than on the horizontal plane.

Another issue involving the tasks used in previous work is the degree to which relational reasoning was actually engaged. For example the children who were successful in Dessalegn and Landau's (2008) tasks, could have simply been visually matching the squares. The evidence from infants is similar in that it involves making a perceptual match that does not require the child to ignore any irrelevant, incongruent information; rather, the location of stimuli (or parts of stimuli) may contain enough information to yield successful performance without cognizing (or labeling). Our work also differs from past studies in that we examined the ability to make dynamic relational judgments that required flexible relational reasoning by implementing a more complex task than has

been previously employed: our task required children to overcome incongruencies in the stimuli's locations. Such incongruencies have been shown to affect both monkeys' (Fortes et al. 2004) and young children's (Smith et al. 1988) performances. For example, both find it more difficult to judge which of two items is *higher* when the items differing in height appear at the bottom of a board (Smith et al. 1988) or a computer screen (Fortes et al. 2004). Examining performance across congruent and incongruent trials enables us to examine the ability to make relational judgments that could be based on simple perceptual matching (on congruent trials) against those that require more flexible relational coding (on incongruent trials). Furthermore, our task did not require non-relational skills (e.g., motor) or other abilities.

A third question that emerges from past work involves how language was made more accessible. In past work (e.g., Loewenstein and Gentner 2005; Dessalagn and Landau 2008) the precise (and correct) relational term was provided by the experimenters. It is not clear whether children spontaneously access and use the terms when they are not explicitly cued to do so. In our study, instead of explicitly providing or training the child on a to-be-used label, we primed children to use a self-generated label by having them perform a verbal task before performing a nonverbal task. Furthermore, in this way, precise, correct labels were not necessarily used (as measured by performance on the verbal task).

The final issue with the findings from past studies is the effectiveness of the labels tested. First, having the word in the child's vocabulary was not always enough for successful

performance in each study, particularly in knowing the precise label. Second, different types of labels (novel vs. familiar) led to different performances. These mixed findings in combination with animal and infant studies suggest that it cannot be that using (precise) labels is *necessary* for the ability to make nonverbal relational judgments to emerge - unless monkeys and infants are performing the task qualitatively differently than older human children and adults. So, then, how does language help? Must the words be in place in the child's vocabulary before they can make flexible relational judgments? That is, is having the words enough (i.e., acquisition-dependent and necessary)? Or, do they have to use the words before they can exploit the advantage of language (i.e., acquisition-independent and optional)? These are the two main questions our study will answer.

4.2.3 **Discovering the role of language**

The goal of this study was to offer evidence on how verbal and nonverbal knowledge of vertical and horizontal spatial relations (*above, below, right and left*) develop in children: the first study to directly compare these two relational directions across six age groups. Remarkably, the ability to make these verbal and nonverbal judgments has not been studied in a single experiment within one group of children, let alone across more than one age group. Relational knowledge has been shown to develop extensively from ages 4 to 5 years, when children become more flexible in relational categorization strategies (Gentner et al. 2011). In four experiments, we compared within group differences on these types of judgments. In the first experiment, we examine a developmental range (5-10-year-olds) to find the best age group on which to focus the subsequent experiments. This experiment indicated that 6- and 7-year-olds, as a group, showed the ideal mix of

knowing and not knowing the relational terms while (unlike 5-year-olds) attaining above chance performance on the nonverbal task. Furthermore, this is an age group that has been shown to display better verbal knowledge of the terms *above* and *below* than *right* and *left* in previous studies (Clark 1973; Cox and Richardson 1985; Martin and Sera 2006). This difference in language knowledge within the same group of children should constitute a naturally-occurring “manipulation” of language that should be independent of more general cognitive skills and is ideal for comparing verbal performance to nonverbal performance. Thus, if language systematically precedes and causes the ability of nonverbal relational judgments to emerge (i.e., nonverbal performance is language acquisition-dependent and language is obligatory), we should find better nonverbal performance along the vertical (*above-below*) plane than the horizontal (*right-left*) plane. It is currently unclear whether there exists a general planar bias in visual cognition for *above-below* over *right-left* (e.g., Clark 1972; Hayward and Tarr 1995; Landau and Hoffman 2005): this study will, in part, clarify this.

Our predictions across the four experiments were as follows. In Experiment 1, we predicted that if language was responsible for flexible relational coding, then performance on the nonverbal task should parallel performance on the verbal task: children who do well on the verbal task should also do well on the nonverbal task. Specifically, children who do well on the incongruent trials of the nonverbal task (i.e., the trials that *require* relational reasoning) should also know the corresponding relational terms. Another question we addressed involved performance on the horizontal versus the vertical plane. Based on evidence from Goodwin and colleagues’ (2012) studies with

monkeys, we would expect to find better performance on *right-left* judgments, since their monkeys were more accurate and faster at making *right-left* judgments than *above-below* judgments, and since our design is based on their task, but only if performance is tied to some evolutionary bias for these relations. On the other hand, we would expect superior performance on *above-below* judgments if monkeys' performances were based on order of acquisition (monkeys learned *right-left* relations first). In Experiment 2, we predicted that modifying the verbal task from a static task to be as dynamic as the nonverbal task would not change the patterns of performance observed in Experiment 1, if true knowledge of labels was being assessed. In Experiment 3, we predicted that increased accessibility to verbal codes would affect subsequent performance on the nonverbal task. Importantly, we examined children's self-generated use of language instead of providing them with particular terms and labels as has been typically done in previous studies, which makes our study an important addition to the literature. Finally, in Experiment 4 we examined the potential role of practice on performance.

4.3 EXPERIMENT 1

The goal of this experiment was to examine the relation between the ability to encode and remember the relations *above*, *below*, *right* and *left* nonverbally and knowledge of the corresponding words in 5-10 year olds. Previous studies have suggested a strong relation between verbal encoding of spatial relations and performance on spatial memory tasks. We expect to find differential nonverbal performance of the two sets of relations if such knowledge is predicated by knowledge of the corresponding terms. So, if language causes

improvement in the ability to extract and remember these relations, we should find better performance for *above* and *below* than for *right* and *left* in our nonverbal task as well as in the verbal task, since knowledge of the words *above* and *below* should be firmly in children’s vocabulary at these ages while *right* and *left* may not be. In order to avoid the experiment (and instructions) from activating the precise verbal codes, all children participated in the nonverbal task before the verbal task. Our verbal task was modified from Cox and Richardson (1985) while our nonverbal task is new and adds an important empirical factor that has been missing in the current literature.

4.3.1 Method

4.3.1.1 *Participants*. These are the same children who participated in the study described in the previous chapter. Their age descriptive are included in Table 1 and are broken down by sex and age group.

Table 4.1 Descriptive information of participants. Each group comprised 10 girls and 10 boys for a total of 20 children per age group.

Age (year)	Girls			Boys		
	<i>Mean</i> (months)	<i>Range</i>	<i>SD</i>	<i>Mean</i> (months)	<i>Range</i>	<i>SD</i>
5	66.3	60-71	4.03	65.2	61-70	2.74
6	77.2	72-83	3.33	77.2	72-83	3.49
7	90.6	86-95	3.92	89.3	84-95	3.62

8	101.3	97-106	3.06	101.2	96-106	4.32
9	113.2	109-118	3.01	113.7	109-117	2.79
10	126	122-131	3.30	124.5	120-128	2.59

4.3.1.2 *Nonverbal relational judgment task*. This is the same task described in the General Methods section.

4.3.1.3 *Verbal relational judgment task*. This is the same task described in the previous chapter. To remind the reader, no training and no feedback were provided; however, for the production task, children were encouraged to use precise terms if they first offered only a vague term, such as “here” or if they pointed to the board in lieu of producing any term. For one child, the experimenter made an error in placing a magnet out of order and this case was marked but not removed from analyses. Children’s answers were considered correct if they produced the words *above*, *below*, *right* or *left*, or a closely related but equally specific term such as “on top” for *above* following Cox & Richardson (1985) since we were more interested in children’s knowledge of the vertical and horizontal spatial relations than on these rather specific and often interchangeable terms. “Side” was not accepted as a correct response for *right* or *left*, but children were encouraged to think of a different word that was more specific since “side” is an otherwise accurate but nonspecific spatial term. In the comprehension task, there were 3 (of 8) locations that would be counted as “correct”: the canonical position (e.g., directly above the circle) or two adjacent corners (e.g., top-right corner or top-left corner for “above”). Only two children utilized the corners of the board. Chance was set at 37.5% (3

out of 8 possible locations) for the comprehension task, but there was no chance level set for the production task since children could produce any number of terms.

4.3.2 Results

We were interested in two questions: (1) whether performance was consistently better on *above* and *below* relations than *right* and *left* relations across the tasks; and (2) whether performance on the verbal task was related to performance on the nonverbal task. For the verbal tasks, we compared performance on the two relational planes (i.e., *above* and *below* as the vertical plane, *right* and *left* as the horizontal plane), rather than on each relation, since children learn relational pairs together, first learning that they are opposites then learning the correct spatial mapping (Clark 1972; Landau and Hoffman 2005); we compare performance on each relation separately for the nonverbal task. For each analysis, we used nonparametric tests since performances were highly skewed toward the extremes and we looked at each age group separately so that we could map the developmental trajectory of relational knowledge. We will use these results to focus on the most relevant age group in subsequent experiments. Lastly, there were no gender differences found for either verbal task or for the nonverbal task; therefore, I will not discuss sex differences further.

4.3.2.1 *Verbal tasks.* For the production task, a Wilcoxon Signed Rank test comparing performance on the two planes indicated that performance was better for *above-below* judgments than for *right-left* judgments in 5-year-olds ($Z = -3.5$, $p < .00$), 6-year-olds (Z

= -2.6, $p < .01$), and 7-year-olds ($Z = -2.0$, $p < .05$), but not significantly different for 8-, 9- or 10-year olds. For the comprehension task, a Wilcoxon Signed Rank test indicated better performance on *above-below* judgments than *right-left* judgments in 5-year-olds ($Z = -2.7$, $p < .01$), but not for any other age group. The data are plotted in Figure 4.1.

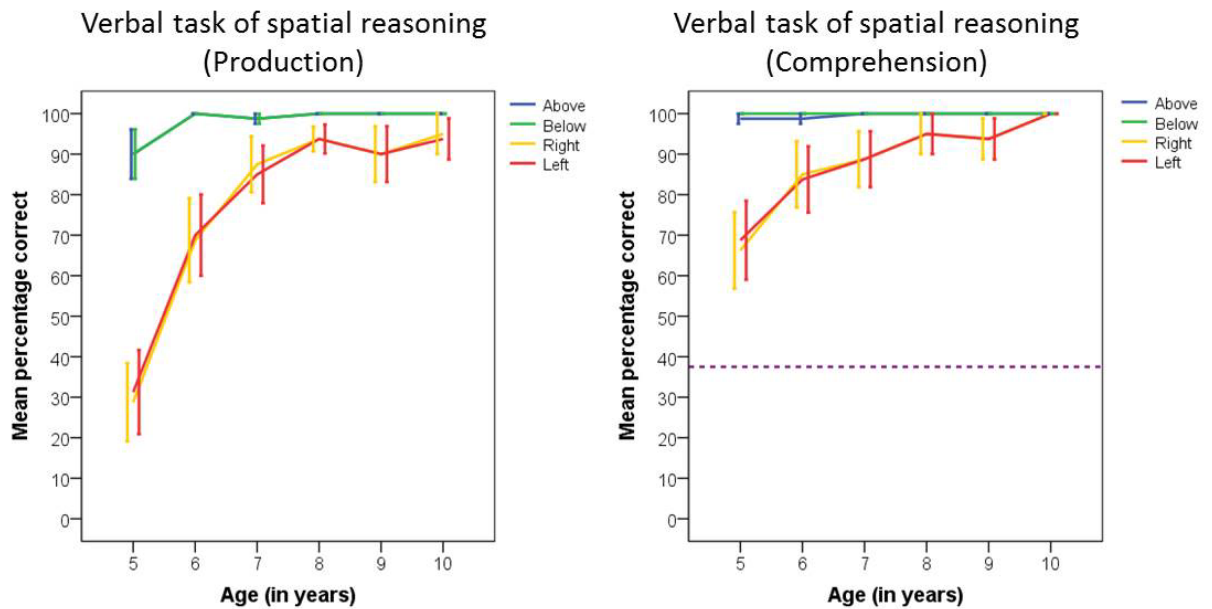


Figure 4.1 Children's performance on the verbal tasks: verbal production (left panel) and verbal comprehension (right panel). There is a steady increase in performance with increasing age in both tasks with children attaining ceiling performance around age 8 years. Only the comprehension task could be measured against chance (dotted line), which was set at 37.5% (for 3 out of 8 possible correct locations). [Note: The data points for *above* and *below* are highly overlapping.]

It is clear from Figure 4.1 that most development is occurring with respect to the terms *right* and *left*; performance on *above* and *below* appear to be at ceiling in all six age

groups. It is also clear from Figure 4 that production and comprehension follow the same developmental patterns; however, as has been found in other areas, the ability to correctly comprehend terms develops earlier than the ability to correctly produce these terms (e.g., Benedict 1979; Clark and Hecht 1983). Moreover, within these age groups, it appears that the most development is occurring on the ability to produce the terms, especially *right* and *left*, while comprehension appears much closer to ceiling from the youngest age. Since we are interested in comparing performances of children who know the correct relational terms to children who do not know the correct terms on their nonverbal performance, we will focus on the task that elicited the most variability in performance in subsequent analyses: verbal production. When analyzing the relation between verbal and nonverbal performance we operationalized verbal performance with respect to the production task. Another reason for examining production (vs. comprehension) is that several studies have found that production (and not comprehension) is most closely related to nonverbal performance (Hermer-Vasquez et al. 2001; although see Shusterman 2006).

4.3.2.2 *Nonverbal task.* We used the results from the verbal production task to divide children into 3 groups: the age preceding knowledge of the relational terms (5 years), the age with partial knowledge of the relational terms (6-7 years), and the age with complete knowledge of the relational terms (8-10 years). See Figure 4.2 for nonverbal performance for the three age groups. To further examine the first question, we conducted a Friedman test to determine whether the distribution of performance differed between relations and across congruency types. We chose to analyze each relation separately rather than as a

plane to avoid making any assumptions about nonverbal performance on the different relations *a priori*.

For 5-year-olds, results showed that, overall, distributions were significantly different for congruent and incongruent *above*, *below*, *right* and *left* trials ($\chi^2(7)= 42.6$, $p < .00$). The associated pairwise comparisons with unadjusted significant levels indicated better performance on all congruent trials than all incongruent trials both within and across relations. Table 4.2 lists the significant pairwise comparisons with the unadjusted p-values: we did not adjust for multiple comparisons because they were planned. For 6-7 year olds, results showed that, overall, distributions were significantly different for congruent and incongruent *above*, *below*, *right* and *left* trials ($\chi^2(7)= 18.4$, $p < .01$). The associated pairwise comparisons indicated better performance on most congruent trials than on incongruent right trials (above: $z = 1.9$, $p = .052$; below: $z = 2.7$, $p < .01$; right: $z = 2.3$, $p < .05$; left: $z = -2.2$, $p < .05$) and marginally better performance on congruent below trials than on incongruent left ($z = 1.9$, $p < .055$). No other comparisons were significant; although it is interesting that *above* and *below* incongruent trials are tightly associated and slightly separated from *right* and *left* incongruent trials, which are also tightly associated. For 8-10-year-olds, the distributions of congruent and incongruent *above*, *below*, *right* and *left* trials were not significantly different.

Table 4.2 Pairwise comparisons of nonverbal performances for 5-year-olds. P-values are unadjusted for multiple comparisons since these were planned comparisons. There were no differences within incongruent trials so the results of these comparisons are not shown in the table.

Incongruent trials	Congruent trials							
	Above		Below		Right		Left	
	z	p	z	p	z	p	z	p
Above	2.2	<.05	-3.2	<.01	-2.9	<.01	-3.2	<.01
Below	2.1	<.05	-3.1	<.01	-2.8	<.01	-3.1	<.01
Right	2.2	<.05	3.3	<.001	2.9	<.01	-3.2	<.001
Left	2.4	<.05	3.4	<.001	3.1	<.01	-3.4	<.001

It is clear from Figure 4.2 that most development is occurring with respect to incongruent trials while performance on congruent trials appear to be at ceiling for all age groups. Because congruent trials can be solved by perceptual matching, and incongruent trials require flexible relational judgments, we operationalized the ability to make nonverbal relational judgments in terms of performance on the incongruent trials in subsequent analyses. Furthermore, because *above* and *below* are tightly coupled and *right* and *left* are tightly coupled, we combined the relations within each relational plane in subsequent comparisons.

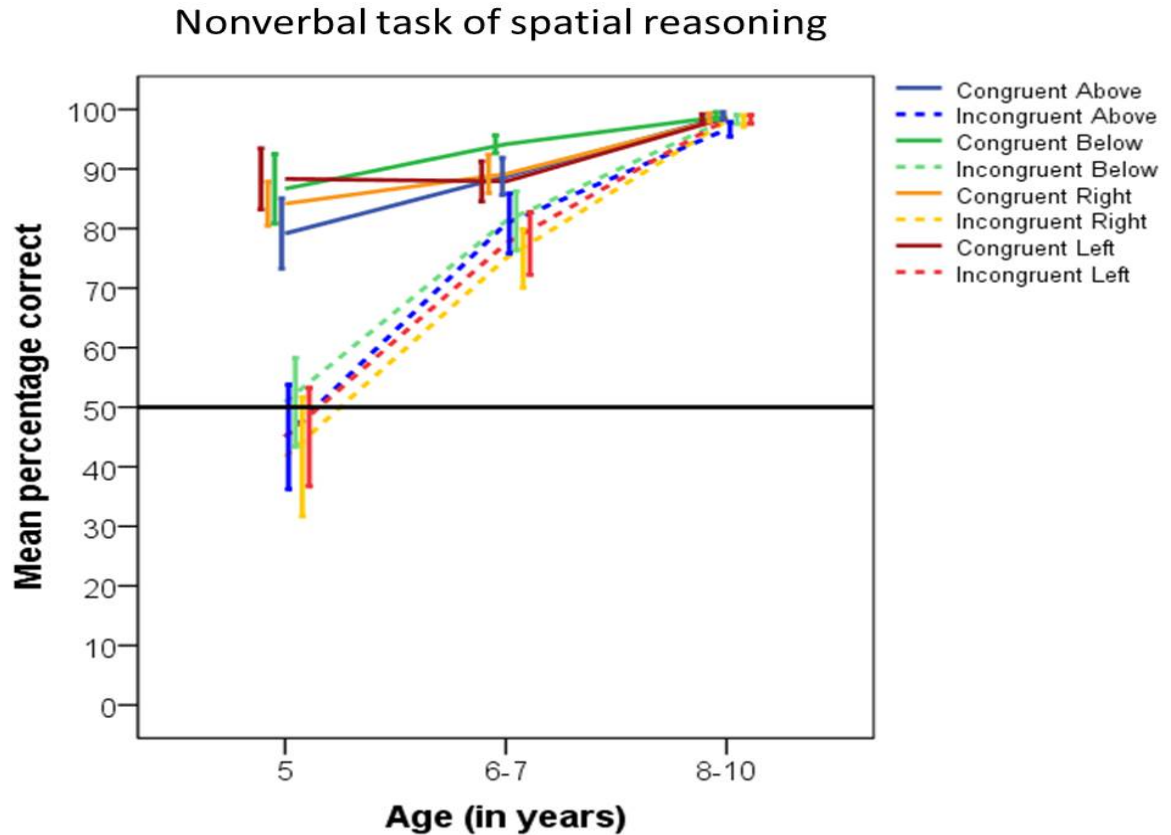


Figure 4.2 Children's performance on nonverbal tasks. Average percent correct on nonverbal tasks of Experiment 1 for each age group. Congruent and incongruent trials of the nonverbal task are displayed separately. Error bars illustrate a standard error of +/- 1 of the means. Chance (black line) is set at 50%.

Overall, I did not find that nonverbal performance on *above-below* trials was reliably, consistently better than performance on *right-left* trials as expected from the hypothesis that language acquisition *causes* improvement in the ability to make nonverbal relational judgments. Therefore, I investigated this hypothesis from an alternative approach by

looking at individual performances and directly comparing a child's verbal performance to their nonverbal performance.

4.3.2.3 *Comparison across tasks.* It could be argued that individual children may be using a linguistic strategy to perform the nonverbal task, if language is accessed automatically. For instance, when children see the dot as being to the “right” of the line a linguistic representation of “right” may be instantly activated (as has been argued in Stroop tasks; Diamond et al. 2002; Dalrymple-Alford 1973; Klein 1964). If children were attaching a correct, precise verbal label to the dot-line relation, then we would expect to find a predictive relation between verbal and nonverbal performance. This possibility was addressed directly by our second question, which asked whether knowing the term for the relations was necessary for (or preceded) successful nonverbal performance. To address this, we examined whether performance by individual children on the verbal task was correlated with their performance on the nonverbal tasks. We compared only the incongruent trials of the nonverbal task to verbal production since success on incongruent trials reflects flexible relational coding (while congruent trials can be correctly judged through perceptual matching) and since children's abilities to produce the terms were still developing. We look at each age group separately since performance varied by age.

Performance was not normally distributed, so we used Spearman's Rho correlation test on the raw percentage scores. Only correlations that matched relations across tasks are relevant to our hypotheses since knowing the relational term is expected to improve performance for the corresponding relation; however we show all correlations in Table 3.

We found only one relevant correlation of verbal production to the nonverbal incongruent trials: producing the term *left* reliably predicted nonverbal performance on left incongruent trials in 8-10 year olds (Table 3). However, children at these ages were at or near ceiling for both tasks, so this correlation is likely driven by a few participants; the same can be said for the positive relationship between incongruent above trials and production of *right*. Additionally, for the younger ages, only 6-7-year-olds showed a (unpredicted) correlation: incongruent below trials and production of *left*. Because the only correlations are with production of *right-left*, it could be that production of these terms shares some cognitive structure with overcoming incongruencies (however, see Scott et al. 2015a for further analyses and discussion concerning the relationship between these tasks).

Table 4.3 Spearman's Rho correlation of verbal production task to incongruent trials of nonverbal task using percent correct performance. Significant values are bolded and marked with an asterisk.

Incongruent trials	Age[^]	Production				Comprehension			
		<i>Above</i>	<i>Below</i>	<i>Right</i>	<i>Left</i>	<i>Above</i>	<i>Below</i>	<i>Right</i>	<i>Left</i>
<i>Above</i>									
	5	.26	.26	-.16	-.1	-.3	--	-.26	-.18
	6-7	-.13	-.13	.17	.28	-.13	--	-.05	.08
	8-10	--	--	.3*	.17	--	--	.13	.13
<i>Below</i>									
	5	.03	.03	.12	.18	-.22	--	-.18	-.13
	6-7	-.13	-.13	.2	.37*	.11	--	.02	.18
	8-10	--	--	-.11	-.11	--	--	-.07	-.07
<i>Right</i>									
	5	.18	.18	-.14	-.09	-.3	--	-.36	-.27
	6-7	-.17	-.17	.13	.22	-.17	--	.00	.12
	8-10	--	--	-.11	-.11	--	--	-.07	-.07
<i>Left</i>									
	5	.39	.39	.01	.06	-.14	--	.06	.1
	6-7	-.14	-.14	.17	.27	-.14	--	-.03	.09
	8-10	--	--	.09	.26*	--	--	.21	.21

* Correlation is significant at the 0.05 level (2-tailed)

[^] Sample sizes for the ages are: 5-year-olds N = 20, 6-7-year-olds N = 40, 8-10-year-olds N = 60

4.3.3 Discussion

We found an advantage for knowledge of the words *above-below* over the words *right-left* for 5-7-year-olds for both production and comprehension, but no difference for 8-10-year-olds who performed at ceiling on both verbal tasks. We did not, however, find an analogous reliable difference in the ability to make nonverbal relational judgments in the *above-below* (vertical) relational plane over the *right-left* (horizontal) relational plane. If language improves the ability to make nonverbal relational judgments, then we should have found better performance on nonverbal judgments of both *above* and *below* compared to *right* and *left*. Converging findings for the independence of verbal and nonverbal knowledge emerged from our analyses of individual performances.

Correlational analyses indicated that verbal performance was not systematically related to nonverbal performance, overall. As such, for any age group, a child could excel on one task yet perform at chance on the other while another child could show the opposite performance. Thus, these findings do not support the idea that knowledge of relational terms by itself consistently drives nonverbal performance.

However, one possible reason for our results might be that our static verbal task was not measuring the same kind of relational knowledge as our dynamic nonverbal task. In our nonverbal task, every relation of *above-below/right-left* appeared in a different position on the screen on every trial, thus requiring children to impose and then abandon a different reference point on each trial. In contrast, our verbal task (which has been widely used by other researchers) only required that children impose one reference point – the middle of the tic-tac-toe board – that could have been used on trial after trial. Perhaps it is

the ability to dynamically impose and abandon relational standards, which language use typically requires, that drives the ability to make dynamic relational judgments. We addressed this possibility in Experiment 2 with a new production task. Again, we only consider production performance in the remaining experiments since verbal production performance was still developing while comprehension was relatively at ceiling for most children.

Our finding of better performance on comprehension than production corroborates many past findings previously published (Clark and Hecht 1983; Li et al. 2007). Furthermore, based on the results of our verbal production task, we focus our following experiments on 6-7 year olds because children at this age are still learning *right-left* relations and, thus, their performances show the full range of knowing and not knowing these terms.

4.4 Experiment 2

The results from Experiment 1 do not support the idea that knowledge of relational terms consistently precedes and, therefore, predicts the ability to make nonverbal relational judgments: that language acquisition leads to automatic label access. However, the pattern of findings could have been due to the fact that a shifting frame of reference was required in one task, but not the other. Therefore, we tested children's verbal knowledge using a task that required dynamic relational judgments. If the strategic tool that language offers is a medium for adopting and abandoning (i.e., shifting) relational standards, then we might find a systematic pattern of results across both relational planes when both verbal and nonverbal tasks require the same dynamic and flexible relational skills. We

use our results from Experiment 1 to validate our focus on verbal production over verbal comprehension, for comparing across relational planes within each task, and for our focus on 6-7-year-olds.

4.4.1 Methods

4.4.1.1 *Participants*. Children from 6;0 to 7;6 years of age were recruited from the same population that participated in Experiments 1, but none had participated in the previous experiment. Twelve boys (mean age = 80.3 months, std. dev. = 5.44) and thirteen girls (mean age = 80.5 months, std. dev. = 5.51) participated for a total of 25 children. An additional 2 children were tested but their data were not used because of an error in the computerized presentation of the stimuli. We chose to limit the age of 7-year-olds to 7.5 since children these ages indicated solid knowledge of *above* and *below* but were still learning *right-left* terms. For our comparison across experiments, then, we only compared performances of the 30 children from Experiment 1 who matched this age range.

4.4.1.2 *Nonverbal relational judgment task*. We used the same nonverbal task that we used in Experiment 1 and, as in that experiment, children performed this task first.

4.4.1.3 *Dynamic verbal task*. For this experiment, the verbal production task consisted of a modified version of the nonverbal computer task. However, instead of touching the screen to indicate a relational judgment as they did in the nonverbal task, the child was asked to label the relation depicted inside the circle. Thus, the final choice screen was deleted and the visual static screen was extended from 3 seconds to 9 seconds, for a total trial length of 10 seconds. Just as in the nonverbal task of Experiment 1, the reference

object appeared in each of the four quadrants in a random order, thus correct performance on this task required flexible and dynamic verbal relational coding.

Unlike the previous verbal task, children were given up to 8 training trials to ensure they understood the task; however, they received no feedback. If a child produced a nonspecific word during training, like “side” for *left* or *right* relations, then they were encouraged to “think of a different word that would help someone who couldn’t see the screen understand where the dot was”, but they were not told the nonspecific word (e.g., “side”) was incorrect. At the end of training, children were asked, “Do you think you know how to play the game?” If the child said “yes” then the test trials were started. Again, children received no feedback on correctness during the test phase nor were they asked to produce a more specific word since a time limit was now imposed on responses.

4.4.2 Results

We were interested in two questions. The main question was whether we would replicate our results of Experiment 1 – of a different pattern between the vertical and horizontal relational planes - using a different verbal task. If we found the same pattern of performance on the verbal and nonverbal tasks as in Experiment 1, then we would be more confident that the results from that experiment and thus, that the static task used in Experiment 1 was tapping the same flexible knowledge of the relations. A second, related, question was whether performance on the dynamic verbal task would correlate with nonverbal performance. Thus, when analyzing performance in Experiment 2, we also analyzed how performance on the verbal task in this experiment compared to

nonverbal performance. We also directly compare overall performances in the two experiments.

4.4.2.1 *Dynamic verbal task.* For the verbal production task, a Wilcoxon Signed Rank test comparing overall performance on the two planes indicated that performance was better for *above-below* judgments than for *right-left* judgments (Figure 6; $Z = -3.1$, $p < .01$).

Performances are plotted in Figure 4.3. However, since the dynamic verbal task included both congruent and incongruent trials, we conducted a Friedman's test to determine whether the distribution of performance differed across congruency types. Results indicated, overall, that distributions were significantly different for congruent and incongruent *above-below* and *right-left* trials ($\chi^2(3) = 25.2$, $p < .00$). Contrary to our findings from the nonverbal task, we did not find differences in distribution between congruencies, but rather only between the relational planes: Incongruent *above-below* trials were performed better than incongruent *right-left* ($Z = 3.0$, $p < .01$) and congruent *right-left* ($Z = -2.2$, $p < .05$) while congruent *above-below* trials were performed better than incongruent *right-left* ($Z = 2.6$, $p < .01$) and marginally better than congruent *right-left* ($Z = 1.9$, $p = .06$). Overall, we replicated our findings in Experiment 1 for the verbal task; namely, of a different pattern of performance across tasks within the *above-below* relational plane compared to the *right-left* relational plane, but using a dynamic verbal production task.

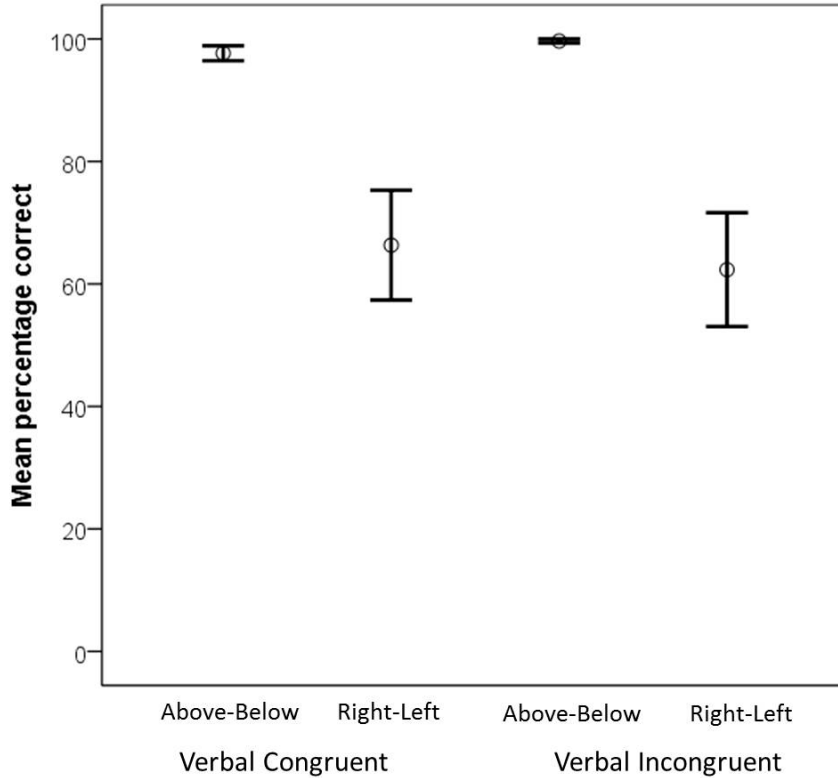


Figure 4.3 Error plot of percent correct on verbal task in Experiment 2. Congruent and incongruent trials are displayed separately. Error bars illustrate +/-1 standard error of the means.

4.4.2.2 *Comparison across verbal and nonverbal tasks.* As in Experiment 1, we investigated a potential relation between verbal and nonverbal performance. Because we have both congruent and incongruent trials in the modified verbal production task, we test these separately; although, it may be expected that verbal incongruent trials would most mirror nonverbal incongruent trials. Our hypothesis was that if language knowledge is enough to elevate nonverbal performance, then verbal performance should have a reliable relationship to (i.e., predict) nonverbal performance, particularly on incongruent trials.

Nevertheless, we use a two-tailed test to account for the opposite relationship: that nonverbal performance drives verbal performance. As in Experiment 1, a Spearman's Rho correlation did not indicate a reliable relationship between verbal and nonverbal performance. Table 4.4 shows the correlation table

Table 4.4 Spearman's Rho correlation of nonverbal incongruent trials and verbal

production task in Experiment 2. Both congruent and incongruent trials of the (modified) verbal task are included.

Nonverbal- Incongruent	Production-Congruent				Production-Incongruent			
	<i>Above</i>	<i>Below</i>	<i>Right</i>	<i>Left</i>	<i>Above</i>	<i>Below</i>	<i>Right</i>	<i>Left</i>
<i>Above</i>	.16	.50*	-.02	-.06	-.14	--	-.12	-.00
<i>Below</i>	.12	.26	.09	.09	-.15	--	-.03	-.16
<i>Right</i>	.06	.41*	.19	.14	-.19	--	.05	.23
<i>Left</i>	.31	.36	.03	-.05	-.17	--	-.08	.10

* Correlation is significant at the 0.05 level (2-tailed)

4.4.2.3 *Comparison between dynamic and static verbal tasks.* The impetus for this experiment was to check if the verbal task used in Experiment 1 was sufficient to tap into true verbal relational knowledge. To this point, we have generally replicated our results

from Experiment 1. Nevertheless, with respect to performance across the two experiments, the most important comparison involved our manipulation of the verbal production task. For comparison purposes, we combined over congruent and incongruent trials of the modified verbal task to get a total performance on each relational plane. A Kolmogorov-Smirnov test on the distributions yielded no significant differences between experiments (see Figure 4.4).

With regards to performance on the nonverbal tasks, we expected no difference in performance since in both experiments the nonverbal task was performed first, and therefore, not affected by the nature of the subsequent verbal task. A Kolmogorov-Smirnov test on the distributions to check that the samples were from the same population indicated no significant differences, so we considered the two experimental groups to be equivalent.

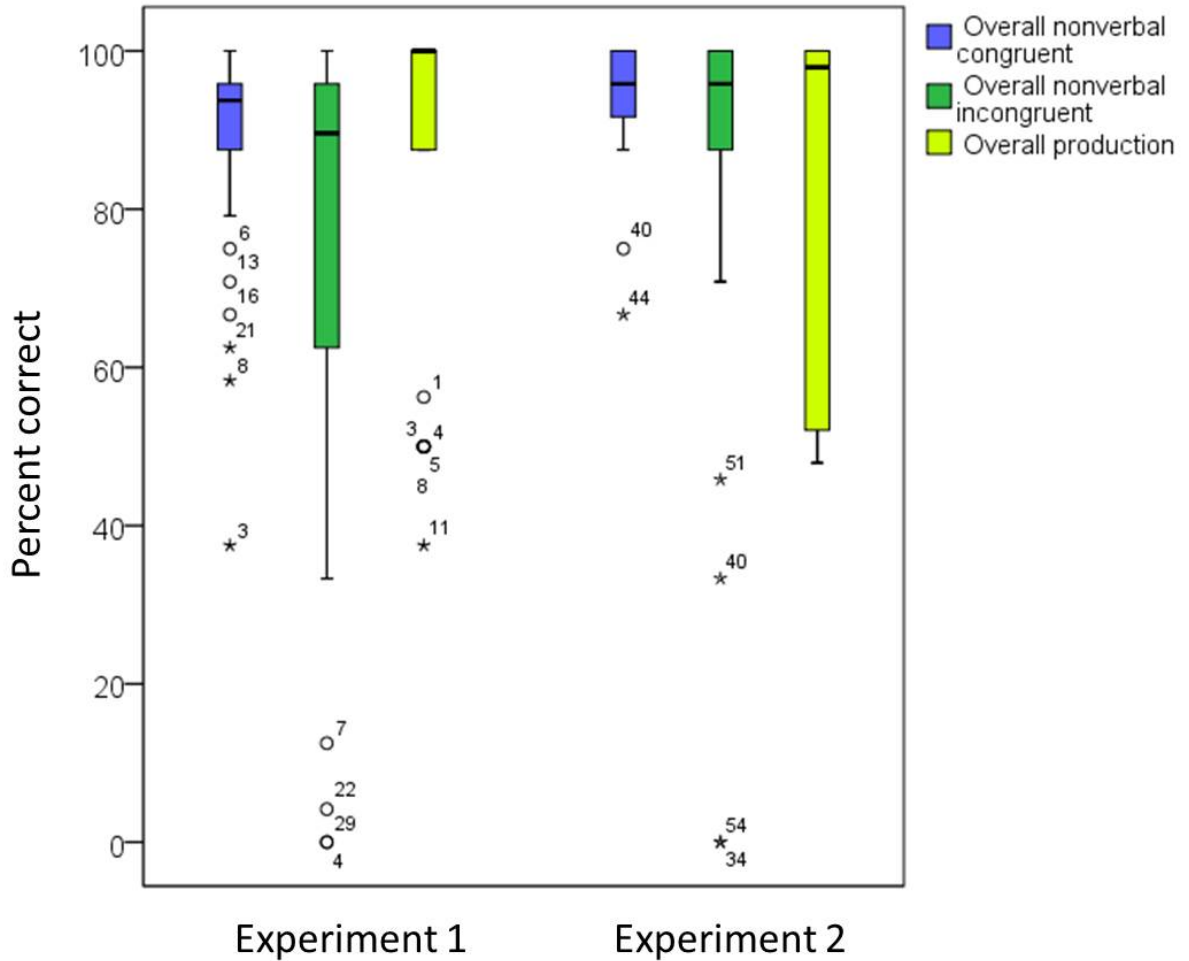


Figure 4.4 Box plot of percent correct on nonverbal and verbal tasks for 6-7.5-year-olds in Experiments 1 and 2. Congruent and incongruent trials of the nonverbal task are displayed separately, but congruent and incongruent trials of the verbal task are averaged for an overall score. The median is displayed as a black line inside the box. Outliers are displayed as a symbol and a numerical tag (to include overlapping scores).

4.4.3 Discussion

After changing the nature of the verbal task from a static to a dynamic one, we replicated our finding in Experiment 1: namely, of a different relation between verbal and nonverbal

performance for each relational plane. We changed the verbal task to include the ability to impose and abandon different frames of reference, but our analyses indicated that this was not a factor in children's ability to name the relations. Additionally, despite the greater computation and attention required to succeed in the dynamic verbal task (as compared to the static verbal task used in Experiment 1), performance on these two verbal tasks were not significantly different from each other. Therefore, the static task that has been previously used seemed to tap into the same flexible knowledge of the relations as the dynamic task and accurately measured verbal knowledge. One new finding was that congruency did not affect verbal performance, despite it having a significant effect on nonverbal performance. This finding suggests that children can overcome incongruencies when using linguistic labels to judge spatial relations.

As in Experiment 1, we tested for a reliable relationship between performance on the verbal production task and the nonverbal incongruent trials and again found none. In other words, we did not find that knowledge of the words systematically co-varied with the ability to make the nonverbal judgments, not even when comparing incongruent verbal trials to incongruent nonverbal trials. Overall, these results, again, do not support the idea that knowledge of the corresponding relational terms, by itself, (i.e., *acquisition*) consistently (and *obligatorily* or *automatically*) affects the ability to make nonverbal dynamic relational judgments in the two relational planes studied.

Nevertheless, although the role of language seems not to be that of causing the ability to make nonverbal relational judgments emerge, its role may be that of providing an

efficient strategy for encoding and remembering relational information. Perhaps verbal knowledge by itself does not lead to improved nonverbal performance, meaning simply having the words in one's vocabulary is not enough. Rather, it is only when verbal knowledge is utilized that it simplifies relational judgments, possibly by allowing children to ignore irrelevant details of the stimuli, as suggested by the results of our modified verbal task. If children use category labels for unifying all instantiations of a relation into a single category (i.e., all *above*), regardless of its location on the screen (i.e., congruency type), then children's performances should converge to be nearly similar (thus reducing variability in performances) and the difference between performance on congruent and incongruent trials might completely disappear. Based on the finding of no effect of congruency in the verbal task, we had reason to believe that labels provide a mechanism for ignoring salient but inappropriate visual details (i.e., overcoming incongruencies). In Experiment 3, we attempted to naturally activate the category labels during the nonverbal task by having children perform the verbal task first.

4.5 Experiment 3

It may be that knowing labels (i.e., having labels available) and accessing them are separate abilities (see Brod et al. 2013 for similar argument of distinguishing between availability and accessibility). If language's role in encoding and remembering relational information is to offer a strategy for abandoning frames of references, then we should find better performance on a nonverbal task when category labels are made more accessible. To increase accessibility, we had children perform the verbal task before the

nonverbal task and examined whether nonverbal performance became less variable across children compared to Experiments 1 and 2, particularly on the incongruent trials.

One potential problem of having children perform the verbal task first is that children might not use the relational terms intended (*above, below, right or left*); however, evidence from other studies indicates that using terms which are less specific (e.g., *side, other side*) or consistently using the same (but wrong) terms to label relations (e.g., say *left* for *right* and vice versa) may nonetheless improve performance on a nonverbal task (e.g., Shusterman et al. 2011). Additionally, based on the correlation analyses from our previous experiments, knowledge of the correct, precise terms should not matter, anyway. Nevertheless, we again assess the degree to which use of precise labels influenced performance by analyzing performance on the nonverbal task as a function of performance on the verbal task. If specifically coding the dot as *to the side* of the line is equivalent as coding it *to the right* of the line then, we should see no difference in performance on the nonverbal task as a function of the specific words used in the verbal task.

4.5.1 Methods

4.5.1.1 *Participants*. Children from 6;0 to 7;6 years of age were recruited from the same population that participated in Experiments 1 and 2, but none had participated in either of the first two experiments. A total of 25 monolingual, native English-speaking children with no known cognitive differences were tested. Eleven boys (mean age = 81.5 months,

std. dev. = 6.36) and fourteen girls (mean age = 82.4 months, std. dev. = 3.57) were tested. An additional 3 children were tested but their data were not used; 1 due to parent interference and 2 due to computer failures.

4.5.1.2 *Nonverbal relational judgment task.* We used the same nonverbal task that we used in Experiments 1 and 2, except in this experiment the task was performed second.

4.5.1.3 *Verbal relational judgment task.* We used the same verbal task that we used in Experiment 2. The only difference was that participation in this task preceded the nonverbal task. It is important to note that, as in the Experiment 1 and 2, no feedback was provided during the testing phase of this task.

4.5.2 **Results**

We were interested in two questions. The main question was whether we would find improved performance on the incongruent trials of the nonverbal task as compared to the previous two experiments. A related question was whether performance would vary systematically on the nonverbal task as a function of performance on the verbal task. With regard to the second hypothesis, we would expect to continue to not find a correlation if the exact term is not necessary for improving performance and if it is rather more an effect of using *some* label.

4.5.2.1 *Nonverbal task.* We conducted a Friedman's test to determine whether the distribution of performance differed between relational planes and across congruency types. Results indicated that, overall, distributions were not significantly different for

congruent and incongruent *above-below* and *right-left* trials ($\chi^2(3)= 1.6, p = .66$). Figure 4.5 illustrates performance means and standard error. It appears that by performing the verbal task first, children were able to overcome the congruency effect in the nonverbal task, making the nonverbal task look more like the verbal task but without the effect of relational plane.

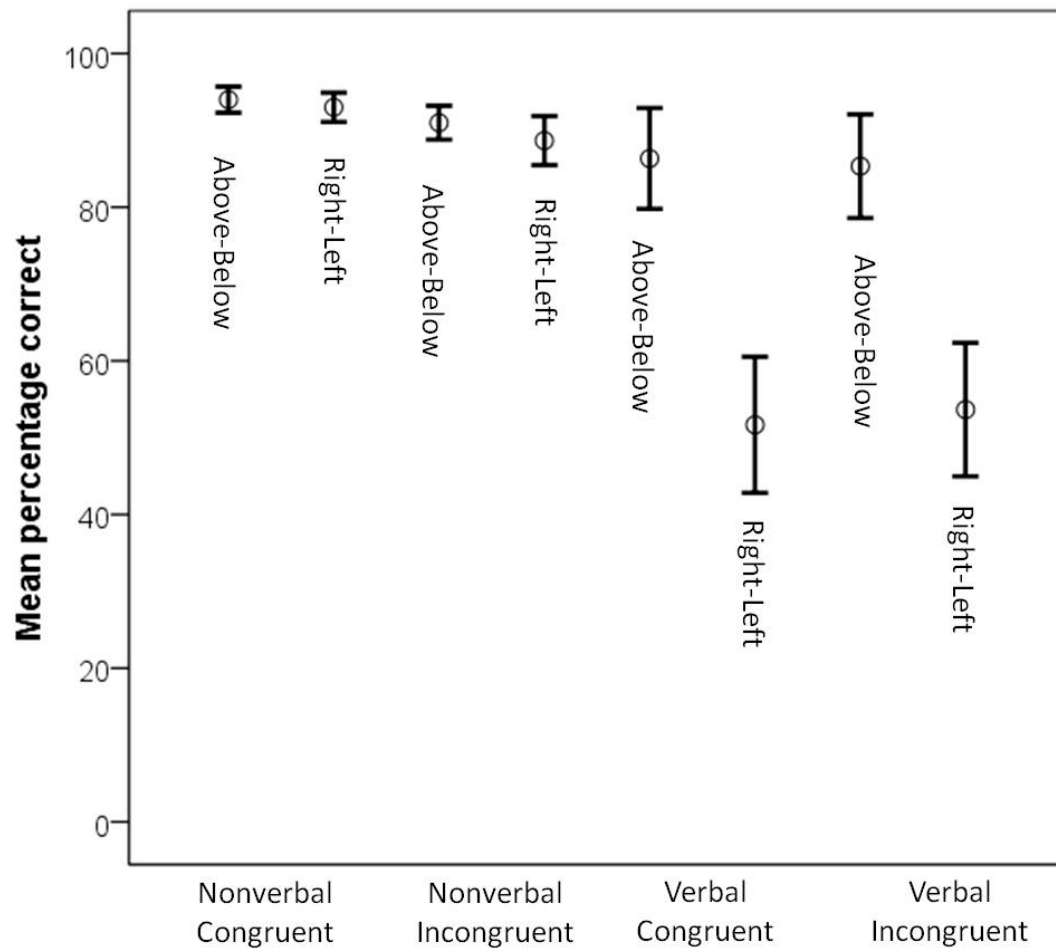


Figure 4.5 Error plot of performance on nonverbal and verbal tasks in Experiment 3.

Congruent and incongruent trials are displayed separately. Error bars illustrate +/- 1 standard error of the means.

4.5.2.2 *Comparison across experiments.* To test for differences in patterns of performance across the three experiments we compared the variance in performances using Levene's test for equality of variances. The most important comparison involved performance on the incongruent trials (Figure 4.6). If nonverbal performance was enhanced in Experiment 3 by virtue of performing the verbal task first, then we should observe better, more consistent overall performance (i.e., less variable) on incongruent trials of Experiment 3 than Experiments 1 and 2 combined. Indeed, overall ($F_{54,24} = 12.0$, $p < .001$), there was significantly less variable performance on the nonverbal incongruent trials in Experiment 3 than in Experiments 1 and 2 (*above-below*: $F_{54,24} = 15.3$, $p < .00$; *right-left*: $F_{54,24} = 8.0$, $p < .01$). Recall there was no significant difference of performance on incongruent trials between Experiments 1 and 2. Furthermore, the range of scores for children in Experiment 3 was much smaller: children in Experiment 3 did no worse than 40% correct performance, whereas children in Experiments 1 and 2 performed as low as 0% correct.

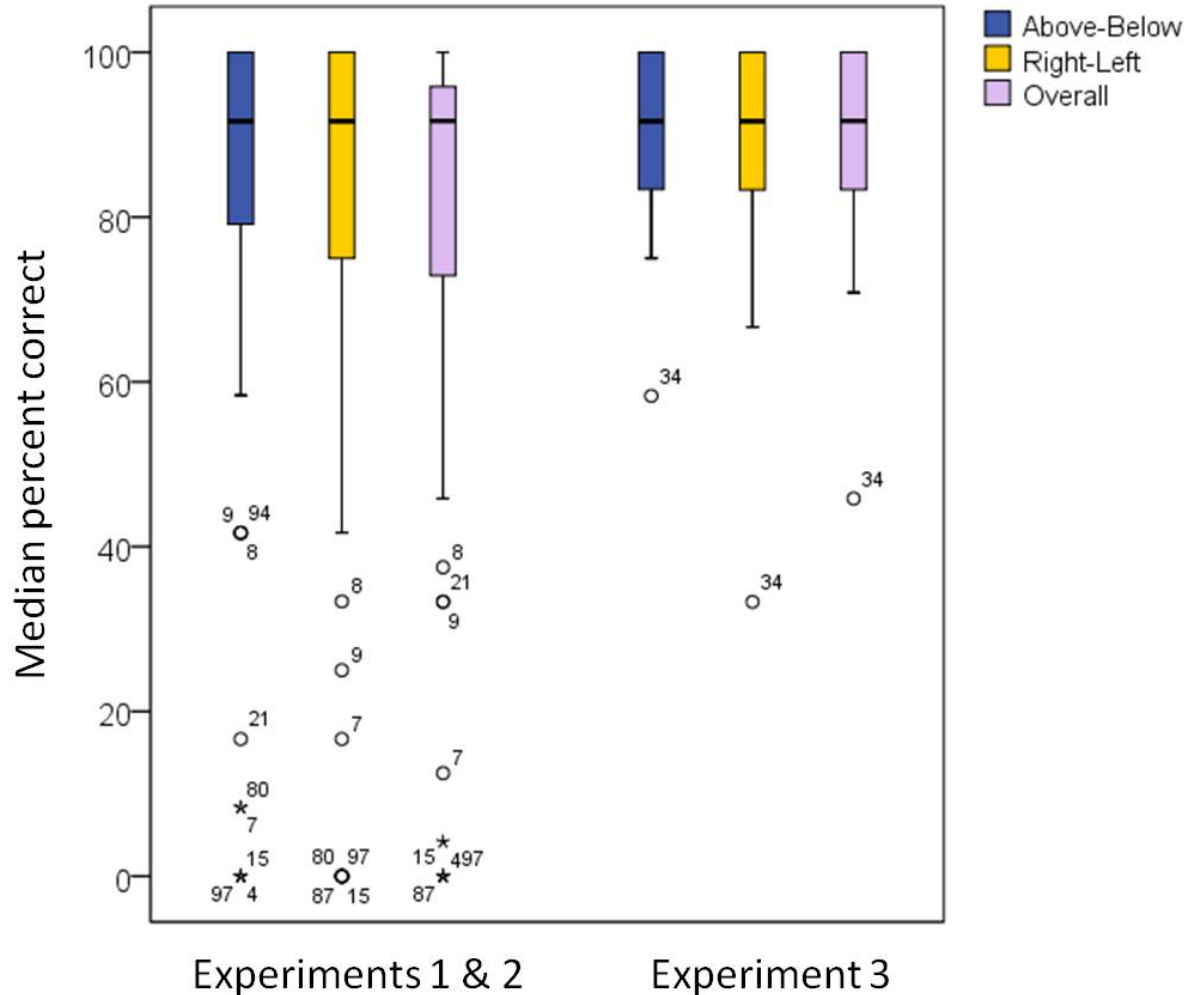


Figure 4.6 Boxplots of performance of children on nonverbal incongruent trials across **Experiments** 1 and 2 and Experiment 3. The variance in performances was significantly different between the three experiments. The median is displayed as a black line inside the box. Outliers are displayed as a symbol and a numerical tag (to include overlapping scores).

4.5.2.3 *Comparison across tasks.* The finding that children performed less variably, and better overall (the lowest performance in Experiment 3 was 40% compared to 0% in the other experiments), on the incongruent trials in Experiment 3 than in Experiments 1 and 2 does not identify the specificity of the language effect. Did coding a relation with any

label (e.g., *to the side*) improve performance? Or did children need to code the location of the dot with the specific label (e.g., *to the right*) to improve their performance (harking back to our original question)? In order to address this question, we examined performance on each task for each relation. Thus, as in Experiment 1, we investigated whether performance on one task was related to performance on the other task. If knowing the precise relational term, and using it correctly, was responsible for improved performance on the nonverbal task from Experiments 1 and 2 to Experiment 3, then we should find a positive correlation between verbal production and performance on the nonverbal incongruent trials. In short, children who accurately produced the terms *right-left* (or *above-below*) in the verbal task should have done better on these relations in the nonverbal task than children who used other terms.

A Spearman's Rho correlation on the raw percentage correct indicated that only one relevant correlation of verbal production to the nonverbal incongruent trials: production of incongruent right was correlated with nonverbal incongruent right trials. As before, only correlations that matched relations across tasks are relevant to our hypotheses since knowing the relational term is expected to improve performance for the corresponding relation; however, again, we show all correlations in Table 4.5. Overall, we found little evidence that precise coding of the relations was responsible for improved performance. Thus, our findings suggest that the improvement we found on the incongruent trials (for both relational planes) was due to increased accessibility to labels, even imprecise ones.

Table 4.5 Spearman's Rho correlation of performance on nonverbal incongruent trials and verbal production congruent and incongruent trials in Experiment 3.

Nonverbal- Incongruent	Production-Congruent				Production-Incongruent			
	<i>Above</i>	<i>Below</i>	<i>Right</i>	<i>Left</i>	<i>Above</i>	<i>Below</i>	<i>Right</i>	<i>Left</i>
<i>Above</i>	.08	-.13	.16	.14	-.14	-.28	.13	.10
<i>Below</i>	-.05	-.25	.56*	.54*	-.34	-.34	.62*	.46*
<i>Right</i>	.17	-.14	.39	.42*	-.11	-.27	.44*	.34
<i>Left</i>	.33	.25	.24	.30	.27	.10	.33	.25

* Correlation is significant at the 0.05 level (2-tailed)

4.5.3 Discussion

We found that asking children to produce the relational terms before they performed the nonverbal task led them to make more successful nonverbal relational judgments, especially on the incongruent trials. We believe that by having children perform the verbal task first, they became accustomed to using linguistic labels, and used this same strategy to encode and remember the relation between the dot and the line on the incongruent trials as well as the congruent trials of the nonverbal task. Furthermore, we found that even if the information contained in the verbal codes was not accurate – based

on verbal production performance – the use of such codes (i.e., any code) was enough to increase performance. These findings suggest that children of this age can use language as a strategy for solving problems in an otherwise nonlinguistic task, but may typically fail to use these strategies spontaneously. It seems, then, that language is not accessed *automatically* once the terms has been acquired, but rather that these terms must be accessed before they can be applied to an otherwise nonverbal task.

Furthermore, the finding that verbal performance was not reliably correlated to nonverbal performance on the incongruent trials lends support to the conclusion that knowing the exact terms is not what helped children perform the nonverbal task, but rather having language as a more accessible strategy for encoding the location of the dot to the line was what led to better perform the nonverbal task. Therefore, we provide some evidence that having a system of contrasting terms (i.e., opposites) may be important in successful nonverbal performance, even if the system is imperfect (i.e., the terms are not used consistently or accurately). We want to emphasize the natural discovery of language as a strategy by these children. Without performing the labeling task first, children of this age did not seem to automatically access labels for use in the nonverbal tasks.

A final concern that arises is the degree to which our findings may reflect practice effects. To address this concern, we conducted a final experiment where children performed a modified version of the dynamic task before they performed the regular nonverbal task used in previous experiments. If children do not perform better on the nonverbal task in

Experiment 4, then the improved performance in Experiment 3 cannot be explained by a practice effect (i.e., by virtue of performing the regular nonverbal task second).

4.6 Experiment 4

If the improved performance on the incongruent trials of the nonverbal task can be attributed solely to having performed the nonverbal task second (a practice effect), then we would expect to find equally improved performance on those trials without of a verbal task being performed first. In this experiment, we gave children a non-verbal version of the dynamic verbal task performed by children in Experiments 2 and 3. In the modified version, we asked children to perform it nonverbally, thus taking away the chance for verbal priming that was provided in Experiment 3. We kept all other aspects of the task (i.e., no feedback and immediate response) the same as in previous experiments, which served to differentiate it from the “regular” nonverbal task (i.e., the nonverbal task used in the previous experiments) that followed.

4.6.1 Methods

4.6.1.1 *Participants.* Children from 6;0 to 7;6 years of age were recruited from the same population that participated in Experiments 1, 2 and 3, but none participated in any of those experiments. A total of 25 monolingual, native English-speaking children with no known cognitive differences were tested. Thirteen boys (mean age = 80.3 months, std. dev. = 3.92) and twelve girls (mean age = 82.6 months, std. dev. = 4.91) were tested. An additional 5 children were tested but their data were not used; 3 were due to over-

scheduling and 2 were due to inattentiveness during the tasks. We excluded the children who were overscheduled in order to maintain similar age distributions across experiments and to use only the first children tested to satisfy age-matching requirements. The data was collected only to avoid cancelling appointments (and potentially disappointing families who were gracious enough to volunteer their time).

4.6.1.2 *Nonverbal relational judgment task.* We used the same nonverbal task used in Experiments 1, 2 and 3. As in Experiment 3, this task was performed second.

4.6.1.3 *Modified relational judgment task.* We modified the verbal task used in Experiments 2 and 3, so that children could respond nonverbally. As many parameters as possible were kept the same. For example, children were able to respond immediately and were not provided any feedback as to the correctness of their responses; however, instead of the white noise screen being extended to 9s and replacing the two-colored response screen, those screens were switched so that the white noise screen did not appear and the two-colored response screen appeared immediately after the stimulus screen and was available for up to 9s. Like in the previous studies, children were provided with practice trials to ensure they understood the instructions associated with the task.

4.6.2 Results

The critical comparison for this experiment is performance on the incongruent trials as compared to the previous experiments. We compared the variances as these were shown to be different between Experiments 1 and 2 and Experiment 3. Levene's test for equality of variances for the incongruent trials of Experiment 4 compared to Experiment 3 indicated a significant difference in the variances ($F_{24,24} = 4.3, p < .05$; Figure 4.7). It seems, then, a practice effect cannot account for the improved performances found in Experiment 3.

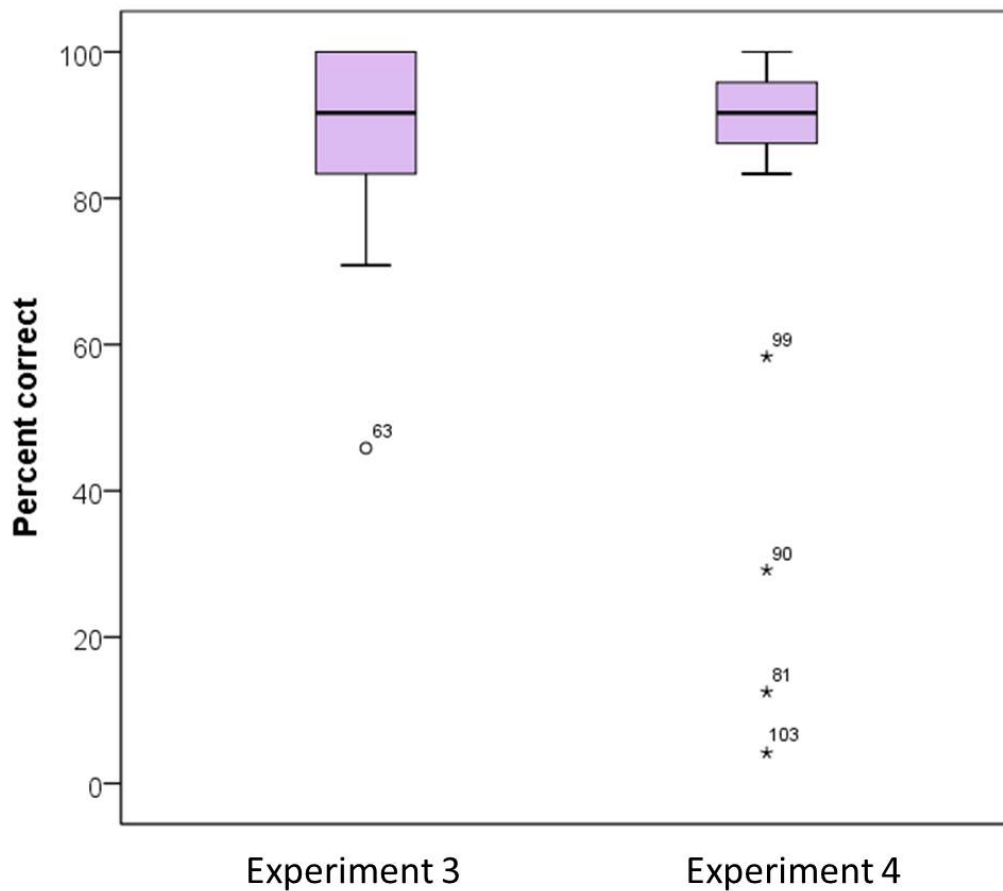


Figure 4.7 Boxplot of performance on nonverbal incongruent trials across Experiments 3

and 4. The variance in performances was significantly different between experiments, with

Experiment 3 resulting in the lowest variance. The median is displayed as a black line inside the box. Outliers are displayed as a symbol and a numerical tag (to include overlapping scores).

4.6.3 Discussion

In this experiment, children were not primed to use the verbal labels attached to each relation. Similar to Experiment 3, they performed the regular nonverbal task second, but we did not find an equal improvement in the performance of incongruent trials.

Therefore, we did not find a practice effect. This finding lends support to our conclusion in Experiment 3 that priming children to use verbal labels significantly improved their performance in a subsequent task. Labels, then, seem to provide a mechanism for ignoring salient but inappropriate visual details and thus moving from a perceptual matching strategy to a flexible, relational one.

4.7 General Discussion

Understanding the order in which different aspects of relational knowledge develop can shed light on how these skills interact in development (Scott et al. 2015a). The purpose of this study was to shed light on the role of language in making flexible relational judgments by examining the relation between verbal and nonverbal abilities as they co-develop in children. Previous work has suggested that language enhances relational reasoning in human adults beyond the limited capacities observed in animals and young children, but there is currently no consensus on the specific role that language plays in achieving this enhancement. Findings such as Gentner's (Gentner 2003; Loewenstein and Gentner 2005) and Hermer and colleagues' (Hermer and Spelke 1994; Hermer and

Spelke 1996; Hermer-Vasquez et al. 1999) suggest that the acquisition of relational terms is the critical piece; yet, other findings suggest that verbal knowledge by itself is not so critical (e.g., Ratliff and Newcombe 2008) or has only a temporary effect (see for review Landau and Lakusta 2009). Our findings suggest that knowing relational terms by itself does not consistently improve the ability to make different flexible relational judgments, but accessing labels is what matters (for a similar conclusion regarding the relation between plural morphology and number memory see Ettliger et al. 2014). Corroborating this interpretation is the literature on relational concepts in nonhuman primates which has shown that those animals with knowledge of symbols (and who have been trained to implement them) perform relational judgments better than those without symbolic experience, even though the exact role that symbols play remains unclear (Thompson et al. 1997). Our findings suggest that symbolic representation, including language, may work in improving relational reasoning beyond what is typically possible by promoting categorization and helping to ignore salient but irrelevant information. It seems that using symbols to facilitate relational judgments is a skill that develops even in humans and is neither automatic nor obligatory. Children first learn language, then, they gradually come to use it.

Furthermore, in this study we were able to distinguish between two viewpoints of language's role in cognition: 1) that language is automatic and obligatory used once acquired versus 2) that language is optional and must be activated. Language-as-obligatory assumes that verbal and nonverbal systems are intertwined such that nonverbal reasoning is dependent upon language acquisition wherein the activation of linguistic

processing is automatic, while language-as-optional considers them as separate systems that must be co-engaged such that success in one modality is relatively independent of success in the other. While our findings that children's nonverbal performance was improved when they were primed to use language leads us to conclude that language is optional and need not be precise, our analyses of the lack of correlation between verbal and nonverbal performance suggest that verbal and nonverbal knowledge are separate systems that must be co-engaged. Gleitman (Gleitman and Papafragou 2005; Snedeker and Gleitman 2004) has made similar arguments that language and other cognitive systems are separate but intertwined wherein language maps onto, otherwise separate, concepts.

I began by asking how language might enhance relational coding. I believe our evidence indicates that by accessing language and applying a linguistic strategy the child's attention is directed to the relevant relation. In this way, the perceptually salient but irrelevant information is more easily ignored and the incorrect frame of reference is abandoned. In this case, language may provide a unifying mechanism for bridging the perceptual gaps between different instances of relational similarity: what is seen and the concept to which it is tied. In their work, Hermer-Vasquez, Spelke, and Katsnelson (1999) suggested that language is necessary to bind together different types of information into a unitary representation, perhaps by acting as a scaffold for building these unified representations. It may do so by making the abstract relational codes more robust, and in our tasks, provide a memory trace of the stimulus to compare to the response screen. In this view, then, language may only have an effect after the stimulus is

experienced rather than altering the stimulus experience upfront, although additional evidence will need to be collected which addresses this potential more directly.

From this argument, then, language could be acting on two levels: encoding the stimulus and remembering the relevant information. Thus, once a unified representation has been constructed, language would further act in working memory by structuring a comparison to some other representation, be it linguistic, logical or perceptual (e.g., Dessalegn and Landau 2008; Christie and Gentner 2013; Loewenstein and Gentner 2005). The comparison process could be sequential (where objects are selected individually over time) or simultaneous (where objects are selected concurrently), but these possibilities need further investigation. It is also unclear in what manner attention was directed for selection of the relevant stimulus elements. Although it is not tested here, there is evidence to suggest such selection, at the stimulus level, occurs sequentially (Franconeri et al. 2011). This could explain why linguistic structure, in particular, has been shown to facilitate subsequent relational judgments.

Alternatively, language, when it is applied, could alter the stimulus experience upfront by providing a mode of thinking (Slobin 1987). Language may, then, provide a category into which the problem constituents can be parsed (e.g., Lupyan and Casasanto 2015) which in turn directs attention to the relevant elements (Boutennet and Lupyan 2015) from the outset, making the process more holistic and ecological. Cross-linguistic studies, particularly on color categorization, have been used to make this argument (see Lupyan 2012 for discussion). In terms of the process, Lupyan (2012) has argued that language

works by having a top-down, warping effect on perceptual representation which pushes it closer to the abstract category representation, yet is a transient process that can be interrupted under the right conditions. He argues that language operates “online” to modulate the ongoing (separate) cognitive and perceptual processes, although its effects are task-dependent and therefore flexible. This view helps explain the mixed results and different interpretations reached by various researchers; it also potentially describes the mechanism by which attention is directed. Also in line with this view of the interrelatedness of language and cognition, aside from promoting categorization into existing categories, is the idea that language facilitates the creation of new categories (e.g. Gopnik and Meltzoff 1986; Li and Gleitman 2002; Snedeker and Gleitman 2004). This possibility may explain why in our study, when applying a label, any label was successful in improving performance, particularly for those children who could not correctly label *right-left* relations.

Another, interpretation of the potential mechanism of language effects is that labels simply provide a robust memory trace of the to-be-remembered relation. It could be effective at reifying the goal wherein the instructions for the task are better remembered or simply effective in marking the to-be-remembered relation. In this way, then, language would be acting as a memory strategy more than as a reasoning strategy, *per se*. Language would still be acting across both the encoding and remembering phases of the task, but it would be acting only as a place-holder and not as a reasoning device; therefore, its effects would occur after encountering the stimulus. This interpretation is simpler than thinking of language as a cognitive strategy acting independently and

provides a mechanism for language interacting in concert with other cognitive processes. In this way, the effects of language would be indirect since language would not be directly involved in the comparison of different representations; however, this interpretation is not necessarily in opposition to the first possibility described above. Consistent with this view is evidence linking language skills with working memory capacity (Baddeley 2003; Just and Carpenter 1992; MacDonald and Christiansen 2002).

Although this experiment cannot point to the exact mechanism of the influence of language, it does suggest that language is not directly linked to nonverbal knowledge nor is it automatically engaged in nonverbal tasks, but rather that it is optional (for the age groups studied) and must be activated before it can influence nonverbal judgments. Furthermore, our research suggests that it works by focusing attention on the relevant information and allowing the irrelevant information to be ignored. We believe, also, that part of its influence is from creating a robust memory to guide future action. Further research must be conducted on the intricacies of linguistic support to determine whether language has multiple mechanisms for influencing reasoning, which may depend on and vary by the task at hand.

In short, there are four aspects of our study that separate it from previous work. The first is that we examined the ability to make verbal and nonverbal dynamic relational judgments for four relations (*above, below, right* and *left*) that had not been previously studied together and directly compared (with the exception of Scott et al. 2015a). The second way our work differs from past studies is that we examined the ability to make

dynamic relational judgments that required flexible relational reasoning. The third is that we examined children's self-generated use of language instead of providing them with particular terms and labels. Finally, children's relational judgments in our tasks were not influenced by non-relational skills (e.g., motor) abilities involved in navigation or orientation tasks.

In examining the ability to make all four types of relational judgments together, our study speaks directly to the inconsistencies found in the previous studies. By examining verbal and nonverbal abilities in both vertical and horizontal relational planes within the same group of children, our findings may help clarify the reasons behind the mixed results. We found that knowledge of the words *above* and *below* were firmly in place before knowledge of the words *left* and *right*, as well as the ability to make any nonverbal incongruent relational judgments. Much of the work suggesting a central role for language has involved the vertical plane (Clark 1973; Gentner 2003). Research involving relational judgments along the horizontal plane has yielded much more mixed results. Our findings suggest that knowledge of the words *above* and *below* is clearly established before children can successfully make nonverbal relational judgments across a variety of stimuli, but knowledge of the words *left* and *right* is still developing and appears to be doing so in parallel. This suggests that understanding how the ability to make relational judgments along the vertical and horizontal relational planes may require different explanations (for similar conclusions see Landau and Hoffman 2005). This may help explain why some researchers have found that knowledge of relational labels leads the ability to make nonverbal relational (Loewensteing and Gentner 2005) and spatial

(Hermer and Spelke 1996; Hermer-Vazquez et al. 2001) judgments whereas other researchers have failed to find such effects (e.g., Ratliff and Newcombe 2008).

The second way that our work differs from past work is that we were able to contrast simple perceptual matching strategies (i.e., performance on congruent trials) with more flexible (i.e., incongruent) and truly relational judgments in our dynamic tasks. Previous studies that have examined knowledge of these same relations have used tasks that required relational coding with respect to a single, static frame of reference (Dessalegn and Landau 2008; Quinn 2007), much like our congruent trials, which can be solved by simple perceptual matching (or mismatching in the case of dishabituation results). In our incongruent trials, children had to be flexible enough to abandon the potentially incorrect but more salient frame of reference (i.e., the position of the stimulus on the computer screen) for the correct one (i.e., the relation of the dot to the line). In our study, then, if children relied on the incorrect frame of reference, they would solve all of the congruent trials correctly. This is essentially a perceptual matching strategy and one that cannot be ruled out in some previous work. If this strategy were applied to the incongruent trials, then children would attain 0% correct performance. Only a flexible strategy, that is a truly relational, would lead to perfect performance on both congruent and incongruent trials in our task. We found that both children who had and had not acquired relational terms could use the relational strategy but did so in a fragile manner. They used it, on average, about 75% of the time in the incongruent trials of Experiments 1 and 2. However, when use of a verbal code was more accessible in Experiment 3, the use of the relational strategy became more robust and less susceptible to interference from the

perceptual matching strategy. In fact, correct performance went up to 90% in this condition. Perhaps children (and nonhuman primates) who perform nearly perfectly on tasks of relational reasoning are spontaneously using symbolic coding to bolster their performance.

The third aspect of our study that is unique is that we allowed children to use any strategy in the nonverbal task, and never directly suggested a specific strategy: this includes the choice of label to apply, if any. Instead we led children to better performance by having them engage with a linguistic strategy in a preceding task. In contrast, for example, Loewenstein and Gentner (2005) provided children with a label upfront during their encoding period and as the experimenters hid the object on a shelf. Furthermore, by never providing corrective feedback children were free to use a label of their choosing throughout the experimental task, regardless of its preciseness or correctness, and to abandon and switch labels as they found suitable. Thus, our results reflect children's self-generated use of relational terms in nonverbal reasoning rather than an experimenter-guided solution, and is, therefore, more reflective of everyday performance outside of the laboratory. This approach also gave us the opportunity to compare the correctness of self-generated labels to performance on the nonverbal task.

Our fourth and final contribution is that our findings complement previous works since our results do not reflect any added demands that might have been factors in previous studies – such as navigation, search or object matching. Thus, our tasks measure a more pure and isolated ability to make relational judgments. Importantly, the ability to make

relational judgments needs to be studied with techniques that capture neural correlates such as fMRI and MEG among others (discussed in Chapter 5). Indeed our task was designed to be used in conjunction with these paradigms as well as with animals.

Finally, one aspect of our findings raises the possibility that the same underlying mechanisms may not be recruited in relational reasoning by humans and monkeys, if monkeys' performances were not linked to order of acquisition. Unlike Goodwin and colleagues (2012), we did not find better performance on *right* and *left* judgments than on *above* and *below* judgments. However, because the monkeys in their study were trained on *left-right* relations first, then their findings could reflect an order of acquisition effect, and thus our findings may not be so inconsistent from theirs. Examining the neural correlates of performance would also shed light into whether the same underlying neural mechanisms are being recruited to perform the task by different species, particularly in terms of how each plane is coded: *above-below* in the adult human brain should parallel *right-left* in the brain of these monkeys, if order of acquisition drives neural coding. Alternatively, if symbolic coding is the key to differential performance on *above-below* and *right-left* then the neural mechanisms should not be similar since these monkeys were not trained to use symbols.

In conclusion, our findings are consistent with the idea that language strengthens basic relational reasoning abilities. Using language to encode and remember stimulus attributes (e.g., spatial relations) expands the capacity for relational reasoning, and may free up resources to solve other problems. See Scott et al. (2015a) for a more expanded proposal

of how these spatial abilities might unfold over a 6-year age range. Clearly, many questions remain regarding the role of language in the evolution of human intelligence, and these findings offer a solid step towards better understanding the continuities and discontinuities that exist.

Chapter 5 Effects of Handedness on Verbal and Nonverbal Relational Judgments

5.1 Overview

Handedness is often linked to hemispheric specialization, particularly to speech processing. One reason is because each side of the body is controlled by the opposite side of the brain. Another reason, is because humans have evolved both the tendency to be right-handed and have language: two skills typically controlled by the left hemisphere. In this chapter, I describe a study which investigates the degree of handedness with both verbal and nonverbal spatial relational abilities in 5-10-year-olds. One hypothesis is that handedness promotes verbal performance such that children showing stronger laterality will show better verbal performance since laterality is thought to promote hemispheric development; however, nonverbal performance may also be promoted since spatial processing, generally, is also highly lateralized – albeit, in the right hemisphere. However, I found few consistent significant correlations between handedness and either verbal or nonverbal performance.

5.2 Introduction

The left and right sides of the brain have been shown to perform different functions, and there is some evidence that this specialization leads to optimal processing of such functions (Levy 1976; Vallortigara 2006). For example, the left brain has been tied to language and general reasoning, while the right brain has been tied to emotional and

spatial processing (Hellige 2001). Additionally, the left and right sides of the brain are responsible for the contralateral side of the body in terms of motor actions. This means that right-handed dominance is controlled by the left brain while left-handed dominance is controlled by the right brain. Handedness has been tied to brain lateralization, where right-handers and left-handers show different levels of abilities and generally utilize the hemispheres slightly differently. For example, the majority of right-handers use their left brains for language whereas left-handers are slightly less likely to use their left brains exclusively for this skill. However, one study showed that 27% of left-handers processed speech in the right-hemisphere as did some strong right-handers (4%) and ambidextrous people (15%): this indicates that handedness and speech lateralization are relatively independent of each other on the individual level, although there is almost a linear relationship between the two measures (Knecht et al. 2000b).

Many aspects of relational reasoning have been linked to left-hemisphere processing (Bunge et al. 2005, Christoff et al. 2001); however, many neural studies exclusively test right-handers because of their greater within-group consistency of left-hemisphere processing. That being said, Niebauer (2001) suggests a left hemisphere advantage for processing categorical relations (i.e., is a dot *above/below* a line) and a right hemisphere advantage for processing coordinate spatial relations (i.e., is the dot *near/far* from a line). Therefore, if lateralization of hand dominance is directly linked to lateralization of the brain, then I might expect to see a bias towards better performance on the nonverbal task for children who are more lateralized. However, the importance of brain lateralization on the development of cognition continues to be a debate, even in the animal research (e.g.,

Hopkins et al. 2007) as animal studies do not always corroborate the human evidence (Vauclair et al. 2006).

Some researchers have proposed that the population-level right-handedness of humans is a consequence of the evolved ability to produce and process language (Annett 2002), while others maintain that these two abilities evolved independently of one another (Kinsbourne 1997; Witelson 1990; in Michel et al. 2013). A number of species show handedness preferences (chimpanzees: Hopkins et al. 2007; capuchin monkeys: Phillips and Thompson 2013; kangaroos: Giljov et al. 2015; however, see Smith and Thompson 2011 for lack of evidence in saki monkeys), and at least nonhuman primates show associated hemispheric asymmetry. Moreover, there may be a link between right-hand-use and communicating in some animals (chimpanzees: Hopkins et al. 2005; nonhuman primates: Meguerditchian et al. 2013).

Many species also show eye dominance (e.g., Vallortigara 2006) which may support the claim for the evolution of asymmetry as a selected trait both at the population-level – an individual is more likely to survive an attack when their whole group moves in the same direction – and at the individual-level – an individual is better able to defend themselves from their dominant side. In terms of human cognition, some work suggests that children who are left-lateralized (left dominance in either eyedness or handedness) make more reading mistakes than right-lateralized children (Muehl 1963).

Sex differences have been shown in humans for language skills and lateralization for language, with women exhibiting stronger skill and men exhibiting greater left-lateralization (McGlone 1980); however, these findings have not always been replicated (e.g., Knecht et al. 2000a; Knecht et al. 2000b; Sommer et al. 2008; see Plante et al. 2006 for discussion). Additionally, more men are left-handed than women (Sommer et al. 2008). Studies with children have indicated sex differences in linguistic performance from an early age (e.g., Rome-Flanders and Cronk 1995; Bauer et al. 2002; Martin and Hoover 1987), but concordant neural studies have failed to show significant differences in laterality (Plante et al. 2006). Therefore, if sex differences affect brain organization for language in children, then we might expect girls to show less of an effect of handedness relative to boys on verbal performance.

Michel and colleagues (Michel et al. 2013) have provided evidence that infants who showed a preference for one hand in object retrieval were more advanced on their language skills as 2 year olds than children who had not exhibited handedness as infants. Furthermore, studies that have found the strongest connections between handedness and communication skills have been reported for ages of significant language development (in Michel et al. 2013: e.g., Vauclair and Imbault 2009; Bates et al. 1986). In my study, I test much older children (5-10-year-olds) for direct connections between hand dominance and language ability (spatial relational term use) as well as nonverbal spatial relational reasoning. Because previous findings suggest that individuals become more handed with age (Porac and Cohen 1981 in Gabard et al. 1991), I will test if strength of handedness continues to strengthen from 5 to 10 years.

Furthermore, knowing that one has a preferred hand and being able to correctly identify that hand as the *right* or *left* hand may provide a good strategy for making *left-right* judgments. Therefore, I will check for a correlation between knowing the correct label for the preferred hand and performance on the verbal task. Since children had unlimited time to respond in the verbal task, labeling the hands first then mapping these labels to the board would be a successful strategy. It may be unlikely, however, that I will find a correlation with knowing the preferred hand and performance on the nonverbal task since this task had a tight time limit which may have constrained the ability of children to map the hand to the dot's relative location. I will check for a correlation between knowing the correct hand and nonverbal performance, anyway.

Footedness is also connected to brain lateralization and neuropsychological functioning (Chapman et al. 1987; Peters 1988), with each foot controlled by the contralateral hemisphere. Some researchers suggest that footedness becomes lateralized later in life than handedness since up to a quarter of the populations tests showed no dominance at the age of 5 years (Belmont and Birch 1963; Gabard et al. 1991; Porac et al. 1980) with little change in dominance from 3 to 8 years of age (Gabbard et al. 1991; Gentry and Gabbard 2001) followed by an increased tendency for right-footedness from 11 years of age into adulthood (Bell and Gabbard 2000; Gentry and Gabbard 2001). Footedness does not appear to be tightly tied to handedness considering children show much more mixed preferences for foot dominance and, once established, is less likely to be right-lateralized than is handedness (Gabbard et al. 1991); however, it does not appear that many studies

have directly correlated these two measures. Although footedness has not been connected to communication processing, it is still an indicator of brain lateralization, so I include it as measure in our analyses despite not having any specific hypotheses regarding it. I will also measure concordance of hand preference and foot preference, as well as eye preference, within individuals.

I had a number of hypotheses which I tested. First, I expected to see a correlation between strength (absolute handedness) or degree (extent of right- or left-handedness) of handedness and performance on the verbal or nonverbal tasks if lateralization of the brain (as measured by handedness) accompanied improving relational coding performance. Strength of handedness provides an indication of lateralization and hemispheric specialization whereas degree of handedness provides a measure of left-hemispheric advantage, assuming that left-handers are less left-lateralized. Degree of handedness also provides a means of comparing performance of left-handers to right-handers. Secondly, since eyedness and footedness have also been implicated in previous work, I also checked for correlations between absolute footedness and performance on verbal and nonverbal tasks as well as between degree of eyedness and performance on verbal and nonverbal tasks. Third, I compared performances of children who knew or did know the correct label for their preferred hand with the assumption that knowing that you are right- (or left-) handed serves as an explicit strategy for making either verbal or nonverbal judgments: the first hypothesis covers the possibility that this serves as an implicit strategy. My fourth hypothesis is that handedness strengthens with age, so I will correlate children's age (in months) with their strength of (absolute) handedness. Finally, I will

compare boys and girls for differences in the correlations between their strength of handedness and performance on the verbal task under the assumption that girls may be less lateralized than boys in terms of hemispheric specialization and, therefore, it should be less likely that I would find a positive correlation between handedness and performance for girls.

Again, the rationale is that, in terms of brain lateralization, as a child becomes more “handed” (especially right-handed) then the left side of the brain may become “stronger”, and, therefore, the language centers additionally benefit from more connections. Following from this, I especially expected to see these correlations with performance on the verbal task, but if a similar strengthening were occurring in the right hemisphere, then it should be expected that performance on the nonverbal task should improve as well. Footedness, then, should similarly follow the pattern seen in handedness but the degree of handedness should follow a separate pattern in that previous work has shown effects on eye dominance rather than strength of laterality. In terms of knowing which hand is which, this is a labeling skill, so I expected to see a correlation with verbal skills; however, strong correlations with nonverbal performance may indicate a language advantage in these children such that either they are applying labels in the nonverbal task or their knowledge of the correct labels is promoting nonverbal performance in some other way. Overall, if laterality has an effect, then I should find significant results for *left-right* judgments, in particular: it will be more difficult to interpret correlations with *above-below* judgments since these directions do not map onto laterality.

5.3 Methods

5.3.1 Participants

The same 120 5-10-year-olds described in Chapter 3 and Chapter 4.2 were included in this study.

5.3.2 Degree of handedness test

In this game, children were asked to perform the actions when “Simon says” (Table 5.1, see Appendix B for test sheet example). I used Oldfield’s (1971) Edinburgh Handedness Inventory, but modified two of the categories (strike a match and hold a knife) because these were unlikely events for children. I replaced these two events with “open a bottle” and “hammer a nail” since these were likely more familiar events and ones children had participated in before. For each child, the order of actions was pseudorandomized between actions requiring the hands, feet or eyes: this was done in an attempt to get the truest evaluation of a side preference without the confound of repeating a just performed action. The degree of handedness, footedness and eyedness were calculated according to Oldfield (1971) and values range from -100 to +100 for each measure. Strength of handedness and footedness were also calculated: since these are measures of absolute values, the resulting values range from 0-100.

Following the end of the game, the child was asked whether they knew if they were right or left handed and their response was recorded. Regardless of their response, the child was then asked to raise either their right or left hand and this was also recorded.

Responses were recorded as a “1” if children could correctly identify each measure or a “0” if they could not correctly identify these.

Table 5.1 List of tasks used to measure handedness, footedness and eyedness. The last two actions in the table were requested four times so that strength of footedness and eyedness, respectively, could be assessed most accurately.

TASK	LEFT	RIGHT
Write your name in the air		
Draw a smiley face in the air		
Throw a ball		
Use scissors to cut a piece of paper		
Brush your teeth		
Hammer a nail		
Eat ice cream with a spoon		
Sweep the floor with a broom		
Open a pop bottle (twist)		
Take the lid off of a box		
Kick a ball		
Keep one eye open		

5.3.3 Analyses

I measured the correlation between degree (left, right or mixed) and strength (absolute value) of handedness and performance on each relation in both the verbal and nonverbal tasks as well as the relatedness of these measures to foot preference and eye preference. I will also test for effects of age, sex and knowing the label for each hand. The data were highly skewed toward right-handedness, therefore correlations were conducted using

Kendall's tau-b. Although they produce similar results, Kendall's tau is better with small group data than Spearman's Rho and is better at dealing with tied ranks. However, Kendall's tau provides results in terms of the probabilities of observing consistency in ranks, whereas Spearman's Rho is a measure of the variance explained. All performances are in percentages; however, the correlation analyses order these and therefore all statistics are conducted on ranks. All tests are two-tailed.

5.4 Results

5.4.1 Correlations between age, handedness, footedness and eyedness

In relating degree and strength of handedness with age (in months), I found no evidence that either measure of handedness increases with age. Furthermore, there was no correlation of age in months or handedness to strength of footedness or degree of eyedness. I analyzed strength of footedness to test for effects of overall lateralization and I analyzed degree of eyedness to test for effects of left hemisphere specialization since eyedness has been connected to language, specifically and footedness has not. These results suggest that any age-related changes in verbal performance (i.e., increases in verbal performance with age found in Chapter 4) are not linked to increased right-handedness or increased lateralization more generally.

5.4.2 Handedness and Performance

Despite not finding a correlation between handedness and age, I looked at both the whole group and the individual age groups for correlations to performance. The first reason for

doing this is that if handedness is a strong driver of performance, then the whole group analysis should be sufficient in finding a correlation. The second reason is that if there are maturational effects outside of lateralization, then only correlations conducted at the age group level will result in a relationship between handedness and performance.

5.4.2.1 *Whole group.* When looking at the whole group, there were no reliable correlations of strength of handedness and performance on the verbal tasks. Only a few nonverbal task conditions (congruent trials: *right*: $\tau_b = 0.18$, $p < 0.05$; *above*: $\tau_b = 0.15$, $p < 0.01$) were correlated to strength of handedness. Degree of handedness was only correlated to congruent *right* trials ($\tau_b = 0.15$, $p < 0.05$). This finding offers limited support for an effect of handedness on nonverbal performance, likely only for the side ipsilateral to the preferred hand since the population tested was predominately right handed.

5.4.2.2 *Age groups.*

When looking at the three age groups separately (5-year-olds, 6-7-year-olds, 8-10-year-olds; as defined in Chapter 4) different correlations emerged. Five year olds showed significant negative correlations of strength of handedness and comprehending the terms *right* ($\tau_b = -0.445$, $p < 0.05$) and *left* ($\tau_b = -0.421$, $p < 0.05$); but, there was no correlation with producing the terms. Additionally, 5-year-olds had a reliable correlation between degree of handedness and comprehension of *right* ($\tau_b = -0.51$, $p < 0.01$) and *left* ($\tau_b = -0.48$, $p < 0.05$). Performance by 6-7-year-olds did not reliably correlate with either strength of or degree of handedness. However, 8-10-year-olds, somewhat similar to 5-year-olds, showed significant correlations of strength of and degree of handedness to verbal

performance. Unlike 5-year-olds, 8-10-year-olds had negative correlation of strength of handedness to producing the term *right* ($\tau_b = -0.23$, $p < 0.05$) and reliable negative correlation of degree of handedness to production of *right* ($\tau_b = -0.25$, $p < 0.05$) but only marginal correlation to production of *left* ($\tau_b = -0.21$, $p = 0.054$). Additionally, strength of handedness was reliably positively correlated to nonverbal congruent right trials ($\tau_b = 0.25$, $p < 0.05$) for this older group.

In consideration of these findings, although the significance was not large, there is a trend for *right* judgments to be correlated with strength of (absolute) and degree of handedness. This bias likely is related to the *right* bias of the world in which children are developing, but further studies must be performed before this can be concluded.

5.4.3 Knowing correct hand and performance

I conducted a Mann-Whitney U test on the whole group to compare performances of those children who could and could not label their preferred hand. I chose the Mann-Whitney U test because of differences in sample sizes (110 vs. 10, respectively). Children who could correctly label their hand were better at producing the terms for *right* ($U = 1012$; $p < .00$) and *left* ($U = 958$; $p < .00$), and were better at comprehending the terms *above* ($U = 600$; $p < .05$), *right* ($U = 882$; $p < .00$) and *left* ($U = 831$; $p < .00$). In terms of the nonverbal task, children who could correctly label their hand performed better on incongruent *below* trials ($U = 803$; $p < .01$) and congruent *right* trials ($U = 748$; $p < .05$), and only marginally better on incongruent *left* trials ($U = 711$; $p = .07$). Thus, it appears that children who can correctly label their hands have an advantage over children who

cannot. This is supported by the behavioral observation that some children used mnemonic devices to label the sides, such as forming a “L” with the left hand or referring to their dominant hand then correctly recalling the label they had been told referred to their handedness (i.e., “I know that I am right-handed, this is the hand I use, therefore, this is my right hand).

5.4.4 Correlations of performance to footedness and eyedness

For the whole group performance analysis, the only correlation to footedness was for comprehending *above* ($\tau_b = 0.179$, $p < 0.05$). There were no reliable correlations of eyedness to performance; however, there was a marginal correlation with comprehending the terms *right* ($\tau_b = -0.16$, $p = 0.063$) and *left* ($\tau_b = -0.16$, $p = 0.053$).

For the three age groups, a few additional correlations emerged. For 5-year-olds, strength of footedness was positively correlated to comprehension of *above* ($\tau_b = -0.69$, $p < 0.01$), while only marginally correlated to nonverbal incongruent *right* trials ($\tau_b = -0.4$, $p = 0.06$). With respect to eyedness, 5-year-olds showed positive correlation with incongruent *above* trials ($\tau_b = 0.43$, $p < 0.05$) and incongruent *right* trials ($\tau_b = 0.52$, $p < 0.01$). For 6-7-year-olds, only strength of eyedness and nonverbal congruent *above* trials ($\tau_b = 0.286$, $p < 0.05$) were correlated, while no performances were correlated to footedness. No correlations between performance and either foot or eye preference were detected for 8-10 year olds.

5.4.5 Sex differences

When the group was divided by sex, no reliable correlations emerged for strength of handedness and verbal performance. Furthermore, there were no significant differences between the mean strength or degree of handedness using independent samples t-test. Similarly, there were no differences in the distribution of these measures between the sexes, using Mann-Whitney U tests. There were no sex differences for strength of footedness or degree of eyedness according to a Mann-Whitney U test.

5.4.6 Comparison of right-handers and left-handers performances

Since I found a correlation between degree of handedness and performance on right judgments, I compared performances of right-handers (N = 101; index scores of +25 to +100) and left-handers (N = 11; index scores of -25 to -100) on the nonverbal and verbal tasks using a Mann-Whitney U-test. I chose this test because of difference in sample sizes. There were no reliably significant differences between these two groups in performance on any of the relations in the verbal or the nonverbal tasks. These results suggest that handedness is generally not associated with verbal or nonverbal *left-right* knowledge; specifically, that left-handers are generally more confused than right-handers on these relations.

5.5 Discussion

One idea promoting an effect of handedness was that *right* and *left* are visually symmetric, but an asymmetry is created when one hand is favored over the other. Therefore, I hypothesized that children who are more asymmetric in their hand use (i.e.,

stronger handedness) would find it easier to map *right* and *left* onto their right and left hands. It turned out that being able to correctly label the hands was more useful to children than strictly having a preferred hand. Previous studies have found age and sex differences in handedness, but I found neither in my sample of 120 children.

Furthermore, I did not find age effects for foot or eye preferences and I found few correlations of dominance of any type (including handedness) to performance on the verbal or nonverbal tasks. However, when reliable correlations were found, these tended to involve *right* judgments, which suggest that right-handed children and more lateralized children are more sensitive to these judgments. However, contrary to expectations, these correlations were negative, indicating that performance was *worse* on these judgments than children who used their two hands more equally (i.e., were less lateralized).

I expected to see a correlation between strength of handedness and performance on *right/left* decisions if lateralization of the brain accompanied hand preference, particularly for verbal tasks with respect to left-hemisphere specialization. Although I did find that both degree and strength of handedness were correlated with performance on *right* congruent trials, these correlations were generally negative: the opposite direction expected. Furthermore both degree and strength of handedness were both correlated with comprehending and producing the term *right* for 5-year-olds and 8-10-year-olds, respectively. Again, these correlations were negative, which was opposite of what I expected: if lateralization of the brain promotes both language skill and hand dominance, then these correlations should have been positive. Overall, I did not find that handedness was related to nonverbal or verbal reasoning.

It does appear that knowing which-hand-is-which affects performance, but mainly for the verbal tasks. Children who could correctly label their hands were better at producing and comprehending *left-right* relations than children who could not attach the correct label. Again, it does not appear that laterality – in terms of the body’s asymmetry or in recognizing the asymmetry – has a reliable effect on nonverbal relational reasoning. Although I did find a few correlations with the nonverbal task - with incongruent *below* and congruent *right* trials – there was no clear pattern of relationship; therefore, I cannot draw strong conclusions. One reason why knowledge of which-hand-is-which (a labeling skill) helped performance in the verbal tasks could be that these children knew right from left in any situation, although it could also be due to the lack of a time constraint in responding which allowed children more opportunity to reason about their judgments. However, behavioral observation supports the conclusion that some children used mnemonic devices to correctly label the sides, such as forming a “L” with the left hand or referring to their dominant hand then correctly recalling the label they had been told referred to their handedness (i.e., “I know that I am right-handed, this is the hand I use, therefore, this is my right hand).

In line with other studies, I did not find a sex difference in handedness or footedness (Gabbard et al. 1991). Unlike previous studies, I did not find an increase in laterality with age (Gentry and Gabbard 2001; however, see Gabbard et al. 1991 for corroborating evidence). Adding to the literature, I did not find a correlation between strength of handedness and strength of footedness nor did I find a correlation between degree of

eyedness and degree of handedness: most studies I have reviewed only looked at consistency in laterality. Lastly, unlike previous research (Muehl 1963), I did not find differential performance between right- and left-handers on the different tasks, although my findings did suggest a slight effect of eyedness with left-dominance marginally correlated with better performance on *left-right* comprehension.

In terms of brain lateralization, we assumed that as a child becomes more handed (especially right-handed) then the left side of the brain becomes "stronger", and, therefore, the language centers benefit from more connections, as well. We especially expected to see these correlations with performance on the incongruent trials in the nonverbal (computer) task. However, few of the expected correlations were found. Overall, handedness does not seem to promote relational reasoning.

Chapter 6 Neural Correlates of Relational Judgments

6.1 Overview

Children learn the words for *above-below* relations earlier than for *left-right* relations, despite treating these equally well in our dynamic nonverbal task. Additionally, children struggle when a spatial relation is depicted in a spatially incongruent manner with respect to its position on a screen, as we illustrated in Chapter 4. In this study, I investigated the neural correlates of encoding and maintaining *above-below* and *left-right* relations in 12 adults using magnetoencephalography (MEG) in order to discover whether the verbally later-learned relations of *left* and *right* are represented by the brain differently than the verbally earlier-learned relations of *above* and *below*. I additionally compared neural activity associated with congruent and incongruent judgments. Adults performed perfectly on the task behaviorally, so any differences in neural activity were attributed to the stimuli's cognitive attributes. In comparing *above-below* to *left-right* relations during encoding, I found the greatest differences in neural activity in areas associated with space and movement. In comparing congruent to incongruent trials, I found the greatest differential activity in premotor areas. For both comparisons the brain areas activated in the encoding phase remained active during the maintenance phase of the task: this provides evidence that those brain areas are particularly important in representing the relational planes or congruency types. When comparing the relational planes in working memory additional right posterior areas were implicated, whereas the congruent-

incongruent contrast implicated additional bilateral frontal and temporal areas. These findings are consistent with the hypothesis that the later-learned relations (*left-right*) are represented differently than the earlier-learned relations (*above-below*).

6.2 Introduction

Human adults live in a three-dimensional world in which they constantly make decisions relating to the spatial relations they share with the objects with which they interact. Yet, adults sometimes confuse *left* and *right* spatial relations (Hannay et al. 1990; Jordan et al. 2006) despite never confusing other spatial relations, such as *above-below*, *up-down* or *forward-backward*. This differential confusion exists linguistically in children, as they learn the labels for these spatial relations, but not non-linguistically (Scott et al. 2015b). For example, children learn terms for *above-below* around the age of 3 years, but learn the terms for *left-right* around ages 6 or 7 years (Cox and Richardson 1985; Martin and Sera 2006). On the other hand, children have been able to categorize things as “to the left” or “above” since early infancy (Gava et al. 2009; Quinn 2007). Categorizing and compartmentalizing space is important not just for navigating in a three-dimensional world, but for promoting other cognitive skills, such as structuring comparisons and quantification (Stieff et al. 2013; Uttal et al. 2013; Verdine et al. 2014; Vendetti et al. 2015). Although there is a wealth of behavioral data supporting the idea that differences exist between the horizontal (*left-right*) relational plane and the vertical (*above-below*) relational plane (Cox and Richardson 1985; Landau and Hoffman 2005; Dessalegn and Landau 2008), there is a dearth of neural studies seeking evidence of such differences. Our (Scott, Sera, Leuthold, Georgopoulos, submitted)³ study investigates whether

differential neural activity exists for *above-below* compared to *left-right* spatial judgments.

Human infants seem to come prepared to recognize and categorize spatial relations (Gava et al. 2009; Quinn 2007). Infants can make correct visual matching judgments of *above*, *below*, *left* and *right* relative positions; yet, once they reach childhood they seem to have difficulty matching the relational category to the verbal label. Much of the literature concerning the development of spatial relational knowledge describes a “privilege” of the vertical axis (i.e., *above-below*) – especially the positive direction (i.e., “top” or “above”) – in verbal labeling (Clark, 1973; Clark 1980; Cox and Richardson 1985; Landau and Hoffman 2005). This “privilege” can sometimes be found in children’s non-linguistic matching performance where performance on the horizontal axis (i.e., *left-right*) is worse than performance on the vertical axis (i.e., *above-below*) in both typically developing (Dessalegn and Landau 2008) and children with Williams Syndrome (Landau and Hoffman 2005; Semel and Rosner 2003).

It is also apparent that when observing an object, adults automatically assign a “top” to the object, although this judgment is somewhat dependent on the item’s spatial orientation (e.g., Carlson et al. 2002). Together, these studies suggest that the *above-below* is treated differently from the *left-right* plane early in life in terms of attention and cognition, even in a disordered population, and this differential accessibility seems to persist into adulthood. What seems to develop, then, is the ability to label and remember spatial relations, rather than the ability to partition a space into categories, with the

different relational planes following different trajectories. How this is realized in the brain is yet to be determined; however, we set out to describe the end-state of these relations as represented by adult neural activity.

There has been little research on the neural correlates of encoding or remembering the spatial relations of *above*, *below*, *right* and *left*. The majority of studies investigating relational reasoning have focused on a general type of reasoning, such as analogical reasoning (Bunge et al. 2005; Wright et al. 2008) or matrix reasoning (Christoff et al. 2001; Crone et al. 2009; Baldo et al. 2010), or set out to differentiate between the different steps in the reasoning process (Krawczyk et al. 2011; Wendelken et al. 2012). Each of these studies has focused on the prefrontal cortex (PFC), and many have attempted to differentiate the specific areas within PFC that are responsible for specific aspects of reasoning. One study which did investigate neural correlates of spatial relations (Damasio et al. 2001) looked at the whole brain but relied on verbal retrieval and did so in the context of object recognition and tool use. Furthermore, they did not differentiate between the different sets of relations (i.e., relational planes). Nevertheless, Damasio and colleagues (2001) found neural activity specific to spatial relations in left frontal operculum, left posterior middle frontal gyrus, left inferior temporal cortex (when subtracting the control condition from the spatial relations condition), left inferior temporal cortex, right supramarginal gyrus (when subtracting activity from naming spatial relations using abstract shapes from naming spatial relations using tools/utensils), and left supramarginal gyrus (when subtracting the naming of implements from the naming spatial relations).

A recent study with monkeys (Goodwin et al. 2012), using a simple relational task similar to our own, directly compared *above-below* to *left-right* relations. In their study, two monkeys made simple relational judgments as their neural activity was recorded from prefrontal (along the principal sulcus) and parietal areas (along the intraparietal sulcus). The monkeys performed better at and had stronger neural activity – particularly in parietal areas – associated with *left-right* decisions compared to *above-below* decisions; however, it should be noted that both monkeys learned to differentiate *right* from *left* before learning *above* from *below* so the results may indicate an order of learning effect rather than a deeper evolutionary root of differential neural activity. These two possible outcomes represent a developmental effect and a phylogenetic effect, respectively: we will consider both possibilities in our results. Combined, these studies suggest that prefrontal areas will be activated in our spatial relational task, but it is not clear whether we will find differential activity in this area, as previous work has generally not compared activity associated with specific relations. The work of Goodwin and colleagues does suggest that we may find differential neural activity in parietal areas; however, their data acquisition was through single cell recording and relied on temporal differences, so these detailed techniques may not translate to similar findings in our study which used more holistic analyses and a different neural recording technique, magnetoencephalography (MEG).

In an MEG study by Franciotti et al. (2013) participants saw a pair of animals and had to judge whether a subsequent pair of the same animals shared the same spatial relations or

if these had changed with respect to spatial category or coordinate distance. The subsequent pair could be categorically different if one animal was facing a different *left-right* direction from before, coordinately different if the two animals were closer together than in the sample, or there could be no change in their spatial relations. The researchers saw increased activity in visual cortex, superior parietal lobule, inferior parietal lobule and middle frontal gyrus for categorically different pairs compared to coordinately different pairs and exact matches. Left inferior parietal lobule appeared to be particularly important for categorical judgments considering the researchers found differential activity between different types of cues within these judgments, while right inferior parietal lobule was differentially activated within coordinate judgments. This left-lateralized specialization for categorical spatial relations (and right-lateralization for coordinate spatial relations) is supported by other studies (Amorapanth et al. 2009; Baciuc et al. 1999; Kosslyn et al. 1998; Slotnick et al. 2001). Furthermore, a study by Amorapanth et al. (2009) suggested greater activity in superior and inferior parietal cortices (especially on the left) and posterior middle frontal cortices bilaterally when participants were asked to attend to the categorical spatial relations compared with the identity of objects; they verified the left-lateralization of categorical relations with a lesion study. Although our designs differ, the results from their study can be used to predict neural areas that we may expect to see differentially activated for the two relational planes, if the two relational planes are represented by the same networks but by different activity levels.

Behaviorally, there is no difference in the performance of *above-below* judgments from *left-right* for human adults in a simple relational task (Hayward and Tarr 1995).

Therefore, to capitalize on establishing differential neural activity in our study without the confound of differential performance, we used the same relational task that we developed for children, one in which adults encoded the relation of a dot to a line, remembered the relation for three seconds and then responded by reporting the relation via a button press. While adults performed the task, their neural activity was recorded using MEG.

Our broad predictions are, then, that these two sets of spatial relations (*above-below* vs. *left-right*) are represented in the brain differently despite a lack of matching differential results in performance (i.e., adults should perform a simple relational task perfectly).

Specifically, we expect to find areas of the brain that are differentially activated for one set of relations compared to the other set. Since few studies have explored a similar line of inquiry, we do not make predictions regarding specific areas of differential neural activity, although we may expect to find similar areas as described in Damasio et al.

(2001) or Franconeri et al. (2013) if the areas implicated in their studies are accessed to different extents for the different planes (i.e., by increased or decreased activity).

In addition to comparing neural activity for the relational planes, we compared neural activity for congruent to incongruent – where the relative position of something doesn't match its global position – trials. As discussed in the General Introduction of this thesis, two common tasks used to test congruency effects are the spatial Stroop and Simon tasks.

Neural imaging studies using spatial Stroop and Simon tasks suggest that neural areas activated for overcoming incongruency include: anterior cingulate, supplementary motor area, visual association areas, inferior temporal cortex, inferior parietal areas, dorsolateral prefrontal cortex, inferior frontal areas, and caudate nucleus (Peterson et al. 2002).

However, one study investigating neural areas activated by the Simon task indicated similar, but adjacent areas: pre-supplementary motor area, superior parietal lobule and cuneus (Wittfoth et al. 2006).

Furthermore, we will attempt to explain our findings with respect to the currently available literature. For example, one proposition regarding why *left-right* relations are confused is that symmetry tends to occur across the *horizontal* direction rather than the *vertical* direction, especially in nature, and the human visual system is adapted to detect *left-right* symmetry (Brandt and Mackavey 1981). This theory rests on the explanation that asymmetry in neural functioning (hemispheric specialization) provides better discrimination ability (in Brandt and Mackavey 1981: Mach 1897; Coballis and Beale 1970). It might be the case, then, that *left-right* reasoning may tap into the same neural areas used in reasoning about incongruencies. In this case, it may be that the relative relationship objects share in the *left-right* direction sometimes mismatches with the viewer's own egocentric frame of reference (Li and Gleitman 2002) and additional processing is necessary to overcome an initial judgment (e.g., change the frame of reference to map onto the object(s) to be judged). Therefore, we might find that similar neural areas are differentially activated in a congruent-incongruent comparison as for a spatial relational set comparison. On the other hand, early-learned words have been

shown to activate different neural areas than later-learned words – specifically in the precuneus and lateral inferior PFC areas (Fiebach et al. 2003) – so we may garner similar findings in both these brain areas in the relational plane contrast.

One last comparison I will draw is between the encoding and working memory (or maintenance) phases of the task. In the encoding phase, as you may recall from Chapter 2, the stimulus is presented for 1 second. It is at this point in the trial when categorization should occur and there may be differential activation of attentional networks, such as the *dorsal attention network* which is thought to be responsible for focusing attention on a task via top-down processing and consists of bilateral intraparietal sulcus and frontal eye fields (Farrant and Uddin in press) or the orienting network which comprises the superior parietal cortex, temporoparietal junction and frontal eye fields (Pozuelos et al. 2014). In the working memory phase, the participant must maintain the spatial relation for 3 seconds before they are able to respond. It is during this point in the trial where we should see visuo-spatial working memory network activity: bilateral visual association cortex, bilateral posterior cingulate and bilateral medial frontal gyrus (Ruff et al. 2003). Activity associated with reasoning and maintenance often overlap, but when compared, maintenance requires greater activity in right inferior parietal gyrus, right precuneus and an area in the junction of the left middle temporal and inferior parietal gyrus (Ruff et al. 2003). It is possible that motor planning will be differentially activated *within* each of these phases if one set of contrasts (relational plane or congruency) is judged more automatically than its comparison set of trials.

6.3 Methods

6.3.1 Participants

Twenty-six right-handed adults from 20-39 years of age (Female = 10; Male = 10) were recruited from the Twin Cities metro area. Only a subset of 12 participants were included in the analyses (Female = 4; Male = 8) and these individuals had a mean age of 27 years (± 5 years, standard deviation). The remaining participants were excluded due to a malfunction in the eye-tracking system (N=8) or due to artifacts in the neural signaling (e.g., dental work, non-removable metallic substances, N=6). The Montreal Cognitive Assessment (MoCA) was given to each participant to ensure they had normal cognitive functions; subjects averaged a score of 28 out of 30 (± 1.6). Participants also filled out a handedness survey to ensure they were right-hand dominant (Oldfield 1971): unlike the survey given to children, adults filled out the sheet on their own and were not asked to act out any of the actions. The twelve adults ranged in handedness values from 67-100 (85 ± 15).

This study was approved by the University of Minnesota and Minneapolis Veterans Affairs Medical Center institutional review boards and informed consent was obtained from all individual participants included in the study. All participants were paid for their time.

6.3.2 Task design

Participants performed the same computerized nonverbal task used in other studies. In this study, a trial progressed as a series of 3 screens, followed by 1 second of empty black screen: (1) the stimulus appeared against a black background for 1 second (the stimulus encoding phase), (2) replaced by static white noise for 3 seconds (the working memory phase), (3) replaced by a response screen (the response phase) that disappeared after a response was given or after 5 seconds had passed. The response screen comprised a single orange line against a black background: the line bisected the entire screen in the same direction as the line that had bisected the circle earlier in the trial. Responses were provided via a button box onto which the relations directly mapped (i.e., right button = *right*, top button = *above*, etc.). No training was provided. Participants received only verbal instructions and received no feedback on any trial to avoid eliciting an experimentally irrelevant neural response. Responses were provided for every trial and we recorded whether participants pressed a button prior to the appearance of the response screen (this occurred only 6 times over 576 trials: about 1% of all trials).

6.3.3 Equipment and set-up

Participants performed the nonverbal task while their neural activity was recorded using a 248-channel axial gradiometer magnetoencephalography system (MEG: Magnes 3600WH, 4-D Neuroimaging, San Diego, CA). MEG signal was sampled at 1017.25 Hz and filtered down to 0- 400 Hz during acquisition. The MEG was located in a shielded room that reduced electromagnetic and environmental noise. Participants lay supine on a

bed with their head inserted into the cryogenic helmet-shaped dewar which housed the 248 sensors.

During trial presentation, the images were projected into the MEG room via a projector and periscope mirror system onto a screen that subtended approximately 10 degrees of visual angle. The screen was positioned 62 cm in front of the participant. The button box was placed on participants' right sides, since all were right-handed. Participants were instructed to use only their pointer finger for pressing buttons.

Participants' eye positions were tracked using a nonmagnetic eye tracking system (RK-726PCI Pupil/Corneal Reflection Tracking System, model ETL-400, ISCAN, Inc., Burlington, MA). The system captures pupil/corneal reflection using a video feed (sampled at 60 Hz). Eye positions were calibrated before and after the experimental task.

6.3.4 **Data analysis**

6.3.4.1 *Task phase analysis.* First, we used a noise reduction technique to decrease variance in the signal. Then, we accounted for covariation of neural signal with experimentally extraneous variables, then we averaged the MEG signal over each trial period of interest. To account for the variation in neural signal due to experimentally extraneous variables, we performed a multivariate general linear model (SPSS v20) where the sensor was the dependent variable and the covariates were (1) the x,y coordinates of the circle on the screen, and (2) the x,y coordinates of the eyes; we saved

the unstandardized residuals to use as the dependent variables in subsequent analyses. We then averaged the adjusted neural data (e.g., the residuals) for each trial for each subject so that we had a single value for the encoding phase of the trial (1 second of stimulus appearance) and for the working memory phase of the trial (3 seconds of static white noise). In this way, the data were detrended and any relationship between neural activity and task parameters could be assumed to be real and unaffected by the position of the stimuli, by eye movements, or by nonstationarity of the neural signal. Furthermore, because the response was not included in the analysis, the results are not confounded by motor activity.

6.3.4.2 *Relation of neural activity to task parameters.* The main objective of this study was to assess the relation of neural activity to two sets of spatial relations (i.e., relational planes) as well as the neural activity associated with incongruency (as compared to congruency). We used the same statistical analyses to assess both comparisons. For our analyses, we ran a univariate ANOVA for each MEG sensor for each trial, where the sensor was the dependent variable and the independent variables were (1) relational plane and (2) congruency. Therefore, we had two sets of comparisons: (1) differential activity for congruent versus incongruent trials and (2) differential activity for the *left-right* versus the *above-below* trials. Subjects were included as random factors in this univariate model. Univariate ANOVAs were run for the entire subject group and for each gender separately. Interactions were not included as they are difficult to interpret.

6.3.4.3 *Localization of neural activity.* The low frequency, sustained activity of interest in this study does not lend itself well to source reconstruction techniques, but the region of

sensitivity for the gradiometer coil used here is substantially more compact than for magnetometer MEG coils or for EEG leads. To localize the neural source for MEG sensors that indicated differential activation, we recreated sensor space over the cortical space of a representative cortical surface reconstruction and noted the cortical area each gradiometer coil is pointed toward. Our recording method primarily records only from the cortical surface and not from deeper structures. We used BESA/Brain Voyager for the cortical surface reconstruction and to overlay sensor locations on that image, then rotated the brain/sensor space for each sensor to obtain a viewpoint that aligned the sensor with the neural area over which it was positioned, eliminating parallax error. There is a small region of maximum sensitivity for each gradiometer coil, around the identified cortical location for that coil. We report both the probable sulci and gyri over which the sensor was pointed. In this way, we could report the general area of the brain from which the neural signal originated, with the caveat that these are approximations. We used Damasio's (2005) brain atlas to identify the indicated brain areas.

6.4 Results

6.4.1 Behavioral performance

All participants performed the task without any errors. There was no significant advantage in reaction time for either relational plane (one-way ANOVA: $F_{1,574} = 2.13$, $p = .15$) or congruency type (one-way ANOVA: $F_{1,574} = .40$, $p = .53$). When men and women were analyzed separately, there continued to be no significant reaction time advantage; however, generally, men showed much larger, though not significant, differences in reaction time in both comparisons than did women.

6.4.2 Neural activity contrasts

F-values taken from the univariate ANOVAs of each sensor were used to plot the comparison results in MATLAB. F-values are plotted in a heatmap to account for variance emanating from the sensor for relational plane differences (Figure 6.1) and congruency differences (Figure 6.2), separately. All analyses are uncorrected. Each heatmap is scaled to its maximum F-value then down to 0. See Table 1 for the implicated brain areas and their associated significant F-values. Because we were localizing the source of signal for each sensor but did not have accompanying MRIs, Art Leuthold and I independently mapped the location of the probable neural source. In comparing the mapped sources, we each pointed to the same location for 28 out of 38 neural sources. Of the 10 time there was not agreement, the disagreement was over which side of a sulcus the source had originated. In these instances, we listed both potential sources in Table 6.1.

6.4.2.1 *Above-below vs. left-right trials.* For the encoding phase (Figure 6.1, left panel), differential neural activity was found around the areas of the right cerebellum, right superior temporal gyrus and left temporal-parietal-occipital junction areas; particularly, between the left superior temporal sulcus, anterior occipital sulcus and transverse occipital sulcus. For the working memory phase (Figure 6.1, right panel), differential neural activity was found in 7 of the 9 areas indicated in the encoding phase, including the same inferior parietal areas, right superior temporal areas, right cerebellum and along the left temporo-occipital junctions. Additional areas of differential activity during the

working memory phase include the left inferior temporo-occipital areas, right superior frontal areas, and a focused area of the right parietal lobe. Unlike congruency contrasts, the strength of differences was slightly higher for the encoding phase than the working memory phase. See Table 6.1 for a more precise description of the differentially activated areas.

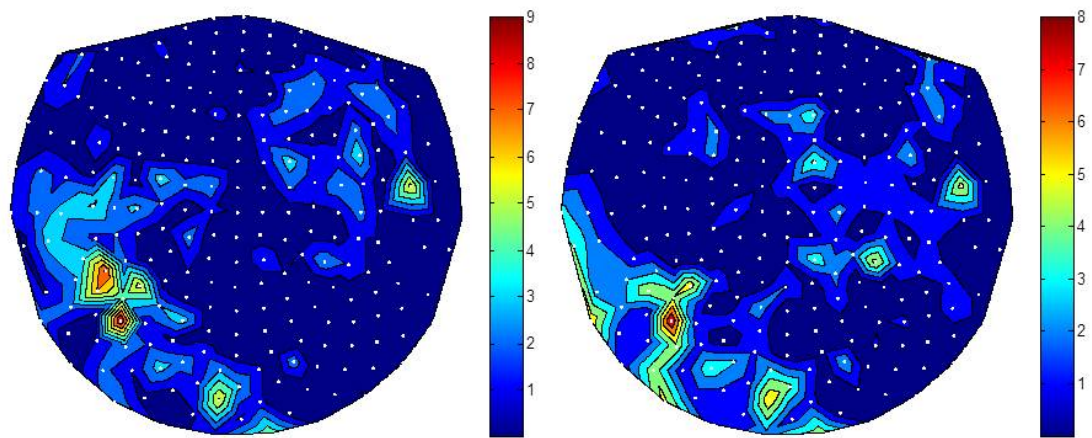


Figure 6.1 Heatmap of relational plane contrast based on F-values. Values are scaled and represent differential neural activity for encoding (left panel) and working memory (right panel) phases of trials.

6.4.2.2 *Congruent vs. incongruent trials.* For the encoding phase (Figure 6.2, left panel), differential neural activity was found exclusively on the left side of the brain in two areas of the frontal lobe and one area of the parietal lobe. The frontal areas included activity around the precentral sulci, over the most posterior areas of the middle frontal gyrus and

possibly the most posterior and inferior portion of the superior frontal gyrus. This likely is premotor cortex. The parietal area included an area around the postcentral sulci over the supramarginal gyrus of the inferior parietal lobule. For the working memory phase (Figure 6.2, right panel), differential neural activity was mostly bilateral (but not symmetrical) and spread across similar frontal areas, inferior and posterior temporal areas, near the temporal-parietal-occipital junctions, and cerebellum. Two of the three areas indicated in the encoding phase remained differentially activated in the working memory phase (one of the frontal sensors showed only marginally significant differences; $F_{1,562} = 3.4$, $p = .065$), and many of the sensors indicated in the working memory phase were located nearby and covered additional extents of the same neural areas. It is of notable interest that the strength of differential activity (as indicated by the F-value) is higher in the working memory phase compared to the encoding stage. See Table 6.1 for a more precise description of the differentially activated areas.

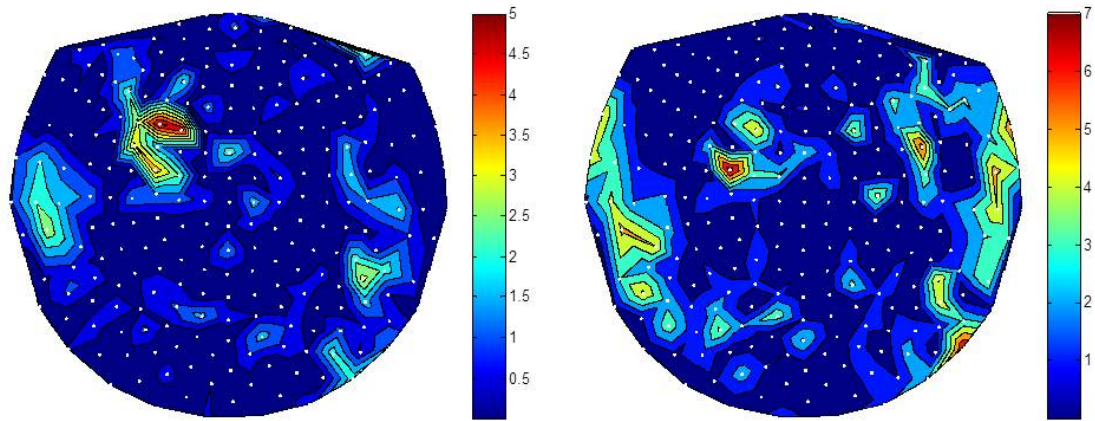


Figure 6.2 Heatmap of congruency contrast based on F-values, which are scaled and represent differential neural activity for encoding (left panel) and working memory (right panel) phases.

Table 6.1 List of probable brain areas involved in contrasts. This list is divided by task phase: encoding or working memory (WM). Sensors which indicated significantly different activity between contrasts are included, as is the degree of significance.

Contrast	Task phase	Sensor	Region	F-value
Above-Below v. Left-Right	<i>Encoding</i>	130	Left superior temporal sulcus; middle or superior temporal gyrus	4.1*
		132	Left superior temporal sulcus; inferior parietal lobule or lateral occipital area	8.1***
	<i>Encoding & WM</i>	101	Left transverse occipital sulcus/lateral occipital sulcus; angular gyrus	6.4*/5.7*
		133	Left transverse occipital sulcus; angular gyrus or superior occipital	4.2*/4.9*
		160	Left angular gyrus	7.1**/4.7*
		161	Left lateral occipital sulcus; lateral occipital gyrus	9.2***/8.0***
		172	Right superior temporal gyrus	6.3*/5.4*
		203	Left calcarine fissure; occipital pole	6.1*/5.9*
		239	Right cerebellum	4.9*/4.8*
	<i>WM</i>	16	Right middle frontal sulcus/longitudinal fissure; superior frontal gyrus	4.2*
		79	Right inferior parietal sulcus; inferior parietal lobule or temporo-occipito-	5.3*

			parietal junction	
		183	Left calcarine fissure	4.9*
		186	Left or right lateral fissure	4.3*
		214	Left cerebellum	3.9*
		217	Left cerebellum	4.7*
		234	Left cerebellum	5.7*
		236	Left cerebellum	5.3*
Congruent v. Incongruent	<i>Encoding</i>	41	Left precentral sulcus; middle frontal gyrus or precentral gyrus	5.1*
	<i>Encoding & WM</i>	22	Left precentral sulcus; middle or superior frontal gyrus	4.8*/ 5.1*
		43	Left postcentral sulcus; supramarginal gyrus	3.9*/ 7.7**
	<i>WM</i>	34	Right mid frontal sulcus or superior frontal sulcus; superior frontal gyrus	4.4*
		54	Right central sulcus; postcentral gyrus	4.5*
		114	Right central sulcus; precentral gyrus	6.4*
		148	Right inferior frontal gyrus	4.1*
		159	Left angular gyrus	5.0*
		162	Left transverse occipital sulcus; lateral occipital gyrus	4.2*
		169	Right lateral occipital sulcus/anterior occipital sulcus; temporo-occipital junction	5.1*
		180	Left inferior temporal gyrus	5.3*
		190	Right anterior occipital sulcus; lateral occipital gyrus or temporo-occipital junction	4.7*
		198	Left inferior temporal gyrus or fusiform gyrus	4.3*
		199	Left lateral occipital gyrus	5.2*
		209	Right inferior temporal gyrus or fusiform gyrus	5.0*
		210	Right inferior temporal sulcus; inferior temporal gyrus	5.5*
		225	Right cerebellum	3.9*
		231	Left lateral temporo-occipital sulcus; inferior temporal gyrus or temporo-occipital gyrus	4.9*
	232	Left lateral temporo-occipital sulcus; temporo-occipital gyrus or inferior temporal gyrus	5.6*	
	242	Right cerebellum	7.0**	
246	Right inferior temporal gyrus	5.8*		

* p < .05

** p < .01

*** p < .005

6.4.2.3 *Sex differences in neural activity.* Because sex differences have been shown in brain lateralization, particularly for language processing, we analyzed the data for the men and women separately. Our findings suggest that these group plots may be largely driven by the male participants. Women, when analyzed separately, showed non-overlapping areas of differential neural activity from men which were largely bilateral and in fewer areas. Additionally, women showed a much smaller difference effect, with an F-value of only 4, suggesting that women are largely treating the opposing conditions (within each comparison set) similarly. However, since the sample size was small and skewed toward men (N = 8; women: N = 4) we do not show the data here. Nevertheless, we mention this potentially interesting and important sex difference to encourage further work on parsing out these differences, especially considering that there were no performance differences.

6.5 Discussion

This study is the first to implicate differential neural activity for two sets of spatial relations. We also observed differential activity for congruent trials compared to incongruent trials in approximately the same number of areas that were indicated in the relational plane contrast. Some of the implicated areas for the two contrasts overlapped, although the precise sensor differed which indicates that the exact neural source was different. For each contrast, most of the neural areas consistently showed differential activity across both the encoding and working memory phases of trials, suggesting these

areas are especially important for making those (relational plane or congruency) judgments. Overall, it was a rule rather than exception that the working memory phase included an expanded area of differential activity compared to the encoding phase. It should be noted that from our results we cannot point to directionality in terms of which set of relations (or congruency type) drove the observed differences and we cannot distinguish whether these differences in activity are due to increases or decreases from baseline activities; therefore, we cannot speak to whether these differences are due to separate cognitive systems or changes in activation within a single system. Despite this caveat, we can make a number of coherent conclusions, and align these to the current literature.

The first conclusion is that the two sets of spatial relations we examined have distinct neural signatures. Our relational plane contrasts indicated differential activity mostly over left occipital-parietal-temporal junction areas, and cerebellar areas. Additional areas included single parts of the right superior temporal gyrus, right frontal gyrus, and right cerebellum. The importance of left inferior parietal lobe in categorical relations, generally, is supported in the literature (Amorapanth et al. 2009; Damasio et al. 2001; Franciotti et al. 2013), although we are the first to show that this area is differentially activated for different sets of spatial relations. Furthermore, our findings support Damasio et al.'s (2001) results for the importance of right inferior parietal lobule (in their study, the supramarginal gyrus); however, in our study the differential activity was due to working memory processes while in their study it was due to differences from naming spatial relations using abstract shapes and naming spatial relations using implements

which may suggest that our participants were accessing labels in this phase of the trial or otherwise doing something similar to Damasio et al's participants. We did not, however, match previous findings of left superior parietal activity or left posterior frontal (Amorapanth et al. 2009; Damasio et al. 2001) or middle frontal activity (Franciotti et al. 2013); although we did find minimal difference in right frontal activity.

In comparison to other studies, it has been suggested that the right superior temporal gyrus (STG) subserves spatial awareness and encoding (Karnath et al. 2005) as well as shifting attention (Yantis and Serences 2003), while the left STG contributes to language processing: any of these attributes could explain why STG was differentially activated in our study, but future investigations are needed to address this issue. Differential activation of left temporal-parietal areas could be explained by increased activity for *left-right* judgments compared to *above-below* since this area (the angular gyrus, specifically) has been implicated in *left-right* confusion (Gertsman 1940; Hirnstein et al. 2009). This finding may be due specifically to *left-right* incongruent trials if these trial types required additional processing that *above-below* incongruent and *left-right* congruent trials did not require, possibly due to automaticity of those other judgments. Our parietal findings match those of Goodwin and colleagues (2012), which indicated stronger neural activity for one set of relations over the other. Their results (Goodwin et al. 2012) pointed to stronger activity for *left-right* judgments – the spatial relations learned first for two monkeys – than for *above-below* judgments. However, Goodwin and colleagues also reported differential activity in prefrontal areas: areas which we did not find any differential activity. In fact, prefrontal areas were not implicated in either of our contrasts.

The second conclusion is that congruency contrasts implicated areas that have been previously shown to be involved in overcoming incongruencies as well as areas associated with motor planning and visual spatial working memory. Areas previously indicated for overcoming incongruency include inferior temporal cortex, inferior parietal areas and inferior frontal areas (Peterson et al. 2002). Furthermore, the areas implicated in our study have been linked to object-based and perspective-based transformations, including the areas in occipital, temporal, parietal, and posterior frontal cortices, and a substantial portion of the cerebellum (Zacks and Michelon 2005), which may be important in adjusting category assignment. For the encoding phase of the task, specifically, premotor areas were differentially activated which may suggest that some motor planning was affected more for one congruency type than the other. A likely explanation is that the congruent trials promoted an automatic response and therefore led to a stronger, sustained motor planning signal than the incongruent trials – which likely had a delayed motor response. However, these frontal areas are also associated with visual working memory, so the activation could just as likely be due to early engagement of working memory processes. During the working memory phase additional neural areas were activated. Additional areas included mostly bilateral temporo-occipital areas as well as right cerebellum and singular parts each of the right superior frontal gyrus and left angular gyrus. Bilateral temporo-occipital areas, including fusiform and inferior temporal gyri, have been implicated in survey encoding (Shelton and Gabrieli 2002), topographical memory (Corkin 2002), and object processing (Damasio et al. 2001): it may be that incongruent trials necessitate these kinds of additional processing (or strategies) in order

to make the correct judgment whereas congruent trials are processed and remembered automatically and without further processing. Both the left supramarginal and left angular gyri have been implicated in *left-right* confusion (Gertsman 1940; Hirnstein et al. 2009) but it is not clear whether *left-right* incongruent judgments are driving this result considering these same neural areas also showed differential activity in the relational plane contrast. Finally, superior frontal sulcus, which divides the middle and superior frontal gyri, is associated with working memory (Klingsberg et al. 2002) and although the same sensors were not implicated in both contrasts, these sensors were adjacent to each other suggesting that a similar function may have been performed in each condition.

Contrary to our hypothesis, there was no evidence for differential activity in the expected areas for early (*above-below*) compared to later (*left-right*) learned words. Specifically, we expected to find differential activity in the lateral inferior prefrontal cortex and precuneus (Fiebach et al. 2003). One possible reason why we did not see differential activity in these areas is because of our method. First, Fiebach et al.'s (2003) study subtracted from baseline activity whereas we differenced between conditions. Secondly, our design did not investigate linguistic strategy use explicitly or in any way prime participants to use a linguistic strategy (as the afore-referenced studies did). Behaviorally, language has been implicated in the encoding and retrieval of spatial information, elsewhere, but with mixed results (Hayward and Tarr 1995; Hermer-Vasquez et al. 1999; Loewenstein and Gentner 2005; Dessalegn and Landau 2008). So, although it may be true that language use helps in terms of strategy use, it does not appear that language is differentially accessed for the two relational planes or congruency types in adults. Our

findings may still support the hypothesis that later-learned words (*left-right*) are neurally represented differently than earlier-learned words (*above-below*) despite comparable performance and even though the implicated areas differ from those suggested by Fiebach and colleagues (2003). Another possible reason is that labels were not utilized by our participants and so those neural areas were not activated. We use caution when assigning function to cortical areas since there is rarely a 1-to-1 mapping (Price and Friston 2005), but would nevertheless expect to see differential neural activity if these areas were involved in the cognitive systems tapped for our task.

Another hypothesis that was not validated was that relational planes map to similar neural areas as congruency. We did not find overlapping areas of differential neural activity for the relational and congruency contrasts as expected if symmetry was a factor (for supporting behavioral evidence see Sholl and Egeth 1981). However, this could be because our stimuli were simple and did not have (biologically) relevant axes onto which a canonical top could be assigned or front-back could be distinguished. Future work should consider if similar differences are found for oriented faces, bodies or other biologically relevant stimuli.

Our third conclusion is that the consistency in differential activity across encoding and working memory phases indicates neural areas that are imperative for representing one condition over the other. For the congruency contrast, one of the left premotor areas and an area of the left supramarginal gyrus was consistently differentially activated. Similarly for the dimension contrast, nearly all the areas differentially activated in the encoding

phase were also differentially activated in the working memory phase. These areas, in particular, should be further examined in future work that is focused on congruency (perhaps as it relates to relational complexity) or spatial relations.

Our fourth, and last, conclusion is that gender differences may exist neurally despite concurrent performance differences and this contrast should be pursued in future studies. Our findings may support previous findings that the two sexes utilize different strategies and/or that they have differences in brain use efficiency. On the one hand, previous work – such as that work on spatial navigation – has indicated that men and women apply different strategies for the same task; specifically, women are more likely to use an analytic, or landmark-based, strategy, whereas men are more likely to use a holistic, or Euclidean, strategy (Wang and Carr 2014; see Thomsen et al. 2000 for similar conclusion). Such differences in strategy have been linked to differing ratios of visuospatial working memory to verbal working memory (Wang and Carr 2014) or differences in social skills, such as empathy or embodiment (Kessler and Wang 2012). However, for our task, it may be the case that women are applying a single strategy to the simple relational task while men may be using an array of strategies, varying according to the specific condition. Alternatively, it has been shown that women are more efficient than men in terms of neural processing in a visuospatial task without concurrent performances differences (Christova et al., 2008). Furthermore men and women appear to differentially activate the two hemispheres in certain tasks, further providing supporting evidence of a difference in strategy use (Georgopoulos et al. 2001). Additionally, it has been shown that sex differences may exist across a number of cognitive tasks despite

performance differences, with men showing stronger neural signals and signals in a larger number of areas (Bell et al. 2006; Weiss et al. 2003; Thomsen et al. 2000), similar to our findings.

In light of our overall findings, it may be tempting to conclude that relational reasoning is left lateralized in the brain; however, the importance of brain lateralization on the development of cognition continues to be a debate, even in the non-human research (e.g. Hopkins et al. 2007). Niebauer (2001) suggests a left hemisphere advantage for processing categorical relations (i.e. is a dot *above-below* a line) and a right hemisphere advantage for processing coordinate spatial relations (i.e., is the dot *near/far* from a line; see also Franciotti et al. 2013 for similar findings). Our current study echoes this left hemisphere processing of categorical relations.

Considering our overall findings more generally, and in the context of other studies, our conclusions add to the current literature on relational reasoning despite not being able to corroborate all the previous findings. This may be due to our methods of neural recording and analysis or to differences in task requirements. Many studies of relational reasoning have focused on the connections between prefrontal cortex and parietal areas and these fronto-parietal connections are well documented and central to spatial encoding in both humans (Krawczyk 2012; Wendelken et al. in press) and monkeys (Chafee et al. 2007; Goodwin et al. 2012). Our current analysis did not investigate these connections, specifically, or in terms of their temporal coordination, but we will investigate these in future analyses. In terms of localization, prefrontal areas were not differentially involved

in either of our experimental contrasts, although parietal areas were. Left prefrontal cortex has been pointed to as an important center for judgments of relational complexity (frontopolar cortex; Bunge et al. 2005), for manipulating self-generated information and integrating the outcomes of two or more cognitive operations (rostrolateral prefrontal cortex; Christoff et al. 2001; Crone et al. 2009), as well as for evaluating whether relations match (monitoring and manipulating representations held in working memory) and mediating reasoning processes by supporting analogical mappings (dorsolateral prefrontal cortex; Bunge et al. 2005). The lack of differentiated activity in our study suggests that these cognitive resources were not tapped more for one contrast than for the other; the performance results corroborate this conclusion.

In summary, we provide the first evidence for differential neural activity for two sets of spatial relations. Due to our approach, it is unclear whether these differences are due to separate cognitive systems or to changes in activation within a single system; therefore, further work is needed. In terms of localization of neural signals, fMRI or other neural imaging technique would contribute necessary supporting evidence. Future steps should also include investigating the strength and timeline of connectivity across brain regions. We predict that *left-right* relations likely require increased activity in the indicated areas compared to *above-below* if these relations are truly more difficult. Furthermore, to get closer to the answer of whether *left-right* relations are the more difficult relations to judge, a future study should require participants to respond as fast as possible rather than allowing a response delay as in our study: faster response times for *above-below* judgments would be expected if *left-right* judgments are more difficult. Our findings

suggest that future work also should be aimed at further discerning and discovering gender differences in neural signaling, without concurrent performance discrepancies. The current analysis was largely exploratory, so few a priori hypotheses were formed regarding what neural areas should show differential neural activity. This was largely the case because there were no precedents to suggest differential neural activity for *above-below* versus *left-right* judgments; therefore, further inquiry into this line of questioning and further analyses of the implicated neural areas are causes worthy of further pursuit.

Chapter 7 General Discussion

7.1 Discussion

The impetus of this thesis was to investigate relational reasoning in humans in terms of 1) its development, 2) its reliance (or lack thereof) on language, 3) its connection to lateralization, and 4) the neural mechanisms underlying it. Previous studies have suggested that relational reasoning is a specific kind of mental computation that develops slowly in humans and so late in primate evolution as to perhaps be unique to humans (e.g., Christoff et al. 2001; Penn et al. 2008; Halford et al. 2010). Some researchers tie relational reasoning to language and have gone so far as to suggest that it is dependent upon language (Gentner 2003; Baldo et al. 2010). Our work, in consideration of Goodwin et al. (2012) – the work that inspired it – suggests that relational reasoning is not as dependent on language acquisition as previously thought, but instead language can be engaged as a strategy for dealing with relational judgments. This is an important distinction with three implications: 1) animals can learn to make these judgments if properly trained (e.g., Fagot and Thompson 2011; Goodwin et al. 2012), 2) animals trained to apply symbols to representations should outperform non-symbol-trained animals, and 3) humans exhibit superior performance only when they apply a linguistic (or symbolic) strategy, not by virtue of having language alone. This is an important distinction because it supports the idea of continuity between humans and other animals – that human cognition is not different from animal cognition in *kind* but rather in *degree* (Darwin 1871) – that some researchers dispute (e.g., Penn et al. 2008).

In collating my specific findings, I have provided ample behavioral evidence that the same underlying cognitive mechanisms are at play in the ability to extract the spatial relations *above*, *below*, *right* and *left* using a nonverbal task by humans (both children and adults). However, the neural evidence suggests that differences emerge at the neural level, although it is unclear whether the difference is in the neural network involved or the degree to which a single network is activated. In consideration of our behavioral evidence (and the neural evidence provided by Goodwin et al. 2012), I suggest that the difference lies in the degree to which a single network is activated. Previous work has suggested that more challenging tasks require increased neural activation in the areas responsible for that particular ability (relational reasoning: Crone et al. 2009; Wendelken et al. 2008; flow: Ulrich et al. 2014; bimanual coordination: Ullen et al. 2003); therefore, it is likely that *left-right* relational judgments required greater activation, which drove the difference in activations. This conclusion is partially supported by the idea that order of acquisition affects neural activation, a finding that is suggested in Goodwin et al. (2012) and some behavioral studies with typically developing children (Dessaiegn and Landau 2008) and children with Williams syndrome (Landau and Hoffman 2005).

In support of my conclusion that language acquisition, alone, is not responsible for enhanced reasoning ability, I did not find superior nonverbal performance on *above-below* judgments compared to *left-right* judgments in children or adults. This is despite finding that knowledge of the words *above* and *below* precedes the ability to accurately extract the relations in a nonverbal task: strong evidence for the idea that the ability to extract the relations is linked to language should have yielded better performance in the

nonverbal task for *above* and *below* in comparison to *right* and *left* (as found in Landau's studies). However, there was evidence that knowledge of which hand is which (a labeling skill) does seem to help performance in both modalities, though much more on the verbal tasks where children had no time constraint in responding. One reason for this finding could be that children who knew the correct label had enough time in the verbal task to reason through their judgment, since this task had no time constraint. There is evidence for this from the observation that many children who performed well on the verbal task would hold out their hands and label each one before making a verbal judgment (often using the "my left hand forms an *L*" strategy). Final support is evident in the finding that many children who did not know the correct label for each hand still did well on the nonverbal task (the critical comparison); therefore, the effectiveness of language was evident mostly in its use and less so in the sheer act of having it.

Further evidence against the reliance of nonverbal relational reasoning on verbal ability rests on our study of the order of skill acquisition (Chapter 3). In that study we offered new insights into the process of cognitive development; namely, the mechanisms of restructuring (Piaget's assimilation and accommodation) that occur as knowledge is added to the cognitive system. Our analyses revealed the progressive treatment of different tasks as being similar (i.e., chunking) as these tasks became hierarchically organized with cognitive development. We found that, first, verbal tasks became clustered – each cluster beginning as a pair of antonyms within a specific task – and, then, slowly the nonverbal tasks became chunked. Although this finding supports the idea that verbal knowledge is attained first, followed by the consolidation of nonverbal

knowledge, our correlational analyses provided the necessary support to show that these two skills are not dependent on one another. So, although one skill may precede the other, our results suggest that they are fairly independent processes, at least at the age groups tested.

That being said, I want acknowledge that these processes can be used to enhance one another (e.g., Gopnik 2001). Previous work has suggested that learning new words can create the opportunity for concept-formation (which is a nonverbal process: Waxman and Markow 1995; Casasola 2005; Lupyan and Casasanto 2015). In my own work, I have shown that language can enhance nonverbal reasoning when labels are utilized as an encoding and memory strategy. I have argued that by accessing language, and applying a linguistic strategy, a mechanism is provided to direct attention to the salient information, and therefore to ignore the irrelevant information. It could be that the activation of a linguistic strategy biases perception (or search strategy) toward the category which it labels; however, my studies cannot speak to that interpretation.

Based on my findings, I suggest that the role of language is to provide a unifying mechanism for bridging the perceptual gaps between different instances of relational similarity: what is seen and the concept to which it is tied. This tying together of different visual information and concept by way of a label can work by switching the roles of concept and label, which supports previous work (Snedeker and Gleitman 2004). Therefore, my findings do not discount the possibility for perceptual warping (as argued by Lupyan 2012), but rather speak only to the later-occurring comparison step of

relational reasoning. Further work is necessary to explore the possibility of linguistic effects in early processing; however, based on the current literature, I think that it is likely that effects from language can be seen either at early processing or later in processing, or perhaps even at both levels of reasoning.

In short, my findings are consistent with the idea that language can strengthen basic relational reasoning abilities such that using language to encode and remember stimulus attributes (e.g., spatial relations) expands the capacity for relational reasoning, and may free up resources to solve other problems. In this way, then, once language skills are strong enough (perhaps when all verbal instantiations form a single concept in the child's cognitive architecture) then adequate resources are freed up for other aspects of reasoning (such as overcoming an incongruence): a mechanism which is suggested in our cognitive organization study. Furthermore, it may be that language is being used as a strategic tool for adopting and abandoning (i.e., shifting) relational standards: a possible explanation which is supported by our finding of similar performance across both relational planes when a "linguistic" strategy is applied in the nonverbal task.

Coming back to the underlying neural mechanisms, it may be tempting to conclude that relational reasoning is left-lateralized in the brain: that it drives left brain activation. Both contrasts of relational plane and congruency indicated significant differential activity in mostly the left hemisphere for encoding the stimulus, although working memory was much more bilateral. However, since we did not compare neural activity to a baseline, we cannot say whether the left-hemisphere is truly predominant for this type of reasoning or

whether only areas in the left-hemisphere were differentially activated. It should be kept in mind that all the adult participants were right-handed, so I cannot eliminate the possibility that some of the left-hemisphere activity was due to motor responses, at least for the relational plane contrast since each relation required a unique finger movement. Motor response cannot account for the congruency effects since all four finger motions are represented in these samples. Bringing in the findings from the handedness study, and working from the assumption that children's neural activity highly corresponded to adults' neural activity (Wendelken et al. 2011; Wright et al. 2008), I can infer that lateralization (handedness) did not drive performance on the relational planes. Therefore, relational reasoning may drive left-hemisphere specialization, but the reverse is not true. However, it could be that lateralization did drive verbal performance, although this would need to be specifically tested in a future study.

Keeping those concerns in mind, there are a few conclusions that I can draw concerning the left-lateralization of brain activity in relational judgments. The most significant left-hemisphere specialization findings from other studies involved categorization task (compared to coordinate judgment tasks) and PFC activation. With respect to categorization, generally speaking, my task was a categorization task. This may explain why I found differential activity predominately in the left hemisphere. With respect to PFC activations being predominately left-lateralized, since I did not find differential activity in the PFC in either the left or the right hemisphere, it may be that my task did not tap into the specific aspects of relational reasoning that have been associated with PFC activity (see Appendix C for list of PFC-associated cognitive processes). For

example, it could be that my task was simple enough for human adults to not require much integration of object or relational information. Furthermore, it is possible that my task did not require semantic retrieval or that the two contrasts did not differ in their requirements of working memory.

My last general conclusion is that gender differences may exist neurally despite a lack of concurrent performance differences. My study with adults suggests this finding, but follow-up studies should be conducted with a larger sample of adults and with children. Previous work with adults has suggested that men and women engage different neural patterns on the same task (Bell et al. 2006; Weiss et al. 2003; Thomsen et al. 2000) without differences in performance (Christova et al. 2008); however, it is yet unclear whether boys and girls engage different neural patterns on the same task with similar performances. Sex difference in performance in children can be manipulated to emerge or disappear, so any study would need to be careful in its instructions and to avoid empowering biases (Baennenger and Newcombe 1995; Stieff et al. 2013; Uttal et al. 2013a). These differences should be investigated in future studies.

7.2 Implications

The implications for this research are vast. First, this research sheds new light on the relationship between language and cognition, especially in terms of concept development and retrieval. Because relational reasoning is so important for building math and science skills (National Research Council 2006; Vendetti et al. 2015), it is critical that relational

reasoning (in all its manifestations) be taught in the classroom. Our study on the order of development of relational reasoning skills suggests that classroom training might begin by verbally pairing up polar opposites (e.g., *above/below*, *right/left*), in concordance with previous findings that suggest children learn two words are opposites before they fully map the terms to their relations (Clark 1972). Only after opposites are mastered children might be taught to make nonverbal perceptual matching judgments, like our nonverbal congruent trials. Finally, these congruent judgments should be the basis for teaching how to make the more difficult incongruent relational judgments. In short, our findings suggest how a unified system of knowledge for making relational judgments might be built— by appealing to the natural progression by which these skills develop.

Furthermore, overcoming incongruency is an equally important skill to learn, which requires children to ignore irrelevant information. For example, in analogical studies, children have been shown to be highly susceptible to irrelevant perceptual features (Ratterman and Gentner 1998; Richland et al. 2006) which distract them from the relevant relationships at the core of the analogy. Our study on the co-development of verbal and nonverbal relational knowledge suggests that labels may help children attend to the key relationships and draw their attention away from the irrelevant information. Although perceptual similarities may serve as a distractor, they can also be used to scaffold learning by drawing attention to the key elements of the stimulus or task (Namy and Gentner 2002; Gentner et al. 2007), particularly when these features share a label, which is useful in a classroom setting (reviewed in Vendetti et al. 2015). In fact, simply

providing detailed instructions to children can be enough for them to overcome incongruencies (Theeuwes et al. 2014).

Our neural study has implications for discovering the role of biology and physiology over the role of experience in spatial relational judgments. From my work, it is unclear whether attentional networks play a role in differentiating one pole from the other (in either the vertical or horizontal directions), although future work could determine the involvement of these networks. In terms of everyday implications, knowing one's *left* from *right* and being able to tell *above* from *below* is an extremely important ability to have. In fact, this ability has important implications for navigation, particularly for individuals working in environments that lack environmental or gravitational cues that parse these directions from each other, such as pilots, divers and astronauts. It is interesting to note that nautical and aeronautical directions avoid *left-right* terms and instead implement the terms *port* and *starboard*, respectively. Historically, humans appear to be less able to tell *left* from *right* than other directions such as *above* and *below* and our neural evidence supports this observation. Further research as to why these differences exist could have important implications for training individuals (particularly drivers, pilots and captains) to have higher efficacy in identifying these directions, particularly the *left-right* directions.

7.3 Future directions

We designed our nonverbal task to be used in future cross-species studies. In fact, the potential to apply this task in different animal studies was a major factor in choosing to

model it from Goodwin et al.'s (2012) task. Of particular interest is to further explore the effects of language on nonverbal reasoning ability. Specifically, it would be ideal to follow previous attempts to identify differences in ability between symbol-trained and non-symbol-trained animals. If symbolic representation (of which language is a type) truly promotes relational reasoning, then we should find, as others have, a performance advantage for those animals that have access to symbols.

As thinking for saying follows different pathways in the brain than *thinking for doing* we would expect, in humans, to find an erosion of the latter by the former when the task becomes more reliant on language. In spirit of this prediction, future studies include manipulations in the task such as more explicit directions on how to perform the task or how to respond (i.e., repeating the answer silently to one's self rather than eliciting a motor response). Another manipulation is that we may also want to examine whether language affects the length of time that the relations are encoded or remembered because past work suggests that language's effects are most apparent when longer times are required between relational coding and a behavioral response (e.g., Hermer and Spelke 1996). However, it would be equally interesting to speed up the task such that engaging a linguistic strategy would be impossible: if language's effect is weak (as we suggest) then performance should not be affected, although there is a possibility that the neural pathways involved will be different. This is an important question to answer and gets more specifically at the role of strategy in performance.

Our study on the neural components of relational reasoning suggest that gender differences emerge at the neural level, but without differential performance on the task, we cannot identify in what ways their reasoning differs (if at all). It could be that men and women differ at the neural organization level rather than at the strategy level, but this is a difficult argument to make in terms of how those differences would have evolved. Further work should concentrate on determining whether gender differences actually exist. One important finding of this future work is discovering the biological versus the environmental component of such a difference (if one exists). For example, Piaget's developmental theory proposed that cognitive development is based on sensori-motor activity through endogenous and biologically determined cognitive processes (accommodation, adaptation) that drive children through a series of universal stages. Since individuals of both sexes go through these stages it is difficult to argue that they utilize their environments differently; however, studies on play suggest that children might actually do this (Fagot 1974). Gender differences have important implications for learning, not just at school but also at home, particularly for how children should be encouraged to play with both gender-specific and gender-neutral toys. We are currently experiencing this shift at the national level, with many programs pushing girls to pursue STEM education (Uttal et al. 2013a; Uttal et al. 2013b); therefore, this is an important line of research to pursue.

Our current analysis did not investigate neural activity with respect to temporal coordination of different brain areas, but this is an important avenue to pursue. We currently have the data needed to analyze cortical relationships, but have yet to find the

best approach. Once these analyses are performed, it would be of utmost importance to compare the temporal information to the temporal information examined in Goodwin et al.'s monkeys. Few studies, if any, have directly compared human and monkey neural activity as it progresses from cortical area to cortical area across time. This type of analysis would be eye-opening with respect to the evolution of the primate brain and cognition and would fill an important gap in the literature.

Notes

¹ There are many ways to talk about the role of language, and particularly the mechanism by which it exerts an effect on reasoning. One way is to talk about *when* in reasoning an effect of language can be observed. As I argue in the main text, some researchers conceptualize language as emitting an effect only during the reasoning phase, when different kinds of information are being manipulated (Hermer-Vasquez et al. 1999; Loewenstein and Gentner 2005), while other researchers argue that language is less of an “add-on” or mediating feature and more of a blended, modifying feature the effects of which can be seen at both early (perceptual) and late (reasoning) cognitive processes (Lupyan 2012). However, the timing of the effect is not the only way to investigate the role of language. It is also useful to think about *how* language affects reasoning, which requires an investigation into whether language is mediating, modifying or one and the same as reasoning. Yet a different approach is to investigate whether language can affect multiple levels of reasoning (which aligns with looking at both the perceptual and reasoning aspects of language’s effects).

In discussing the *how* of language’s influence, I find it easiest to borrow from Loewenstein and Gentner (2005; reiterated from Gentner and Goldin-Meadow 2003):

The language as lens view is the classic Whorfian hypothesis that the grammatical structure of a language shapes its speakers’ perception of the world. At the other extreme, the language as category shifter view maintains that conceptual categories are universal, but language can influence their boundaries. In the language as tool kit view, language provides concepts and strategies that augment, but do not supplant, other methods of representation and reasoning. This view is related to Vygotsky’s (1962) claim that language is instrumental in learning to direct mental processes, but differs in emphasizing specific semantic and grammatical devices.

Loewenstein and Gentner verify that they are in the *language as tool kit* camp, which is the camp most everyone I cite in this thesis would likely agree to be in, including Lupyan. However, I do not think that Lupyan would with Gentner’s ideas about the timing of the effect. I also feel that Lupyan and Gentner are discussing different levels of reasoning in interpreting their results and also in designing their studies. These two research groups again seem to be at odds when the role of language is approached in yet a different way.

This different way of conceptualizing the role of language is to consider how language affects concept categories. As discussed in Hayward and Tarr (1995), language (or spatial terms) function to map onto existing category, or to create a new category, or are essentially the same as the concept category. Landau and Hoffman (2005) similarly discussed the possible co-structure of verbal and nonverbal reasoning (including dependence of one on the other) versus the independence of these modalities. In this thesis, I provide evidence supporting a probable role of language as mapping to an

existing category (see Gleitman and Papafragou 2001; Snedeker and Gleitman 2004) as well as that language can help create new categories (Casasola 2005), but not for language and nonverbal knowledge as being one and the same. Even my own findings suggest that language and nonverbal reasoning likely share some structure, but are otherwise independent. Overall, this conceptualization of language-dependence or independence approaches the problem from a different point of view, one that is at the same time more focused (on categories) and generic (it does not consider timing effects). Further exploration by way of this approach would need to consider how linguistic descriptors can be coarse or precise in representing space, which leads down a whole new path from the one I have forged in this thesis, but is important nonetheless.

One last consideration is how language is defined. If language is considered under the umbrella of symbols (as it should be), then isolated symbols, such as labels, should also show effects on reasoning. In this thesis I have given examples of how propositional strings affect nonverbal reasoning (Dessalegn and Landau 2008; Franconeri et al 2012). I have also provided evidence of solitary symbols (such as labels, Arabic numerals or tokens) aiding in reasoning (Thompson et al 1997; Casasanto 2005). Since these tokens are acting to represent the to-be-reasoned-about concept, then there is no need to assume propositional encoding is occurring at all, which has implications for the extent of language's reach. Taken together, then, different conclusions can be drawn on the role of language. The evidence for isolated symbols does not necessarily support the claims of Dessalegn and Landau (2008) and Premack (1976, 1983). Etc. that "language" proper (propositional strings) is the key factor promoting nonverbal reasoning, but rather suggests that having *some* place holder is good enough to promote reasoning to some higher level, likely because cognitive resources have been freed-up. A process of freeing-up of resources was described in Chapter 3, where concepts became clustered together as a single "chunk" of information. Perhaps, then, language is just one mechanism by which information gets chunked, subsequently freeing-up resources which leads to the effects found by other researchers.

In summary, it is difficult to compare and contrast researchers' stances when they do not specify when in a trial they expect to see an effect and/or then design a task which actually tests that specific hypothesis, when they use their own terminology in discussing the potential role of language, when they do not specify what level of analysis they are investigating (which affects how results can be interpreted), and when they define language differently than their peer researchers.

² It was suggested by one reader that I explain why infants do not talk despite the language areas being more-or-less developed. One reason is that much development is still occurring in the white matter pathways, particularly within hemispheres (Perani et al. 2011). These pathways are important for linking up distant areas of the brain, including Broca's Area and Wernicke's Area, which are in the frontal and posterior temporal lobes respectively. Although white matter tracts between these areas are evident from birth, these connections will continue to grow and be defined with maturation. Furthermore,

infant brains respond to phonemic information early on, but not to lexical or syntactic information. Therefore, these language pathways are serving specific purpose at beginning, and will only later on take on new aspects of language learning as the pathways continue to develop. So, in the beginning, infants are primarily listening; later on, they will begin to speak.

³ This paper has since been published (as of October 2015) in modified form: Scott NM, Leuthod A, Sera MD, Georgopoulos AP (2015) Differential neural activity patterns for spatial relations in humans: a MEG study. *Exp Brain Res* 10.1007/s00221-015-4467-6

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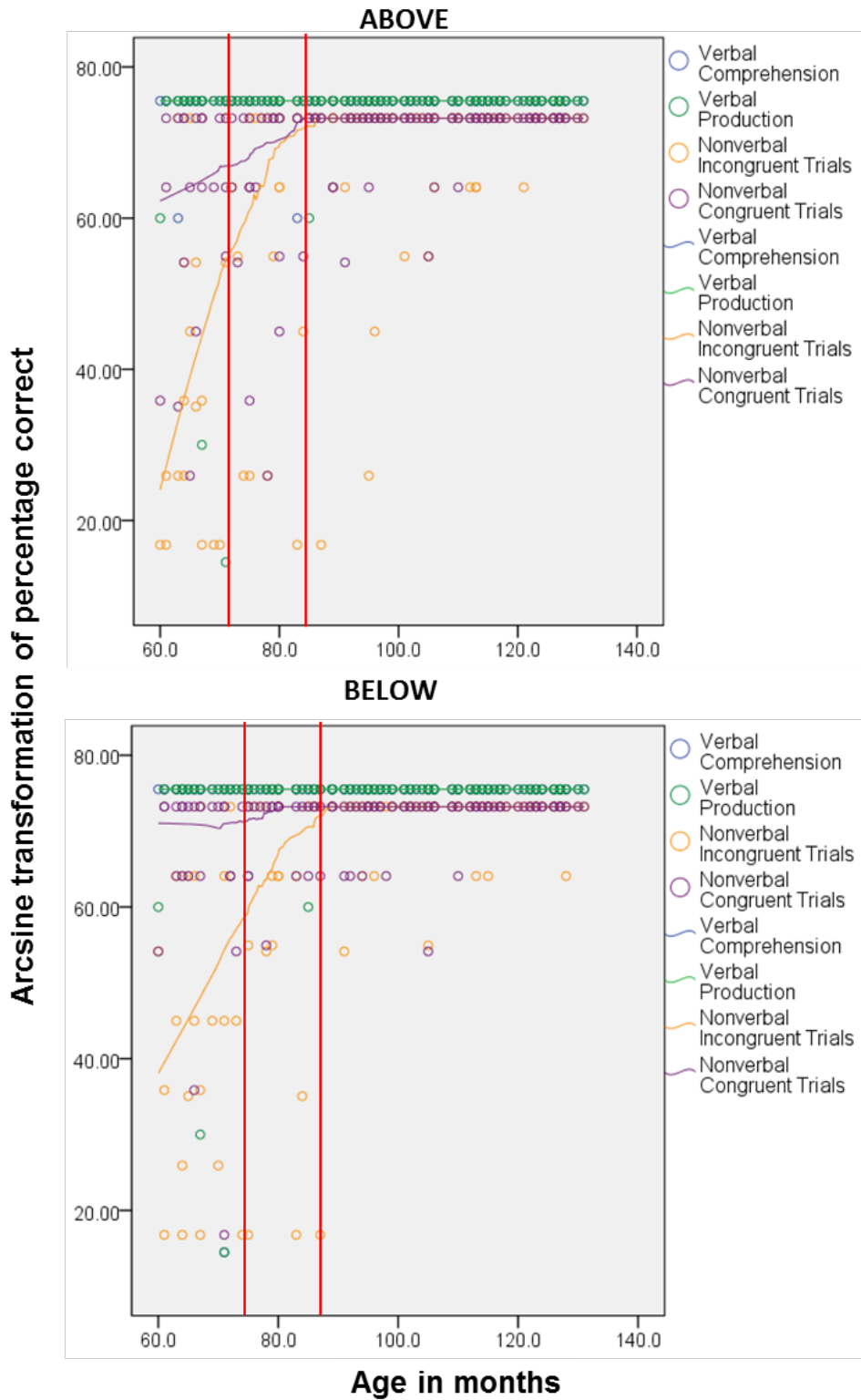
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Appendix A: Development as a moving window

On a different scale, I show the average performance of children on each task within a specified age group using a sliding window approach (i.e. a Loess graph). This approach calculates the average performance of the youngest 36 children in the sample (i.e. $n_1:n_{20}$) and represents that average as an unfilled circle (see Figure A1), then the window slides over to include the next older child and calculates an average performance for that child and the 35 children immediately younger (i.e. $n_2:n_{21}$). This approach smooths out individual differences in performance and finds the average for the age group, thus making the data easier to interpret and generalize. Indeed, the pattern of performance illustrated in these plots indicates that verbal ability does appear to lead nonverbal ability but only slightly. In fact, this rendering (Figure A1) also suggests a third factor that accompanies the development of both verbal and nonverbal abilities. These graphs of Loess curves indicate that verbal comprehension precedes verbal production and success on congruent trials in the nonverbal task precedes success on incongruent trials. There, again, appears to be a difference between the *above/below* relational plane and the *right/left* relational plane. In the *above/below* relational plane both verbal abilities precede both nonverbal abilities; however, in the *right/left* relational plane verbal comprehension and success on congruent trials precedes verbal production which increases alongside success on incongruent trials until about the age of 80 months, at which point verbal production reaches ceiling performance but absolute success on incongruent trials has not yet been attained.



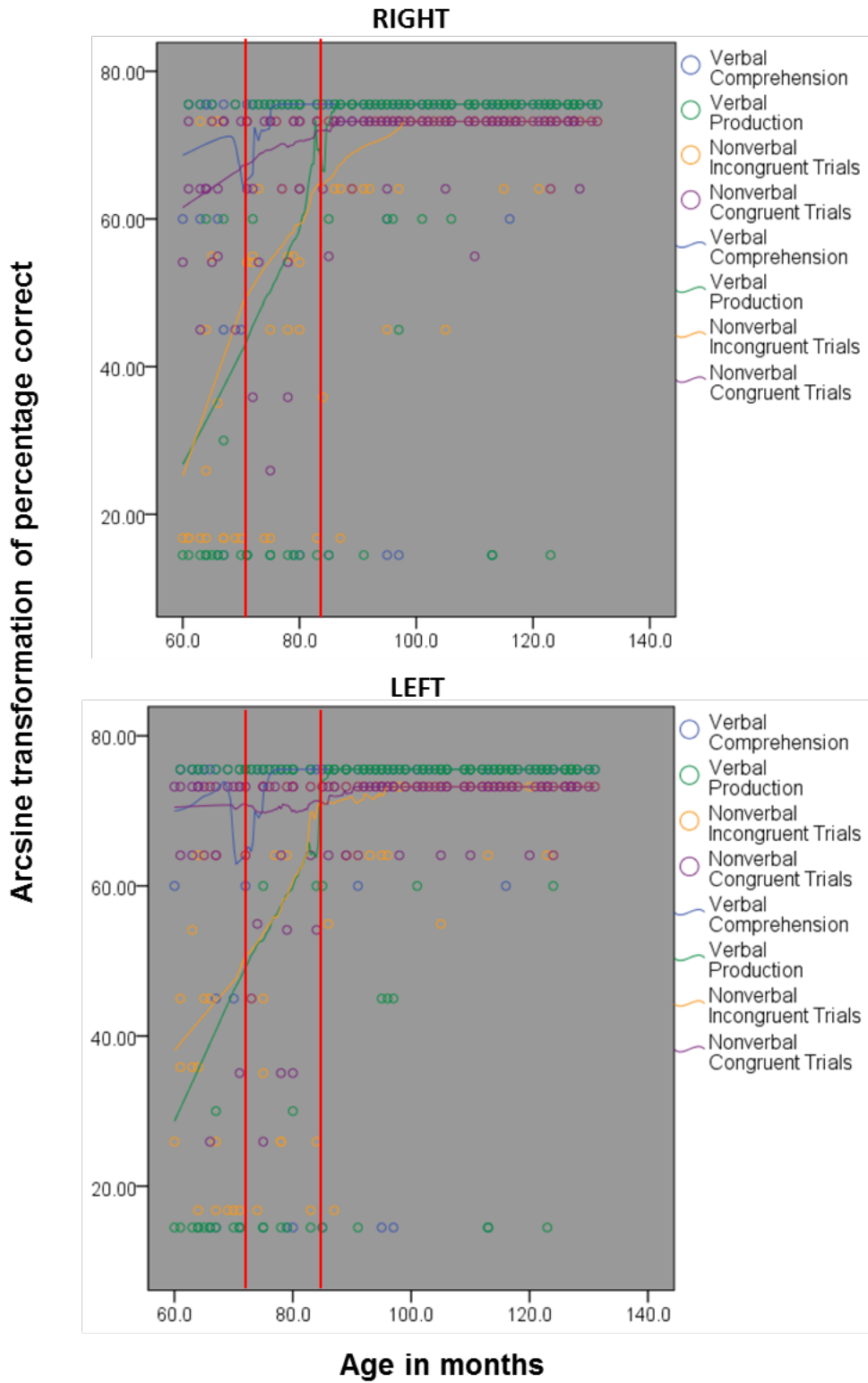


Figure A1: Scatterplots of performance on the nonverbal and verbal tasks according to age in months. Each directional relation is represented in a separate plot. The two tasks are divided into two subtasks: congruent and incongruent trials for the nonverbal task and production and comprehension of the linguistic term for the relation for the verbal task. Each circle captures the performance of an individual child. The blue, green, yellow and purple lines reflect the best-fitting regression line that captures the developmental trajectory of performance on each task. The vertical red lines indicate the age at which performance changes to near perfect on all tasks (i.e. 72-84 months).

Appendix B: Edinburgh Inventory scoring sheet

EDINBURGH HANDEDNESS INVENTORY			
SURNAME:		FIRST NAME:	
DATE OF BIRTH:		SEX:	
Results of the 'Simon Says' game played at start of participation study.			
* means repeated task			
	Task	Left	Right
1	Write your name in air		
2	Draw a smiley face in air		
3	Throw a ball		
4	Scissors		
5	Toothbrush		
6	Hammer a nail		
7	Spoon		
8	Broom (upper hand)		
9	Open a (pop) bottle		
10	Open a box (lid)		
* i	Kicking a ball		
* ii	One eye open		
L.Q.		DECILE	
From RC Oldfield, 1970			

Appendix C: Regions of interest and their observed functions

BRAIN REGION	SIDE	TASK	NOTES	REFs
FRONTAL				
Superior frontal sulcus	B	WM; visual spatial and visual nonspatial	correlated w? WM & age	Klingberg, Forsserg, and Westerberg, 2002, J COG NEUROSCI (+ others, see their REFs)
Precentral sulcus (anterior side)	B	WM; visual spatial and visual nonspatial	correlated w? WM & age	Klingberg, Forsserg, and Westerberg, 2002, J COG NEUROSCI (+ others, see their REFs)
Superior frontal sulcus	L	WM	correlated w? WM capacity & WM activity	Klingberg, Forsserg, and Westerberg, 2002, J COG NEUROSCI
orbitofrontal cortex		moral judgements; personal social conduct		Dolan, 1999 NATURE NEUROSCIENCE
anterior inferior PFC	L	controlled semantic retrieval	activity modulated by associative strength of word pairs	Bunge, Wendelken, Badre, Wagner, 2005, CEREBRAL CORTEX
frontopolar cortex	L	integration & evaluation; relational complexity	word pair association task (analogy); episodic details	Bunge, Wendelken, Badre, Wagner, 2005, CEREBRAL CORTEX; Christoff et al, 2001, NEUROIMAGE
frontopolar cortex	R	integration & evaluation based on familiarity	conceptual or perceptual episodic gist	Bunge, Wendelken, Badre, Wagner, 2005, CEREBRAL CORTEX; Wagner et al. 1998
dIPFC	R	response selection; WM	challenging tasks	Bunge, Wendelken, Badre, Wagner,

		monitoring & manipulation		2005, CEREBRAL CORTEX; Owen, Evans, Petrides 1996 in D'Esposito
anterior cingulate		ToM; reason underlying motor intention		see Vogeley & Fink 2003 for refs
principal sulcus, Lpfc		working memory	monkey single cell recording studies	see D'Esposito et al 1998
middle frontal gyrus		spatial working memory	animal studies	Goldman-Rakic 1987 (in D'Esposito et al 1998)
inferior frontal gyrus		nonspatial working memory	animal studies	Goldman-Rakic 1987 (in D'Esposito et al 1998)
inferior frontal gyrus	L	late learned words	visual & auditory lexical decision task	Fiebach et al 2003
ventral PFC	R	spatial working memory	info received from posterior assoc areas; comparisons made	D'Esposito et al 1998
inferior frontal gyrus - caudal	R	intention encoding	understanding motor acts (fMRI)	Iacoboni et al 2005 (in Rizzolatti 2010 NATURE NEURO)
inferior frontal gyrus	L	integration process in language		(Hagoort 2005) in Spotorno et al 2012 NEUROIMAGE
ventral PFC	L	nonspatial working memory	info received from posterior assoc areas; comparisons made	D'Esposito et al 1998
anterior insula	L	late learned words	visual & auditory lexical decision task	Fiebach et al 2003

rIPFC	L	relational integration & reasoning; manipulating self-generated info	RPM 2-relational problems; further abstracting new info	Christoff, Prabhakaran et al 2001 NEUROIMAGE
rIPFC	R	episodic retrieval; evaluation of self-generated info		Cabeza & Nyberg 2000 (in Christoff, Prabhakaran et al 2001 NEUROIMAGE)
vmPFC		emotion & decision making link		Waltz, Knowlton, Holyoak et al. 1999 PSYCHOLOGICAL SCIENCE (see refs)
vmPFC		ToM processing		(Ma et al 2011) in Spotorno et al 2012 NEUROIMAGE
mPFC		general inference making		(Ferstl & von Cramon, 2002) in Spotorno et al 2012 NEUROIMAGE
mdlfc		monitoring		Champod & Petrides, 2007
anterior cortex	L	personal body space (imaging body rotations)	clinical pop.	see Brandt & MacKavey, 1981
PARIETAL				
Intraparietal sulcus	B	WM; control of visual attention; any modality cues	correlated w? WM & age	Klingberg, Forsberg, and Westerberg, 2002, J COG NEUROSCI (+ others, see their REFS)
Intraparietal sulcus	B	body schema? Integration of extra- & peri-personal space	Japanese macaques	Iriki, Tanaka & Iwamura, 1996
Intraparietal sulcus	B	perception of spatial positions in egocentric frame of ref	humans/# objects in scene	wolbers, hegarty et al 2008 NATURE NEURO
Intraparietal	L	WM; response	correlated w? WM capacity	Klingberg, Forsberg, and Westerberg,

sulcus		preparation/temporal & motor orienting	& WM activity	2002, J COG NEUROSCI (+ others, see their REFs); Cotti...Coull, 2011 NEUROIMAGE
Inferior parietal cortex	L	WM; control of visual attention; any modality cues; spatial categorical judgments	correlated w? WM capacity & WM activity	Klingberg, Forsserg, and Westerberg, 2002, J COG NEUROSCI (+ others, see their REFs); Cotti...Coull, 2011 NEUROIMAGE; Franciotti et al 2013 PONE
Inferior parietal cortex	R	egocentric calculations; spatial coordinate judgments	with allocentric spatial info	Maquire et al 1998 (in Vogeley & Fink 2003); Franciotti et al 2013 PONE
medial parietal cortex	B	ego-movement	egocentric calculations + allocentric spatial info?	Maquire et al 1998 (in Vogeley & Fink 2003)
precuneus	B	early learned words	visual & auditory lexical decision tasks	Fiebach et al 2003
precuneus	B	inspection of internal images; construction of internal rep	construction in spatial context, spatial updating independent of upcoming action	Burgess et al 2001 (in Vogeley & Fink 2003); Wolbers, Hegarty et al 2008 NATUR NEURO
precuneus		integrating a sentence into context	situation model upating	(Speer et al, 2007) in Spotorno 2012 NEUROIMAGE
superior parietal lobule	B	perception of sptial positions in egocentric frame of ref	humans/# objects in scene	wolbers, hegarty et al 2008 NATURE NEURO
superior parietal lobule	R	shift attention (to new object or location)	transient activation (to modulate synchrony?)	Yantis & Sperences 2003 CURRENT OPINION NEUROBIO

superior parietal lobule	B	1-relational decisions ?	compared to no relations or 2-relations	Christoff, Pabhakaran et al 2010 NEUROIMAGE
caudate -head	B	relational reasoning	with increasing complexity	Christoff, Pabhakaran et al 2010 NEUROIMAGE (and see refs)
posterior parietal		manipulation	with working memory	Zacks & Michelon refs; Champod & Petrides, 2007
posterior cortex	L	extrapersonal space (orientation/ imagining rotation)	clinical pop.	see Brandt & MacKavey, 1981
inferior parietal lobule		spatial neglect? Hemianopia	when lesioned; ;humans and monkeys	see Karnath, Ferber, and Himmelbach 2001 NATURE
supramarginal gyrus	L	left-right confusion	Gerstmann's syndrome (neurological)	Gerstmann 1940 (in Hisnstein....Hausmann 2009 CORTEX)
angular gyrus	L	left-right confusion	Gerstmann's syndrome (neurological)	Gerstmann 1940 (in Hisnstein....Hausmann 2009 CORTEX)
angular gyrus	R	out of body experience	focal lesion studies	see Blanke 2012 NATURE NEURO
TEMPORAL				
temporo-parietal junction		orienting; reason underlying motor intention; body self-consciousness	experimental & clinical (heautoscopy)	temporo-parietal junction
temporo-parietal junction	R	ToM	with diff 1PP from 3PP	see Vogeley & Fink 2003
parahippocampal	R	spatial memory	lesion studies	Bohbot et al (1998) in Corkin, 2002

cortex				NATURE
parahippocampal gyrus		receives spatial info from posterior parietal cortex	direct connection	Suzuki et al (1994) in Corkin, 2002 NATURE
hippocampus		conscious recollection of the learning episode	complex picture recognition task	see Corkin 2002 NATURE
perirhinal cortex		familiarity judgements (w/out episodic content)	complex picture recognition task	see Corkin 2002 NATURE
superior temporal gyrus	R	spatial neglect; multimodal sensory convergence	when lesioned; BA 22 & 42; 'where' & 'what' streams diverge	Karnath, Ferber, and Himmelbach 2001 NATURE
superior temporal gyrus	L	language	in humans	see Karnath, Ferber, and Himmelbach 2001 NATURE
inferior parietal lobule		spatial neglect? Hemianopia	when lesioned; humans and monkeys	see Karnath, Ferber, and Himmelbach 2001 NATURE
temporo-parieto-occipital junction		spatial neglect? Hemianopia	when lesioned; humans and monkeys	see Karnath, Ferber, and Himmelbach 2001 NATURE
temporal operculum	L	early learned words	visual lexical decision task	Fiebach et al 2003
anterior superior temporal sulcus		iconic memory	visual shape processing?	Keysers et al 2005 COG NEUROPSYC
inferior temporal cortex		iconic memory	visual shape processing?	reviewd in Keysers et al 2005 COG NEUROPSYC
posterior superior	B	self-location & 1st person perspective	out of body experiences	see Blanke 2012 NATURE NEURO

temporal gyrus			
p inferotemporal cortices	L	object processing, name retrieval at subconscious level?	Damasio, Grabowski et al 2001 NEUROIMAGE
NETWORKS			
allocentric coordinate system		right hemisphere structures, right post-parietal cortex	McNaughton et al (1991) in Corkin 2002 NATURE
topographical memory		rRetrosplenial cortex, pCingulate G, occipitotemporal area	parahippocampal G, rHippocampus, mParietal L see Corkin 2002 NATURE
first-person perspective		amPFC, mParietal, pCingulate cortex, lateral temporoparietal cortex	see Vogeley & Fink 2003 TRENDS IN COG SCI
spatial navigation		mParietal, Rinferior Parietal, pCingulate cortex, hippocampus	Maguire et al 1999 (in Vogeley & Fink 2003)
route encoding		MTL, anterior superior parietal cortex, postcentral gyrus	areas not included in survey encoding Shelton & Gabrieli 2002 JNEUROSCI
survey encoding		B fusiform and inferior temporal gyri, pSuperior parietal cortex	also found in route encoding, but in greater activation Shelton & Gabrieli 2002 JNEUROSCI
spatial working	R	parietal cortex projections to	see D'Esposito et al 1998 COG BRAIN RES

memory		DIPFC		
nonspatial working memory	L	temporal cortex projections to VIPFC		see D'Esposito et al 1998 COG BRAIN RES
illusotry limb ownership		bilateral PMC, IPS, insula, sensorimotor cortex, cerebellum, SMA, aCingulate, posterior parietal		see Blanke 2012 NATURE NEURO
self-identification		IPS, PMC, possibly: sensorimotor cortex, EBA and temporoparietal cortex, putamen		see Blanke 2012 NATURE NEURO
third-person perspective		right TPJ, IPS, precuneus, parahippocampal gyrus	imagined spatial environment	see Blanke 2012 NATURE NEURO
limbic/core affect generation		MTL, Subgenual ACC, OFC	emotion, pain, motivated behavior, autobio memory	see Lindquist & Barrett 2012 TRENDS
salience/body-directed attention		aMCC, dorsal anterior Insula, frontal operculum	emotion, aversion, romance, pain, language, atteniton	see Lindquist & Barrett 2012 TRENDS
default network		mPFC, retrosplenial area, PCC/precuneus, MTL, STS	emotion, self, autobio memory, ToM, moral, context-sensitive self	see Lindquist & Barrett 2012 TRENDS
executive control		dIPFC, inferior parietal lobe & sulcus, precuneus, mCC	task switching, alerting, WM	see Lindquist & Barrett 2012 TRENDS
visuospatial		FEF dpParietal cortex, fusiform	top-down control of	see Lindquist & Barrett 2012 TRENDS

attention	gyrus, area MT+	visuospatial attention	
attentional control	PFC to SPL (switch attn) to IPS and extrastriate (maintain attn)	model of top-down control of attention (spatial & object)	see Yantis & Serences 2003 CURRENT OPINION
theory of mind	mPFC, precuneus, b-ITPJ,	and irony? Some aspects of language processing?	see Spotorno et al 2012 NEUROIMAGE
knowledge-building?	mPFC, MTL/HC	emergence & application of prior knowledge	
spatial relations	b IPL, bMFG, mSPL, visual cortex	MEG cluster of activation (diff't timespans)	Franciotti et al 2013
reasoning ability (devel'pt)	L RLPFC, L IPL	see model in paper	Wendelken...Bunge, 2015 CER CORTEX
reasoning v. maintenance	R anterior cingulate/MFG, L MFG, B Insular cortex, L STG; R cerebellum	comparison design	Ruff et al 2013 NEUROPSYC
maintenance v. reasoning	R IPG, R precuneus, L MTG	comparison design	Ruff et al 2013 NEUROPSYC
reasoning vs. rest	B MOG, B cuneus, L posterior cingulate, B precuneus, B precentral gyrus, B mFG, R parahippocampal gyrus		Ruff et al 2013 NEUROPSYC
maintenance v. rest	L MOG, R IOG, B posterior cingulate gyrus, B m/SFG, B mFG		Ruff et al 2013 NEUROPSYC

alerting network	locus coeruleus, frontal & parietal cortices		Peterson & Posner 2012 (in Pozuelos...Rueda 2014 DEV PSYCH)
orienting network	superior colliculus, SPL, temporoparietal junction, FEF		Peterson & Posner 2012 (in Pozuelos...Rueda 2014 DEV PSYCH)
executive attention	anterior cingulate cortex, IPFC, vPFC, basal ganglia		Peterson & Posner 2012 (in Pozuelos...Rueda 2014 DEV PSYCH)
semantic > fixation	bDLPFC, rVLPFC, rIPL, premotor & visual cortices, basal ganglia	children activate subset of these	Wright..Bunge et al 2008 FRONTIERS
analogy > semantic	bVLPFC, parietal & visual cortices, basal ganglia	children activate subset of these	Wright..Bunge et al 2008 FRONTIERS