Précis of

The Roles of Inference and Associative Learning in the Construction of Mappings Between Number Words and Numerical Magnitudes

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Abstract

How do we learn to use language to describe our perceptual experiences? This dissertation uses the test case of number language to understand how learners relate disparate systems of knowledge to one another. It does so by asking how the verbal number system – a precise, learned linguistic system for representing number – becomes related to the approximate and evolutionarily ancient nonverbal number system. Using both adult and child data, I argue that two processes guide the connection of the verbal and nonverbal number systems: item-by-item associative learning and analogically-based structural inference. This dissertation answers core questions in psychology (e.g., "how do we learn?"; "how does our knowledge change during development?"), linguistics (e.g., "how do words gain their content?"; "what is the role of linguistic structure in shaping language use?"), philosophy (e.g., "what are the origins of mathematical thought?"; "what are the roles of rational inference and experience in shaping conceptual content?"), and education (e.g., "what do children know about number?"; "how can we predict math success?").

Introduction

Humans represent large numbers via two systems: a non-verbal number system and a verbal number system. The evolutionarily ancient non-verbal number system, known as the Approximate Number System (ANS), allows individuals to quantify numerical magnitudes without counting. Because the ANS is governed by Weber's law, it is ratio-dependent, so that the ease of discriminating two numerical quantities depends on the ratio between them (it is equally easy to differentiate 3 from 4 as it is to differentiate 300 from 400; see Dehaene, 1997 for review). In contrast, the verbal number system is a relatively recent human invention, and allows us to precisely represent number via culturally-specific symbols (e.g., via words like *seventy* and numerals like *700*). These two systems differ radically in their representational formats and content. Despite this, we know that humans eventually connect their verbal and nonverbal number systems: children and adults can rapidly label quantities with number language, and these estimates exhibit signatures of Weber's law, suggesting a role for the ANS (Whalen, Gallistel, & Gelman, 2001). While we know from estimation research that the verbal and nonverbal number systems become related to one another, little is known about the mechanism by which language becomes related to non-verbal number. This is the question addressed by my dissertation.

In my dissertation, I describe the process of connecting the verbal and nonverbal number systems as a process of mapping; I then describe and test the mapping mechanisms that give content to number words like *forty* and *eight*. I argue that two processes – associative mapping and structure mapping – guide the formation of connections between our verbal number system to our nonverbal number system. In what follows, I outline the learning mechanisms under consideration and describe the results of three empirical research projects testing these mechanisms (Chapters 1-3 of my dissertation, also available as journal articles: Sullivan & Barner, 2012; Sullivan & Barner, 2014a;b and conference proceedings of the Cognitive Science Society: Sullivan & Barner, 2010; Sullivan & Barner, 2011). I show that while it is possible that associative learning guides the mappings for relatively small number words, structure mapping – an analogical process – plays a substantial role in connecting number language to nonverbal representations of number.

Associative Mapping. Theories of associative learning – which describe how two things (ideas, words, concepts, events) become related to one another via experience – have deep roots in philosophy (e.g., Aristotle; Locke, Hume), and throughout the 19th century, scholars argued that experience-based item-by-item associations between words and content were crucial for connecting language to thought. As Vygotsky noted, "From the point of view of the old school of psychology, the bond between word and meaning is an associative bond… A word calls to mind its content as the overcoat of a friend reminds us of that friend" (Vygotsky, 1934/1986; pp. 212-213). Similar descriptions of associative learning are found throughout human history, even in strongly nativist philosophical descriptions of human nature, like that of Plato:

> "Well, you know that lovers, whenever they catch sight of a lyre or a cloak or anything else which their favorites are in the habit of using, experience this: they recognize the lyre and at the same time receive in their minds the image of the youth to whom the lyre belonged; which is recollection: just as a man by seeing Simmias is often reminded of Cebes, and so on doubtless in an infinite number of cases of the same kind".
> -- Plato, *Phaedo*

While Vygotsky argued that an associative theory of word learning was outdated, modern psychologists often cite associative learning as a viable mechanism for language acquisition (e.g., Gomez & Gerken, 2000; Shanks, 1995). By this view, a learner hears a word (e.g., *twenty*) refer to something (e.g., a classroom of 20 students), and via association connects the word to the set of things in the world that it refers to. This perspective implicitly (and sometimes explicitly) underlies much of the current research on estimation (e.g., Ansari, 2008; Dehaene & Changeux, 1993; Fias et al., 2003; Lipton & Spelke, 2005, Piazza, Pinel, Le Bihan, & Dehaene, 2007; Siegler & Opfer, 2003; Verguts & Fias, 2004)[1]. In my dissertation, I call this process **Associative Mapping (AM)** and describe it as the creation of item-by-item associations between particular number words and the mental magnitudes that they represent, which are formed via experience with the world. For example, for a word like *twenty,* the creation of an AM involves associating the word *twenty* with a nonverbal (ANS) representation of approximately 20, via experience in the world with instances of 20 things (e.g., '20 students', '20 crackers', '20 minutes', etc.). While AM is often implicitly endorsed in the estimation literatures, a problem with the hypothesis is that humans get only limited experience with the denotations of some number words, and no experience at all with others. It seems implausible, for example, that experience with 1 million things would be required to support estimates for sets of this size. Instead, inferential abilities *must* be required to support estimation for unfamiliar quantities, perhaps on the basis of more familiar amounts.

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[1] Lipton & Spelke (2005) proposed two alternatives for how the verbal number system might become mapped onto the nonverbal number system. The first was that "children might learn the mapping by forming direct associations between individual number words and nonsymbolic numerosity representations…they might learn that the word 'hundred' refers to approximately the number of marbles that would fill a vase". The second alternative was that counting skills might precede the formation of mappings, such that "As they produce each number word [when counting], they may associate with the set of objects counted thus far". In both cases, the process described is what I – and the authors – would call "associative mapping".

Structure Mapping. An alternative to Associative Mapping (AM) is **Structure Mapping (SM).** SM involves creating a single link between the verbal and nonverbal number systems on the basis of their similar structure (Gentner & Namy, 2006; Carey, 2009; Gentner, 2010). While AM relies on rote learning, SM is a largely inferential (and analogical) learning process. For example, in forming SM, a child might notice the ordinal structure of both the verbal and nonverbal number systems – e.g., that the word *fifty* comes later in the count sequence than *forty*, and should therefore be used to label relatively larger sets. By noticing the ordinality of the verbal and nonverbal number systems, the child might then create a holistic mapping between the two systems, based on their shared structures. As I explore in detail in Chapter 3, the SM relation could also encode more complex relationships between number words and the magnitudes they represent. For example, a child might notice that *forty* comes twice as far along in the count list as *twenty*, and therefore use the word *forty* to label sets that are twice as large as those labeled by *twenty*. If SM underlies the connection between verbal and nonverbal number systems, then a single analogical link is created between the verbal and nonverbal number systems on the basis of the structural similarities between them. As a result, individual mappings are *not* independent of each other: The content of one number word is dependent on the content of all others.

Predictions of AM and SM. To understand the predictions that AM and SM make, it is instructive to consider how they might be deployed online, while doing estimates. By the AM hypothesis, each number word is associated with a particular ANS representation, such that mappings are independent from one another. This predicts that in estimation experiments, an adjustment to the mapping for the word *twenty* (e.g., via feedback, learning, or training) won't automatically affect other mappings (e.g., the mapping for the word *forty*). Also, because mappings constructed via AM are linked directly to particular ANS representations via experience-based associations, adults should, on average, use unique number words for each discriminably different magnitude (e.g., a different number word should be assigned to sets of 10 and 20). Thus, to the extent that two magnitudes are reliably discriminable, subjects should not assign them the same label (e.g., adults should almost never guess that a set of 40 contains *twenty*, since they discriminate sets in a 2:1 ratio with very high accuracy). Thus, two predictions of the AM hypothesis are that AMs should not be easily influenced by feedback regarding other number words, and that, when shown two sets, it should be easy to choose which set corresponds to a provided number word, so long as they two sets are readily discriminated by the ANS (e.g., they should easily judge whether *fifty* applies to a set of 50 or a set of 100).

In contrast, according to the SM hypothesis, the verbal and nonverbal number systems become analogically mapped onto each other on the basis of their structural similarity (Carey, 2009; Gentner, 2010; Gentner & Namy, 2006). Because SM involves connecting two global structures, the mappings for individual numbers should be non-independent, and instead should be defined in relation to one another. This hypothesis makes several clear predictions about estimation performance. First, a subject's estimate for one set should constrain their estimates for other sets (such that bigger sets receive bigger estimates). Also, when a subject's response for a given quantity is changed via feedback (i.e., calibrated), responses for other quantities should also change correspondingly, potentially beyond the range of predicted by error in the ANS (see Tversky & Kahneman, 1974, for a conceptually related discussion of anchoring and adjustment in numerical judgments). Finally, because SMs are constructed based on context-dependent inference, it is possible that, across different situations, subjects will fail to provide distinct labels for discriminably different sets (e.g., a subject might label a set of 40 as forty in one context, and call a set of 20 forty in another context).

Experiments

Chapters 1 and 2 test the proposal that adults and children (respectively) connect number language to nonverbal number representations via two learning mechanisms: Associative Mapping and Structure Mapping. Data from four tasks provide evidence that adults rely on Associative Mappings for number words up to about 12, and Structure Mapping for larger number words; while 5- to 7-year old children rely on AM for number words up to about 6, and SM for larger number words. This suggests that multiple learning mechanisms aid in connecting number language to the numerical content that it represents.

To arrive at this conclusion, we tested whether there was evidence for AM in adults and children. To do this, we created the Number Matching task: subjects were asked to match a provided number word (e.g., *twenty*) to one of two visually presented sets of dots that differed by a 1:2 (or also, in adults, 3:4) numerical ratio. Performance on this task was compared to participants' performance on a Number Discrimination task. The Number Discrimination task used identical visual stimuli to the Number Matching task, but participants only had to decide which of two sets was larger (a purely nonverbal, ANS-based judgment). Comparing performance on these tasks allowed us to assess whether participants possess veridical and stable mappings between number words and magnitudes. We predicted that if participants had strong AMs, then they should use these mappings to restrict judgments in the Number Matching task. For example, to the extent that a subject can reliably discriminate sets of 20 and 40, they should never assign the number word *twenty* to a set of 40 dots, provided that AM guides mappings for *twenty*. However, if AM does not support estimates for *twenty,* then subjects may not reliably apply it to sets of 20 rather than sets of 40.

We found that there was no substantial difference in performance across tasks (Number Matching vs. Discrimination) for the smallest magnitudes tested (up to 12 vs. 24 for adults; Fig. 1a; up to 6 vs. 12 for children; Fig. 2a and 2b), but that there was a difference for larger numbers. This is consistent with the view that AM guides the mappings between small number words and the numerical quantities they refer to, but is surprising if AM guides the mappings for larger number words. In Chapters 1 and 2, we rule out several alternative explanations for these data. Taken together, these data suggest that it is possible that AM guides mappings for small number words, and that there is developmental change between age 7 and adulthood in the strength of AMs. These data also suggest that insofar as adults and children possess AMs for large number words, they are quite weak: adults and children frequently attached the word *one hundred* to sets containing 50 (when a set containing 100 was also an option).

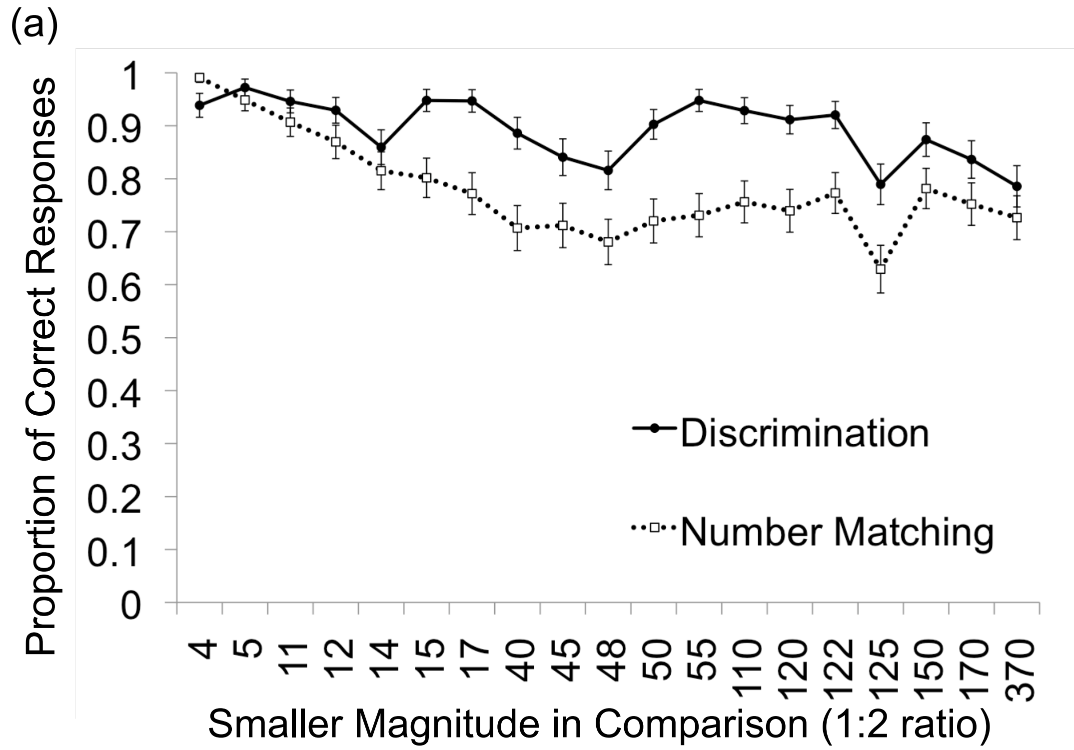

Figure 1a: Adults' performance on the Number Matching task (dotted line) and on the Numerical Discrimination task (solid line). Error bars are SEM; all magnitudes are at a 1:2 ratio.

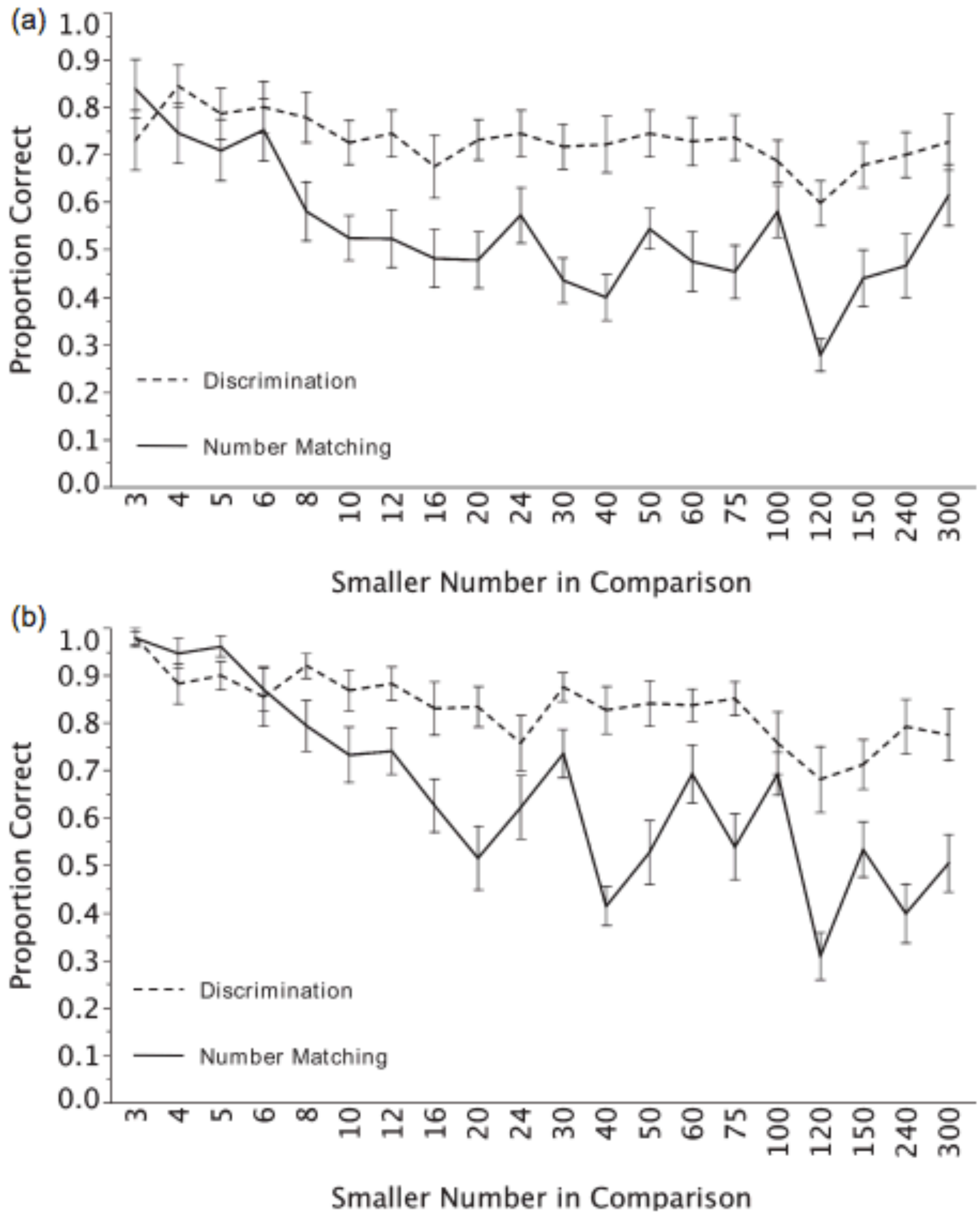

Figure 2: Performance on the Number Matching task (solid line) and on the Numerical Discrimination task (dashed line) for (a) Five-year-olds; (b) Seven-year-olds. Error bars are SEM; all magnitudes are at a 1:2 ratio; the smaller number in each comparison is represented on the x-axis.

We next tested whether there was evidence for SM in children and adults. To this end, participants completed an Uncalibrated estimation task and a Calibrated estimation task. In the Uncalibrated estimation task, participants saw arrays of dots, and had to label them verbally (without counting); the Calibrated estimation task was identical, except participants were given misleading feedback about the largest set of dots that they would see (e.g., that the largest set size they would see would be 750, when it was really 350). The logic was that feedback should not influence participants' estimates for quantities that have strong AMs, but should influence estimates for all magnitudes with SMs. We found evidence that adults' and children's estimates were influenced by misleading feedback, and that the effect of feedback was strongest on large numbers (and generally absent for numbers smaller than around 20). These findings are inconsistent with the view that adults and children possess AMs for large numbers. Instead, calibration had substantial effects at all ages, suggesting that by age 5, children connect verbal and nonverbal number representations to one another via a structural inference.

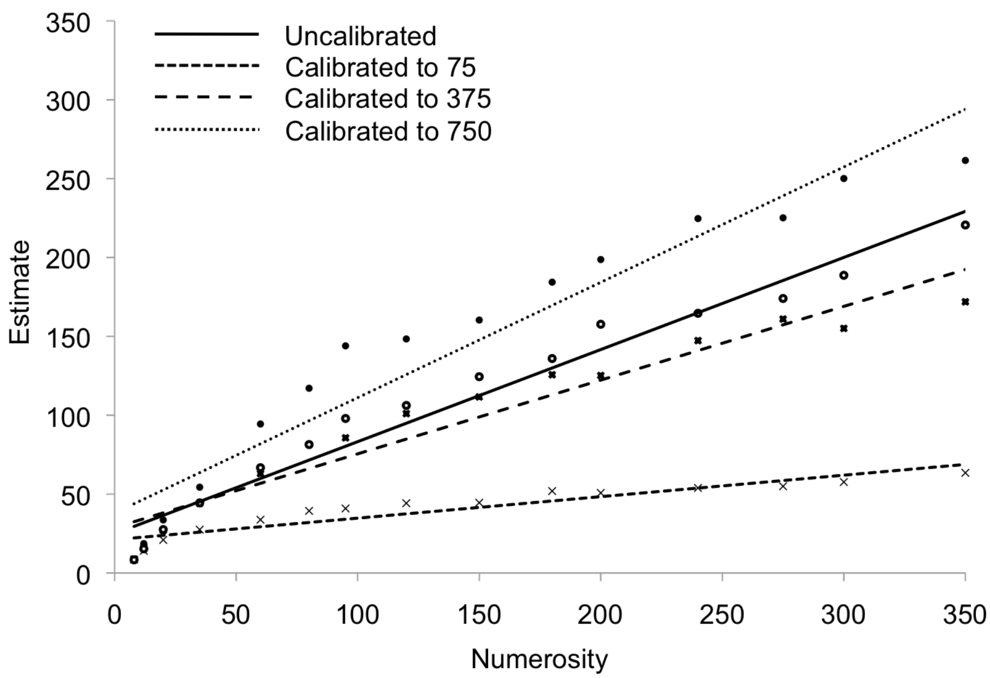

Figure 3: Estimation performance in adults; points are means; lines indicate different calibration conditions. Child data was similar and is in Chapter 2.

In addition to demonstrating the roles of AM and SM in supporting estimation in children, Chapter 2 made several additional contributions. First, it showed that developmental changes in estimation ability – which have been of primary concern to researchers studying estimation in both the fields of psychology and education – cannot be explained by qualitative differences in the use of mapping mechanisms at different ages (e.g., by an early reliance on AM that is supplemented by a later reliance on SM). Second, measures of estimation ordinality (the rate at which estimates are internally consistent and obey the structure of the count list; an estimate is ordinal if and only if it is in the correct direction relative to the previous estimate) were consistently above-chance and did not differ between ages 5- and 7-, suggesting (a) that by age 5-, children have knowledge of the ordinal structure of the count list and of the nonverbal number system (a prerequisite for SM), and (b) developmental changes in estimation ability cannot be due to changes in rates of ordinal responding. Chapter 2 also makes explicit connections between these findings and the field of education. Recent studies have shown that estimation ability in school-aged children predicts success in mathematics (e.g., Booth & Siegler, 2008; Siegler & Ramani, 2009; Siegler & Booth, 2004), although the reason for this relation is unknown. I argue based on the data in Chapter 2 that it is unlikely that those who are better at estimating (and thus better at math) have a relatively richer set of associative mappings. While educators often focus on providing manipulatives (e.g., toy blocks) to help children visualize the quantities symbolized in math problems (e.g., Burns, 1996; see Uttal, Scudder & DeLoache, 1997, for another view on the role of manipulatives), even the strongest estimators lacked strong AMs, suggesting that item-specific connections between language and visual representations of magnitudes are unlikely to drive early math success. I propose a different explanation for the relation between estimation and education outcomes: both draw on children's structural knowledge of the number system. Early math education contains explicit instruction about the place value system, which reinforces knowledge of the structural relations between number words (which I argue is fundamental to estimation). For example, basic arithmetic involve relating symbolic representations of number to each other. Children who know that 20 + 20 = 40 may be better estimators because both estimation and early arithmetic draw on knowledge of the relation between number words. If this is the case, then focused instruction on the structure of the count list (and not just the routine of counting) may be the best way to improve both math and estimation outcomes.

Chapter 3 focuses on understanding the *structure* that guides children's SM's. The chapter begins by arguing that number-line estimation tasks – by their very nature – are analogical, and require SM. I propose two possible structures that could underlie SM – one based on the relative ordering of numbers and the other based on the relative distance between numbers. Finally, I addresses the question of whether children make inferences about the structural relation between number language and nonverbal quantity representations on a trial-to-trial basis or over a more extended period of time.

First, consider the structural relations that might support SM. The first structural relation that children might use is based in ordinality. Ordinality can be found in the ordering of number words (e.g., that 100 is larger than 50), in the ordering of perceptual sets (e.g., a set containing 100 appears more numerous than one containing 50), and in the ordering of marks on a number-line (e.g., a mark to the left occurs earlier on the line than one on the right). For example, a child who relies on ordinality to estimate the location of '50' on a 0-100 number-line (using the endpoint of the line '100' as a reference point) should first note that '50' is smaller than '100' and therefore place his estimate somewhere (anywhere!) to the left of the endpoint. In this way, the ordinal relation between numerals is what constrains estimates. As described in Chapter 2, by age 5, children have a strong understanding of ordinality, and can use it to guide estimates.

The second structural relation that children might construct is based in the relative distance between numbers. For example, a child who has knowledge of the relative distance between numbers might note that '50' comes halfway between the beginning of the count list and '100', and use this information to place their estimate at the midpoint of the line. A child who uses their previous estimate – e.g., of '10' – might note that '50' refers to a quantity that is 5 times greater than is referred to by '10', and therefore place '50' 5 times further from the start of the number line than they had placed '10'.

To test these relations, participants completed a number-line estimation task: they saw a line that went from 0-100, and had to indicate the location of numbers (e.g., '20'). We manipulated several elements of this task: some participants had visual access to previous estimates (making it easy to use previous estimates as for on-line calibration) while others did not; we also induced some participants to over-estimate early in the task and others to under-estimate, in order to test whether early errors carry through to later estimates (as predicted if participants attend to the relative-distance between numbers); finally, we measured the accuracy and ordinality of participants' estimates. To further strengthen our argument that structural analogy underlies estimation, we ran several computer simulations (which we then related to our children's data) of estimation data that provided empirical support to our predictions for how estimates should look if (a) participants calibrate their estimates on-line; (b) if participants only attend to the ordinal structure of the number-list when using SM; and (c) if participants attend to the relative-distance between numbers in the number-list when using SM.

We found that 5-year-olds made more accurate and ordinal estimates when they had access to their previous estimates, suggesting that trial-to-trial calibration is important to estimation success. This means that SM is dynamically adjusted online – each estimate constrains all other estimates (see Vul, Sullivan, & Barner, 2013 for computational evidence of this). Second, we found developmental changes to the type of structural relation that children relied on when recruiting SM: only 7-year-olds showed evidence of tracking relative-distance information, while 5- and 7-year-olds tracked ordinality. This is important because it provides a mechanism of change in estimation ability between the ages of 5 and 7 (a time period during which there is substantial improvement in estimation ability). Because interventions meant to improve estimation performance are often successful (e.g., Opfer & Siegler, 2007) – educators and scientists alike should have a deep interest in understanding *which* learning mechanisms children recruit when improving estimation performance. One possibility is that children who are better able to analogically extend the relative-distance between numbers to the nonverbal domain (e.g., use relative-distance SM to estimate) – are also most likely to succeed at math. However, this raises further questions, currently under exploration in my lab: does the precision of a child's SM predict their math success, and if so, to what extent is this mediated by domain-general analogical reasoning skill?

Future Directions

In sum, my dissertation tested development of estimation ability (a topic of broad interest to educators) in order to understand how inference and experience converge to give content to (number) language. As noted in the last pages of my dissertation, my ongoing and future work continues this line of research, and does so in a distinctly interdisciplinary way (e.g., by exploring the *pragmatics* of number language – a topic closely tied to linguistics). In addition, while Chapter 3 of my dissertation used relatively simple computer simulations to model children's estimation, more recent work presented at Cog Sci explicitly used computational methods to understand the inferential processes that guide estimation (e.g., Vul, Sullivan, & Barner, 2013). Also, ongoing work with the UCSD PING project uses structural MRI to understand how changes to estimation might be related to changes in neural connectivity between the IPS and other regions of the brain. Finally, in recent years I have experimentally tested the relation between math education and estimation: as part of a successful multi-year math intervention

(Barner et al., under review), I also administered estimation tasks in order to understand whether (and how!) changes in math skill over time are causally related to changes in estimation ability (and how any changes are related to analogical reasoning skill and reliance on SM; presented at Cog Sci, Sullivan et al., 2014c). Thus, this dissertation serves as a basis for continued interdisciplinary exploration of the development of number knowledge.

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