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Representing Quantitative Information: Developmental and Neural Comparisons of Mental Magnitudes

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Representing Quantitative Information: Developmental and Neural Comparisons of Mental Magnitudes

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B.S. (Honors), University of Maryland, College Park, 2008

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An abstract of

A dissertation submitted to the Faculty of the

James T. Laney School of Graduate Studies of Emory University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in Psychology

2013

Abstract

Representing Quantitative Information: Developmental and Neural Comparisons of Mental Magnitudes
By: Justin W. Bonny

The ability to estimate and represent non-symbolic quantities is essential to cognition. Representations of non-symbolic quantities, known as mental magnitudes, are essential for quick judgments and have been found to be related to symbolic math skills. Mental magnitudes have been found to underlie all types of quantities, ranging from number to time to area. Despite the importance of mental magnitudes in cognition, the nature of these representations is unclear. Specifically, it is unclear whether there are shared mental magnitudes for different quantities, or, if mental magnitudes are specific for each quantity. In the present dissertation, I examine the specificity of mental magnitudes by comparing behavioral performance and neural signatures of two types of quantities, cumulative area and non-symbolic number.

In Study 1, I compared cumulative area and non-symbolic number by examining the developmental changes in each magnitude as well as the impact of different spatial arrangements on discrimination performance. Children (four- and six-year-olds) were presented with cumulative area and non-symbolic number stimuli either within a single spatial field (Experiment 1) or separated in two spatial fields (Experiment 2). Discrimination performance was lower for non-symbolic number when presented with spatially intermixed versus separated stimuli, but there was no difference in performance for cumulative area. Developmental analyses indicated that there was similar improvement in performance with age for both magnitudes regardless of spatial arrangement.

In Study 2, I compared the neural processing of cumulative area and non-symbolic number information using event-related potentials (ERPs). I compared the onset of ratio and congruity effects for cumulative area and non-symbolic number in the ERP waveforms when each magnitude was presented more or less independently each other. I found evidence of magnitude differences in the onset of each mental magnitude when presented independently (Experiment 1) and evidence of similarities when magnitudes were presented simultaneously (Experiment 2).

The results of both studies suggest there are partially overlapping representations for non-symbolic magnitudes. I provide a new framework to explain how partially overlapping representations are formed and contrast it to previous models of magnitude representation.

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Acknowledgements

I would like to thank my advisor, Stella Lourenco, for all of her guidance during my graduate student career to help me become the academic I am today. I would also like to thank my dissertation committee members, Lawrence Barsalou, Patricia Bauer, Robert Hampton, and Laura Namy, for their time, advice, and support throughout my dissertation. I would like to thank the members of the Spatial Cognition Lab, including Edmund Fernandez for their assistance in data collection for Study 1. I would also like to thank members of the ERP Reading Group and members of the Memory at Emory Lab for their assistance during data collection for Study 2 as well as Patricia Bauer for allowing me to use her ERP equipment. Support from a Department of Defense SMART Scholarship and Laney Graduate School Research Award made this research possible. I would also like to thank my friends and family for their support during my graduate student career with a special thanks to my wife Jackie Leventon.

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Representing Quantitative Information: Developmental and Neural Comparisons of Mental Magnitudes

General Introduction

Every day in our lives, we are constantly presented with quantitative information in our environment that we must process in order to accurately perform our daily activities. The vast majority of this information is non-symbolic, and can come from a wide range of quantities, from the distance between your car and a stop sign, to the number of people waiting for a bus. In order to make use of this non-symbolic quantitative information in decision making, it first must be estimated and represented by the brain. A wealth of research examining non-symbolic magnitudes in judgment tasks has identified signature characteristics indicative of the use of mental representations of quantity that all tested magnitudes display [e.g., (Gallistel & Gelman, 1992). Furthermore, research has found evidence that infants, children, as well as adults can represent magnitudes [e.g., (Cantlon, Platt, & Brannon, 2009)], suggesting mental magnitudes play a role in cognition across development. Additionally, accumulating research has identified some of the neural mechanisms that play a role in creating mental magnitudes, although this has been limited to just a few types of quantity, most notably non-symbolic number [e.g., (Nieder & Dehaene, 2009)]. Yet despite these different lines of study, the nature of magnitude representation is unclear. Specifically, given evidence of similar performance characteristics across mental magnitudes, past and present debates have centered around the question of whether there are shared representations underlying all non-symbolic magnitudes [e.g., (Dehaene, 2011; Walsh, 2003)]. The present dissertation aims to build upon previous research by examining the specificity of magnitude representations using a number of techniques. To examine whether there are shared mechanisms for representing non-symbolic magnitudes, the present studies examine two distinct types of mental magnitudes by comparing developmental changes, sensitivity to stimulus manipulations, and neural correlates of each magnitude.

Mental Magnitudes Are Approximate Representations of Quantity

The environment is filled with various types of non-symbolic quantities, ranging from brightness to volume, all of which can be aligned on a more-versus-less scale. The ordinal nature of quantities, known as prothetic dimensions differentiates them from other physical characteristics in the environment, or metathetic dimensions (Stevens, 1957), and makes them available for measurement. In contrast to objective quantity, which has veridical value, mental magnitudes are subjective representations and are estimates of non-symbolic quantities. Mental magnitudes, also referred to as “analog representations” or “approximate magnitude representations” in the literature, are subjective mental representations that attempt to capture objective quantities. The “analog” aspect of mental magnitudes entails that they are isomorphic to the quantities in the environment that they represent such that any difference in the objective quantity is matched in the mental magnitude (Gallistel & Gelman, 1992). For example, just as a set of ten coins is numerically twice as large as a set of five coins, the mental magnitude representing ten coins is twice as large as the one representing five coins. The quantitative value of mental magnitudes is generated by a process through which a summary representation of an objective quantity is expressed on a subjective internal continuum (Dehaene, 1992;

Gallistel & Gelman, 1992; Moyer & Landauer, 1967). Critically, the summary representation of the objective quantity is an estimation, theorized to be a Gaussian distribution centered on the objective value, making it inherently variable and imprecise (Halberda & Feigenson, 2008; Nieder & Dehaene, 2009; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Pica, Lemer, Izard, & Dehaene, 2004).

The imprecision of mental magnitudes is believed to be the result of perception and memory processes (Gallistel & Gelman, 2000). Whereas objective quantities in the environment can be expressed on a limitless scale, the sensitivity of perceptual systems are limited to just a subset most relevant to the organism (e.g., there are many objects in the environment that are smaller in length than a millimeter that are readily differentiated by a fruit fly, but not by humans). Our perceptual systems are limited in how precisely they can represent a specific quantity. A common demonstration of this imprecision is Weber’s law, which states that the just-noticeable-difference between two quantities is dependent on the ratio between the two quantities (Moyer & Landauer, 1967). For example, it is easier to detect the numerical difference between two sets of objects when they differ by a 2.00 ratio (e.g., 12 vs. 6 objects) than a 1.25 ratio (e.g., 10 vs. 8 objects).

Models that depict how mental magnitudes are formed have primarily focused on how representations of non-symbolic number are created from visual arrays [e.g., (Dehaene & Changeux, 1993; Verguts & Fias, 2004)].[1] Specifically, these models describe how numerical representations are created from visual displays of non-symbolic quantity (e.g., set of visual dots) despite the potential presence of conflicting magnitude

[1] There are models for how mental magnitudes are created for quantitative information presented in other sensory modalities [e.g., sound; (Meck & Church, 1983)]. For the dissertation, I will primarily focus on empirical research as well as models that describe how visual information is represented using mental magnitudes.

information To do so, some models of non-symbolic number representations have proposed that numerical information is abstracted in such a way that the representation is devoid of other quantitative information such as the total area that a visual array occupies (Dehaene & Changeux, 1993; Verguts & Fias, 2004). The level of abstractness proposed in models of numerical mental magnitudes raises the issue of how, or even if, other magnitudes fit within these models. It is unclear whether models of numerical representation are similar, or even identical, to the way representations of other magnitudes are created, or, whether there are specific mechanisms for creating representations of different magnitudes.

Shared versus Specific Representations of Mental Magnitudes

Historically, discussions regarding the specificity of magnitude information have focused on whether the ways in which quantities appear in the environment are similarly reflected in the mind. Locke (1690/1975) argued that the presence of strong correlations between different magnitudes in the environment, such that when one domain is increased, another does as well, the mind should treat them in a similar manner. Such a correlation has since been observed in human perception as demonstrated by empirical research [e.g., (DeLong, 1981)]. Beyond perception, the execution of actions may also lead to the coupling of different magnitudes. According to Walsh and colleagues multiple representations of magnitude are habitually called upon to perform an action (Bueti & Walsh, 2009; Walsh, 2003). For example, when a pedestrian is crossing a busy street, he or she needs to take into account the number of vehicles, the speed of traffic, and how far it is to the opposite curb in order to coordinate and execute his or her action.

The coordination of different representations may lead to strong associations between magnitudes, to the point where representations of magnitudes are shared (Bueti & Walsh, 2009; Walsh, 2003). Due to these predictable connections in the environment and actions, similar mental magnitudes may be used to represent information from different magnitude domains (Bueti & Walsh, 2009; Gallistel & Gelman, 1992, 2000; Lourenco & Longo, 2010; Walsh, 2003).

Despite reasons for shared magnitude representations, there are also pressures to have distinct and separate mental magnitudes for different quantities. In many situations, when we are required to estimate one quantity, it would be disadvantageous to conflate that estimate with other quantities. For example, when estimating which of two sets of objects is larger in number, spatial extent is irrelevant to that judgment and may be misleading (e.g., the set that is larger in number may be smaller in total area). Furthermore, it could be detrimental to have one type of representation for all quantities as there could be confusion as to what quantity the mental magnitude refers to. For these reasons, it has been proposed that distinct and separate representations are used for different magnitudes (Dehaene, 2011; Odic, Libertus, Feigenson, & Halberda, 2012).

In order to compare the shared and specific views of mental magnitudes, a definition of what counts as shared magnitude representation needs to be provided. Typically, it is assumed that there is a distinction between magnitude representations and the mechanisms by which they are processed, although not always [see (Cohen Kadosh & Walsh, 2009) for discussion]. For example, in some models of numerical mental magnitudes, it is proposed that an accumulator is the mechanism by which perceptual information is summed together to create a magnitude representation (Dehaene &

Changeux, 1993). Additionally, in some proposals for specific mental magnitudes, it has been offered that whereas the magnitude representations themselves are distinct, common mechanisms are used to compare different mental magnitudes (Bonn & Cantlon, 2012; Cantlon et al., 2009). In the present dissertation, the term shared mental magnitude refers to the representation that carries the quantitative information, not the mechanisms that act on that information (e.g., comparison mechanism).

To examine the specificity of mental magnitudes, rather than the mechanisms that act on them, behavioral and neural research has focused on characteristics that are believed to be due to properties of magnitude representations. Evidence of specificity can emerge as differences in behavioral performance, neural regions that are sensitive to magnitudes, and temporal onset of neural activity. Similar behavioral performance for different magnitudes has been argued to be evidence of shared magnitudes, but, depending on the particular experimental manipulation, not sufficient evidence against specificity (Cantlon et al., 2009). Similarly, evidence that spatial regions of the brain are similarly sensitive to different magnitudes as measured by neuroimaging techniques can be interpreted as in favor of, but not sufficient for, evidence of shared mental magnitudes (Cohen Kadosh & Walsh, 2009). Additionally, differences in the temporal onset of neural activity for different magnitudes can be interpreted as evidence in favor of specific magnitudes, but not sufficient evidence against shared magnitudes (Cohen Kadosh, Lammertyn, & Izard, 2008). In the present dissertation, similar to previous research (Cohen Kadosh & Walsh, 2009; Pinel, Dehaene, Rivière, & LeBihan, 2001), magnitude differences in more than one of these lines of research is taken as strong evidence of specificity in mental magnitudes.

Of the many characteristics used to compare the specific and shared views, two types of effects that have been extensively used in behavioral and neuroimaging research to compare the mental magnitudes will be the focus of the present dissertation research. As mentioned above, there is a level of imprecision in mental magnitudes as described by Weber's law. This imprecision is reflected in what is known as the ratio effect, which is reduced performance (e.g., lower accuracy; slower reaction times) when judging which of two magnitudes is larger in quantity the closer the ratio between the two magnitudes is to one [e.g., 12 vs. 6 objects, a 2.00 ratio, is easier to discriminate than 10 vs. 8 objects, a 1.25 ratio; (Cantlon et al., 2009; Dehaene, 1992; Moyer & Landauer, 1967)]. In a standard discrimination task, across trials participants are given two quantities to compare as the ratio between them is varied from difficult (e.g., close to 1.00) to easy (e.g., > 2.00). The behavioral ratio effect is captured as a decrease in performance with a reduction in ratio. The ratio effect has been observed with a wide variety of quantities [e.g., non-symbolic number, (Halberda & Feigenson, 2008; Xu & Spelke, 2000); cumulative area, (Barth, 2008; Hurewitz, Gelman, & Schnitzer, 2006; Lourenco, Bonny, Fernandez, & Rao, 2012); duration, (Droit-Volet, Tourret, & Wearden, 2004; Roitman, Brannon, Andrews, & Platt, 2007)] and should be observed with any type of magnitude dimension (Bueti & Walsh, 2009; Stevens, 1957). Individual differences have also been observed using the ratio effect (Halberda & Feigenson, 2008; Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Lourenco et al., 2012). If the mental magnitudes of a person contain relatively more variance than that of another person, they will be less likely to differentiate small changes in non-symbolic quantity. The processing of different magnitudes can be compared by using the ratio effect as a measure of imprecision in magnitude representations when a quantity is presented independently of others. In the present studies, similar levels of variance across magnitudes, as indicated by similar ratio effects, was taken as evidence in favor of shared mental magnitudes.

Another type of effect reflects the amount of interaction between the mental magnitudes of two different quantities. In previous research, this effect has been observed during magnitude comparison tasks where participants are asked to discriminate between a pair of stimuli. Each of the stimuli contains two kinds of magnitude information and the relationship between those quantities has been found to impact behavioral performance. Specifically, when the two quantities are congruent with each other (e.g., in the same direction), performance is typically better compared to when the two quantities are incongruent with each other (e.g., in different directions). This is known as the congruity effect and is a type of Stroop effect (Henik & Tzelgov, 1982). A task that has been commonly used to demonstrate the congruity effect presents participants with two Arabic numerals that differ in physical size and have participants make a speeded judgment as to which of the numerals is numerically, or physically, larger. The relationship between the two quantities in the stimuli is varied across the task to create congruent (e.g., 8 vs. 2) and incongruent (e.g., 8 vs. 2) trials. The congruity effect is reflected in a lower number of errors and faster reaction times when participants are presented with the congruent versus incongruent pairs [e.g. (Cohen Kadosh, Lammertyn, et al., 2008; Henik & Tzelgov, 1982)]. The congruity effect is believed to be due to interactions between the processes underlying different mental magnitudes, although it is unclear whether this interaction occurs early in processing or not until a motor response is being prepared (Cohen Kadosh et al., 2007; Schwarz & Heinze, 1998).

The congruity effect compliments the ratio effect as a method of measuring the amount of interaction between the processing of two quantities. In the present dissertation, the presence of an early emerging congruity effect was taken as evidence in favor of shared mental magnitudes.

Selected Magnitude Comparison: Cumulative Area and Non-symbolic Number

In order to address the long-standing discussion of the specificity of mental magnitude processes, over two studies I compared a pair of carefully selected quantities across multiple contexts. Specifically, I compared the mental magnitudes produced by non-symbolic number and cumulative area. Non-symbolic number refers to the quantity displayed by a stimulus that contains a set of discrete objects that could, in principle, be enumerated. The mental magnitude generated to estimate the number of objects in a set does so without any use of numerical symbols (e.g., number words) or explicit enumeration (e.g., counting). This type of quantity is used in a variety of judgments, such as estimating which of two sets of objects is numerically larger (when counting is prevented). Cumulative area refers to the spatial quantity displayed by a stimulus that contains a set of objects. The mental magnitude generated to estimate the cumulative area of the set of objects does so by estimating how much space a set of objects occupies on a two-dimensional plane. Again, this quantity is used without any type of symbol (e.g., square meters) and, similar to non-symbolic number, can be recruited to perform a variety of judgments.

I chose cumulative area and non-symbolic number for my studies because of their similarity as well as potential differences. Both types of magnitudes are quantitative properties of visual sets. This means that, unlike other pairs of non-symbolic quantities, cumulative area and non-symbolic number can be perceptually presented using an identical stimulus (in contrast to, for example, individual element size and symbolic number). Because of this, both cumulative area and non-symbolic number information are simultaneously present in a stimulus, requiring the other to be accounted for when generating a mental magnitude. Although they are created using perceptually identical stimuli of visual sets of objects, the types of quantity they represent are fundamentally different. The quantitative information of non-symbolic number is discrete, or countable, whereas cumulative area is a continuous or un-countable quantity (Butterworth, 2010). The perceptual overlap and fundamental difference between these two quantities provides an ideal test of whether there are distinct mental magnitudes for each quantity. If so, this would provide strong evidence of specificity in mental magnitude quantities given the high level of similarity between cumulative area and non-symbolic number.

To examine the specificity of the underlying mental magnitudes of cumulative area and non-symbolic number, across two studies I use multiple contexts to compare behavioral performance when discriminating between each pair of magnitudes. One type of context I varied was age by examining mental magnitudes at different points in development. Although there have been many studies examining the ratio and congruity effects of non-symbolic number, relatively little research has directly compared non-symbolic number and cumulative area in adults [e.g., (Barth, 2008; Hurewitz et al., 2006; Lourenco et al., 2012)] and infants [e.g., (Cordes & Brannon, 2009)], with no studies with children. It is unclear whether mental magnitudes of cumulative area and non-symbolic number undergo similar developmental changes. In addition to development, I varied how quantitative information was presented. In Study 1, I examined how varying the spatial arrangement of stimuli influenced cumulative area and non-symbolic number discrimination performance. Previous research has found that non-symbolic number representations are influenced by the spatial arrangement of the stimuli [e.g., whether presented within a single or two separate spatial fields (Price, Palmer, Battista, & Ansari, 2012)]. Whether a similar impact is observed on cumulative area representations has yet to be examined. In Study 2, I examined how a different stimulus manipulation, the presentation of quantitative information more or less independently of other magnitudes, influenced cumulative area and non-symbolic number discrimination performance. Although there is evidence in previous research that the simultaneous presentation of each magnitude reduces performance [e.g., (Barth, 2008)], it is unclear whether representations of each magnitude are impacted to a similar degree compared to when each magnitude is presented more independently of each other. It is important to compare the relative impact of these different contexts on behavioral performance for each magnitude (e.g., context affects only one versus both magnitudes) to examine the specificity of mental magnitudes.

As described previously, the presence of a congruity effect suggests an interaction is taking place at some point as mental magnitudes are processed. The key to understanding the congruity effect concerning whether there are distinct representations for different magnitudes is determining when the interaction occurs. If the interaction occurs early in processing, it would suggest that the congruity effect is due to shared representations, whereas if it emerges later in processing, it would suggest it is due to information conflicting when preparing for a motor response (e.g., pressing left or right button) rather than shared representations (Cohen Kadosh et al., 2007; Gebuis, Kenemans, de Haan, & van der Smagt, 2010; Santens & Verguts, 2011; Schwarz & Heinze, 1998). Previous research has examined the onset of congruity effects by comparing symbolic number and size using neuroimaging techniques, specifically electrophysiology paradigms, that are suited for measuring the temporal emergence of congruity and ratio effects in neural activity (Cohen Kadosh et al., 2007; Gebuis et al., 2010; Schwarz & Heinze, 1998). Evidence of a congruity effect emerging with or before the ratio effect, which indicates the initial presence of magnitude representations, would suggest that there are shared representations for processing different magnitudes. However, to my knowledge, no research has examined the ratio and congruity effects generated with cumulative area using neuroimaging paradigms. In order to examine the specificity of mental magnitudes underlying cumulative area and non-symbolic number, in Study 2, I use the neuroimaging paradigm of event-related potentials to examine the processing of cumulative area and non-symbolic number during a judgment task when each magnitude was presented relatively independently from versus simultaneously with the other. In the dissertation, I used behavioral and neural paradigms as well as different contexts to compare the impact spatial arrangement and development has on the ratio effects for each magnitude (Experiment 1) as well as the neural basis of congruity effects when each magnitude was presented relatively independently or simultaneously with the other (Experiment 2). I will discuss both studies in detail below.

Introduction to Study 1

In Study 1, I used different developmental and spatial contexts to examine the link between cumulative area and non-symbolic number magnitude representations. Examining mental magnitudes for each type of quantity across different developmental contexts, in this case different age groups, allowed for a comparison of how cumulative area and non-symbolic representations develop in regard to each other. Specifically, it could be seen whether the maturational and learning processes that occur over development have similar or differential effects on mental magnitudes. If there are shared mental magnitudes, it is predicted that the developmental changes in cumulative area representations would be mirrored in non-symbolic number representations. However, if there is specificity in the underlying processes, developmental changes in one mental magnitude may differ from those in another.

As discussed in detail in Study 1, there is reason to believe that the extensive symbolic number instruction children receive in modern societies may lead to specific developmental changes in non-symbolic number representations (Carey, 2009). One of the hallmarks of early math education is children's acquisition of symbolic forms of number, specifically number words and numerals. Counting is believed to be the mechanism through which children learn the principles of symbolic number (Gelman & Gallistel, 2004; Wynn, 1992) and is only achieved through years of experience and training (Carey, 2009; Le Corre & Carey, 2007). The process of counting transforms a non-symbolic set of objects into a symbolic representation, and to be successful, children must focus specifically on the numerical value of the set instead of other qualitative and quantitative properties (e.g., type of objects, size of objects, etc.). Interestingly, although there is debate as to whether non-symbolic number mental magnitudes play a role in counting and learning symbolic number (Gallistel, 2007; Le Corre & Carey, 2008), it is agreed that a key sign of a mature symbolic number system is the integration of numerical mental magnitudes (Le Corre & Carey, 2007; Sarnecka & Carey, 2008). Evidence of this integration between symbolic and non-symbolic representations of number comes from a wealth of research demonstrating the occurrence of a ratio effect when two symbolic numbers are compared in adults [e.g., (Moyer & Landauer, 1967)] as well as in children who have just learned the cardinality of symbolic number (Le Corre & Carey, 2007; Sarnecka & Carey, 2008). Although typically not as strong as those observed with non-symbolic number, a ratio effect is observed when older children and adults judge which of two numerals or number words are larger (Buckley & Gillman, 1974; Dehaene, 1992; Moyer & Landauer, 1967). Based on these results, in addition to other types of evidence of overlap [e.g., shared brain regions, (Nieder & Dehaene, 2009)], multiple models of number representations have proposed a common abstract number representation that is accessible from symbolic and non-symbolic number stimuli (Butterworth, 2010; Dehaene, 1992; Verguts & Fias, 2004). The potential connection between symbolic number and non-symbolic representations of number could result in a large disparity in experience and practice in mental magnitudes of number versus other quantities (e.g., reading number words would activate numerical mental magnitudes). If this disparity is present, the difference would become especially pronounced in early childhood. Between three and six years of age children are increasingly exposed to counting routines and begin to learn to recognize symbolic number (Gunderson & Levine, 2011). Furthermore, extensive training in different types of symbolic math continues into adulthood. To examine whether there are differences in the mental magnitudes of cumulative area and non-symbolic number, I compared the ratio effects of cumulative area and non-symbolic number as measured by discrimination tasks given to children (four- and six-year-olds) and adults (college students).

Previous research has used ratio effects to compare mental magnitudes across infancy [e.g., (Brannon, Lutz, & Cordes, 2006; Brannon, Suanda, & Libertus, 2007; Xu & Arriaga, 2007)]. Most of the studies examining cumulative area have compared it to non-symbolic number in infant samples. It had been previously shown with non-symbolic number, size, and duration that infants can detect a change in quantity if it differed by a specific ratio that is dependent on age. For example, whereas six-month-olds detect up to a 2.00 change in non-symbolic number, ten-month-olds detect an even smaller 1.50 ratio change (Xu & Spelke, 2000; Xu & Arriaga, 2007). Similar performance has been observed in infant studies using size (Brannon et al., 2006), as well as time, (Brannon et al., 2007). In contrast, there has been less research examining the development of cumulative area. Interestingly, the few studies that have examined infants' ability to discriminate cumulative area found that the ratio required to detect changes was twice as large at that for non-symbolic number, suggesting there may be differences in the underlying representations (Cordes & Brannon, 2008a, 2009). Research has also examined cumulative area representations with adults in which, instead of examining the threshold ratio that adults can detect, the ratio effect of mental magnitudes was measured as performance on a discrimination task across a range of different ratios. When compared to performance on a comparable non-symbolic number task, adults had similar levels of performance, and furthermore, performance on both tasks was positively correlated (Lourenco et al., 2012). However, other studies have found evidence that, in adults as in infants, cumulative area performance is worse than non-symbolic number (Barth, 2008; Nys & Content, 2012). The contrasting, and mixed, results from the adult and infant studies, underlines the importance of examining the developmental trajectory of mental magnitude changes during childhood.

In addition to development, the spatial arrangement of magnitude information can be used to examine the link between cumulative area and number. As discussed in detail in Study 1, research has shown that across development, judgments based on non-symbolic number are influenced by the spatial properties of numerical arrays (Barth, 2008; Cantlon & Brannon, 2005; Cantlon, Fink, Safford, & Brannon, 2007; Hurewitz et al., 2006). For example, in one study adult participants performed worse when judging which of two numerical arrays was numerically larger when the visual arrays were simultaneously presented intermixed within a single spatial field versus two spatially separated fields (Price et al., 2012). This body of research indicates that numerical magnitude representations are sensitive to the spatial arrangement of arrays across development. In contrast, no research to my knowledge has compared the effect of spatial arrangement on non-symbolic number to the effect on cumulative area. If there are shared mechanisms for both mental magnitudes, it is predicted that there should be similar effects of spatial arrangement on judgments for each magnitude. Furthermore, studies that have compared cumulative area and non-symbolic number discrimination with infants and adults have used different spatial arrangements, highlighting the need to examine the effect of spatial context at different age groups.

Connected to the impact of spatial properties on magnitude judgments is the question of how properties of the stimulus can affect task performance. As discussed in

Study 1, it has been proposed that the relative difficulty observed in infants discrimination of cumulative area versus non-symbolic number is due to an inherent numerical bias for discrete sets of objects (Cordes & Brannon, 2008b). On this view, when any person, not just infants, observes a set of objects, they are biased to detect the numerical value of the array first and then may be able to focus on other attributes such as cumulative area, although interference is still present. This leads to the possibility that if the numerical bias is removed, or at least reduced, the discrimination performance of cumulative area would be more similar to non-symbolic number. One study that has indirectly addressed this issue required adult participants to judge whether there was more blue or green color when the colors were either presented as arrays of discrete objects (numerical judgment), or blended together as amorphous patches [spatial judgment; (Castelli, Glaser, & Butterworth, 2006)]. The amorphous stimuli were images that were filled with patches of blue and green color, created in such a way that there were no discrete borders between the patches (see Study 1, Figure 4 for a similar example). Behaviorally, it was observed that performance was similar for each type of judgment, suggesting that when there is no opportunity to form a numerical bias, spatial and numerical representations are equivalent. Although the study was conducted with adults, a similar comparison can be done with any age group to examine whether potential numerical biases can be reduced by presenting cumulative area more independently using amorphous stimuli. In Study 1, we presented participants with cumulative area information as discrete and amorphous arrays to examine whether any potential differences in performance in comparison to non-symbolic number can be reduced using amorphous stimuli. Furthermore, this allowed us to examine whether any differences in performance due to the type of cumulative area used would be consistent across development. Given that research with infants has observed worse performance with cumulative area compared to non-symbolic number, and research with adults, though mixed, suggests similar levels of precision for both magnitudes, it is possible that any potential gain in cumulative area performance by using amorphous stimuli may change over development.

In summary, in Study 1 I examined specificity of cumulative area and non-symbolic number representations by presenting magnitude judgments tasks to participants in different age groups as well as under different spatial contexts. By examining performance under different developmental and spatial contexts, Study 1 was able to examine possible differences in the mental magnitudes of cumulative area and non-symbolic number. If there are shared representations that underlie different magnitudes, then it is predicted that developmental changes and the impact of spatial arrangement on performance will be similar for cumulative area and non-symbolic number.

Study 1:

Differential Effects? Impact of Spatial Arrangement on Cumulative Area and Number Judgments in Children and Adults

Differential Effects? Impact of Spatial Arrangement on Cumulative Area and Number Judgments in Children and Adults

Introduction

The ability to quickly generate and represent estimates of non-symbolic quantities is fundamental to human cognition. Research suggests that estimates of non-symbolic quantities, or mental magnitudes, are used in decision making and are important in symbolic math operations, (Bonny & Lourenco, 2013; Bueti & Walsh, 2009; Gallistel & Gelman, 2000; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Lourenco et al., 2012; Walsh, 2003). Evidence of mental magnitudes has been observed with a variety of quantities such as number (how many objects are in a set) and area (how much space do objects occupy), as well as across different species (Nieder, 2005), and points in development (Ansari, 2008; Cantlon et al., 2009) all of which emphasizes the importance of these representations in cognition (Nieder & Dehaene, 2009). Despite the widespread presence of mental magnitudes, as well as their importance, the nature of these representations remains unclear. Given evidence of mental magnitudes across different types of quantities (Cantlon et al., 2009; Lourenco & Longo, 2010), it is unknown whether different types of quantitative information are supported by shared or specific mental magnitudes (Bueti & Walsh, 2009; Dehaene, 2011; Walsh, 2003).

The goal of the present study is to examine the specificity of the mental magnitudes underlying estimates of cumulative area and non-symbolic number. Both of these non-symbolic quantities can be presented using perceptually similar stimuli, yet remain conceptually distinct, making them an ideal test of the specificity of magnitude representations. To the examine specificity of mental magnitudes, we[2] compared discrimination task performance that was based on either magnitude in different developmental and spatial contexts. Previous developmental research has only compared performance based on cumulative area and non-symbolic number in infants and adults and has yielded mixed results as to whether there is specificity in underlying mental magnitudes (Cordes & Brannon, 2009; Lourenco et al., 2012; Nys & Content, 2012). Furthermore, there has been no comparison of cumulative area and non-symbolic number judgments in children, nor examination of age-related changes making it unclear whether the specificity of these mental magnitudes changes across development. In addition to developmental contexts, we compared performance on cumulative area and non-symbolic number judgment tasks across different spatial arrangements of stimuli. Previous research has found that non-symbolic number judgments are heavily influenced by the spatial layout of the stimuli [e.g., presented in a single versus separated spatial fields; (Price et al., 2012)]. However, it remains unknown whether the spatial context of other non-symbolic quantities, such as cumulative area, similarly affects performance. To address these outstanding questions, in the present study, we examined the specificity of cumulative area and non-symbolic number representations at different points in development and spatial arrangements. Across two experiments, we compared the accuracy of children's and adults' judgments of cumulative area and non-symbolic number to examine whether each type of judgment is similarly affected by spatial arrangement across development.

[2] In the dissertation I use the personal pronoun "I" outside of study manuscripts and "we" within study manuscripts. This is done to reflect the point of view that would be used if the manuscripts were to be presented in an academic journal.

Characteristics of Mental Magnitudes

Mental magnitudes are inherently imprecise estimates of quantities. The level of imprecision is believed to be due to variability in magnitude representations which are modeled as Gaussian distributions on an internal more versus less continuum (Halberda et al., 2008; Piazza et al., 2004; Pica et al., 2004). A key signature of this imprecision is the presence of a ratio effect. Following Weber's law, the ratio effect refers to a decrease in performance the closer the value, or the smaller the ratio difference, between two quantities (e.g., lower accuracy and slower reaction time when discriminating 10 versus 9 objects, a 1.11 ratio, compared to 10 versus 5 objects, a 2.00 ratio). It has been proposed that the ratio effect reflects the amount of overlap between mental magnitudes such that when values are close, there is more overlap in the representations making it more difficult to discriminate between them. Studies have used the ratio effect as a way to not only determine whether mental magnitudes are used during a task, but also as a way to compare the variance, or precision, of magnitude representations. If a mental magnitude has higher variance in one domain than another, it is indicated by poorer performance when attempting to discriminate quantities that are relatively close in value. Using the ratio effect, the precision of different mental magnitudes has been examined across development.

Developmental Changes in Mental Magnitudes

Studies have found the use of mental magnitudes across human development (Ansari, 2008; Halberda et al., 2012) with the earliest evidence of ratio effects emerging in infancy. Using looking time paradigms, in which infants were habituated to the same non-symbolic quantity and then presented with a novel quantity during test trials, studies have found that six-month-old infants look longer to the novel stimulus if it differed by a 2.00, but not 1.50 ratio, with quantities such as number, size, and time (Brannon et al., 2006, 2007; Xu & Spelke, 2000; Xu & Arriaga, 2007). Furthermore, research using the neuroimaging technique of event-related potentials, where the electrical activity of the scalp is measured in response to a stimulus, has provided evidence of ratio effects with numerical stimuli in 3-month-old infants (Izard, Dehaene-Lambertz, & Dehaene, 2008). Altogether, these studies suggest that mental magnitudes can be represented by infants, however, as indicated by ratio effects there is a large amount of variance in these representations. Research with older age groups suggests that as children become older, they can successfully discriminate smaller ratio differences. For example, whereas four-year-olds can reliably discriminate a 1.33 ratio between two non-symbolic numbers, six-year-olds are reliable at a smaller 1.17 ratio (Halberda & Feigenson, 2008). The improvement in performance at smaller ratios is believed to be due to a reduction in the variability of mental magnitudes which means there is less overlap between two close values (Halberda & Feigenson, 2008; Halberda et al., 2012). Improvements during childhood have also been observed for spatial extent (Odic et al., 2012) and duration (Droit-Volet, Clément, & Fayol, 2008), and, for at least non-symbolic number, precision has been found to continue increasing into early adulthood (Halberda et al., 2012). Overall, developmental research indicates that mental magnitudes for various quantitative information can be represented early in life and that the key change between infancy and adulthood is the reduction of variability in the representations.

Mixed Evidence for Developmental Differences in Precision of Cumulative Area and Non-symbolic Number Representations

The similarities in ratio effects observed with various magnitudes have raised the question of whether representations of magnitude are shared by different quantities. Contrasting views have been proposed, disagreeing on whether a common mental magnitude is used for different quantities. The shared magnitude view proposes that despite perceptual and conceptual distinctions between different magnitudes, a single type of mental magnitude is used to represent all quantities (Bueti & Walsh, 2009; Walsh, 2003). The specific magnitude view proposes that perceptual and conceptual distinctions between magnitudes are reflected in the underlying representations such that there are specific mental magnitudes for each quantity (Dehaene, 2011; Odic et al., 2012). This debate has been given much attention in the developmental literature, focusing on whether there is evidence for specific magnitudes representations early in development. Research that has examined this question across development has focused on whether infants and adults are able to discriminate different types of magnitudes at a similar or different level of performance. Two magnitudes in particular, cumulative area and non-symbolic number have been directly compared in infancy since they are created from the same perceptual stimuli, specifically a visual set of objects. Additionally, since both types of information are present in a set of objects, they each require extraneous information, particularly each other, to be disregarded for accurate representations. However, each magnitude represents a fundamentally different type of quantity. Similar to the count – mass distinction in language (Bloom & Wynn, 1997), non-symbolic number is a perceptually discrete, or countable, quantity whereas cumulative area is a perceptually continuous, or un-countable, quantity. The key question is whether, despite the perceptual similarities, there are still specific representations used for each quantity.

The majority of the research comparing non-symbolic number and cumulative area performance has been conducted with pre-verbal infants. When studies first began to provide evidence that infants could discriminate between non-symbolic number arrays (Starkey, Spelke, & Gelman, 1990), it was argued that performance may have been based on spatial information instead (Mix, Huttenlocher, & Levine, 2002a). Subsequent research with infants indicated that they could discriminate arrays based on spatial information even when conflicting numerical information was present as well (Clearfield & Mix, 1999). The focus of research then shifted to comparing the similarity of the ratio effects for a particular type of spatial information, cumulative area, to non-symbolic number in infancy. Across multiple studies, infants were found to have much more difficulty detecting changes in cumulative area, requiring the ratio to be twice as large in comparison to number (4.00 vs. 2.00) to be able to notice a change (Cordes & Brannon, 2008a, 2008b, 2009). These differences suggest that there may be a level of specificity in the underlying mental magnitudes, perhaps even distinct representations, for cumulative area and non-symbolic number.

In adult populations, cumulative area and non-symbolic number representations have been compared using explicit judgment tasks. This research, however, has yielded mixed results. On tasks that have directly pitted numerical and cumulative area information against each other (the array that is larger in number is smaller in cumulative area), mixed results have been found as to whether judgments about each magnitude are disrupted to a similar degree when conflicting information is present (Barth, 2008; Hurewitz et al., 2006; Nys & Content, 2012). However, when each magnitude is presented using controls to reduce the salience of extraneous information, there is evidence of comparable performance for cumulative area and non-symbolic number and, furthermore, performance is positively correlated between the two measures (Lourenco et al., 2012). In light of these differences across adult studies, it is difficult to compare the patterns between cumulative area and non-symbolic number in infancy and adulthood.

In contrast to research with infants and adults, there have been no studies comparing performance on non-symbolic number and cumulative area discrimination tasks with children. The lack of research comparing these two magnitudes with children makes it unclear whether there are developmental changes in the underlying mental magnitudes, and if so, whether changes are similar for both quantities. Previous research examining non-symbolic number judgments has found that children's numerical judgments are affected by extraneous congruent and incongruent spatial information (Cantlon et al., 2007; Gebuis, Cohen Kadosh, de Haan, & Henik, 2009; Halberda & Feigenson, 2008; Lonnemann, Krinzinger, Knops, & Willmes, 2008). However, since cumulative area has not been directly examined, it is unclear if children's pattern of performance on number and cumulative area discrimination tasks would be more similar to those of infants or adults. By comparing adults' and children's cumulative area and non-symbolic number discrimination performance, it can be clarified as to whether there are differences between these magnitude domains as well as whether there are differences in the developmental changes in the underlying mental magnitudes.

Possible Developmental Pressures for Dissociations and Convergence in Cumulative Area and Non-symbolic Number Representations

A reason for comparing developmental changes in cumulative area and non-symbolic number representations during childhood is the substantial improvement in symbolic number and math skills. These changes in number and math knowledge may provide developmental pressures for mental magnitudes to become more or less specific. For example, if there are shared mental magnitudes early in development, the acquisition of symbolic number may lead to differentiation in representations. Starting between the ages of three and five, children learn the symbolic value of number words and digits (Le Corre & Carey, 2007; Wynn, 1992). One of the characteristics of a mature understanding of number is the emergence of ratio effects with symbolic numerals, suggesting that non-symbolic number representations become integrated with symbolic number (Carey, 2004, 2009; Le Corre & Carey, 2007; Sarnecka & Carey, 2008). During childhood, the development of symbolic forms of number and their integration with non-symbolic number representations could lead to substantial increase in the use of numerical mental magnitudes in comparison to those of other quantities (e.g., writing Arabic numerals). This could in turn lead to an increase in specificity between non-symbolic number and other magnitudes such as cumulative area.

Alternatively, if there are specific mental magnitudes early in development, connections between magnitude representations and math skills could provide developmental pressure for shared mental magnitudes. In addition to symbolic number, children are taught formal math skills including how to use mathematical operations to manipulate numerical symbolic symbols (Mix, Huttenlocher, & Levine, 2002b).

Interestingly, accumulating evidence suggests that numerical and spatial mental magnitudes are linked to proficiency on symbolic math tests. Children who perform better on non-symbolic number tasks also perform better on tests of symbolic math skills (Bonny & Lourenco, 2013; Libertus et al., 2011). This has also been found with adults as well as with other types of magnitude. Adults who performed higher on non-symbolic number or cumulative area discrimination tasks score higher on tests of arithmetic and geometry than their peers (Lourenco et al., 2012). In contrast to the developmental pressure suggested above, the link between magnitude representations and math skills may strengthen the connection between number and cumulative representations once these skills are acquired and refined. By comparing changes in cumulative area and non-symbolic number judgments during childhood, it can be examined if there are changes in the specificity of mental magnitudes.

Dissociations in Magnitude Judgments Caused by Spatial Properties

Research that has examined the nature of magnitude representations has made use of different spatial arrangements in addition to different developmental contexts. This research has focused primarily on whether non-symbolic number judgments of adult participants are influenced by the spatial arrangement of numerical arrays. For example, when comparing discrimination performance as the size of the spatial field (area in which the elements are displayed) is varied, participants overestimate numerosity as the spatial field size increases (Dakin, Tibber, Greenwood, Kingdom, & Morgan, 2011; Tibber, Greenwood, & Dakin, 2012). These studies suggest that manipulating spatial arrangements within a single visual field can affect numerical judgments. However, varying the number of spatial fields in which the arrays are displayed has also been found to influence performance (see Figure 1 for example of spatially separated fields). In one study, adult participants judged which of two arrays were numerically larger while the spatial field of the arrays was varied: on some of the trials, the numerical arrays were presented intermixed within one spatial field, whereas on other trials, each numerical array was presented in separate, adjacent spatial fields (Price et al., 2012). Participants were significantly worse at discriminating between the arrays when they were intermixed within one spatial field versus when they were separated across spatial fields. Although the reason for why spatial field manipulations affect non-symbolic number performance is still under debate (Delvenne, Castronovo, Demeyere, & Humphreys, 2011; Delvenne & Holt, 2012), these studies indicate that the performance of adults on numerical discrimination tasks can be heavily influenced by manipulating the spatial properties of the presented stimuli.

In contrast to non-symbolic number, little research has examined the influence of spatial arrangement on judgments of other magnitudes, such as cumulative area. Despite this, it has been suggested that stimulus properties do affect cumulative area performance. In light of infant research indicating poorer performance on cumulative area versus non-symbolic number discriminations, it has been proposed that the type of stimuli used in these studies may create a bias detrimental to cumulative area representations. Specifically, it has been argued that arrays of discrete objects prime (invite) numerical evaluations and lead to interference with other magnitudes (Cordes & Brannon, 2008b). This suggests that the nature of the stimulus, specifically whether it is a discrete set of objects, could influence how precisely cumulative area information is represented. The impact of the use of more versus less discrete stimuli on cumulative area performance has not been directly examined. It has been shown with adults that the use of amorphous cumulative area stimuli (e.g., set of objects that do not have clear boundaries) during a discrimination task yields behavioral ratio effects similar to non-symbolic number (Castelli et al., 2006). However, no research has directly examined discrimination performance of cumulative area information when it is more versus less discrete and it is yet to be seen whether spatial arrangement manipulations influences performance to a similar degree as non-symbolic number.

Present Study

To examine the specificity of mental magnitudes in judgment tasks, across two experiments we compared the effects of development as well as spatial arrangement on cumulative area and non-symbolic number discrimination performance. We focused on three groups of participants, four-year-olds, six-year-olds, and adults, to examine how performance may change across development. We chose four- and six-year-olds for two reasons. First, during pilot testing we found that four-year-olds were the youngest age group that could reliably complete explicit cumulative area discrimination tasks. Second, by comparing four- and six-year-olds we were able to examine performance both before and after children typically undergo substantial development in symbolic number and math. It has been found that between four and six years of age, children acquire a mature understanding of counting (Le Corre & Carey, 2007) as well as knowledge of how to perform symbolic arithmetic (Levine, Jordan, & Huttenlocher, 1992). By using these age groups, we indirectly examined how the impact of age-related math experience and development affects the link between cumulative area and non-symbolic number representations.

The spatial arrangement of the stimuli was varied across two experiments. In Experiment 1, participants judged which of two arrays was larger in non-symbolic number or cumulative area when each array was arranged in spatially separated fields (see Figure 1 for example of spatially separated fields). In Experiment 2, participants made similar judgments, except that the two arrays were intermixed within one spatial field. Moreover, in Experiment 2, cumulative area arrays were presented as amorphous (array elements had no clear boundary), rather than discrete stimuli. By using two different spatial arrangements, we were able to examine whether potential developmental changes would be present when arrays were spatially separated, intermixed, or both. If developmental pressures lead to changes in cumulative area and non-symbolic number representations, we predicted that the coupling in performance on each task would change across each age group and affect the impact spatial manipulations have on performance.

Experiment 1 – Spatially Separated Cumulative Area and Non-symbolic Number

Method

Participants. Twenty four-year-olds (10 girls, M_{age} = 54.8 months, *range* = 48.9 to 59.3 months), twenty six-year-olds (10 girls, M_{age} = 78.7 months, *range* = 73.9 to 82.4 months), and 13 adults (10 females, M_{age} = 20.0 years, *range* = 17.4 to 24.5 years) participated in this experiment. An additional five children were excluded from data analyses as they failed to follow instructions. Children were recruited from a metropolitan community and were tested either in a university laboratory or at their preschool using a protocol approved by the local Institutional Review Board (IRB). Adult participants were undergraduate students who were enrolled in an introductory psychology course and completed the study for course credit.

Equipment and Stimuli. Children and adults completed the task using similar computer programs. Children were tested using a custom program (Visual Basic, Microsoft Corp.) running on a laptop computer (33.1 x 20.7 cm screen; Dell, Inc.) fitted with a touch screen (Keytec, Inc.). Adults were tested using a custom program (E-Prime, PST, Inc.) running on a desktop computer. Children were presented with either cumulative area or non-symbolic number stimuli (randomly assigned) using a pair of images whereas adults were presented with both (see Figure 1). Each image was created by placing a set of rectangles (each of which varied in aspect ratio and size) within an 8.7 by 11.2 cm frame. Within each image, the spatial locations of rectangles were randomly determined and both sets of rectangles were of the same color within each trial (color varied randomly across trials). Each pair of images differed in relative number or cumulative area whereas other extraneous parameters were systematically varied across trials. During the task, children were presented with six different ratios (largest to smallest: 2.00, 1.50, 1.33, 1.25, 1.17, 1.11) whereas adults were presented with an additional difficult ratio (1.09) to ensure performance was not at ceiling for these participants. Due to this additional ratio, when describing the dimensions of the stimuli we made note of differences between children and adult stimuli when they were present.

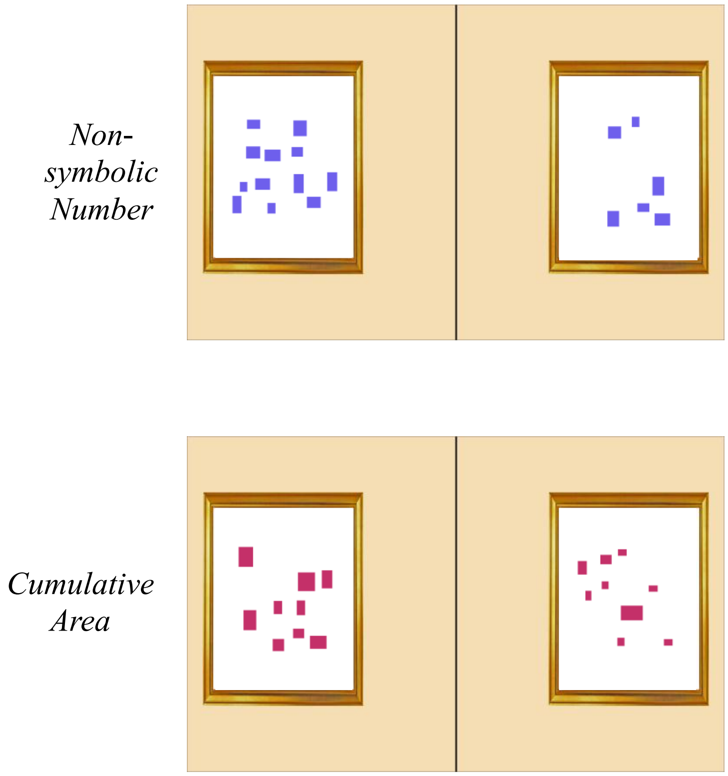


Figure 1. Sample stimuli (2.00 ratio) from Experiment 1. Each pair of images was presented for 1200 ms. Afterwards, participants chose which image had more boxes (Non-symbolic Number) or more paint (Cumulative Area).

For the cumulative area task, the total area of the rectangles in each image was varied to create specific ratios (dimensions of each array: *M* = 6.2 cm^2, *SD* = 1.7 cm^2, *range*: 3.3 to 10.7 cm^2; adults, *M* = 6.1 cm^2). Similar to previous research (Lourenco et al., 2012), the number of rectangles in each image was equated across each pair and varied across trials (7, 9, or 13 rectangles in each image) to prevent the use of number as a cue during the task. In addition to varying the size and aspect ratio of individual elements within each set of rectangles, the largest rectangle in each image was matched to reduce the likelihood that element size would be used as the basis for a response.

For the non-symbolic number task, the number of rectangles in each image was varied (from 6 to 12) to create a specific ratio. Similar to previous research (Holloway & Ansari, 2009; Lourenco et al., 2012), three types of controls were used across trials to discourage the use of extraneous spatial information during the task. On trials in which cumulative area was controlled, the cumulative area of both sets of rectangles was equated (cumulative area dimensions of each array: *M* = 7.8 cm^2, *SD* = 1.8 cm^2, *range*: 5.3 to 10.6 cm^2; adults, *M* = 7.4 cm^2, *SD* = 2.0 cm^2, *range*: 4.1 to 10.6 cm^2). On trials in which element size was controlled, the average size of individual rectangles for each set was equated (cumulative area dimensions of each array: *M* = 6.6 cm^2, *SD* = 1.8 cm^2, *range*: 3.3 to 10.5 cm^2; adults, *M* = 6.4 cm^2). On trials in which there were no controls, or free-parameter trials, the cumulative area and individual element size for each set of rectangles was allowed to vary randomly (cumulative area dimensions of each array: *M* = 7.4 cm^2, *SD* = 1.8 cm^2, *range*: 4.5 to 11.1 cm^2; adults, *M* = 7.3 cm^2, *SD* = 1.7 cm^2).

Procedure. Testing procedures differed for children and adults and thus are discussed separately. Children made their responses using a touch screen stylus.

Following previous research (Bonny & Lourenco, 2013), children were first given a short game, unrelated to the task, to become familiar with using the stylus to make responses. Afterwards, children were given a brief presentation where the experimenter verbally and visually described that they were going to play a game with Bert and Ernie (shown as images on the left and right sides of the computer screen) where they would see pictures that Bert and Ernie had painted. Children were then shown two sample pictures that differed by a large ratio (3.00) and were either asked to judge who had more paint (Cumulative Area task) or more boxes (Non-symbolic Number task) in their picture. Images were embedded within a gold picture frame to depict the stimuli as paintings. After this presentation, children were given the discrimination task (either Cumulative Area or Non-symbolic Number) and verbally told the instructions by the experimenter. Children had to first poke a red on-screen button to start the trial, after which the stimuli were displayed for 1200 ms on the left and right sides of the screen (see Figure 1). Previous research has found that 1200 ms is sufficient for children to see both stimuli but short enough to discourage counting[3] (Halberda & Feigenson, 2008). After the stimuli were removed, images of Bert and Ernie were presented and children were told to touch the photo of the character that had more paint ("who has more paint") or more boxes ("who has more boxes"). To familiarize children with the instructions, they were first given four practice trials where the stimuli differed by a large ratio (3.00) and corrective feedback was given. No corrective feedback was given on test trials. For each test trial, the experimenter oriented children towards the stimuli and prompted the child to make their judgment. A total of 54 test trials (nine for each ratio) were administered, across

[3] If children attempted to count the boxes, the experimenter interrupted them and said this was not a counting game.

which ratio and correct response side were counterbalanced. After nine test trials, children were presented with a reward animation and reminded of the instructions.

Testing procedures for adults were similar to those used with children, with two main differences. First, no cover story was used, and task instructions were presented as part of the computerized task. Adults were told that they would see two images presented on the left and right side of the screen and would have to judge which image had "more color" (Cumulative Area task) or which had "more boxes" (Non-symbolic Number task). Instructions emphasized both speed and accuracy. The second difference was the manner in which the stimuli were presented. At the start of each trial, a fixation cross was presented for 1000 ms, after which the pair of stimuli were presented for 750 ms. Presentation time of this length has been found to be long enough for adults to observe both stimuli, and short enough to prevent counting (Halberda & Feigenson, 2008). Participants were then presented with a question mark that remained onscreen until they judged which image was larger using corresponding keyboard keys ("O" for left image; "P" for right image). Adults were given four practice trials with feedback (3.00 ratio) and 63 test trials without feedback. All counterbalancing was the same as in the version used with children.

Results

Mean accuracy of correctly choosing the larger stimulus at each ratio was used as the dependent measure. Separate sets of analyses were conducted for child and adult. All tests are two-tailed with $\alpha = .05$.

Analyses of children's performance using a mixed analysis of variance (ANOVA) with age group (4-year-olds, 6-year-olds; between-subjects), magnitude (Cumulative

Area, Non-symbolic Number; between-subjects), and ratio (2.00, 1.50, 1.33, 1.25, 1.17, 1.11; within-subjects) as factors revealed main effects of age group, $F(1, 36) = 18.640$, $p < .001$, $\eta_p^2 = .341$, magnitude, $F(1, 36) = 67.048$, $p < .001$, $\eta_p^2 = .651$, and ratio (Greenhouse-Geisser corrected), $F(4.055, 145.990) = 21.323$, $p < .001$, $\eta_p^2 = .372$. No interactions between factors reached statistical significance (all *p*s > .08). The main effects of age and magnitude were driven by higher accuracy for 6-year-olds than 4-year-olds and higher accuracy for non-symbolic number compared to the cumulative area (see Figure 2). A linear contrast analysis indicated that the main effect of ratio was driven by higher performance as the ratio increased, $F(1, 36) = 92.370$, $p < .001$, $\eta_p^2 = .720$ (see Figure 2). Overall accuracy, which was performance collapsed across ratios, was above chance for both tasks at both age groups (see Table 1).

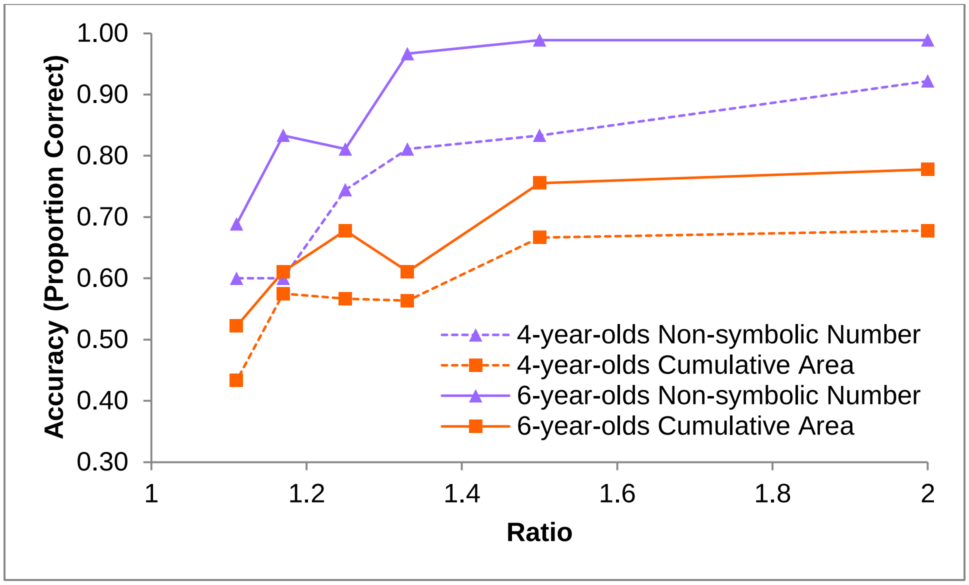


Figure 2. Children's performance (accuracy) on the Cumulative Area and Non-symbolic Number tasks in Experiment 1.

Table 1

Children's accuracy and comparisons to chance (0.5) for the non-symbolic number and cumulative area tasks for Experiment 1 [mean (standard deviation)].

	4-year-olds		6-year-olds	
Ratio	Number	Cumulative Area	Number	Cumulative Area
1.11	0.6 (0.19)	0.433 (0.143)	0.689 (0.172)**	0.522 (0.166)
1.17	0.6 (0.204)	0.575 (0.212)	0.833 (0.094)***	0.611 (0.12)*
1.25	0.744 (0.189)**	0.567 (0.161)	0.811 (0.105)***	0.678 (0.161)**
1.33	0.811 (0.129)***	0.563 (0.169)	0.967 (0.054)***	0.611 (0.224)
1.50	0.833 (0.094)***	0.667 (0.128)**	0.989 (0.035)***	0.756 (0.155)**
2.00	0.922 (0.149)***	0.678 (0.097)***	0.989 (0.035)***	0.778 (0.181)**
Overall	0.759 (0.087)***	0.58 (0.058)**	0.88 (0.051)***	0.659 (0.098)**

*Asterisks indicate significant of t-test comparison to chance. ***$p < .001$, **$p < .01$, *$p < .05$*

Adults' performance was analyzed using a repeated-measures ANOVA with magnitude (Cumulative Area, Non-symbolic Number) and ratio (2.00, 1.50, 1.33, 1.25, 1.17, 1.11, 1.09) as factors. This analysis revealed main effects of magnitude, $F(1, 12) = 9.479$, $p = .010$, $\eta_p^2 = .441$, and ratio (Greenhouse-Geisser corrected), $F(3.424, 41.087) = 43.251$, $p < .001$, $\eta_p^2 = .783$ (interaction $p > .3$). Similar to children, adults had higher accuracy for non-symbolic number than cumulative area and their performance increased as the ratio increased (linear contrast, $F(1, 12) = 215.253$, $p < .001$, $\eta_p^2 = .947$; see Figure 3). Overall accuracy was above chance for both tasks (see Table 2). Follow-up analyses confirmed that the majority of participants had higher overall accuracy for non-symbolic number compared to cumulative area (12 out of 13 participants, $p = .003$, binomial test) and that overall accuracy on both tasks was not correlated, $r(11) = .182$, $p = .551$.

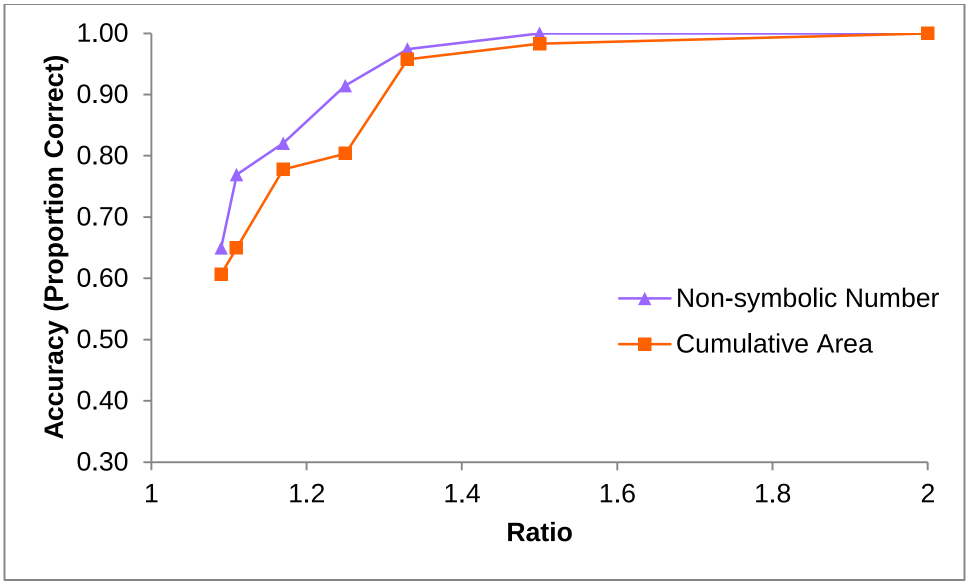


Figure 3. Adult’s performance (accuracy) on the Cumulative Area and Non-symbolic Number tasks in Experiment 1.

Table 2

Adults' accuracy and comparisons to chance (0.5) for the non-symbolic number and cumulative area tasks for Experiment 1 [mean (standard deviation)].

Ratio	Number	Cumulative Area
1.09	0.65 (0.135)**	0.607 (0.167)*
1.11	0.769 (0.147)***	0.65 (0.135)**
1.17	0.821 (0.206)***	0.778 (0.091)***
1.25	0.915 (0.092)***	0.803 (0.145)***
1.33	0.974 (0.049)***	0.957 (0.085)***
1.50	1 (0)***	0.983 (0.042)***
2.00	1 (0)***	1 (0)***
Overall	0.875 (0.053)***	0.825 (0.037)***

Asterisks indicate significant of t-test comparison to chance. ***$p < .001$, **$p < .01$, *$p < .05$

Discussion

In Experiment 1, children and adults displayed ratio effects for spatially separated cumulative area as well as non-symbolic number judgments. Consistent with previous research (Bonny & Lourenco, 2013; Halberda & Feigenson, 2008; Libertus et al., 2011; Odic et al., 2012), ratio and age effects were observed with non-symbolic number. We also found ratio and age effects with cumulative area, replicating previous research with adults (Lourenco et al., 2012) and, for the first time, extending these results to children. Furthermore, the overall accuracy for each task at all age groups was above chance, indicating not only that children and adults were able to access mental magnitudes, but that the representations were precise enough to make accurate judgments. Although performance on the cumulative area and number tasks were similar in that there were ratio effects, there were differences in how well children and adults performed on each task. Participants were more accurate when judging which array was larger in number than cumulative area. Furthermore, this gap in performance was present at each age group. This suggests that, at least when presented in spatially separated images, a dissociation in performance on number and cumulative area discrimination tasks is present and consistent across development despite vast changes in mathematical knowledge. The results from Experiment 1 best fit with the specific magnitude view since there were clear differences in how well children and adults could discriminate cumulative area versus non-symbolic number information. However, the similar improvement in performance across development suggests that there may still be some overlap in the underling mental magnitudes.

Experiment 2 – Spatially Intermixed Non-symbolic Number and Cumulative Area

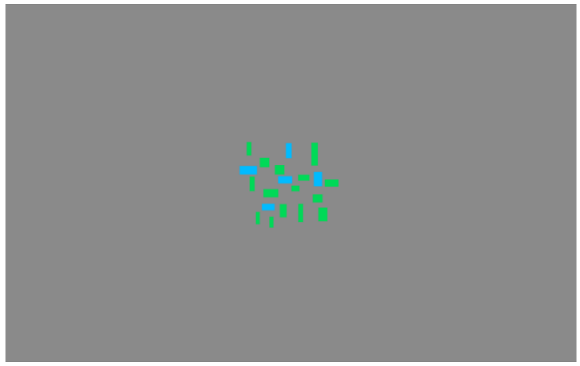
In Experiment 2, we compared performance on cumulative area and non-symbolic number tasks across development using a different type of spatial arrangement. Specifically, the arrays used for each magnitude were intermixed within a single spatial field. Given that previous research has found differences due to spatial arrangement in discrimination performance in adults with non-symbolic number (Price et al., 2012), we examined whether this pattern would be observed earlier in development and whether it extended to cumulative area. Additionally, similar to Castelli and colleagues (2006), we added a manipulation to the cumulative area task by making the arrays less discrete, or amorphous. We did this to examine whether cumulative area discrimination performance would be more comparable to non-symbolic number when the potential bias to focus on numerical information first in discrete elements is removed. If there are shared processes for cumulative area and non-symbolic number, unlike in Experiment 1, there should be similar performance for both magnitudes. Furthermore, if there are developmental pressures for specific magnitude representations, there should be changes in the link between cumulative area and non-symbolic number performance across age groups.

Method

Participants. Twenty four-year-olds (7 girls, M_{age} = 54.6 months, *range* = 48.9 to 59.3 months), twenty six-year-olds (17 girls, M_{age} = 78.2 months, *range* = 72.4 to 84.7 months), and 13 adults (6 females, M_{age} = 20.1 years, *range* = 18.7 to 22.3 years) participated in this experiment. An additional eight children were excluded from data analysis as they failed to follow instructions. Children were recruited from a metropolitan community and were tested either in a university laboratory or at their preschool using a protocol approved by the local IRB. Adult participants were undergraduates enrolled in an introductory psychology who completed the study for course credit.

Equipment and stimuli. The same equipment was used as in Experiment 1. Similar stimuli to Experiment 1 were used with three major differences. First, the sets of rectangles were either blue (rgb color code: 0, 187, 255) or green (rgb color code: 0, 217, 87; matched in luminance) rather than the same color (the background color was also changed from white to gray to match the luminance of the array colors). Second, the arrays were spatially intermixed within one spatial field (13.8 x 10.4 cm). The same sets of arrays from Experiment 1 (although now blue or green in color) were used to create the numerical stimuli. Third, a new set of images were generated to create a set of amorphous cumulative area stimuli. To create a more continuous set of cumulative area stimuli, similar to previous research (Castelli et al., 2006) two sets of rectangles were arranged in a square grid (6.9 x 6.9 cm frame; six rectangles in each row and column). To create a specific ratio difference, the grid lines were adjusted to manipulate the cumulative area for each color. Similar to Experiment 1, the same number of boxes (18) was used in each array. The stimuli were then subjected to a Gaussian blur algorithm (25 pixel radius) in image-editing software (Photoshop, Adobe, Inc.) to smooth over the image (see Figure 4).

Non-symbolic Number



Cumulative Area

Figure 4. Sample stimuli (2.00 ratio) from Experiment 2. Each pair of images was presented for 1200 ms. Afterwards, participants chose which color had more boxes (Non-symbolic Number) or paint (Cumulative Area).

Procedure. Similar to Experiment 1, testing procedures differed for children and adults and are discussed separately. Children were asked to judge whether a picture had more blue or green paint (Cumulative Area task) or more blue or green boxes (Non-symbolic Number task). Similar to Experiment 1, children made their responses using a stylus and, prior to the task, practiced using the stylus by playing a game. Similar to Experiment 1, children were then shown a brief presentation where the experimenter visually and verbally introduced the task. Children were told that they were going to play a game where Tigger (shown as image on computer) would show them some pictures and they would have to judge whether there was more blue or green paint (Cumulative Area task) or more blue or green boxes (Non-symbolic Number task). They were then shown a sample stimulus and asked to make their judgment. Afterwards, children were presented with the discrimination task. Similar to Experiment 1, children touched a central red box to begin the trial. The stimulus was then presented in the center of the screen for 1200 ms, after which a blue and green star appeared on the left or right of the screen (counterbalanced across participants). Children made their response by pressing the star that corresponded to the color they thought was more in either cumulative area or non-symbolic number. Similar to Experiment 1, children received four practice trials with a large ratio (3.00) as well as corrective feedback and then 54 test trials without feedback. During the test trials, children received a reward animation and were reminded of the instructions every nine trials.

Adult participants received a similar task. Adults were instructed to judge whether there was more blue or green paint (Cumulative Area) or boxes (Non-symbolic Number). The trial procedure was identical to Experiment 1 except that the response keys "O" and "P" corresponded to either blue or green (counterbalanced across participants). Unlike child participants, adults received both tasks (counterbalanced order). Four practice trials (3.00 ratio) with feedback were given at the beginning of each task and 63 test trials were presented for each magnitude (cumulative area and non-symbolic number).

Results

Similar to Experiment 1, the mean accuracy for correctly choosing the larger stimulus at each ratio was used as the dependent measure. Two separate sets of analyses were conducted for the child and adult samples. All tests conducted were two-tailed with $\alpha = .05$.

Analyses of children's performance using a mixed ANOVA with age group (4-year-olds, 6-year-olds; between-subjects), magnitude (Cumulative Area, Non-symbolic Number; between-subjects), and ratio (2.00, 1.50, 1.33, 1.25, 1.17, 1.11; within-subjects) as factors revealed main effects of age group, $F(1, 36) = 16.375$, $p < .001$, $\eta_p^2 = .313$, and ratio, $F(5, 180) = 18.884$, $p < .001$, $\eta_p^2 = .344$, but not magnitude, $F(1, 36) = .819$, $p = .371$, $\eta_p^2 = .022$. No significant interactions were observed (ps > .3). The main effects of age and ratio were driven by higher accuracy for 6-year-olds than 4-year-olds and increasingly higher accuracy as the ratio increased (linear contrast, $F(1, 36) = 84.009$, $p < .001$, $\eta_p^2 = .700$; see Figure 5). Overall accuracy was above chance for both tasks at both age groups (see Table 3).

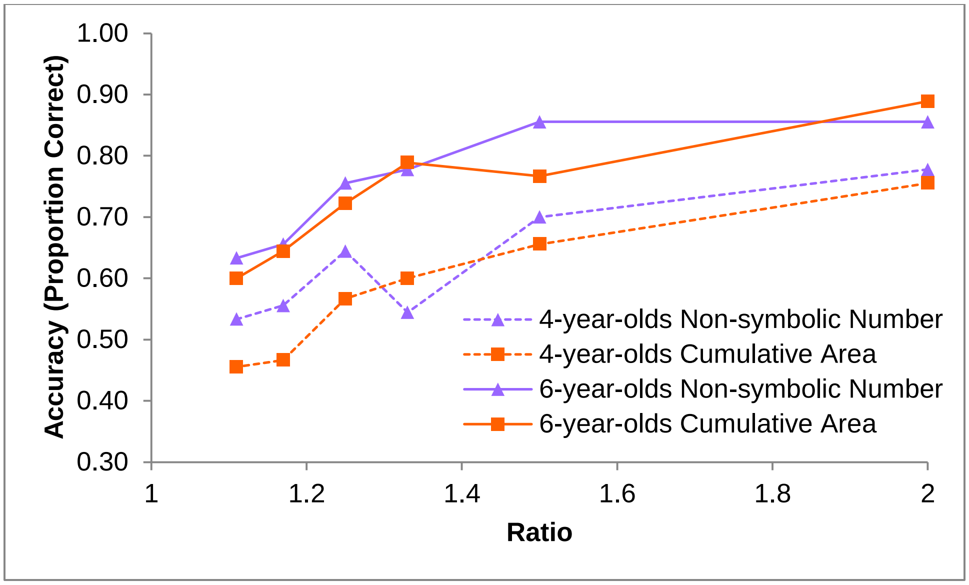


Figure 5. Children's performance (accuracy) on the Cumulative Area and Non-symbolic Number tasks in Experiment 2.

Table 3

Children's accuracy and comparisons to chance (0.5) for the non-symbolic number and cumulative area tasks for Experiment 2 [mean (standard deviation)].

	4-year-olds		6-year-olds	
Ratio	Number	Cumulative Area	Number	Cumulative Area
1.11	0.533 (0.102)	0.456 (0.177)	0.633 (0.189)	0.6 (0.159)
1.17	0.556 (0.157)	0.467 (0.215)	0.656 (0.161)*	0.644 (0.155)*
1.25	0.644 (0.239)	0.567 (0.161)	0.756 (0.215)**	0.722 (0.191)**
1.33	0.544 (0.225)	0.6 (0.107)*	0.778 (0.203)**	0.789 (0.199)**
1.50	0.7 (0.182)**	0.656 (0.097)**	0.856 (0.158)***	0.767 (0.11)***
2.00	0.778 (0.166)***	0.756 (0.115)***	0.856 (0.174)***	0.889 (0.148)***
Overall	0.626 (0.122)*	0.583 (0.074)**	0.756 (0.121)***	0.735 (0.116)***

Asterisks indicate significant of t-test comparison to chance. ***$p < .001$, **$p < .01$, *$p < .05$

Analyses of adult's performance using a repeated-measures ANOVA with magnitude (Cumulative Area, Non-symbolic Number) and ratio (2.00, 1.50, 1.33, 1.25, 1.17, 1.11, 1.09) as factors revealed a main effect of ratio, $F(6, 72) = 22.136$, $p < .001$, $\eta_p^2 = .648$, but not magnitude, $F(1, 12) = 2.537$, $p = .137$, $\eta_p^2 = .174$. No significant interaction was observed ($p > .1$). Specifically, performance increased as the ratio increased across magnitudes (linear contrast, $F(1, 12) = 116.412$, $p < .001$, $\eta_p^2 = .907$; see Figure 6). Overall accuracy was above chance for both magnitudes (see Table 4). Follow-up analyses yielded no significant differences in how many participants had higher overall accuracy for non-symbolic number compared to cumulative area (5 out of 13, $p = .581$, binomial test). Furthermore, overall accuracy for both magnitudes was marginally positively correlated, $r(11) = .551$, $p = .051$.

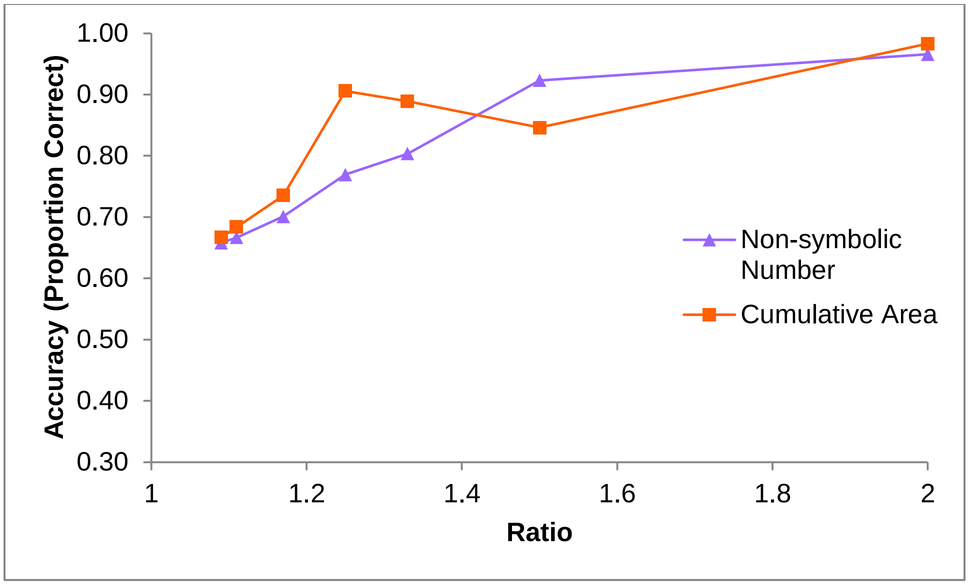


Figure 6. Adults' performance (accuracy) on the Cumulative Area and Non-symbolic Number tasks in Experiment 2.

Table 4

Adults' mean accuracy and comparisons to chance (0.5) for the non-symbolic number and cumulative area tasks for Experiment 2 [mean (standard deviation)].

Ratio	Number	Cumulative Area
1.09	0.658 (0.166)**	0.667 (0.128)**
1.11	0.667 (0.157)**	0.684 (0.127)***
1.17	0.701 (0.224)**	0.735 (0.167)***
1.25	0.769 (0.132)***	0.906 (0.11)***
1.33	0.803 (0.158)***	0.889 (0.128)***
1.50	0.923 (0.083)***	0.846 (0.072)***
2.00	0.966 (0.07)***	0.983 (0.062)***
Overall	0.784 (0.083)***	0.816 (0.066)***

Asterisks indicate significant of t-test comparison to chance. ***$p < .001$, **$p < .01$, *$p < .05$

Discussion

Consistent with Experiment 1, ratio effects as well as improvements in performance across development were observed for both cumulative area and non-symbolic number. For cumulative area, this confirms that ratio effects are observed whether presented as discrete or amorphous stimuli. However, unlike Experiment 2, there was no difference in performance when judging which array was larger in number than cumulative area at any of the age groups, suggesting developmental continuity in the effect. Consistent with previous research with adults using discrete arrays (Lourenco et al., 2012), this suggests that non-symbolic number and cumulative area discrimination is similar when presented within one spatial field. However, the source of this similarity in performance is unclear. It could be due to higher performance for cumulative area as a result of using amorphous, spatially intermixed stimuli or lower performance on the number task due to the use of spatially intermixed stimuli.

General Results: Comparing Both Experiments

In order to examine how the change in stimuli influenced performance within each magnitude (cumulative area and non-symbolic number), additional ANOVAs compared the performance of children and adults across experiments. To focus on the nature of the differences between each experiment and magnitude, overall task accuracy, which collapses performance across ratios, was used as the dependent variable.

For child participants, an ANOVA with age group (4-year-olds, 6-year-olds; between-subjects), magnitude (Cumulative Area, Non-symbolic Number; between-subjects), and experiment (1, 2: between-subjects) as factors revealed main effects of age group (higher performance for 6-year-olds), $F(1, 72) = 32.245$, $p < .001$, $\eta_p^2 = .309$, magnitude, $F(1, 72) = 29.808$, $p < .001$, $\eta_p^2 = .293$, experiment, $F(1, 72) = 4.455$, $p = .038$, $\eta_p^2 = .058$, as well as an interaction between magnitude and experiment, $F(1, 72) = 15.776$, $p < .001$, $\eta_p^2 = .180$ (all other *p*s > .3). Post hoc analyses examining the two-way interaction found that performance was significantly higher on the Non-symbolic Number task in Experiment 1 than Experiment 2, Mann-Whitney $U(38) = 91.000$, $z = 2.958$ $p = .003$, but there was no significant difference between experiments for Cumulative Area task performance, $p > .3$ (see Figure 7).

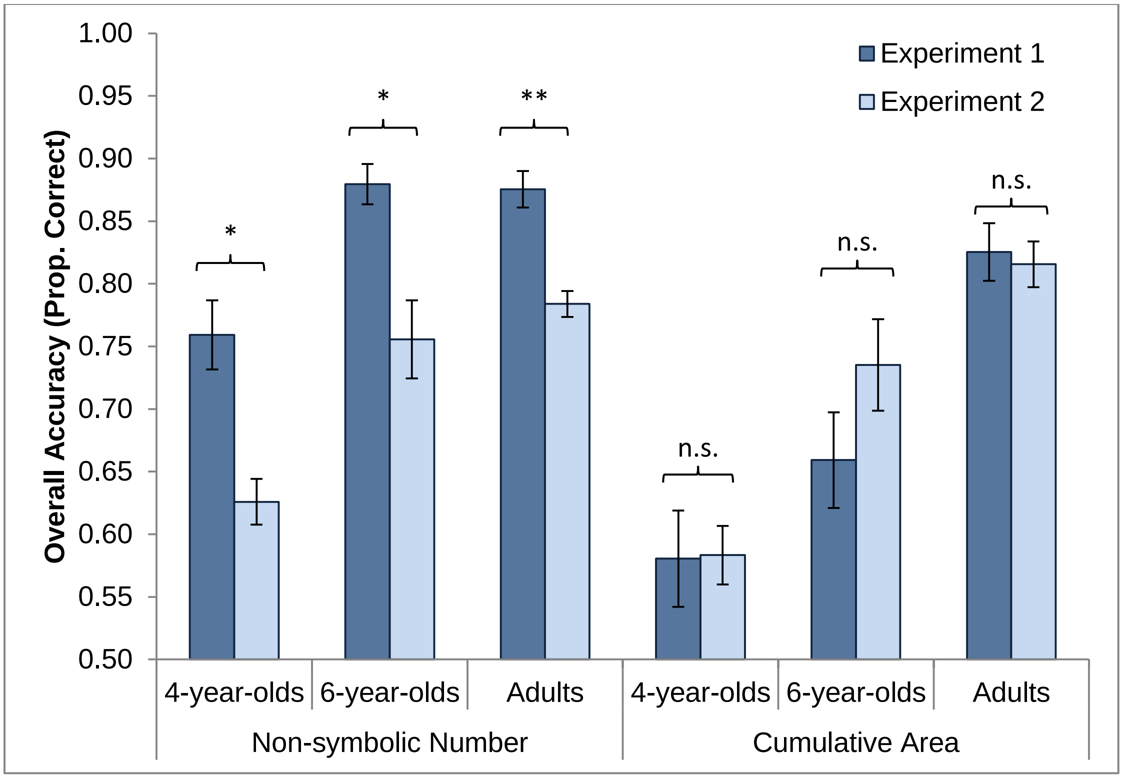


Figure 7. Overall accuracy on the Cumulative Area and Non-symbolic Number tasks in Experiments 1 and 2 for each age group. Error bars represent +/- 1 SEM. Asterisks indicate *p* values (***p* < .01, **p* < .05).

For adult participants, a mixed ANOVA with magnitude (Cumulative Area, Non-symbolic Number; within-subjects) and experiment (1, 2; between-subjects) as factors revealed a main effect of experiment, $F(1, 24) = 6.056$, $p = .021$, $\eta_p^2 = .201$, as well as a significant interaction between magnitude and experiment, $F(1, 24) = 10.114$, $p = .004$, $\eta_p^2 = .296$. Post hoc analyses revealed that significantly higher performance for non-symbolic number in Experiment 1 than Experiment 2, $t(24) = 3.372$, $p = .003$ (see Figure 7) was driving the two-way interaction (no difference in cumulative area performance across experiments, $p > .6$). This suggests that for all age groups the spatial arrangement manipulation led to a decrease in performance on the Non-symbolic Number task in Experiment 2 and little, if any, difference on the Cumulative Area task.

In an attempt to further explore the improvement in performance with age across magnitudes and experiments, we modeled the developmental change in task performance. In previous research, improvement on magnitude discrimination tasks across age groups has been characterized using power functions (Halberda & Feigenson, 2008; Odic et al., 2012; Piazza et al., 2010). In the present study, we conducted an exploratory analysis where we modeled age-related improvement on the cumulative area and non-symbolic number tasks using a power function. We used error rate (proportion of errors across trials) as our measure of mental magnitude precision since, similar to measures used in previous research, it should be higher the less precise or more variable the representation. We split our dataset by experiment as well as magnitude task, with each participant within these categories being treated as an individual data point. Unlike previous research, which has used group means to fit the model, we used the majority of individual data points from all age groups to estimate the confidence intervals for each model parameter. To reduce the likelihood of potential outlier data influencing the fit of each model, the dataset was trimmed. For each age group by magnitude by experiment cell, the participant with the highest and lowest error rate was removed from the analysis (total of 27 data points for each magnitude by experiment cell). To model the improvement in performance over age, we fit a power function with two free parameters ($y = a*x^b$), using age (month age of each participant) as the independent variable and error rate (error rate of each participant) as the dependent variable, for each magnitude by experiment cell using non-linear regressions. In this power function, the parameter *a* indicates the initial error rate (smaller values indicate better initial performance) and the parameter *b* indicates the rate of growth [smaller values indicate a faster growth rate; (Newell & Rosenbloom, 1981)]. The estimated parameters for each group of participants was as follows: Experiment 1 – Cumulative Area, *a* = 4.067 (SE = 1.353), *b* = -.566 (SE = .076), R^2 = .757; Experiment 1 – Non-symbolic Number, *a* = 1.184 (SE = .676), *b* = -.445 (SE = .129), R^2 = .344; Experiment 2 – Cumulative Area, *a* = 3.624 (SE = 1.662), *b* = -.561 (SE = .105), R^2 = .594; Experiment 2 – Non-symbolic Number, *a* = 1.294 (SE = .602), *b* = -.341 (SE = .104), R^2 = .316 (see Figure 8). The confidence intervals (95%) generated for each model indicated that there was no significant difference between parameters estimated for each dataset (see Figure 9). Although there are several limitations to this exploratory analysis, such as the use of cross-sectional data and small number of data points, the results are in line with previous analyses indicating that there was a similar level of improvement for each magnitude under both spatial arrangement conditions.

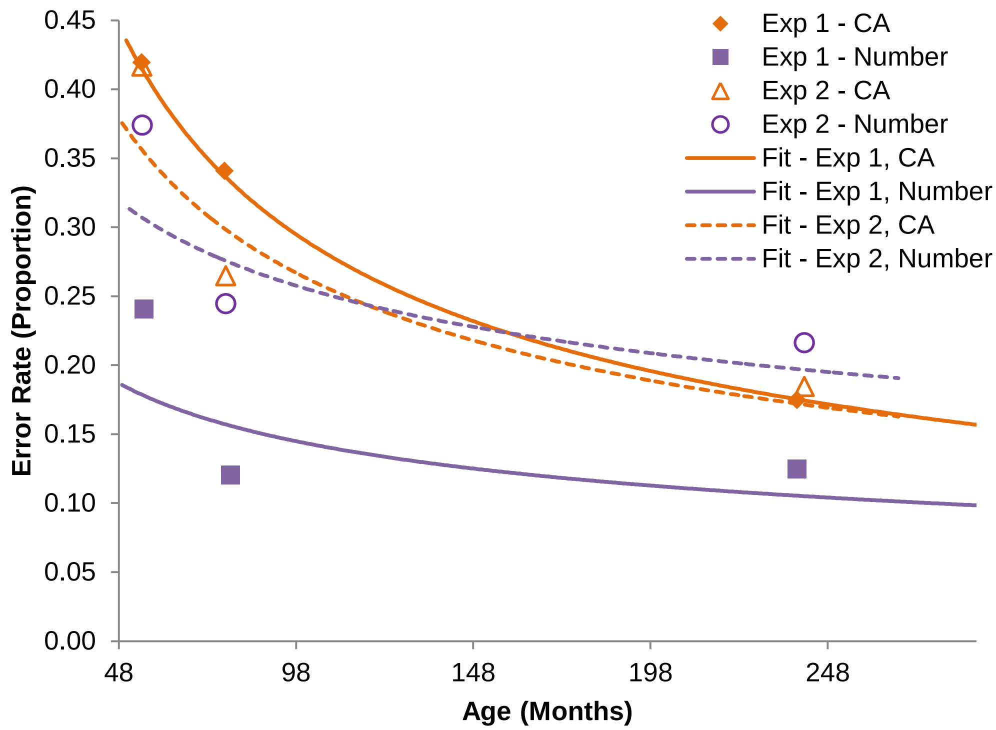
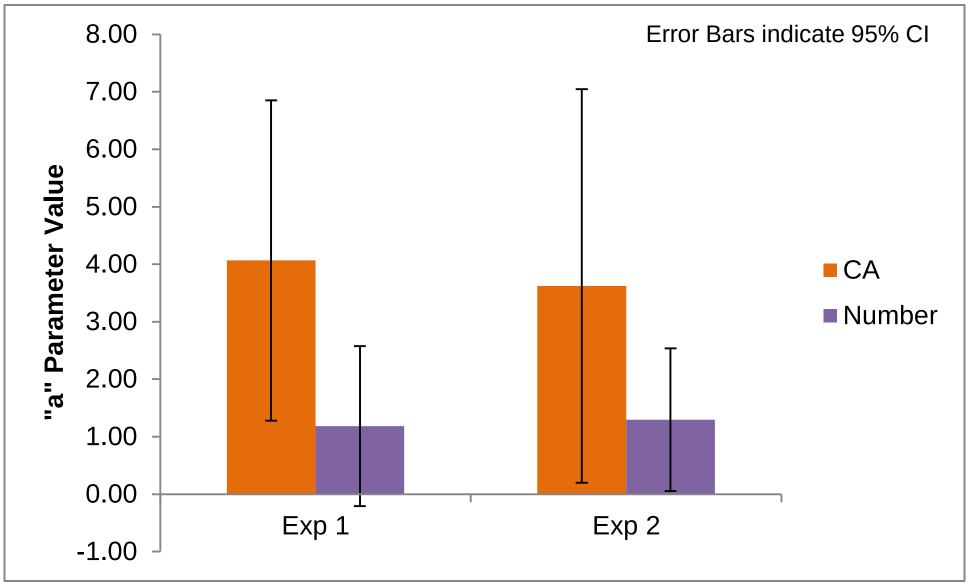


Figure 8. Power function models of error rates for performance on the non-symbolic number (Number) and cumulative area (CA) tasks in each experiment. Data points reflect the average performance and average age for 4-, 6-year-olds, and adults included in the power function models.



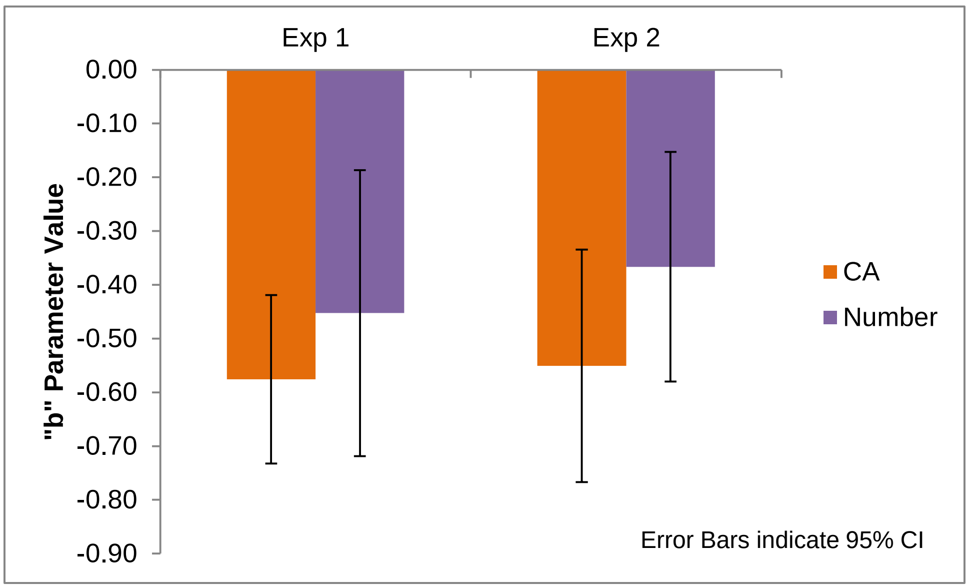


Figure 9. Estimated parameter values with 95% confidence intervals for each power function model per magnitude [non-symbolic number, cumulative area (CA)] and experiment (Exp 1, Exp 2). The "a" parameter indicates the initial level of performance and the "b" parameter indicates the growth rate in performance. No significant differences are present between either set of parameters.

General Discussion

In the present study, we examined the performance of children and adults on cumulative area and non-symbolic number judgment tasks as the spatial parameters of the stimuli were varied. Across both experiments we found that, similar to non-symbolic number, four- and six-year-olds were above chance at judging which of two arrays were larger in cumulative area. Furthermore, we found a ratio effect in children's and adults' performance on the cumulative area and non-symbolic number tasks. These results with non-symbolic number replicate previous research with children and adults (Droit-Volet et al., 2008; Halberda & Feigenson, 2008; Odic et al., 2012) and extended these results to cumulative area. This demonstrates an important continuity in the ability of humans to detect differences in cumulative area which has been previously shown with only infants [e.g., (Cordes & Brannon, 2008a)] and adults [e.g., (Lourenco et al., 2012)].

The spatial manipulation led to differences in performance on the non-symbolic number condition, but not the cumulative area condition. Similar to previous research, adults were worse at judging which numerical array was larger when the arrays were intermixed within one spatial field verses separated into two fields (Price et al., 2012). The present study extends this result to four- and six- year-old children as well. In contrast, the combination of the amorphous and intermixed arrays had no impact on cumulative area performance in comparison to when presented as spatially separated. The presence of a dissociation between magnitudes due to varying spatial arrangement suggests that there may be differences in non-symbolic number and cumulative area representations. However, despite the differences in performance due to spatial arrangement, there were similar developmental improvements observed for both magnitudes. The remarkably similar pattern of results across age groups, as well as the power model parameters, suggests that there is relative continuity in the development of non-symbolic number and cumulative area representations. The similarity in developmental changes suggests that there may be some overlap in the underlying mental magnitudes of cumulative area and non-symbolic number. Each of these implications is discussed below.

Developmental Continuity of Cumulative Area and Non-symbolic Number Performance

The similar pattern of results on the magnitude tasks at each age group suggests that the relative performance on number and cumulative area tasks is stable across development. Multiple studies, including the present experiments, have found improvements in discrimination judgments across development for different magnitudes (Droit-Volet et al., 2008; Halberda & Feigenson, 2008; Odic et al., 2012). Previous developmental research examining whether changes in mental magnitudes judgments are parallel across domains has found some differences. For example, children and adults had higher performance when comparing the size of two objects than the number of two sets of objects, however, the performance gap was consistent across all age groups tested (Odic et al., 2012). Similarly, in Experiment 1, even though performance on both tasks improved at each age group, the difference in performance between non-symbolic number and cumulative area was present at all ages. Additionally, similar levels of performance were observed for each age group in Experiment 2. These results are also reflected in the exploratory power modeling analyses that suggest similar rates of developmental improvement for number and cumulative area across experiments. The pattern of results in the present study suggests that developmental improvements in cumulative area are paralleled in non-symbolic number. This consistency suggests that the acquisition of symbolic number and math skills did not lead to a significant change in the connection between non-symbolic number and cumulative area representations. In summary, the continuity in developmental improvement across cumulative area and non-symbolic number suggests the underlying mental magnitudes undergo similar improvements in precision across development.

The differences in non-symbolic number performance created by the manipulation of spatial arrangement suggest that numerical mental magnitudes are highly malleable depending on the context. The effect of the spatial manipulation on the non-symbolic number task replicates previous research conducted with adults (Price et al., 2012) and was present at both child age groups. Interestingly, almost all non-symbolic number comparison tasks conducted with children use spatially separated stimuli (Bonny & Lourenco, 2013; Halberda et al., 2008; Holloway & Ansari, 2009; Libertus et al., 2011; Odic et al., 2012) making the present study the first to find that spatial manipulations alter children's non-symbolic number judgments. Additionally, the difference in performance on the non-symbolic number task under the two spatial arrangement conditions was stable across development. This suggests that representations of non-symbolic number are flexible across development

It is also interesting that the use of amorphous cumulative area in the spatially intermixed task did not boost performance above what was observed in the spatially separated task. This finding could be the result of two possibilities. First, it could be that, in contrast to what has been proposed for infant studies (Cordes & Brannon, 2008a), the use of discrete stimuli for cumulative area in Experiment 1 did not result in a numerical bias. If so, there was no numerical bias to overcome with amorphous arrays in Experiment 2 resulting in similar performance across experiments. However, it could also be that there was a numerical bias working against cumulative area representations in Experiment 1 and any benefit gained by using amorphous stimuli in Experiment 2 could have been negated by the use of spatially intermixed arrays. This explanation assumes that, similar to non-symbolic number, spatially intermixed arrays lead to lower performance on cumulative area tasks compared to spatial separated arrays. However, we believe that this was not the case. In a previous study, adults' performance on cumulative area and non-symbolic number tasks that used spatially intermixed discrete stimuli for both magnitudes was similar and was positively correlated (Lourenco et al., 2012). This result is similar to what was observed with adults in Experiment 2 making it unlikely that the amorphous version of cumulative area makes a significant difference in performance, at least with adults. If there was to be a benefit of amorphous stimuli, it was expected to emerge with children given the hypotheses about a potential bias in infancy (Cordes & Brannon, 2008a, 2008b). However, like adults, even the youngest age group tested in the present experiment did not show a change in performance. A possibility that remains is that the cumulative area stimuli used in the present Experiment 2 were not amorphous enough to show a boost in performance. Although the borders between blue and green paint were more ambiguous than the discrete arrays in Experiment 1, they could have been even more amorphous than what was used in the present study. Even so, if there was a gain in performance using stimuli that were more ambiguous than the current study, it would still be in line with the present results indicating stimulus properties affect cumulative area and non-symbolic number differently.

Why Spatial Arrangement Only Affected Non-symbolic Number Performance

A question that emerges from the present study is why the spatial arrangement of stimuli influences non-symbolic number, but not cumulative area judgments. As discussed above, the sensitivity of numerical mental magnitudes to variations in spatial arrangement suggests there is a level of flexibility in numerical representations. This has been suggested in previous research as well. When making judgments based on symbolic numerals that varied in physical size, it has been suggested that during difficult numerical judgments (as defined by how small the ratio is) additional magnitude resources, such as neural mechanisms that are not typically used during comparison tasks, are recruited to aid decision making (Cohen Kadosh et al., 2007). The present study provides support for the notion that numerical magnitudes are flexible and further suggests that the level of flexibility may depend on the spatial properties of the stimuli.

The similar level of performance on the cumulative area tasks in the present study suggests that, in contrast to number, cumulative area may be more resilient to stimulus variations. This may be due to how cumulative area information is computed. It has been proposed that cumulative area representations are tightly connected to average size representations, that is, the average size of individual units across a group of objects (Barth, 2008). Under this proposal, when participants are asked to create a cumulative area representation, they first create average size representations (Barth, 2008). Previous research examining the creation of average size representations have found that the level of precision is higher than those of an individual size (Alvarez, 2011; Im & Halberda, 2013). It is this high level of precision that could have a normalizing effect on cumulative area representations, leading to representations with a consistent amount of variability regardless of stimulus properties. However, when comparing across studies that have separately examined the precision of individual size and cumulative area judgments it is commonly noted that the precision of size judgments is better than cumulative area across development [infants: (Brannon et al., 2006; Cordes & Brannon, 2008a); adults: (Barth, 2008)]. This suggests that if cumulative area representations are created from average size, there must be some source of variance, or error, which leads to poorer precision. It seems unlikely that the numerical bias to perceive discrete arrays as numerical first is responsible for this error, as suggested by the lack of a difference in amorphous and separate cumulative area tasks in the present study. It is possible that it is a two-step process to create cumulative area representations, with the first step forming a representation of average size (Barth, 2008) and the second step computing cumulative area based on average size. It is this second step that could be the source of imprecision. This would explain the gap in performance observed in previous research as well as the current study that have compared cumulative area and non-symbolic number.

The differential impact of the spatial manipulation on cumulative area and non-symbolic number raises the question of specificity in the underlying mental magnitudes. These results do indeed indicate some specificity between representations, but not complete separation. In Experiment 1, performance on the tasks was significantly different and there was no significant correlation, indicating specificity in mental magnitude processes. However, in Experiment 2 adults' performance on the cumulative area and non-symbolic number task was marginally correlated, which is in line with previous research using spatially intermixed stimuli (Lourenco et al., 2012), suggesting some shared processes. An alternative view to shared and specific magnitude systems is that there are partially overlapping magnitude representations. In previous research, specific and common patterns of correlations between non-symbolic number and cumulative area performance and different math skills was argued to be evidence for partially overlapping representations (Lourenco et al., 2012). The results of the present study further suggest that the level of overlap between mental magnitudes can be modified using task parameters such as the spatial arrangement of stimuli. Future research will be needed to further examine to what extent the specificity of mental magnitudes depends on stimulus properties.

In summary, we examined cumulative area and non-symbolic number judgments of children and adults when presented in single as well as separate spatial fields. We found evidence that, similar to non-symbolic number, as well as other magnitudes, children could use cumulative area representations accurately during a discrimination task. Furthermore, we found that unlike spatially separated arrays, discrimination performance using spatially intermixed stimuli was similar for cumulative area and non-symbolic number, suggesting partially overlapping magnitude representations. Developmental analyses indicated continuity in the coupling of cumulative area and non-symbolic number judgment performance, regardless of spatial arrangement, suggesting the structure of mental magnitudes are consistent across development.

Discussion of Study 1

The results of Study 1 suggest that there are similar developmental improvements in cumulative area and non-symbolic number judgments and partial specificity between mental magnitudes. Replicating previous research (Bonny & Lourenco, 2013; Halberda & Feigenson, 2008; Odic et al., 2012), performance on non-symbolic number judgments improved with age indicating an increase in the precision, or reduction in variability, of the underlying representations over development. This finding was also extended to cumulative area performance. For the first time, we demonstrated that children could make accurate judgments about cumulative area whether presented using discrete or amorphous stimuli. Although there were differences in performance between non-symbolic number and cumulative area driven by the spatial arrangement of stimuli, these differences remained stable across development. This suggests that that the underlying structure of mental magnitudes is relatively constant across development and established in infancy.

The consistent improvement in performance on both cumulative area and non-symbolic number indicates the underlying representations undergo similar changes in development. Previous studies have suggested that improvements in mental magnitude precision, specifically that of non-symbolic number, comes from general improvements in cognitive processing as well as specific contributions, such as symbolic math skills (Halberda et al., 2012; Libertus et al., 2011). Although Study 1 cannot definitively determine the sources of improvement, the results certainly implicate a large role for improvement in general compared to specific cognitive resources. There are many aspects of cognition that play a role in accurately performing on a magnitude comparison task such as those used in Study 1. For example, general resources, such as executive function and working memory, all play a role in number tasks (Fuchs et al., 2010). However, previous research examining the relation between performance on magnitude comparison tasks and symbolic math skills that have controlled for aspects of general process suggests that there still is a specific contribution of symbolic math to the precision of mental magnitudes (Halberda et al., 2008; Lourenco et al., 2012). Instead of there being a specific connection to numerical mental magnitudes, it could be that symbolic number and math skills are connected to all quantitative domains. This would suggest that any improvement due to math skills would not be specific to number, but to all mental magnitudes. Some evidence for this perspective comes from adult research that indicates both non-symbolic number and cumulative area representations are connected to math skills (Lourenco et al., 2012). Although individual measures of general processing ability of individuals was not tested in Study 1, the similar levels of improvement observed in cumulative area and non-symbolic number suggests that it could be due to maturation of general processes, acquisition of symbolic math affecting all mental magnitudes, or a combination of both.

The impact of the spatial arrangement manipulation on non-symbolic number comparison performance provides evidence of partial overlap in mental magnitudes. When presented in an intermixed spatial arrangement, performance was similar on cumulative area and non-symbolic number tasks. Furthermore, adults' performance on each task was marginally correlated, only in the spatially intermixed condition. The coupling of performance in only the spatially intermixed condition indicates that there are at least some commonalities between cumulative area and non-symbolic number representations. The link between mental magnitudes could either be due to overlap in mental magnitudes, or, the simultaneous activation of two distinct representations. The former suggests that the overlap is due to shared representations early in the comparison process while the latter holds that specific representations are created from independent processes and are only brought together when activated during decision making. In Study 2, these hypotheses are examined using neuroimaging paradigms.

Introduction to Study 2

In Study 2, I examined the specificity of mental magnitudes by comparing the neural correlates of cumulative area and non-symbolic number comparisons. Similar to behavioral paradigms, ratio and congruity effects have been found in neural activity during magnitude comparison tasks (Dehaene, 1996; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Schwarz & Heinze, 1998). Specifically, different levels of neural activity for small verses large ratios has been taken as evidence for a ratio effect across a variety of neuroimaging measures. As introduced above, the specific neuroimaging technique used in Study 2 was event-related potentials (ERPs) which refer to electrical activity that is recorded at the scalp and time-locked to an experimental event [for review see (Woodman, 2010)]. The strongest feature of ERPs in experimental paradigms is the excellent sensitivity to millisecond-level temporal changes in electrical activity. This temporal sensitivity is extremely useful for determining at what point during a magnitude comparison judgment mental magnitudes emerge. In previous research, ERP paradigms have been used to examine the formation of mental magnitudes in response to judgments about symbolic number (Dehaene, 1996), non-symbolic number (Hyde & Spelke, 2011a; Libertus, Woldorff, & Brannon, 2007), individual size (Hagen, Gatherwright, Lopez, &

Polich, 2006; Schwarz & Heinze, 1998), and length of lines (Andreassi & Juszczak, 1984). By using ERPs to examine the processing of cumulative area and non-symbolic number stimuli when presented independently and simultaneously, Study 2 examined whether there is specificity in the underlying neural mechanisms.

In addition to behavioral evidence, the results from neuroimaging research suggest there may be some overlap in the brain regions activated by different mental magnitudes. Initial evidence of overlapping neural regions for mental magnitudes resulted from functional imaging studies that examined whether there are similar mental magnitudes for different forms of numerical information. Similar to behavioral studies, ratio effects, and the closely related distance effect[4], in neuroimaging experiments are characterized as different levels of activation within a brain region. Using functional magnetic resonance imaging (fMRI), numerical ratio effects in response to different symbolic (e.g., numerals, number words) and non-symbolic (e.g., dot arrays) have been compared. The earliest research with numerical ratio effects found that when presented with Arabic numerals during a number comparison task, fMRI activation was modulated by ratio in the intraparietal sulcus [IPS; (Pinel et al., 2001)]. Ratio effects in the IPS have been found using symbolic number words as well (Cantlon, Libertus, et al., 2009; Holloway & Ansari, 2010; Piazza, Pinel, Le Bihan, & Dehaene, 2007). The overlap in the activation of the IPS using different types of symbolic number stimuli has led to the suggestion that a common number representation is used for all numerical formats (Dehaene, Piazza, Pinel, & Cohen, 2003; Nieder & Dehaene, 2009). Furthermore,

[4] The distance effect is closely and functionally related to the ratio effect. The distance effect, which is unique to number, refers to the decline in discrimination performance as the integer distance between two numbers becomes smaller. Thus, the difference rests on the use of integer distance instead of ratio in defining the rate of performance decrease.

computational models of numerical mental magnitudes have provided frameworks for common representation of symbolic and non-symbolic number and the results of simulations using these models closely match observed behavioral results (Dehaene & Changeux, 1993; Verguts & Fias, 2004).

In light of behavioral similarities, neuroimaging research has also provided evidence suggesting overlap in mental magnitudes for different quantities. Based on arguments provided for a common representation of numerical magnitude, neural evidence for overlapping mental magnitudes would be the modulation of fMRI activation in and around the IPS (Walsh, 2003). Multiple fMRI studies have found evidence of the ratio effect modulating activity in the IPS for non-numerical magnitudes such as line length (Jacob & Nieder, 2009), size (Pinel et al., 2004), and area (Castelli et al., 2006). This has been taken as evidence of overlapping mental magnitudes for different quantities (Bueti & Walsh, 2009). Additional evidence for common brain regions underlying magnitude comparison comes from research examining the neural correlates of the congruity effect. Neural activity has been found to be sensitive to the congruity effect (which is reflected by differential fMRI activation for congruent and incongruent trials) in the IPS for symbolic number and size (Ansari, Fugelsang, Dhital, & Venkatraman, 2006; Cohen Kadosh et al., 2007; Kaufmann et al., 2005; Wood, Ischebeck, Koppelstaetter, Gotwald, & Kaufmann, 2009). However, there has also been disagreement about whether this is evidence of overlapping representations, or rather, separate representations that activate a common area (Cohen Kadosh, Lammertyn, et al., 2008; Cohen Kadosh & Walsh, 2009). Specifically, it has been argued that multiple representations could exist within a particular voxel, given that single-cell recording in non-human primates provides evidence that separate neurons within the parietal cortex are sensitive to different magnitudes [e.g., (Tudusciuc & Nieder, 2007)]. In light of limitations of fMRI, corroborating evidence of overlapping mental magnitudes rests on the presence of similar temporal onset in neural processing of different magnitudes.

Across two experiments, in Study 2 I examined the time course of neural activity for ratio effects and congruity effects in response to cumulative area and non-symbolic number judgments. In previous studies, ERP research has focused on the relative emergence of the ratio effects for different magnitudes [e.g., within the number domain; (Dehaene, 1996; Temple & Posner, 1998)] as well as whether congruity effects emerge early or late in processing (Cohen Kadosh et al., 2007; Schwarz & Heinze, 1998). The patterns of neural activity in an ERP paradigm, recorded as changes in the amplitude activity across time, can be characterized by the direction of the change in amplitude (e.g., positive, negative), the time at which the change occurred, and the electrode sites at which the change occurs. Much of the ERP research that has examined the emergence of a ratio effect has focused on symbolic and non-symbolic number.

Studies using ERP paradigms first examined whether there was shared neural processing of different types of symbolic number stimuli. The ratio effect in ERP paradigms is reflected as a difference in either the timing or amplitude of an ERP waveform for smaller versus larger ratios. In a study by Dehaene (1996), when adult participants made comparisons about Arabic numerals and number words, the ratio effect emerged for both types of stimuli in the amplitude of the P200 waveform (positive deflection around 200 ms after stimulus onset). There were differences in earlier components due to notation but, critically, the ratio effect did not interact with notation in the P200, suggesting that numerical mental magnitudes are processed in a similar manner despite notation (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Dehaene, 1996). Further research comparing the emergence of ratio effects with symbolic number (e.g., Arabic numerals) and non-symbolic number (e.g., dot arrays) have found further support that numerical ratio effects emerge in the P200 in a similar manner for symbolic and non-symbolic stimuli (Hyde & Spelke, 2009; Libertus et al., 2007; Temple & Posner, 1998). In combination with results from other research paradigms, such as fMRI research, these studies have been taken as evidence of abstract numerical representations which are created by stripping away non-numerical information, such as size and cumulative area.

The proposal of abstract number representations suggests that the congruity effects observed with Arabic numerals of different sizes are not due to interactions between mental magnitudes. If there are specific mental magnitudes for each quantity, then the congruity effect should emerge late in the decision making process, when a motor response is selected (Schwarz & Heinze, 1998). However, if there are overlapping mental magnitudes, the congruity effect would emerge early in processing when the representations are formed, (Gebuis et al., 2010; Schwarz & Heinze, 1998). It has been proposed that the early view of the congruity effect is inconsistent with the proposal of abstract number representations since it would be evidence of an integrated representation of different magnitudes (Cohen Kadosh et al., 2007; Gebuis et al., 2010; Schwarz & Heinze, 1998). Neuroimaging research that has used ERP paradigms has examined whether the congruity effect emerges early or late in processing. Studies that have used Arabic numerals that vary in physical size have found evidence of early interactions between the magnitudes with a congruity effect emerging in the amplitude and latency of the P300 (positive deflection about 300 ms after stimulus onset; (Gebuis et al., 2010; Schwarz & Heinze, 1998). However, there has also been evidence that under certain conditions the congruity effect occurs late in processing (Cohen Kadosh et al., 2007; Szucs & Soltész, 2007, 2008). It has been argued that under low cognitive load, as defined by an easy versus difficult ratio discrimination, representations do not interact until the motor response is prepared (Cohen Kadosh et al., 2008). An even stronger test of whether congruity effects are the result of overlapping mental magnitudes is whether there are only early effects when magnitudes are presented in a non-symbolic format. The only study that has examined congruity effects with non-symbolic number and physical size (the size of the dots in an array) found evidence supporting an early interaction (Gebuis et al., 2010). However, there has been no examination of the emergence of the congruity effect with cumulative area, which as argued above, is more closely matched to non-symbolic number.

In Study 2, I examined the emergence of ratio and congruity effects of cumulative area and non-symbolic number. In Experiment 1 of this study, I compared the emergence of ratio effects for cumulative area and non-symbolic number when they are presented independently of each other. If there are specific mechanisms for representing different magnitudes, there should be differences in when a ratio effect emerges for each as well as differences in the type of amplitude change (e.g., positive or negative deflection) for each waveform. Both are necessary for evidence of specificity since if there are temporal differences and similar amplitude changes it can be argued that although the same representations are used for different magnitudes, it takes longer for mental magnitudes to be created for some quantities. If there are similar amplitude changes at similar sites for the ratio effect across magnitudes, it would be evidence of overlapping mechanisms. In Experiment 2, I examined whether the congruity effect when cumulative area and non-symbolic number are presented together emerges early or late in processing. If there are specific magnitude representations, there should be no evidence of the congruity effect occurring early in processing. If there are congruity effects early in processing, at the same time as the ratio effect, it would be evidence in favor of the early view of the congruity effect and overlapping representations. The combination of Experiment 1 and Experiment 2 provided a test for determining the level of specificity in mental magnitudes for cumulative area and non-symbolic number.

Study 2:

Electrophysiological Comparison of Ratio and Congruity Effects During Cumulative Area and Non-symbolic Number Judgments

Electrophysiological Comparisons of Ratio and Congruity Effects During Cumulative Area and Non-symbolic Number Judgments

Introduction

When making estimates about non-symbolic magnitudes such as number, space, and time we rely on approximate representations of quantity. Mental magnitudes, otherwise known as analog or approximate magnitude representations, are imprecise by nature and can be used to represent any ordinal quantity that can be placed on a more versus less scale (Cantlon et al., 2009; Feigenson, Dehaene, & Spelke, 2004; Gallistel & Gelman, 1992; Walsh, 2003). Mental magnitudes have been found to be used to make rapid judgments (Bueti & Walsh, 2009; Cantlon et al., 2009; Gallistel & Gelman, 2000) and may play an important role in symbolic math operations (Bonny & Lourenco, 2013; Halberda et al., 2008; Libertus et al., 2011; Lourenco et al., 2012). Although the importance of mental magnitudes has been demonstrated in previous research, the nature of these representations remains unclear. Specifically, given similarities observed for different magnitudes, it is unclear whether different types of quantities are mentally represented via shared or distinct mental magnitudes. Previous research has examined the shared nature of mental magnitudes by comparing the behavioral and neural characteristics of different magnitude domains (Lourenco et al., 2012; Meck & Church, 1983; Odic et al., 2012; Pinel et al., 2004). Much of the research has used non-symbolic number as the standard when comparing the characteristics of other visual magnitudes, such as spatial extent (e.g., area). In the present study, we compared the electrophysiological response to a type of spatial extent that has yet to be compared using this neuroimaging techniques (cumulative area) to non-symbolic number when presented independently (Experiment 1) or simultaneously (Experiment 2) with other magnitudes. We examined the temporal onset as well as pattern of neural responses during magnitude judgment tasks to determine the level of specificity in cumulative area and non-symbolic number representations.

Mental Magnitudes: The Ratio Effect

Research examining the use of mental magnitudes in judgment tasks has focused on the approximate nature of the representations. Magnitudes have been proposed to be mentally represented as Gaussian distributions placed upon a continuum (Cordes, Gelman, Gallistel, & Whalen, 2001; Piazza et al., 2004). The representational overlap between two magnitude representations, determined by the amount of variance within each mental magnitude, leads to a characteristic ratio effect as a result of Weber's law. The ratio effect, similar to the distance effect, is observed when magnitudes are compared, and is reflected as higher difficulty discriminating between the magnitudes the smaller the difference [e.g., 12 vs. 6 objects is easier to discriminate than 12 vs. 10 objects; (Cordes et al., 2001; Dehaene, 1992; Piazza et al., 2004)]. Across multiple paradigms and quantities, ratio effects have been used as a marker for the involvement of mental magnitudes. Behaviorally, ratio effects are instantiated as either a decrease in accuracy or an increase in reaction time the smaller the ratio between quantities [e.g., (Moyer & Landauer, 1967)]. Ratio effects have been found with a variety of non-symbolic quantities, ranging from number to time [see (Cantlon et al., 2009) for a review] as well as with symbolic stimuli [e.g., (Buckley & Gillman, 1974)].

Models of Magnitude Processing: Extent of Representational Overlap

Given that ratio effects have been observed for a variety of quantities, it has been debated whether magnitude representations underlying this effect are shared or distinct for different quantities. Shared magnitude models propose that the processing mechanisms and the resulting representations from different quantities overlap (Bueti & Walsh, 2009; Dakin et al., 2011; Walsh, 2003). Specific magnitude models propose that separate mechanisms process different quantities leading to independent magnitude representations (Butterworth, 2010; Dehaene, 2011). The discussion between these views has primarily focused on whether magnitude representations that underlie number are exclusively numerical. Across most cultures, number is unique from other magnitude domains in that it has multiple dedicated symbolic formats (e.g., number words, digits, etc.) in addition to the non-symbolic form. Although there is debate as to whether there are format-dependent representations even within the domain of number (Cohen Kadosh & Walsh, 2009), a large amount of theoretical and empirical support has provided evidence that there is at least a strong link between numerical representations (Butterworth, 2010; Nieder & Dehaene, 2009). The presence of these links between representations of symbolic and non-symbolic number has led to the suggestion that numerical representations are special and distinct from other types of magnitude representations (Butterworth, 2010; Dehaene, 2011; Odic et al., 2012). Research that has focused on whether there are shared or specific analog representations for number and other magnitudes has approached this question using two kinds of paradigms. One is to examine whether the behavioral and neural ratio effects for different magnitudes are similar in strength when presented independently. The second focuses on whether the simultaneous presence of multiple magnitudes influences behavioral and neural performance of one another.

In addition to behavioral studies, the ratio effect in neuroimaging research has been used to examine the specificity of mental magnitudes. Studies using functional magnetic resonance imaging (fMRI) have examined whether ratio effects generated during magnitude judgments modulate neural activity in similar brain regions. Multiple studies have found that the ratio effect, indicated by differential activity for small versus large differences in stimulus magnitude, modulates neural activity in the intraparietal sulcus (IPS) for a variety of magnitudes such as symbolic numerals (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel & Dehaene, 2010), non-symbolic number (Cantlon, Brannon, Carter, & Pelphrey, 2006; Piazza et al., 2004), line length (Jacob & Nieder, 2009), size (Pinel et al., 2004), and area (Castelli et al., 2006). The presence of ratio effects in the neural activation of the IPS, in addition to behavioral ratio effects, has been taken as support for the shared magnitude view (Bueti & Walsh, 2009; Walsh, 2003). However, it has been argued that ratio effect similarities across magnitudes in fMRI and behavioral research could still be due to specific representations that operate in a similar brain region, and can be distinguished by different temporal onsets, something these research techniques are not sensitive to (Cohen Kadosh & Walsh, 2009; Cohen Kadosh et al., 2011; Cohen Kadosh, Lammertyn, et al., 2008)

The Congruity Effect: Evidence of Magnitude Representation Interaction

Research has used the interaction of different magnitudes when presented simultaneously as an additional way to examine representational overlap. When magnitudes are presented simultaneously during a judgment, the influence they have on each other is referred to as the congruity effect. The congruity effect is generated during Stroop-like tasks where participants are asked to make a more versus less judgment about a target magnitude between a pair of stimuli when a secondary magnitude is pitted against it (Henik & Tzelgov, 1982). On some of the trials, the magnitudes are congruent; that is, they are both in the same direction (e.g., the stimulus that is larger in number is also larger in cumulative area), which can lead to a facilitation effect (e.g., higher accuracy than when secondary magnitude is equated). On other trials, the magnitudes are incongruent or in different directions (e.g., the stimulus that is larger in number is less in cumulative area), leading to an interference effect (e.g., lower accuracy than when secondary magnitude is equated). The presence of either is evidence of a congruity effect indicating mental magnitudes are interacting during the judgment task (Cohen Kadosh et al., 2008; Henik & Tzelgov, 1982; Schwarz & Heinze, 1998). Whereas ratio effects are good at examining mental magnitudes when formed in isolation from other magnitudes, congruity effects go beyond showing when magnitude representations are formed by detecting when mental magnitudes actually interact.

Behaviorally, congruity effects have been observed across multiple studies. Most of previous research has examined the congruity effect by manipulating the numerical value and physical size of a pair Arabic numerals. Typically, participants are presented with two Arabic numerals and are asked to either judge which numeral is larger in numerical value or size when the magnitude information is either congruent (e.g., 2 8) or incongruent (e.g., 2 8). Congruity effects have been found both when participants make a numerical judgment (value of Arabic numeral) as well as when they make a size judgment (size of Arabic numerals) across multiple studies (Cohen Kadosh, Cohen Kadosh, Henik, & Linden, 2008; Duncan & McFarland, 1980; Girelli, Lucangeli, & Butterworth, 2000). Although less research has examined congruity effects with non-symbolic stimuli, such effects have been found when having participants judge non-symbolic number arrays based on the numerical value (number of dots) or size (the size of the individual dots; (Gebuis, Herfs, Kenemans, De Haan, & Van der Smagt, 2009; Gebuis et al., 2010; Gebuis & Reynvoet, 2012)). Additionally, congruity effects have also been observed in using neuroimaging paradigms. Neural activity, as measured by fMRI, in the IPS, as well as other regions, has been found to be modulated by the congruity effect for symbolic number and size (Ansari et al., 2006; Cohen Kadosh et al., 2007; Kaufmann et al., 2005). The combination of behavioral as well as neural congruity effects suggests that mental magnitudes interact during judgment tasks.

Although the presence of behavioral and neural congruity effects suggests mental magnitudes interact during processing, it is unclear at what point the representations interact. The congruity effect could be due to the interaction of magnitudes when mental representations are created (early account) or after representations are formed and a motor response is prepared [late account; (Schwarz & Heine, 1998; Gebuis et al., 2011; Cohen Kadosh et al., 2007; Santens & Verguts, 2011)]. The presence of a congruity effect early in processing would suggest that a shared magnitude representation is used for each magnitude whereas a congruity effect late in processing would suggest that separate representations are created for each magnitude and only interact when executing a motor response. To tease apart these accounts, previous research has used electrophysiological paradigms to examine when congruity effects occur during processing.

Electrophysiological Comparisons of Mental Magnitudes

Despite evidence suggesting the presence of similar ratio effects as well as congruity effects across magnitudes, it has been argued that limitations in behavior and fMRI data do not allow for the conclusion that there are shared representations. As mentioned previously, it has been argued that despite common neural activity in the IPS, there may still be distinct magnitude processes that happen to spatially converge in the region (Cohen Kadosh & Walsh, 2009; Cohen Kadosh et al., 2007, 2008, 2011). The argument rests on, among other things, the limited temporal resolution of fMRI data. It is possible that different magnitude representations are processed by specific mechanisms that operate on different time scales, but in similar brain regions (Cohen Kadosh & Walsh, 2009; Cohen Kadosh et al., 2007) If so, the common activation in the IPS would be due to the co-occurrence of specific processes in a similar spatial area rather than shared representations. To compliment fMRI and behavioral research as well as to distinguish between shared and specific magnitude accounts, electrophysiological paradigms have been used. These paradigms, such as event-related potentials (ERPs), offer excellent temporal resolution of neural processing (Woodman, 2010). In an ERP paradigm, the neural response to a presented stimulus is recorded during an epoch multiple times during an experiment and then averaged together to create an ERP waveform (Woodman, 2010). At each time sample in the ERP waveform, the amplitude of the electrical deflection from baseline is recorded and the change in amplitude over time is used to define waveform components. In the present study, an ERP component refers to a window of time during which a waveform has a peaked deflection. Using ERP paradigms, the temporal processing of different magnitudes during a judgment task has been used by previous research to examine the onset of ratio and congruity effects.

Research that has used ERP paradigms to examine how analog magnitude processing occurs has primarily focused on number. Studies using symbolic number stimuli (Arabic numerals or number words) have found that in the early emerging P200 component (a positive deflection in the ERP waveform from around 150 to 300 ms after stimulus onset) the amplitude of the waveform differed for small versus large ratios (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998; Turconi, Jemel, Rossion, & Seron, 2004) and the amount of time it takes, or latency, for the waveform to reach peak amplitude is longer for the smaller ratio (Dehaene, 1996). Ratio effects have also been observed in a later emerging P400 component (a positive deflection in the amplitude of the waveform around 350 to 600 ms after stimulus onset) in the same direction as the P200 ratio effect (Turconi et al., 2004). Studies using non-symbolic number stimuli have found a similar pattern of ratio effects in the P200 (Hyde & Spelke, 2009; Temple & Posner, 1998) as well as the P400 (Heine, Tamm, Wissmann, & Jacobs, 2011; Libertus et al., 2007; Paulsen & Neville, 2008; Paulsen, Woldorff, & Brannon, 2010). There has been some indication of hemispheric differences in the ERP ratio effect, though they have not been consistently observed across studies (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998). Overall, research examining the neural processing of numerical magnitudes has found evidence of ratio effects emerging in temporally early component (P200) and that it is a sustained effect as it has been observed in temporally later components as well (P400).

In contrast to number, few studies have directly tested for ERP ratio effects using spatial information that is presented independently of other magnitudes. The few studies that have examined the neural processing of spatial information using ERP have found some similarities in the ratio effect. Posterior ratio effects have been found in the amplitude and latency of a slightly later P300 component (positive deflection in the amplitude of the waveform around 275 to 400 ms) when participants had to judge circle sizes (Hagen et al., 2006), grating orientation (Proverbio, Esposito, & Zani, 2002) as well as line lengths (Andreassi & Juszczak, 1984). Similar to numerical ratio effects, there has been some evidence of hemisphere differences in the ERP waveforms, but not all studies have examined laterality effects (Andreassi & Juszczak, 1984; Hagen et al., 2006; Proverbio et al., 2002). Although the types of spatial information tested in these studies varied widely, the similar pattern of results suggests that the ratio effects emerge over similar electrode sites as numerical information, but may be slightly slower to develop (P300 versus P200). However, it remains to be seen whether, when directly compared within a study, differences remain when number and spatial information are presented separately, independent of the other.

Studies that have examined the emergence of the congruity effect using ERP paradigms have focused primarily on symbolic number and physical size. Studies examining at which waveform component a congruity effect emerges have focused on the earlier emerging P300 (a positive deflection in amplitude around 300 to 450 ms after stimulus onset) at posterior electrode sites. Across studies, the congruity effect has been found to affect the amplitude and latency of the P300 component (Schwarz & Heinze, 1998; Szucs & Soltész, 2007, 2008), suggesting that analog magnitudes interact early in processing. However, under certain conditions there have also been congruity effects later than the P300, suggesting that there analog magnitudes may remain independent until a motor response is prepared (Cohen Kadosh et al., 2007, 2008; Szucs & Soltész, 2007, 2008). Additional, albeit less, research that has examined the congruity effect with non-symbolic number and size has found further evidence of the congruity effect emerging at the P300 (Gebuis et al., 2010). With inconsistent results from different types of stimuli, it remains unclear whether the congruity effect emerges early in processing when non-symbolic stimuli are used.

Use of Cumulative Area and Non-symbolic Number

Much of the research examining the specificity of mental magnitudes has compared representations of spatial extent to number, specifically, physical size and symbolic number. In these tasks, participants typically have to decide which of two Arabic numerals are larger in quantity (size the same) as well as which of two Arabic numerals are larger in size (number the same). However, comparing magnitudes that are presented in different formats (e.g., symbolic vs. non-symbolic) can lead to an inherent bias since some magnitude formats are more specialized than others. In the case of comparing symbolic stimuli, only numerical values can be presented using Arabic numerals. In typical congruity tasks, the presentation of numerical information as Arabic numerals and size information as the physical size those numerals, number is being presented using a specialized format. The disparity in formats is further compounded by the use of numerals for size information since even in the neutral condition, numerical information is still present. Furthermore, number and size represent different kinds of magnitude. Specifically, number represents the quantity of a set of objects whereas size represents the quantity of a single object. A more comparable magnitude comparison is between non-symbolic number and cumulative area. Cumulative area refers to the spatial quantity generated when estimating how much space a set of objects occupies on a two-dimensional plane. Both of these magnitudes are set properties; that is, they represent a quantity of a set and are non-symbolic. Additionally, these magnitudes can be generated from perceptually identical stimuli, making this pairing the fairest test of the shared magnitude view. It has also been argued that these two judgments are tightly linked during magnitude comparison tasks (Barth, 2008; Cordes & Brannon, 2008b; Hurewitz et al., 2006). However, much less research has directly compared cumulative area and non-symbolic number in contrast to symbolic number and size, and to our knowledge, there is no study that has examined both magnitudes in an ERP paradigm. In the present study, we used previous research that has compared magnitude representations of number and size to guide our experiments examining the emergence of ratio and congruity effects with cumulative area and non-symbolic number.

The Present Study

In the present study, we examined whether mental magnitudes are distinct for cumulative area and non-symbolic number using ERP paradigms. Previous research that has examined the processing of mental magnitudes using ERP has compared only number and size information and has yielded mixed results. There is developmental evidence suggesting that there may be differences in how cumulative area and non-symbolic number are processed. When infants are familiarized to a cumulative area or non-symbolic number value and then a novel value is presented, they are able to detect a smaller change in non-symbolic number than cumulative area (Cordes & Brannon, 2008a, 2008b, 2009). From this research, it has been suggested that even though the arrays used to present cumulative area and number are perceptually similar, more variance may be present in representations of cumulative area due to an inherent bias to perceive discrete sets of objects as numerical (Cordes & Brannon, 2008a). However, cumulative area can be presented more independently from number using amorphous stimuli (Castelli et al., 2006) than compared to a set of discrete objects (Barth, 2008; Cordes & Brannon, 2009; Hurewitz et al., 2006). In the present study, if there are differences in the ratio effects for cumulative area and non-symbolic number as well as late congruity effects, then it would indicate that for the even the most similar non-symbolic quantities, there are likely separate processing mechanisms. Across two experiments, we compared the ratio effects of cumulative area and non-symbolic number presented independently (Experiment 1) as well as the emergence of a congruity effect when both magnitudes are presented simultaneously (Experiment 2) using an ERP paradigm.

Experiment 1 – Neural Correlates of Amorphous Cumulative Area and Non-symbolic Number

In Experiment 1, we compared the ratio effects of cumulative area and non-symbolic number using an ERP paradigm when each magnitude was presented independently. Similar to previous research, we asked participants to judge which of two arrays of objects was larger in either cumulative area or number (Lourenco et al., 2012). For cumulative area, we used a set of stimuli that were amorphous. Since it has been suggested that a discrete set of objects could prime a numerical judgment (Cordes & Brannon, 2009), we created amorphous cumulative area stimuli that were similar to those used in a previous study (Castelli et al., 2006). In the previous study, behavioral ratio effects similar to non-symbolic number were found using amorphous spatial stimuli, and furthermore, both types of stimuli were found to activate the IPS (Castelli et al., 2006). We aimed to reduce the salience of numerical information in the cumulative area condition by using an amorphous set of stimuli, making for a more independent measure of cumulative area. For non-symbolic number, we created two sets of objects that differed by a numerical ratio while reducing the use of spatial information. Since non-symbolic arrays of objects contain both spatial and numerical information, we reduced the chance participants could use spatial in place of numerical information by varying spatial information across trials. Similar to previous research (Halberda & Feigenson, 2008; Lourenco et al., 2012) on some of the trials, cumulative area was equated for both arrays, whereas on other trials, the average size of the array objects were equated. By doing so, participants were unable to reliably use cumulative area or element size to make their judgments. For the task, participants were asked to judge whether there was either more blue or green “paint” (cumulative area) or “boxes” (non-symbolic number) while varying ratio (small: 1.25, large: 2.00).

We focused our ERP comparison on the onset as well as patterns of ratio effects. Since previous research with number and spatial information has found ratio effects over posterior electrode sites, we focused on central, parietal, and occipital regions. We included these three regions since previous research examining numerical information has found ratio effects at parietal and occipital sites (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998), whereas research examining differences in spatial quantities has found ratio effects over central sites (Andreassi & Juszczak, 1984; Hagen et al., 2006; Proverbio et al., 2002). Using results from previous research, which found evidence of ratio effects early in processing for number and spatial information, we focused on the P200 (evidence of ratio effect for number) and P300 (evidence of ratio effect for spatial information) components. If separate mental magnitudes are used to represent cumulative area and non-symbolic number, we predicted that ratio effects for each magnitude would occur either in different waveform components, take a different shape (e.g., positive or negative amplitudes), or would occur over different electrode sites.

Method

Participants. Twenty-four undergraduate students (17 females, M_{age} = 19.7 years, *range* = 18.1 to 23.8 years) were included in the final analysis for this experiment. One additional participant was not included in the analysis due to excessively slow responses (mean reaction time for correct trials across task greater than three standard deviations above the population mean). All participants were enrolled in an introductory psychology course and completed the study for course credit.

Apparatus. Participants completed the task using a game controller (Logitech, Inc.) that was presented on a CRT monitor (12.7 cm by 9.5 cm) using eevoke software (Advanced Neuro Technology; ANT). Participants were seated approximately 60 cm from the monitor and fitted with a 32 electrode (Ag/AgCl) ANT WaveGuard EEG cap.

The cap was made of lightweight fabric and the electrodes (positioned in a modified International 10-20 system; Jasper, 1958; see Figure 1) and wires were shielded to reduce contamination of the signal from electrical noise from the environment. The electrophysiological signal was recorded using Advanced Source Analysis (ANT) software running on a desktop computer (Dell, Inc.). The signal was amplified 20,000 times and sampled at a rate of 256 Hz. Prior to the test session, ElectroGel (Electro-Cap International, Inc.) was applied to each electrode used to reduce impedances to around or below 15 kΩ.

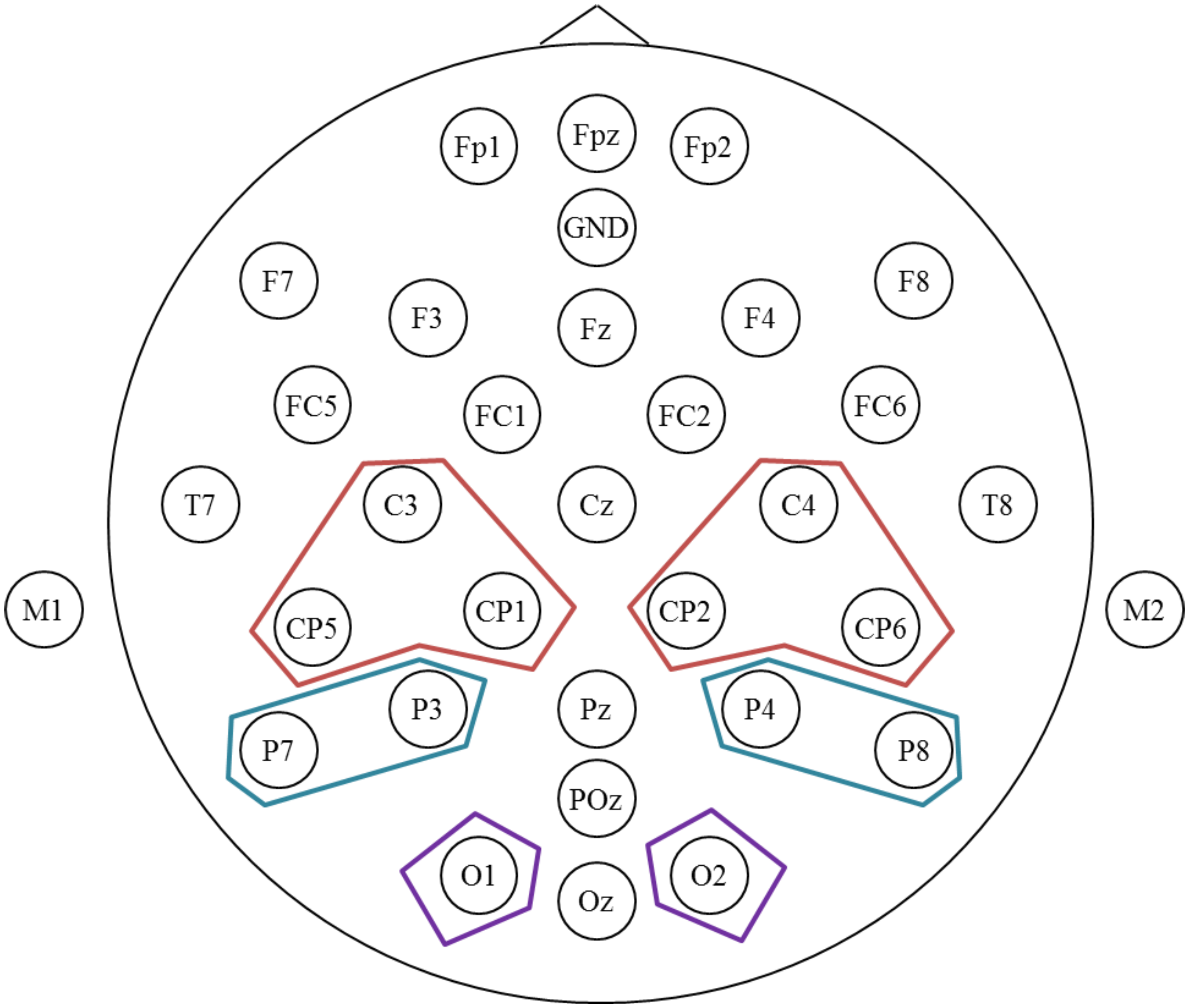


Figure 1. Diagram of electrode placement on ERP cap (including ground) as well as the clusters (red – Central cluster; blue – Parietal cluster; purple – Occipital Cluster).

Stimuli. Images were created to display systematic ratio differences in either non-symbolic number (number of boxes) or cumulative area (amount of color), depending on the magnitude condition. For images that displayed differences in non-symbolic number, two arrays of rectangles, either blue (rgb color code: 0, 187, 255) or green (rgb color code: 0, 217, 87; matched in luminance) were intermixed within an 17.8 by 17.8 cm frame on a gray background (rgb color code: 138, 138, 138; matched in luminance) to create one of two ratios between the two colors (see Figure 2). The spatial position of the rectangles was randomly determined. Similar to previous studies (Halberda et al., 2008; Lourenco et al., 2012), spatial parameters were systematically varied across trials to reduce the influence of non-numerical information during the task. Half of the trials were cumulative area controlled, where the total occupied area of each array was equated (CA = 43.9 cm^2). The other half of trials were controlled for average element size controlled, where the average size of the individual rectangles in each array was equated (M_{Size} = 2.4 cm^2, SD = .5, *range* .8 to 3.7 cm^2). Across all trials, the individual size of the rectangles, as well as the aspect ratio, varied within the parameters of the spatial controls. Furthermore, to reduce the use of individual element size, the size of the largest element was exactly matched in each array.

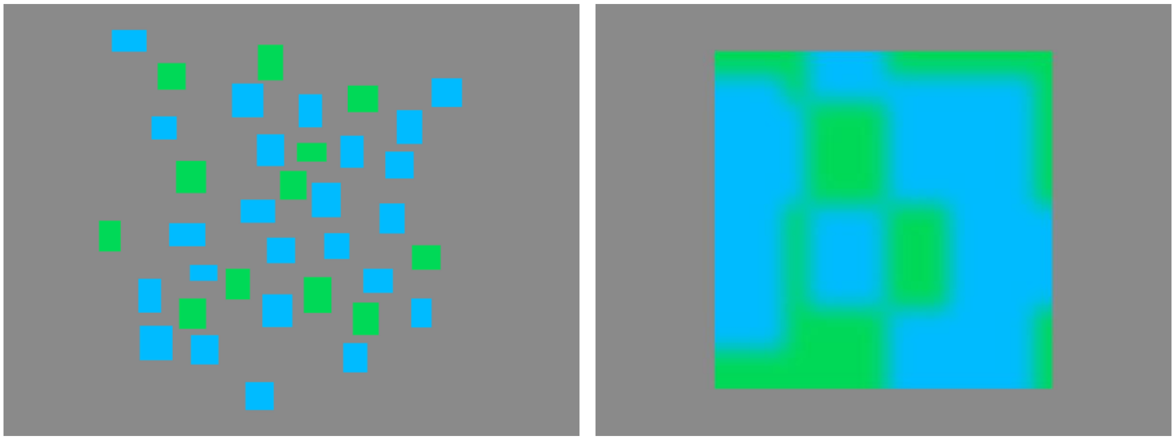


Figure 2. Experiment 1 sample stimuli (2.00 ratio) from non-symbolic number (left) and cumulative area trials (right). Participants were asked to judge whether there was more blue or green boxes (non-symbolic number) or paint (cumulative Area).

For images that displayed differences in cumulative area, the blue and green patches were intermixed within a frame (17.8 by 17.8 cm) to create one of two ratios between blue and green (see Figure 2). To create a more continuous cumulative area stimulus, similar to previous research (Castelli et al., 2006), the two arrays were arranged in a grid (six rectangles in each row and column; 18 total rectangles for each color). The grid lines were adjusted to create the specific difference in cumulative area. The stimuli were then subjected to a Gaussian blur algorithm (25 pixel radius) in image-editing software (Photoshop, Adobe, Inc.) to smooth over the image.

For each magnitude condition, the ratio between the number of rectangles (non-symbolic number) and area (cumulative area) of the blue and green arrays varied. Similar to previous research (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998), the ratio was either large (2.00) or small (1.25) and varied randomly across trials. For non-symbolic number trials, the same total number of rectangles was 36 across both ratios (24 versus 12 for the 2.00 ratio; 20 versus 16 for the 1.25 ratio). Since previous research has found that the ERP waveform is sensitive to changes in total number of objects (Hyde & Spelke, 2011b; Libertus et al., 2007), we avoided this issue by maintaining a constant total number of objects. Although it could be argued that participants could then use the absolute number objects in one array rather than comparing both, we believe this to be unlikely. First, this would require participants to maintain a representation of a set of objects across trials, which would be cognitively demanding and inefficient. Second, since the numerical ratio difference between the larger and smaller arrays is small (either 1.20 or 1.33), it would be much more difficult to discriminate based on these differences, especially when a larger ratio is present for the

2.00 ratio trials. For cumulative area trials, the total area across both arrays remained the same (316.8 cm^2) for both ratios (211.2 vs. 105.6 cm^2 for the 2.00 ratio; 176.0 cm^2 versus 140.8 cm^2 for the 1.25 ratio).

Procedure. After being fitted with the EEG cap, participants were instructed on how to complete the task. They were told that a series of images would be presented onscreen and that they would have to judge whether there was more blue or green “paint” (cumulative area) or more blue or green boxes (non-symbolic number). To make a response, they pressed either the left or right button on the game controller, which corresponded to each of the colors (each marked with a sticker of the target color; counterbalanced across participants). Participants were told they would be presented with blocks of trials that alternated between making judgments about paint or boxes (counterbalanced order). At the beginning of each block, they were presented with a word prompt that indicated which instruction they needed to follow (‘PAINT’ for Cumulative Area; ‘BOXES’ for Number). All prompts were presented in white Arial font (1.5 cm height) on a gray background. For each trial, similar to previous research (Libertus et al., 2007), a fixation point (‘o’ character, Arial font) was presented for a variable amount of time (500 to 1000 ms) after which the stimulus was presented and remained onscreen until the participant made a response. Participants were first presented with four practice trials for each magnitude condition with a highly discriminable ratio (3.00; no feedback was given). Afterwards, participants were presented with eight blocks of test trials. Unbeknownst to the participant, an additional practice trial was presented at the beginning of each block to ensure that changing the instructions did not significantly influence performance on the test trials. Each block contained 20 test trials, for a total of 160 trials.

Behavioral Data Reduction. Performance on test trials was measured by participants' accuracy and mean reaction time. For each magnitude by ratio cell, the proportion of correct responses was calculated. For correct trials for each magnitude by ratio cell, the mean reaction time was calculated.

ERP Data Reduction. For each test trial, the ERP signal was sampled from 100 ms prior to the stimulus presentation until 800 ms after stimulus presentation (231 samples at 256 Hz rate). Using ASA software (ANT), an offline bandpass filter (frequencies less than 0.1 Hz and above 30 Hz, 24 dB/octave gain) was applied to reduce environmental artifacts. Further data reduction was completed using the EEGLAB 10.2.2.4b (Delorme & Makeig, 2004) and ERPLAB 2.0.0.2 (www.erplab.org) toolboxes running in MATLAB R2011b (MathWorks, Natick, MA, USA). Independent component analysis (fastICA algorithm), as well as visual inspection of the components, was used to identify and remove eye blink components for participants (eye blink component was not removed for one participant since algorithm could not reliable identify component). Afterwards, trials that contained amplitudes above or below 100 μV were removed to eliminate remaining artifacts. All remaining test trials where participants responded correctly were used in statistical analyses (all participants contributed at least 10 epochs for each condition). For each of the remaining 24 participants, waveforms were averaged for each magnitude by ratio cell (average of 32.5 trials per cell) using a 100 ms baseline (100 ms prior to the stimulus onset).

Electrode clusters and the time-windows for components were based on previous research and visual inspection of the waveform (see Figure 1). In previous studies, left and right clusters have been created for parieto-occipital and central sites (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998). Combined with visual inspection, which was done to determine the start and end of waveform components as well as similarity across sites, for each hemisphere clusters were created for central (left: C3, CP1, CP5; right: C4, CP2, CP6), parietal (left: P3, P7; right: P4, P8), and occipital (left: O1; right: O2) electrodes (see Figure 1 for electrode positions). In previous research, differences due to magnitude format (e.g., digits vs. dot arrays) have been reported in early emerging waveforms (100-200 ms) and differences due to ratio have been observed in subsequent waveforms [200 – 500 ms; (Dehaene, 1996; Heine et al., 2011; Libertus et al., 2007; Temple & Posner, 1998)]. In combination with visual inspection examining the onset and offset of waves, the following waveforms were identified (labeled by amplitude direction and approximate onset after stimulus presentation): P100 (50 – 150 ms), P200 (151 – 300 ms), P300 (301 – 400), P400 (401 – 600 ms). For each cluster and waveform, the mean amplitude and latency to peak positive amplitude was calculated and used in subsequent analyses.

Results

Behavioral. A repeated-measures analysis of variance (ANOVA) with magnitude (cumulative area, non-symbolic number) and ratio (2.00, 1.25) as factors and accuracy as the dependent variable revealed a main effect of ratio, $F(1, 23) = 151.038$, $p < .001$, $\eta_p^2 = .868$ and a significant interaction between magnitude and ratio, $F(1, 23) = 8.375$, $p = .008$, $\eta_p^2 = .267$. There was no main effect of magnitude ($p > .2$; see Figure 3).

Post hoc analyses indicated that the two-way interaction was driven by significantly higher accuracy for cumulative area than non-symbolic number on the 2.00 ratio, $t(23) = 3.613$, $p = .001$ [no difference on the 1.25 ratio, $t(23) = -.509$, $p = .616$; see Table 1]. Overall accuracy was above chance for both conditions (ps < .001), did not differ between tasks, $t(23) = 1.097$, $p = .284$, and was not significantly correlated, $r(22) = .333$, $p = .112$.

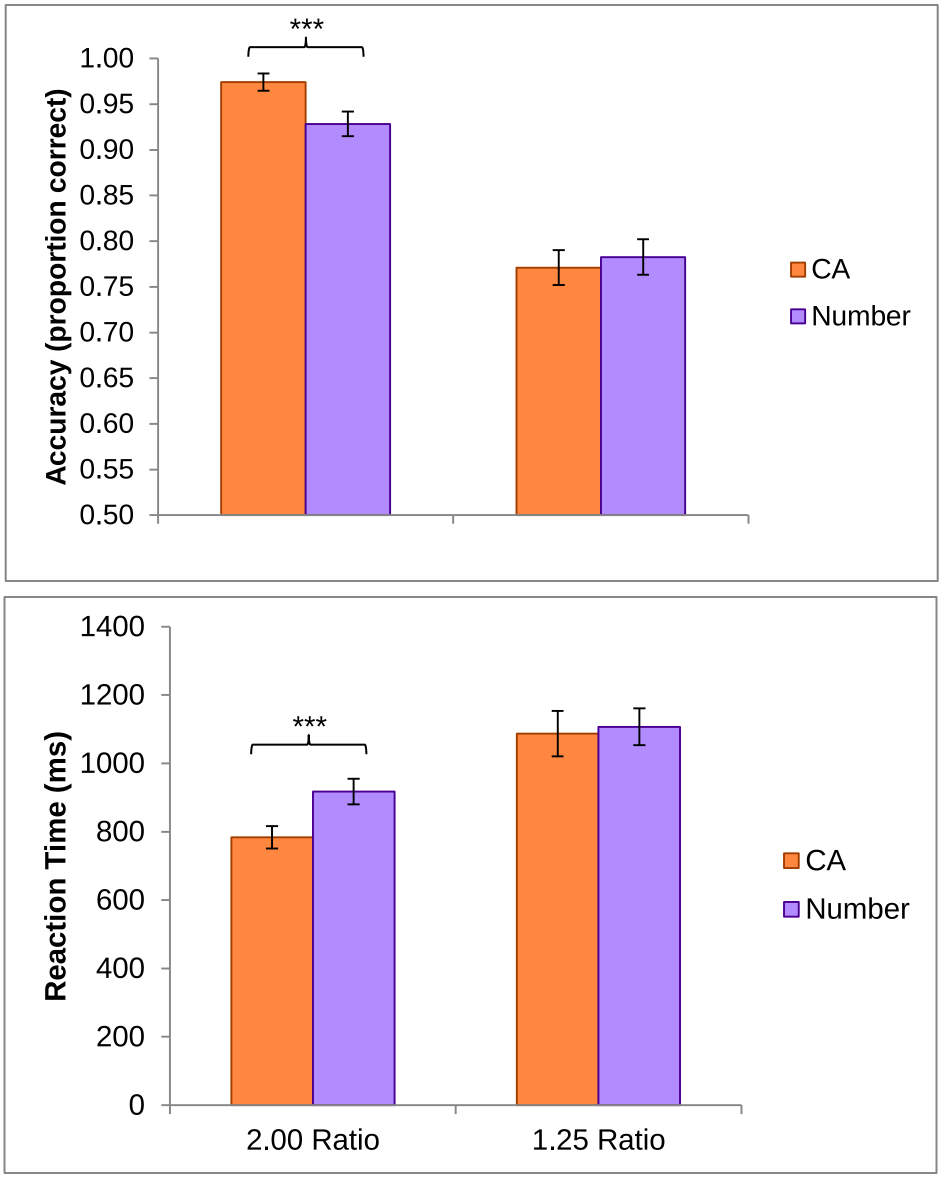


Figure 3. Accuracy and average reaction time on cumulative area (CA) and non-symbolic number (Number) conditions by ratio on comparison task. Accuracy was significantly above chance for all conditions (ps < .001). Performance was significantly different between CA and Number conditions on the 2.00 ratio for both dependent variables (p = .001). Error bars reflect +/- 1 SEM.

Table 1

Descriptive statistics of performance on the non-symbolic number and cumulative area conditions in Experiment 1

		Cumulative Area		Non-symbolic Number	
		2.00 Ratio	1.25 Ratio	2.00 Ratio	1.25 Ratio
Accuracy	*M*	0.974	0.771	0.928	0.783
	SD	0.047	0.047	0.066	0.096
Reaction Time	*M*	783.61	1087.35	917.50	1107.26
	SD	160.83	325.80	182.31	264.66

An ANOVA for reaction times revealed similar effects. There was a main effect of magnitude, $F(1, 23) = 22.615$, $p < .001$, $\eta_p^2 = .496$, and ratio, $F(1, 23) = 49.323$, $p < .001$, $\eta_p^2 = .682$, as well as a significant interaction between magnitude and ratio, $F(1, 23) = 15.766$, $p = .001$, $\eta_p^2 = .407$ (see Figure 3). Post hoc analyses indicated that, similar to what was observed with accuracy, the interaction was driven by significantly faster reaction times for cumulative area than non-symbolic number on the 2.00 ratio, $t(23) = -7.048$, $p < .001$ (no difference on 1.25 ratio, $t(23) = -.831$, $p = .415$; see Table 1). Overall reaction times were significantly faster for cumulative area than number, $t(23) = -4.755$, $p < .001$, and reaction times for cumulative area and number were significantly positively correlated, $r(22) = .941$, $p < .001$.

ERP. Analyses are arranged in progression of waveforms closest to the onset of the stimulus to the end of the trial. Results using mean amplitude (MA) as the dependent measure are discussed first, then latency to peak. Any effects that do not include the factors of interest (ratio, magnitude) are not reported. Analyses focused on the pattern of ratio effects for each magnitude at each component. For central cluster analyses, a repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), hemisphere (left, right), and site (C3/C4, CP1/CP2, CP5/CP6) was conducted (see Figure 4). For parietal cluster analyses, a repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), hemisphere (left, right), and site (P3/P4, P7/P8) was conducted (see Figure 5). For occipital cluster analyses, a repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), and hemisphere (left, right), was conducted (see Figure 6). When a violation of sphereicity was observed, a Greenhouse-Geisser correction was applied. We noted when post-hoc comparisons for an interaction revealed no significant effects when the interaction is first reported. Within each waveform component measure, significant effects were listed for each cluster. When no effects were observed for a cluster within a component, it was omitted from the results section. A summary of the observed main effects and interactions with the variable of ratio is given in Table 2.

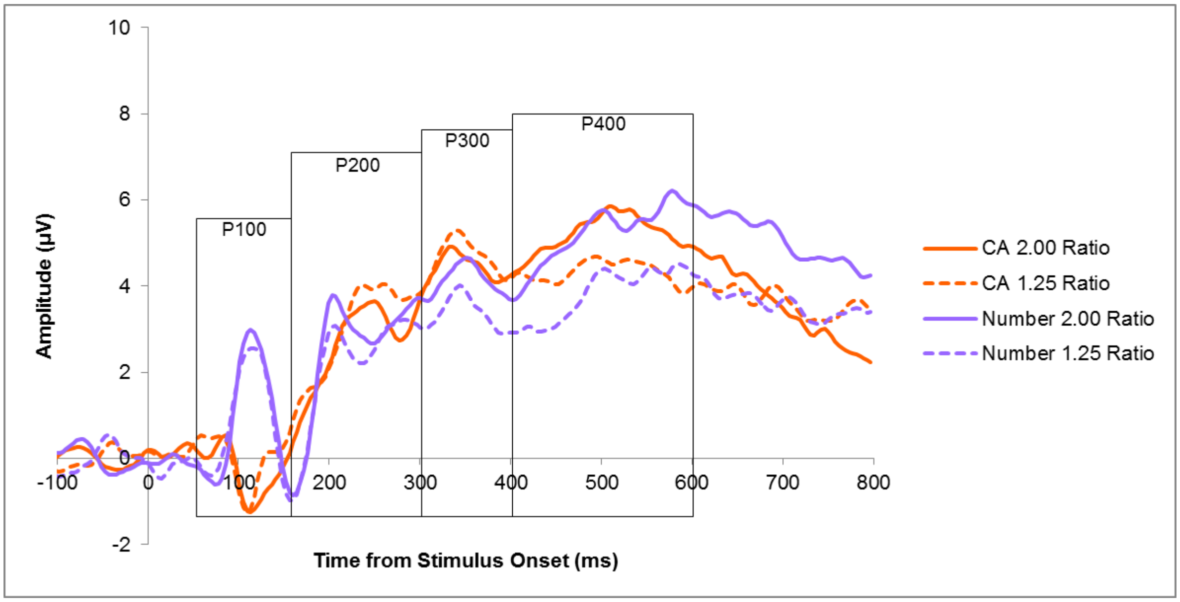


Figure 4. Averaged ERP waveform for each magnitude [cumulative area (CA), non-symbolic number (Number)] by ratio cell from the central cluster. For each window, the mean amplitude and latency to peak was calculated.

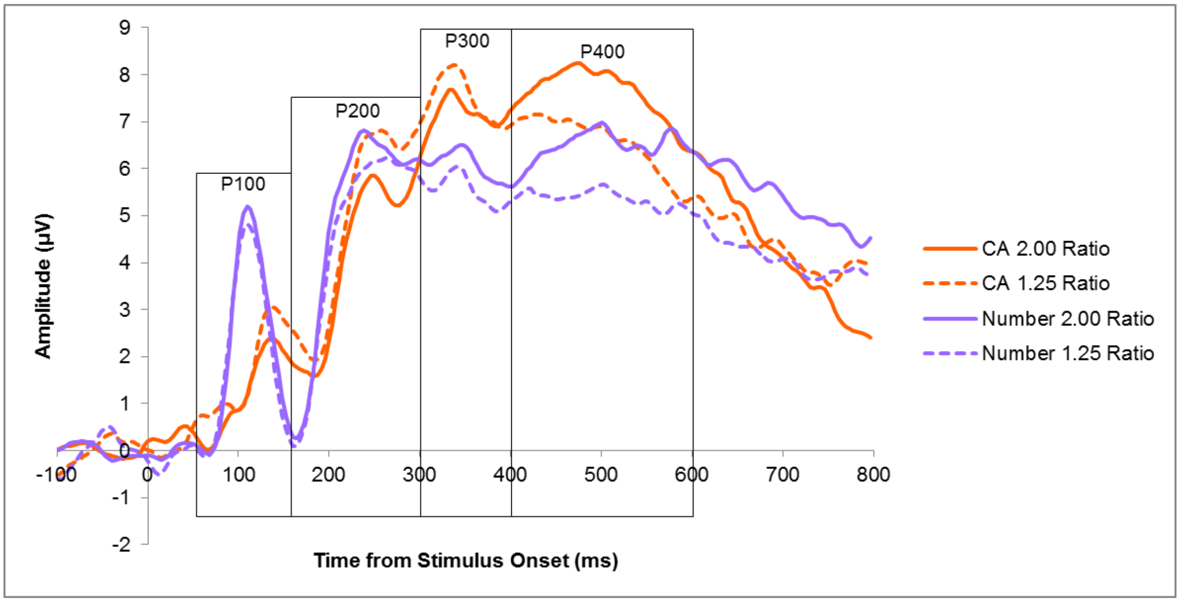


Figure 5. Averaged ERP waveform for each magnitude [cumulative area (CA), non-symbolic number (Number)] by ratio cell from the parietal cluster. For each window, the mean amplitude and latency to peak was calculated.

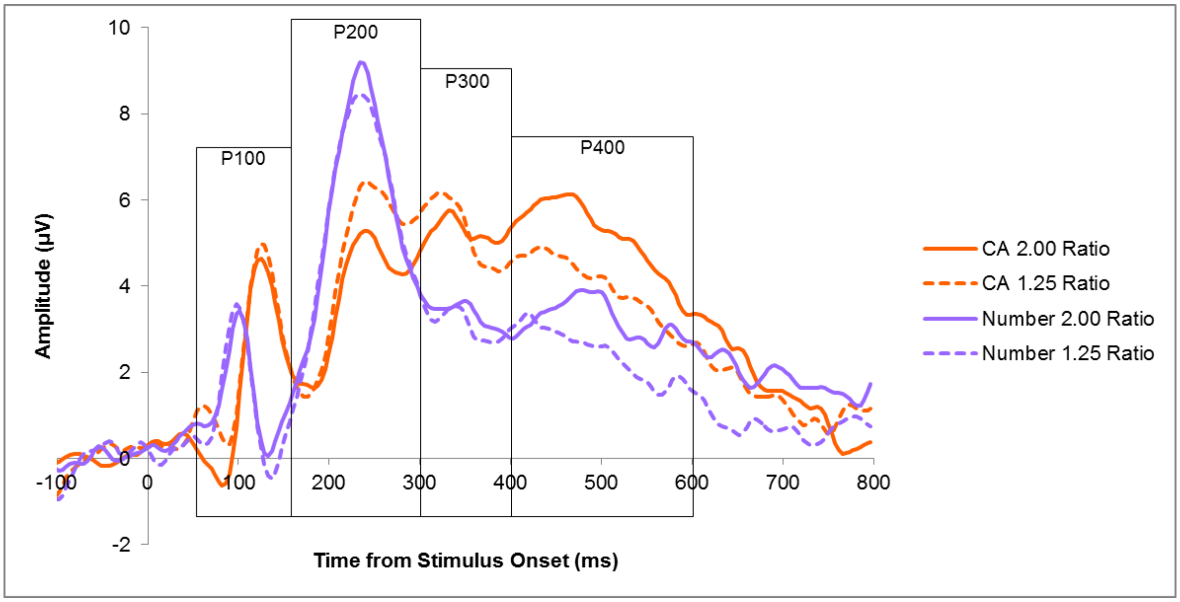


Figure 6. Averaged ERP waveform for each magnitude [cumulative area (CA), non-symbolic number (Number)] by ratio cell from the occipital cluster. For each window, the mean amplitude and latency to peak was calculated.

Table 2

Summary of significant ratio effects in Experiment 1 for cumulative area (CA) and non-symbolic number (Number).

		Mean Amplitude		Latency to Peak	
Window	**Cluster**	**CA**	**Number**	**CA**	**Number**
P100	Central	---	---	---	---
	Parietal	---	---	---	---
	Occipital	---	---	---	---
P200	Central	CP5/CP6: 1.25 ratio > 2.00 ratio, *p* = .047	---	---	---
	Parietal	1.25 ratio > 2.00 ratio, *p* = .01	---	---	---
	Occipital	---	---	---	---
P300	Central	---	---	---	---
	Parietal	---	---	---	---
	Occipital	---	---	---	---
P400	Central	2.00 ratio > 1.25 ratio, *p* = .003	2.00 ratio > 1.25 ratio, *p* = .003	CP5/CP6: 1.25 ratio < 2.00 ratio, *p* = .02	CP5/CP6: 1.25 ratio < 2.00 ratio, *p* = .02
	Parietal	2.00 ratio > 1.25 ratio, *p* < .001	2.00 ratio > 1.25 ratio, *p* < .001	---	---
	Occipital	2.00 ratio > 1.25 ratio, *p* = .002	2.00 ratio > 1.25 ratio, *p* = .002	---	---

P100 Mean Amplitude (MA). At the central cluster, a main effect of magnitude, $F(1, 23) = 10.848$, $p = .003$, $\eta_p^2 = .320$, was observed with significantly higher MA for non-symbolic number ($M = .95$ µV, $SD = 1.73$) versus cumulative area ($M = -.17$ µV, $SD = 1.13$).

At the parietal cluster a main effect of magnitude was also observed, $F(1, 23) = 9.007$, $p = .006$, $\eta_p^2 = .281$, with significantly higher MA for non-symbolic number ($M = 2.23$ µV, $SD = 1.31$) versus cumulative area ($M = 1.31$ µV, $SD = 1.14$).

P100 Latency to Peak. At the central cluster, a main effect of magnitude, $F(1, 23) = 18.044$, $p < .001$, $\eta_p^2 = .440$, as well as significant magnitude by site, $F(1, 26) = 10.551$, $p < .001$, $\eta_p^2 = .314$, and magnitude by ratio by site, $F(1, 46) = 3.318$, $p = .045$, $\eta_p^2 = .126$ (no significant post hoc comparisons were observed, *p*s > .2), interactions were observed. The interaction between magnitude and site was driven by significantly shorter latencies for cumulative area ($M = 86.18$ ms) than non-symbolic number ($M = 105.98$ ms) at the C3/C4 site, $t(23) = -4.561$, $p < .001$, and the CP1/CP2 site $t(23) = -4.282$, $p < .001$ (cumulative area: $M = 86.73$ ms; non-symbolic number: $M = 111.64$ ms), but no difference at the CP5/CP6 site ($p > .1$).

At the occipital cluster, a main effect of magnitude, $F(1, 23) = 21.554$, $p < .001$, $\eta_p^2 = .484$, and a ratio by hemisphere interaction, $F(1, 23) = 5.685$, $p = .026$, $\eta_p^2 = .198$ (no significant post hoc comparisons were observed, *p*s > .1), were observed. The main effect of magnitude was driven by shorter latencies for non-symbolic number ($M = 100.09$ ms, $SD = 18.19$) than cumulative area ($M = 121.16$ ms, $SD = 19.05$).

P100 Summary. Although there were differences in the mean amplitude and latency to peak due to magnitude at some clusters, there were no significant ratio effects.

This suggests that, similar to previous research (Hyde & Spelke, 2009; Libertus et al., 2007), perceptual differences in stimuli influenced the P100 waveforms.

P200 Mean Amplitude. At the central cluster, a significant magnitude by ratio by site interaction was observed, $F(1, 46) = 3.342$, $p = .044$, $\eta_p^2 = .127$. The interaction was driven by a significant ratio effect for cumulative area at the CP5/CP6 site with significantly higher mean amplitude for the 1.25 ratio ($M = 3.04$ μV, $SD = 1.75$) compared to the 2.00 ratio ($M = 2.51$ μV, $SD = 1.60$), $t(23) = 2.097$, $p = .047$ (all other effect *p*s > .1; see Figure 7).

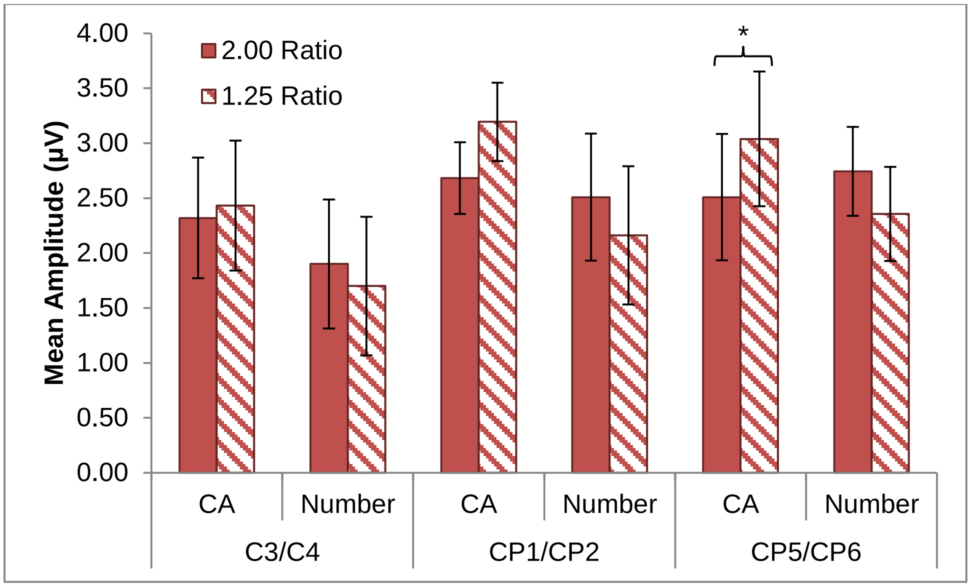


Figure 7. Mean amplitude of P200 waveform for magnitude [cumulative area (CA), non-symbolic number (Number)] and ratio conditions at each central cluster site in Experiment 1. A significant ratio effect ($p < .05$) was observed for cumulative area at the CP5/CP6 site. Error bars reflect +/- 1 SEM. Asterisks indicate p values (*$p < .05$).

At the parietal cluster, significant magnitude by ratio, $F(1, 23) = 7.500$, $p = .012$, $\eta_p^2 = .246$, as well as magnitude by hemisphere by site interactions, $F(1, 23) = 6.662$, $p = .017$, $\eta_p^2 = .225$, were observed. The interaction between magnitude and ratio was driven by a ratio effect for cumulative area such that mean amplitude was significantly higher for the 1.25 ratio (M = 4.78 μV, SD = 1.95) compared to the 2.00 ratio (M = 4.03 μV, SD = 1.78), $t(23) = 2.824$, $p = .010$; there was no such difference for non-symbolic number (p = .261; see Figure 8). The three-way interaction for magnitude, hemisphere, and site was driven by a significantly higher MA at the P8 versus P7 electrode in the cumulative area condition, $t(23) = 2.176$, $p = .040$ (all other ps > . 2).

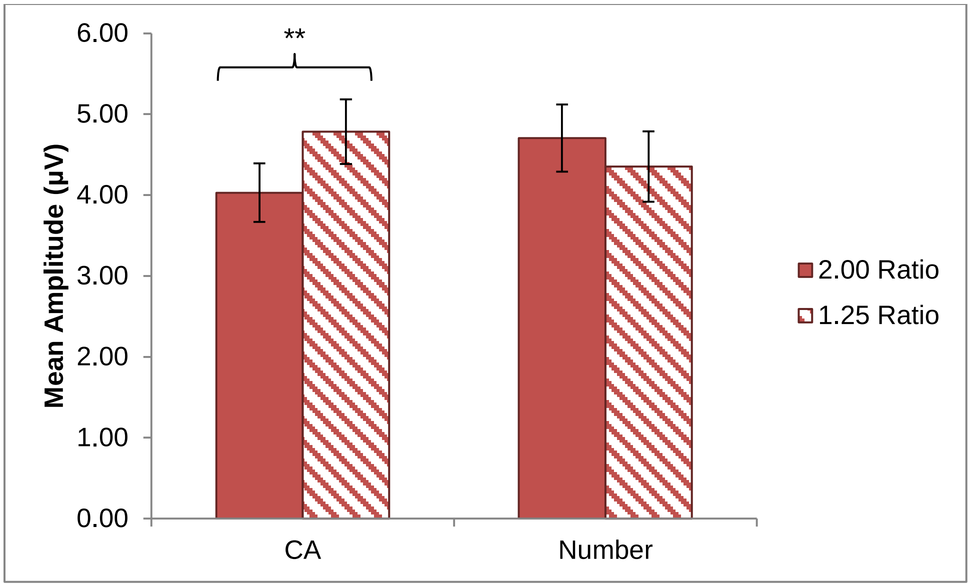


Figure 8. Mean amplitude measurements from the parietal cluster (collapsed across hemisphere and site) in the P200 waveform in Experiment 1. A significant ratio effect was observed for the cumulative area (CA) condition ($p = .010$), but not the non-symbolic number (Number) condition. Error bars reflect +/- 1 SEM. Asterisks indicate *p* values (**$p < .01$).

At the occipital cluster a significant effect of magnitude was observed, $F(1, 23) = 6.955$, $p = .015$, $\eta_p^2 = .232$, with significantly higher MA for non-symbolic number ($M = 5.45$ μV, $SD = 3.78$) than cumulative area ($M = 4.00$ μV, $SD = 3.75$).

P200 Latency to Peak. At the parietal cluster, a significant magnitude by hemisphere by site, $F(1, 23) = 6.324$, $p = .019$, $\eta_p^2 = .216$, interaction was observed. The interaction was driven by significantly shorter latencies at the P4 versus P8 electrode for cumulative area, $t(23) = -3.123$, $p = .005$ (all other *p*s > .1).

P200 Summary. Based on these results, an initial ratio effect for cumulative area was observed in the parietal cluster and a central cluster site with larger mean amplitudes for the 1.25 versus 2.00 ratio. Although the presence of a ratio effect over central sites is similar to previous research with spatial quantities, the effect emerged earlier in the present experiment than what has been observed (Andreassi & Juszczak, 1984; Hagen et al., 2006; Proverbio et al., 2002). The lack of a ratio effect for non-symbolic number in the P200 component differs from what has been observed in previous research (Libertus et al., 2007; Temple & Posner, 1998). Magnitude differences in mean amplitude continued to be observed at all clusters.

P300 Mean Amplitude. At the parietal cluster a significant effect of magnitude was observed, $F(1, 23) = 13.842$, $p = .001$, $\eta_p^2 = .376$, with significantly higher MA for cumulative area ($M = 7.30$ μV, $SD = 2.48$) than non-symbolic number ($M = 5.83$ μV, $SD = 2.58$).

At the occipital cluster, a significant effect of magnitude was observed, $F(1, 23) = 17.184$, $p < .001$, $\eta_p^2 = .428$, with significantly higher MA for cumulative area ($M = 5.26$ μV, $SD = 3.52$) than non-symbolic number ($M = 3.23$ μV, $SD = 4.11$).

P300 Latency to Peak. At the central cluster, a significant interaction between magnitude and site was observed, $F(2, 46) = 4.607$, $p = .015$, $\eta_p^2 = .167$. A post hoc ANOVA revealed that the interaction was driven by non-symbolic number with significantly shorter latencies at the CP5/CP6 site than both the C3/C4 pair and CP1/CP2 pair (ps < .02; Bonferroni corrected).

At the occipital cluster, a significant effect of ratio was observed, $F(1, 23) = 6.112$, $p = .021$, $\eta_p^2 = .210$, with significantly shorter latencies for the 1.25 ratio (M = 342.02 ms, SD = 21.05) than 2.00 ratio (M = 350.64 ms, SD = 25.02).

P300 Summary. There continued to be differences due to magnitude at the parietal and occipital clusters and latency to peak of the waveform for the central clusters. Although there had been significant ratio effects in the mean amplitude of the P200 waveform for only cumulative area, a ratio effect in the latency of the occipital cluster was observed for both magnitudes. The presence of a ratio effect in the latency of the P300 replicates previous research with spatial information (Andreassi & Juszczak, 1984; Hagen et al., 2006).

P400 Mean Amplitude. At the central cluster, a main effect of ratio, $F(1, 23) = 10.948$, $p = .003$, $\eta_p^2 = .322$, as well as magnitude by hemisphere, $F(1, 23) = 9.477$, $p = .005$, $\eta_p^2 = .292$, and magnitude by site, $F(1.232, 28.326) = 10.784$, $p = .002$, $\eta_p^2 = .319$, interactions were observed. The main effect of ratio was driven by significantly higher MA for the 2.00 ratio (M = 5.21 μV, SD = 2.93) than the 1.25 ratio, with no difference between magnitudes (M = 4.08 μV, SD = 2.69; see Figure 9). Post hoc analyses on the magnitude by hemisphere interaction revealed no statistically significant effects (ps > .7). Post hoc analyses examining the magnitude by site interaction found that for cumulative area the C3/C4 site pair had a significantly smaller MA than both the CP1/CP2 and CP5/CP6 (*p*s < .001; Bonferroni corrected), but for non-symbolic number only C3/C4 was smaller than the CP1/CP2 site ($p = .002$; Bonferroni corrected).

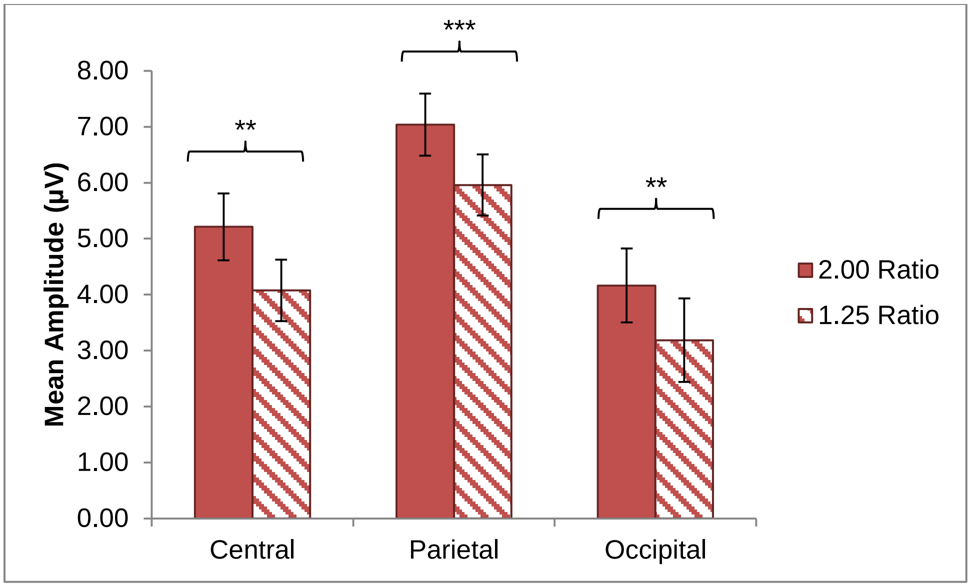


Figure 9. Ratio effects in the mean amplitude measurements in the P400 waveform (collapsed across all other factors) in Experiment 1. A significant ratio effect was observed for all clusters ($p < .01$), and did not differ across magnitude conditions. Error bars reflect +/- 1 SEM. Asterisks indicate *p* values (***$p < .001$, **$p < .01$).

At the parietal cluster, main effects of magnitude, $F(1, 23) = 12.202$, $p = .002$, $\eta_p^2 = .347$, ratio, $F(1, 23) = 19.109$, $p < .001$, $\eta_p^2 = .454$, as well as a ratio by site interaction, $F(1, 23) = 5.354$, $p = .030$, $\eta_p^2 = .189$ (no significant post hoc comparisons were observed, *p*s > .4), were observed. The main effect of magnitude was driven by significantly larger MA for cumulative area (*M* = 7.07 μV, *SD* = 2.72) than non-symbolic number (*M* = 5.93 μV, *SD* = 2.78). The main effect of ratio was driven by significantly larger MA for the 2.00 ratio (*M* = 7.04 μV, *SD* = 2.72) versus the 1.25 ratio (*M* = 5.96 μV, *SD* = 2.68; see Figure 9).

At the occipital cluster, main effects of magnitude, $F(1, 23) = 26.177$, $p < .001$, $\eta_p^2 = .532$, and ratio, $F(1, 23) = 11.750$, $p = .002$, $\eta_p^2 = .338$, were observed. Specifically, MA for cumulative area (*M* = 4.54 μV, *SD* = 3.34) was significantly higher than non-symbolic number (*M* = 2.80 μV, *SD* = 3.62) and was significantly higher for the 2.00 ratio (*M* = 4.16 μV, *SD* = 3.24) than the 1.25 ratio (*M* = 3.18 μV, *SD* = 3.66; see Figure 9).

P400 Latency to Peak. At the central cluster, a main effect of magnitude, $F(1, 23) = 6.739$, $p = .016$, $\eta_p^2 = .227$, and a significant interaction between ratio and site, $F(1.345, 30.933) = 4.292$, $p = .036$, $\eta_p^2 = .157$, were observed. Latencies were significantly shorter for cumulative area (*M* = 504.45 ms, *SD* = 38.49) than non-symbolic number (*M* = 525.74 ms, *SD* = 39.44). Follow-up analyses revealed that the interaction was driven by a ratio effect at the CP5/CP6 site, $t(23) = -2.490$, $p = .020$, with shorter latencies for the 1.25 ratio (*M* = 500.05 ms, *SD* = 42.02) than the 2.00 ratio (*M* = 523.63 ms, *SD* = 33.34).

At the parietal cluster, a significant magnitude by hemisphere by site, $F(1, 23) = 5.460$, $p = .029$, $\eta_p^2 = .192$, interaction was observed. Follow-up analyses revealed that the magnitude by hemisphere by site interaction was driven by significantly shorter latencies for the P3 versus P4 site only for non-symbolic number, $t(23) = -2.771$, $p = .011$ (all other *p*s > .05).

P400 Summary. Similar ratio effects were observed for mean amplitude at all clusters. This was the first significant mean amplitude ratio effect observed for non-symbolic number. However, unlike the ratio effects observed for cumulative area in the P200 waveform, in the P400, it was the 2.00 ratio that had higher mean amplitude than the 1.25 ratio. Although there was no significant difference between ratios for non-symbolic number in the P200 waveform (see Figures 7 and 8), the direction of the ratio effect was similar to that observed in the P400 waveform (see Figure 9). In contrast, the ratio effect for cumulative area reversed direction between the waveforms; that is, instead of having higher mean amplitude for the 1.25 ratio, for the P400 the mean amplitude of the 2.00 ratio was higher. This type of mean amplitude ratio effect has sometimes been observed in previous research in the P400 waveform for non-symbolic number (Paulsen & Neville, 2008; Paulsen et al., 2010; Turconi et al., 2004). It has only been observed in the P300 for spatial information (Hagen et al., 2006).

Discussion

In line with previous research, the present experiment confirms that judgments of non-symbolic number yield a behavioral and electrophysiological ratio effect. Similar to previous ERP research (Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998), the numerical ratio effect was present over parietal sites, but the initial onset was not until the P400 window. Furthermore, we demonstrate, importantly, that the ratio effect for cumulative area can be detected using electrophysiological measures. Similar to previous research examining the discrimination of spatial information (Andreassi & Juszczak, 1984; Hagen et al., 2006; Proverbio et al., 2002), we observed a ratio effect in the mean amplitude and latency of ERP waveforms. However, unlike previous ratio effects with different types of spatial information, the ratio effect here was observed in early (P200) as well as late (P400) windows. Overall, these results suggest that a similar ERP paradigm can be used to measure the ratio effects of cumulative area and non-symbolic number.

The results of Experiment 1 indicate that when presented using more independent types of stimuli there are differences in the way in which cumulative area and non-symbolic number are processed. The first ratio effect of cumulative area was observed in the P200 window at the central and parietal sites with higher mean amplitude for the smaller 1.25 ratio. In contrast to cumulative area as well as previous research (Hyde & Spelke, 2009; Libertus et al., 2007; Temple & Posner, 1998), the first mean amplitude ratio effect for non-symbolic number was observed in the P400 window with higher mean amplitude for the 2.00 ratio and in the latency of the P300 window with slower latencies for the 2.00 ratio. The difference in the onset of the ratio effects for cumulative area and non-symbolic number, as well as the initial direction of the mean amplitude effect, is evidence in favor of specificity in the underlying mental magnitudes. However, the striking overlap across magnitudes in the ratio effects in the P400, despite the early differences in the P200 window, indicates that there is likely overlap in the underlying magnitude representations prior to a motor response.

As expected, there were magnitude differences observed at every time window in line with previous research that has shown that differences in stimulus features lead to differences in the ERP waveform (Cohen Kadosh & Walsh, 2009; Dehaene, 1996). However, the source of the magnitude difference is difficult to determine given the design of the experiment. The use of amorphous stimuli for cumulative area likely reduced any bias of numerical information on performance, as indicated by behavioral results, but was perceptually markedly different than the stimuli used for non-symbolic number. Given these circumstances, it is unclear whether the nature of the stimuli or independent processing mechanisms drove magnitude effects in the P100, P200, and P300 time windows. Furthermore, since the controls used for stimuli in each magnitude were used to reduce the influence of other magnitudes, it is difficult to tell whether there was any early interaction between the underlying representations. Although the difference in onset and direction of the ratio effects for each magnitude indicates there are differences in how each mental magnitude emerges, it is unclear whether there are distinct processes or rather differences in the temporal onset of a shared process that led to these results.

Experiment 2: Emergence of Congruity Effects when Cumulative Area and Non-symbolic Number are Presented Simultaneously

To examine whether there is overlap in the underlying processes used to create mental magnitudes, in Experiment 2 we compared the onset of both the ratio and congruity effect for cumulative area and non-symbolic number using ERP. Unlike the ratio effect, the presence of a congruity effect indicates an interaction between two representations at a particular point in processing. In previous ERP research, the presence of a congruity effect between two magnitudes early in processing has been taken as evidence of overlap in magnitude representations (Gebuis et al., 2010; Santens & Verguts, 2011; Schwarz & Heinze, 1998). However, as highlighted by Santens & Verguts (2011), the criteria used to determine whether a congruity effect occurs early in processing has varied widely, ranging from 300 ms to over 600 ms (Cohen Kadosh et al., 2007; Gebuis et al., 2010; Schwarz & Heinze, 1998; Szucs & Soltész, 2007). To avoid creating a somewhat arbitrary time window and assuming it is early processing, we defined early processing as the earliest time window in which a ratio effect is observed. Since a ratio effect has been argued to be evidence of a magnitude representation (Cantlon et al., 2009; Dehaene, 1996; Gallistel & Gelman, 2000; Walsh, 2003), the occurrence of a congruity effect at the earliest ratio effect would indicate an interaction between representations. Using this definition, we examined whether there is evidence of shared mechanisms between cumulative area and non-symbolic number.

In the present experiment, we further built upon previous research by examining multiple waveforms and electrode sites for the presence of congruity effects. Much of previous research has only focused on one or two central and parietal electrodes and two waveforms when searching for a congruity effect (Cohen Kadosh et al., 2007; Gebuis et al., 2010). We sought to expand the number of electrodes used in our analyses for two reasons. First, evidence from previous research (Dehaene, 1996; Hagen et al., 2006), as well as Experiment 1, indicates that ratio effects for spatial and numerical quantities can emerge in different waveforms as well as electrode locations. Second, we wanted to ensure that if there was a different time course in the congruity effects for cumulative area and non-symbolic number that we were able to determine whether the electrodes where the congruity effects emerged were different for each magnitude. This would indicate whether there was a common process that differed temporally for each magnitude, or rather, if there were temporally and spatially specific processes. For these reasons, we examined a larger number of waveforms and electrodes than what has typically been done in previous research.

The task used in Experiment 2 was largely similar to the previous experiment, with two main exceptions. First, the stimuli used for both magnitudes were composed of discrete arrays of objects. By using perceptually similar stimuli for both cumulative area and non-symbolic number, stimulus-level differences can be eliminated as the source of potential differences due to magnitude. Second, three different types of conditions were used to test for a congruity effect. Previous ERP studies examining the congruity effect have varied as to whether they have included only congruent and incongruent conditions (Gebuis et al., 2010; Schwarz & Heinze, 1998), or an additional neutral condition as well (Cohen Kadosh et al., 2007; Szucs & Soltész, 2007). In Experiment 2, we included congruent, neutral, and incongruent conditions due to the difficulty in making *a priori* predictions about how differences in congruity between magnitudes would be reflected in ERP waveforms. In behavioral studies, performance is highest for the congruent condition, lowest for the incongruent condition, with the neutral condition falling in between (Cohen Kadosh et al., 2005; Henik & Tzelgov, 1982). In previous ERP studies, the congruity effect has been found to vary, ranging from the type of pattern observed in behavioral performance to no difference between congruent and incongruent trials (Cohen Kadosh et al., 2007; Schwarz & Heinze, 1998). The inclusion of a neutral condition aids in interpreting any lack of a difference in congruent and incongruent conditions. If there is truly no congruity effect then there should be no differences among all three conditions. If there is a congruity effect, with the presence of facilitating or interfering information having a similar effect then they both should be different from the neutral condition. We predicted that if there was any overlap in the processes used to form cumulative area and non-symbolic number representations, congruity effects would be present during the initial onset of ratio effects for both magnitudes. Similar to Experiment 1, we focused on the overall patterns of the ratio and congruity effects for each magnitude in our ERP analyses. When comparing the overall patterns of the effects for each magnitude at each component, we predicted that if there were shared mental magnitudes, then we would observe similar patterns for cumulative area and non-symbolic number.

Method

Participants. Twenty-four undergraduate students (19 females, M_{age} = 19.8 years, *range* = 18.1 to 23.5 years) were included in the final analysis for this experiment. An additional seven participants were not included in the analysis due to excessively low accuracy (2), excessive noise in the mastoid electrodes (3), excessively low trial counts after filtering (1) and a software glitch (1). Adult participants were college students and members of a psychology department and received either course credit or gift cards as compensation.

Apparatus. The equipment used was the same as Experiment 1.

Stimuli. In Experiment 2, images were created to display systematic ratio differences in non-symbolic number (number of boxes) and cumulative area (amount of color). The images displayed differences in non-symbolic number and cumulative area with two arrays of rectangles, either blue (rgb color code: 0, 187, 255) or green (rgb color code: 0, 217, 87; matched in luminance) that were intermixed within an 17.8 by 17.8 cm frame on a gray background (rgb color code: 138, 138, 138; matched in luminance). The spatial positions of the rectangles were randomly determined.

To create differences in congruity, the arrays were manipulated to create three conditions which were determined by the relation between the target magnitude and secondary magnitude. For congruent trials, target and secondary magnitudes were in the same direction (e.g., the array that was larger in cumulative area was also larger in number). For neutral trials, the target magnitude was manipulated between arrays while the secondary magnitude was equated across arrays (e.g., the array that was larger in cumulative area had the same number of rectangles as the other array). For incongruent trials, the target magnitude and secondary magnitudes were pitted against each other (e.g., the array that was larger in cumulative area was less in number). For trials that were congruent or incongruent, the secondary magnitude varied by the same amount as the target magnitude (e.g., for a congruent trial, if the target array was larger in cumulative area by a 2:1 ratio, it was also larger in number by a 2:1 ratio).

For each congruity condition, the ratio between the number of rectangles (non-symbolic number) and area (cumulative area) of the blue and green arrays varied. Similar to Experiment 1, the ratio was either large (2.00) or small (1.25) and varied randomly across trials. For non-symbolic number, the number of rectangles in each array was varied (24 versus 12 for the 2.00 ratio; 20 versus 16 for the 1.25 ratio). For cumulative area, the total area of both arrays was constant across trials (30.9 cm^2) but the area of each array varied according to ratio (20.6 cm^2 versus 10.3 cm^2 for the 2.00 ratio; 17.2 cm^2 versus 13.7 cm^2 for the 1.25 ratio). Similar to Experiment 1, the largest rectangle in each array was matched in size to reduce the chance that participants would rely on a single rectangle to make their decision. In combination with the congruity and magnitude conditions, the study was a 2 (magnitude: cumulative area, non-symbolic number) by 2 (ratio: 2.00, 1.25) by 3 (congruity: Congruent, Neutral, Incongruent) design yielding twelve types of trials (see Figure 10).

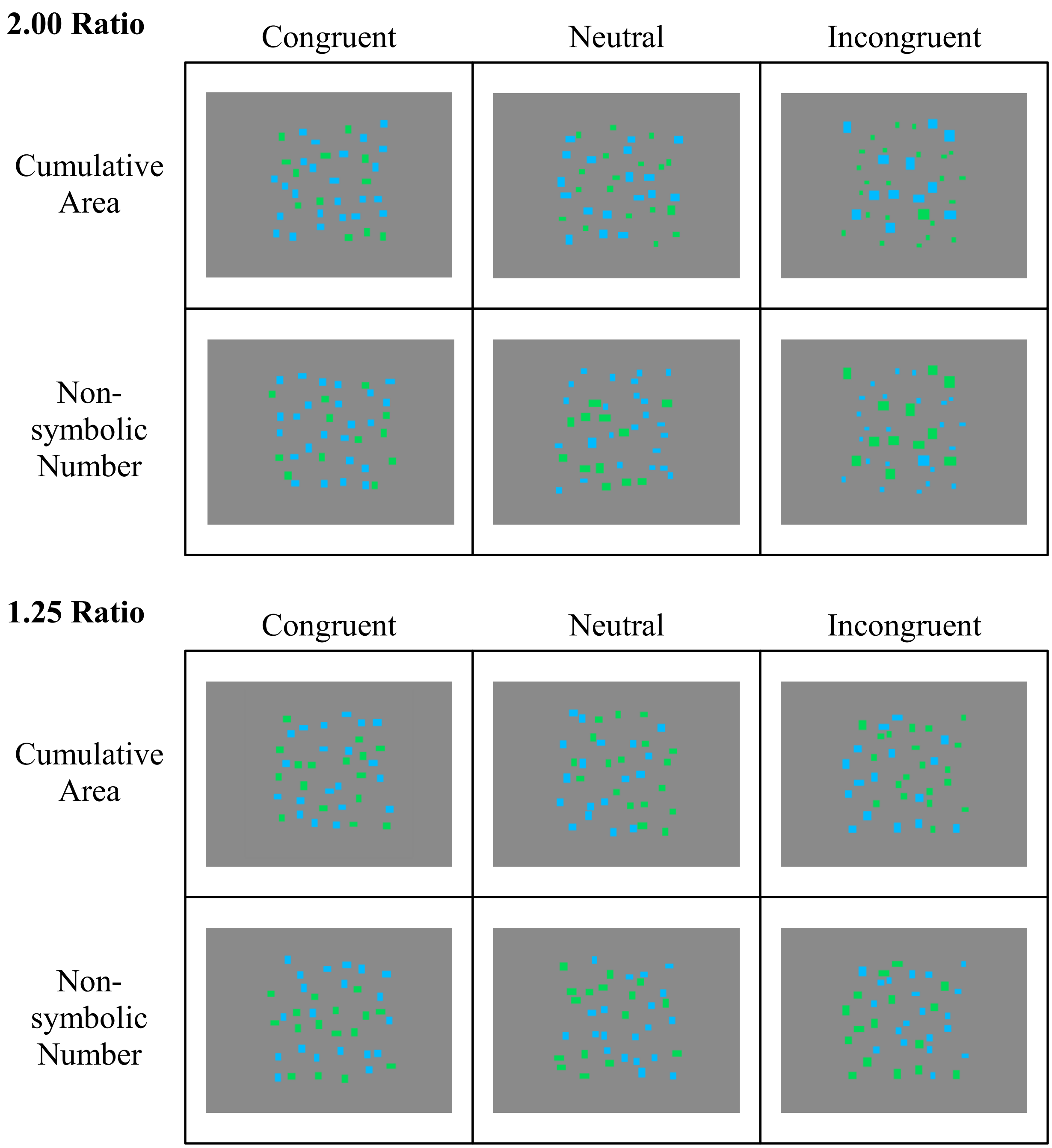


Figure 10. Sample stimuli used for each magnitude by ratio by congruity cell in Experiment 2.

Procedure. The testing procedure was the same as Experiment 1 except for the length of the experiment. There were 24 blocks of test trials, each containing 20 test trials, for a total of 480 test trials.

Data Reduction. Behavioral data reduction was identical to Experiment 1. For ERP data, participants contributed at least 10 trials for each magnitude by ratio by congruity cell (average of 31.2 trials per cell) to the final data sample and the waveforms were averaged using a 100 ms baseline (100 ms prior to the stimulus onset).

Electrode clusters were the same as in Experiment 1. The time windows for the P200 and P300 waveforms differed slightly from Experiment 1. After visual inspection, it was determined that the onset of the P300 window started earlier than in Experiment 1 and the boundary between the two adjacent windows was adjusted accordingly. For Experiment 2, the time window for each component was as follows (time window in parentheses): P100 (50 – 150 ms), P200 (151 – 260 ms), P300 (261 – 400), P400 (401 – 600 ms). For each cluster and waveform, the mean amplitude and latency to peak positive amplitude was calculated and used in subsequent analyses.

Results

Behavioral. A repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), and congruity (congruent, neutral, incongruent) as factors and accuracy as the dependent variable revealed a main effect of magnitude, $F(1, 23) = 22.901$, $p < .001$, $\eta_p^2 = .499$, ratio, $F(1, 23) = 444.700$, $p < .001$, $\eta_p^2 = .951$, congruity, $F(2, 46) = 83.186$, $p < .001$, $\eta_p^2 = .783$, a significant interaction between magnitude and ratio, $F(1, 23) = 12.363$, $p = .002$, $\eta_p^2 = .350$, a significant interaction between magnitude and congruity (Greenhouse-Geisser corrected), $F(1.36, 31.28) =$

7.616, p = .005, η_p^2 = .249, and a significant magnitude by ratio by congruity interaction (Greenhouse-Geisser corrected), $F(1.45, 33.3) = 4.958$, p = .021, η_p^2 = .350 (see Figure 11). Post hoc ANOVAs with magnitude and congruity as factors for each ratio condition indicated the three-way interaction was driven by magnitude differences in the congruity effect for the 1.25 ratio (Greenhouse-Geisser corrected), $F(1.29, 29.66) = 8.155$, p = .005. Specifically, performance on the 1.25 ratio did not differ between cumulative area and non-symbolic number on congruent trials (p = .347), but performance was significantly lower for cumulative area than non-symbolic number on the neutral, $t(23) = 4.813$, $p < .001$, and incongruent trials, $t(23) = 3.996$, p = .001 (see Table 3). In combination with a significant congruity effect for the 2.00 ratio (pairwise comparisons: congruent > neutral > incongruent significant, Bonferroni corrected, ps < .04), these results suggested that the lack of congruent information (neutral trials) and presence of interfering information (incongruent trials) adversely affected cumulative area more than non-symbolic number on the more difficult 1.25 ratio. Overall accuracy was above chance for both magnitude conditions (ps < .001), significantly higher for non-symbolic number than cumulative area, $t(23) = 4.785$, $p < .001$, and performance on both magnitude conditions was significantly correlated, $r(22) = .686$, $p < .001$.

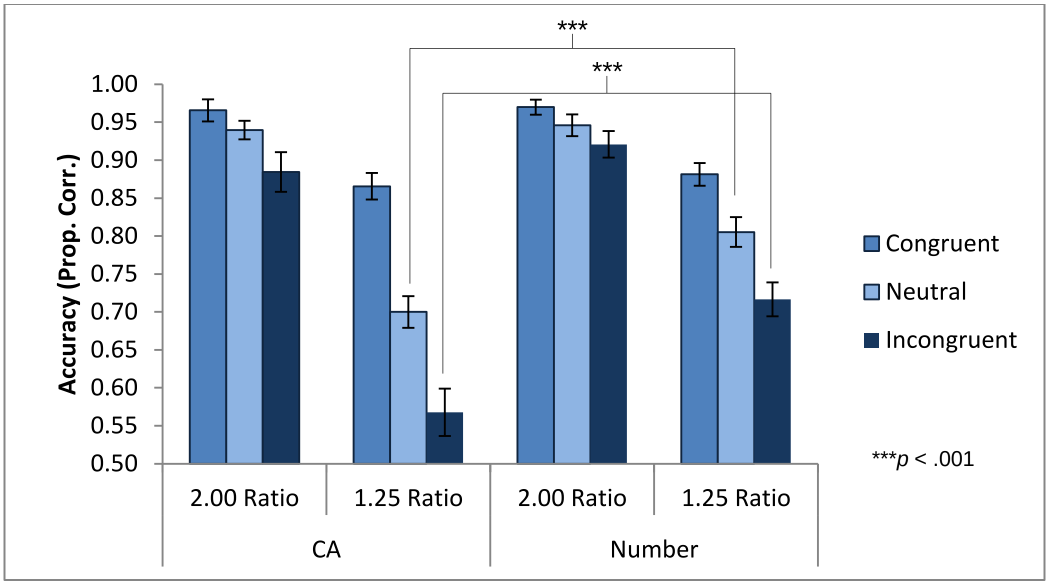


Figure 11. Accuracy on judgment task in Experiment 2 for the cumulative area (CA) and non-symbolic number (Number) conditions. All conditions were significantly above chance (*p*s < .05). Furthermore, congruity effects were observed for each magnitude by ratio cell (*p*s < .01). A full congruity effect was observed for all cells (Congruent > Neutral > Incongruent, p*s* < .05, Bonferroni corrected), besides number at the 2.00 ratio (Congruent > Incongruent, *p* = .004, Bonferroni corrected). Error bars represent +/- 1 SEM.

Table 3. Descriptive statistics of performance [*M* (*SD*)] on the cumulative area and non-symbolic number conditions in Experiment 2.

		Cumulative Area		Non-symbolic Number	
		2.00 Ratio	1.25 Ratio	2.00 Ratio	1.25 Ratio
Accuracy	Congruent	0.966 (0.071)	0.866 (0.085)	0.97 (0.048)	0.881 (0.073)
	Neutral	0.94 (0.059)	0.7 (0.103)	0.946 (0.07)	0.805 (0.096)
	Incongruent	0.884 (0.129)	0.568 (0.153)	0.921 (0.085)	0.717 (0.11)
Average Reaction Time	Congruent	957.54 (174.11)	1377.94 (373.23)	963.88 (235.93)	1362.7 (387.08)
	Neutral	1144.56 (323.26)	1518.96 (506.61)	1054.93 (295.01)	1485.07 (419.87)
	Incongruent	1271.52 (380.99)	1500.68 (503.42)	1170.21 (331.1)	1442.65 (392.78)

An ANOVA with mean reaction time as the dependent variable revealed some similar, as well as some different, effects from those in the accuracy analysis. There was a main effect of ratio, $F(1, 23) = 60.720$, $p < .001$, $\eta_p^2 = .725$, congruity, $F(2, 46) = 27.544$, $p < .001$, $\eta_p^2 = .545$ and a significant interaction between ratio and congruity, $F(2, 46) = 7.417$, $p = .002$, $\eta_p^2 = .244$ (all other *p*s > .4; see Figure 12). Post hoc analyses indicated that the interaction was driven by a full congruity effect for the 2.00 ratio (congruent < neutral < incongruent; Bonferroni corrected, *p*s < .002) whereas for the 1.25 ratio, the congruity effect was driven by faster responses on congruent trials compared to both neutral and incongruent trials (Bonferroni corrected, *p*s < .03; see Table 3). Overall reaction times did not differ between cumulative area and non-symbolic number conditions, $t(23) = 1.212$, $p = .238$, and reaction times on both magnitude conditions were significantly positively correlated, $r(22) = .820$, $p < .001$.

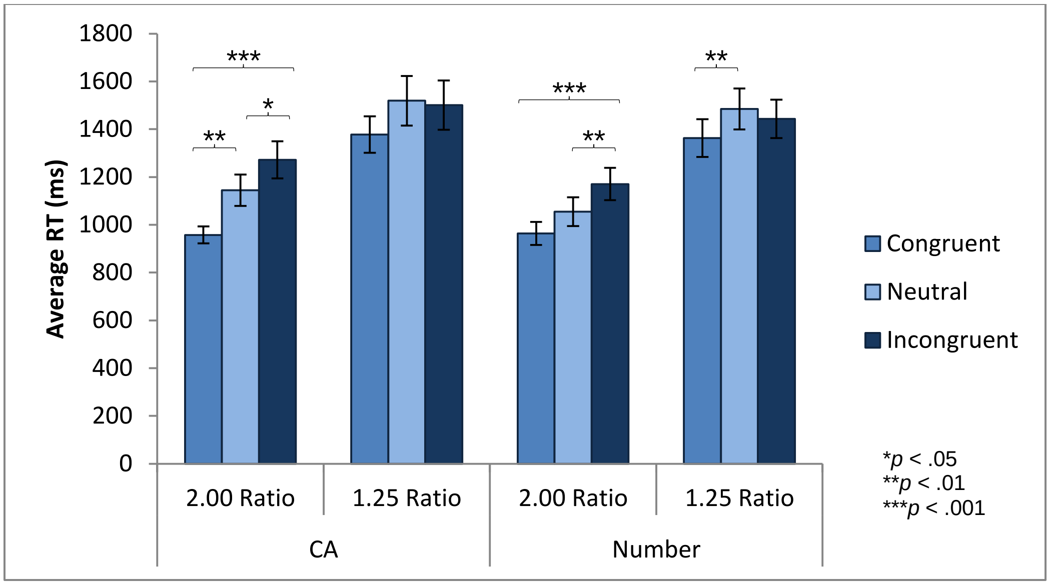


Figure 12. Average reaction times for correct trials in the cumulative area (CA) and non-symbolic number (Number) conditions on the judgment task in Experiment 2. Congruity effects were observed for each magnitude by ratio cell (*p*s < .05), although different patterns were observed for each cell (Bonferroni corrected; pairwise comparisons did not reach significant for cumulative area at 1.25 ratio). Error bars represent +/- 1 SEM.

ERP. Analyses are arranged in progression of waveforms closest to the onset of the stimulus to the end of the trial. Results using mean amplitude as the dependent measure are discussed first, then latency to peak. Any effects that do not include the factors of interest (ratio, magnitude, congruity) are not reported. For central cluster analyses, a repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), congruity (congruent, neutral, incongruent), hemisphere (left, right), and site (C3/C4, CP1/CP2, CP5/CP6) was conducted (see Figure 13). For parietal cluster analyses, a repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), congruity (congruent, neutral, incongruent), hemisphere (left, right), and site (P3/P4, P7/P8) was conducted (see Figure 14). For occipital cluster analyses, a repeated-measures ANOVA with magnitude (cumulative area, non-symbolic number), ratio (2.00, 1.25), congruity (congruent, neutral, incongruent), and hemisphere (left, right), was conducted (see Figure 15). When a violation of sphereicity was observed, a Greenhouse-Geisser correction was applied. A summary of the observed mean amplitude main effects and interactions with the variables of ratio and congruity by magnitude is given in Table 4.

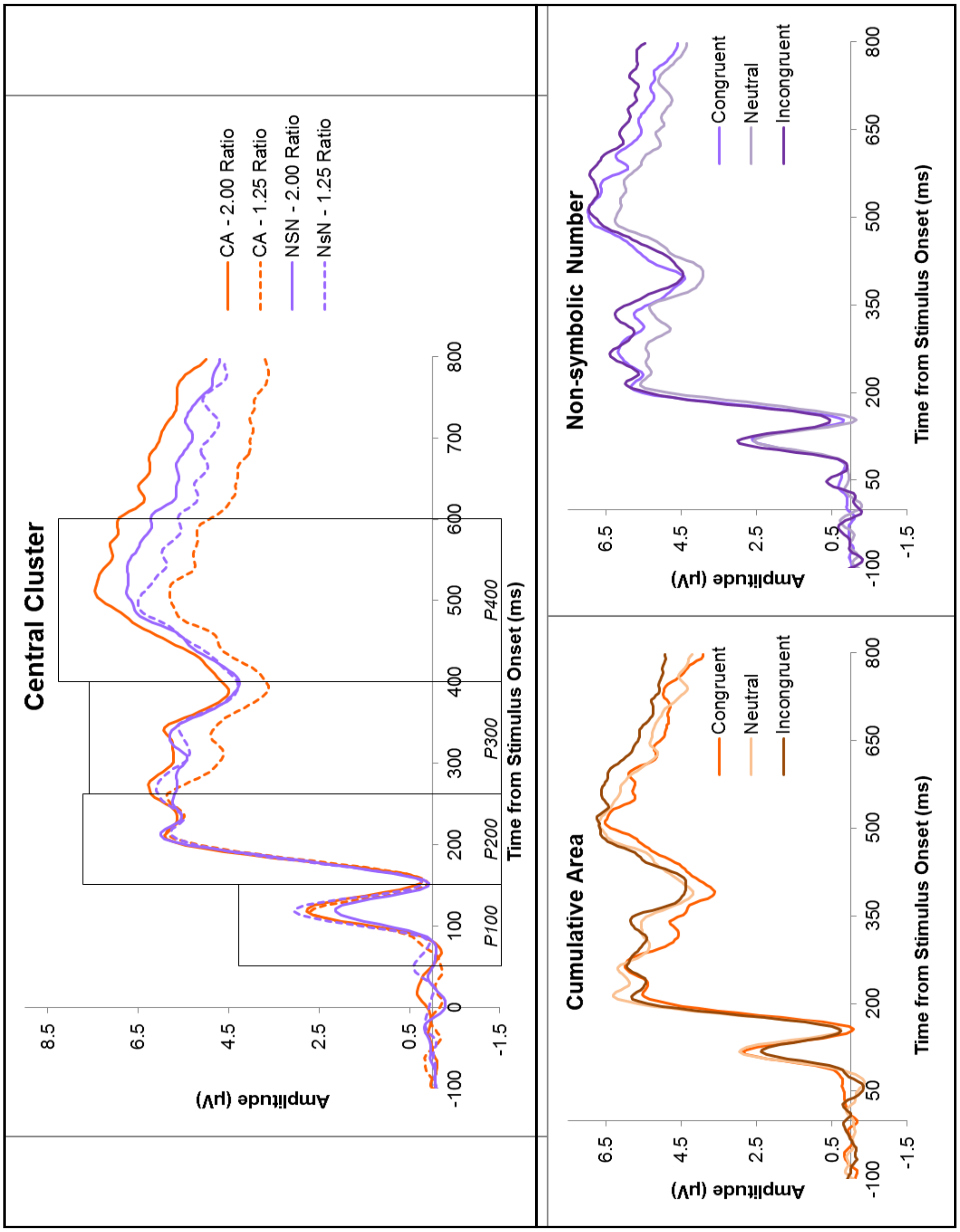


Figure 13. Waveforms for central cluster averaged across hemisphere and site. Top panel indicates the ratio conditions per magnitude and the bottom panels indicate the congruity conditions per magnitude.

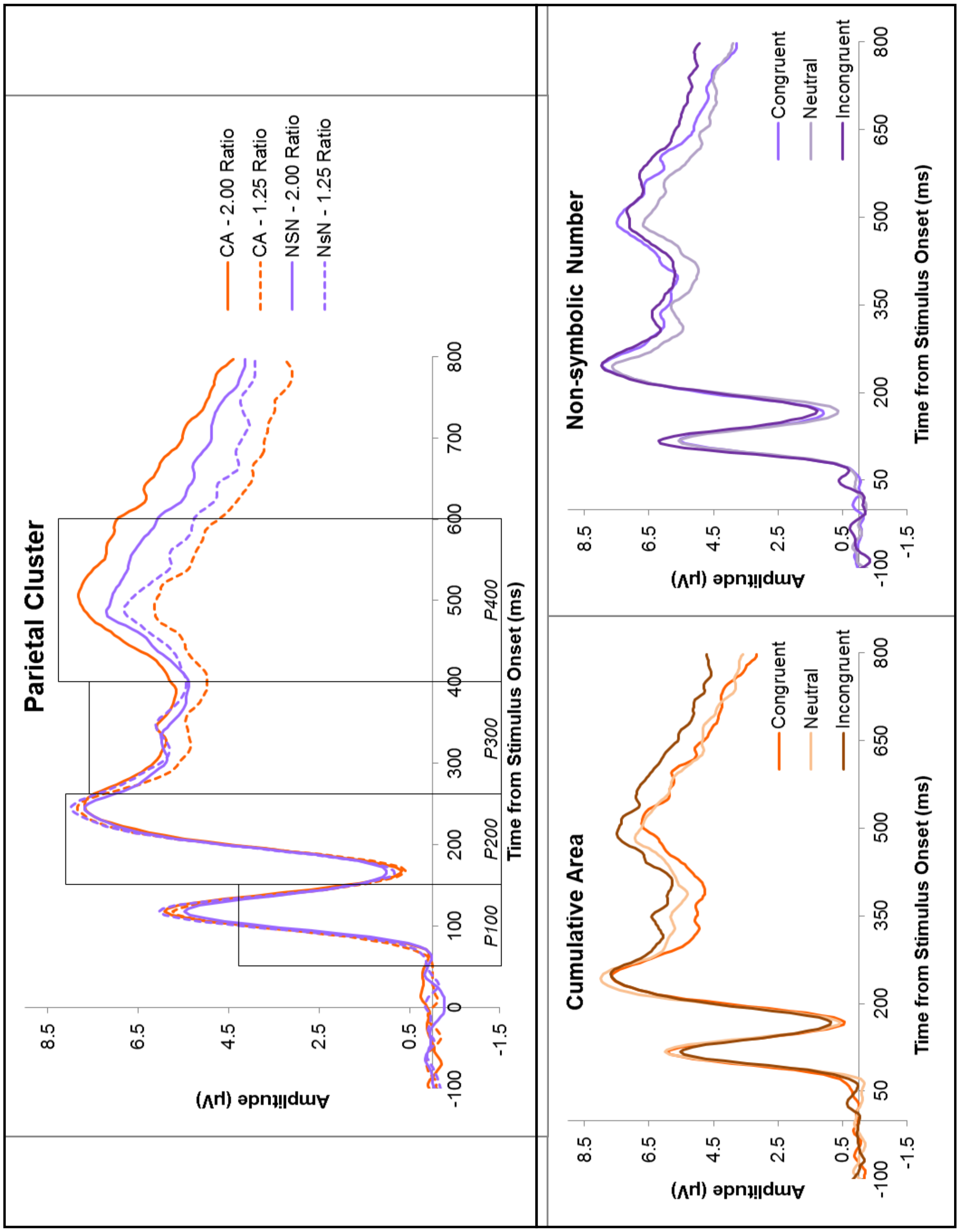


Figure 14. Waveforms for parietal cluster averaged across hemisphere and site. Top panel indicates the ratio conditions per magnitude and the bottom panels indicate the congruity conditions per magnitude.

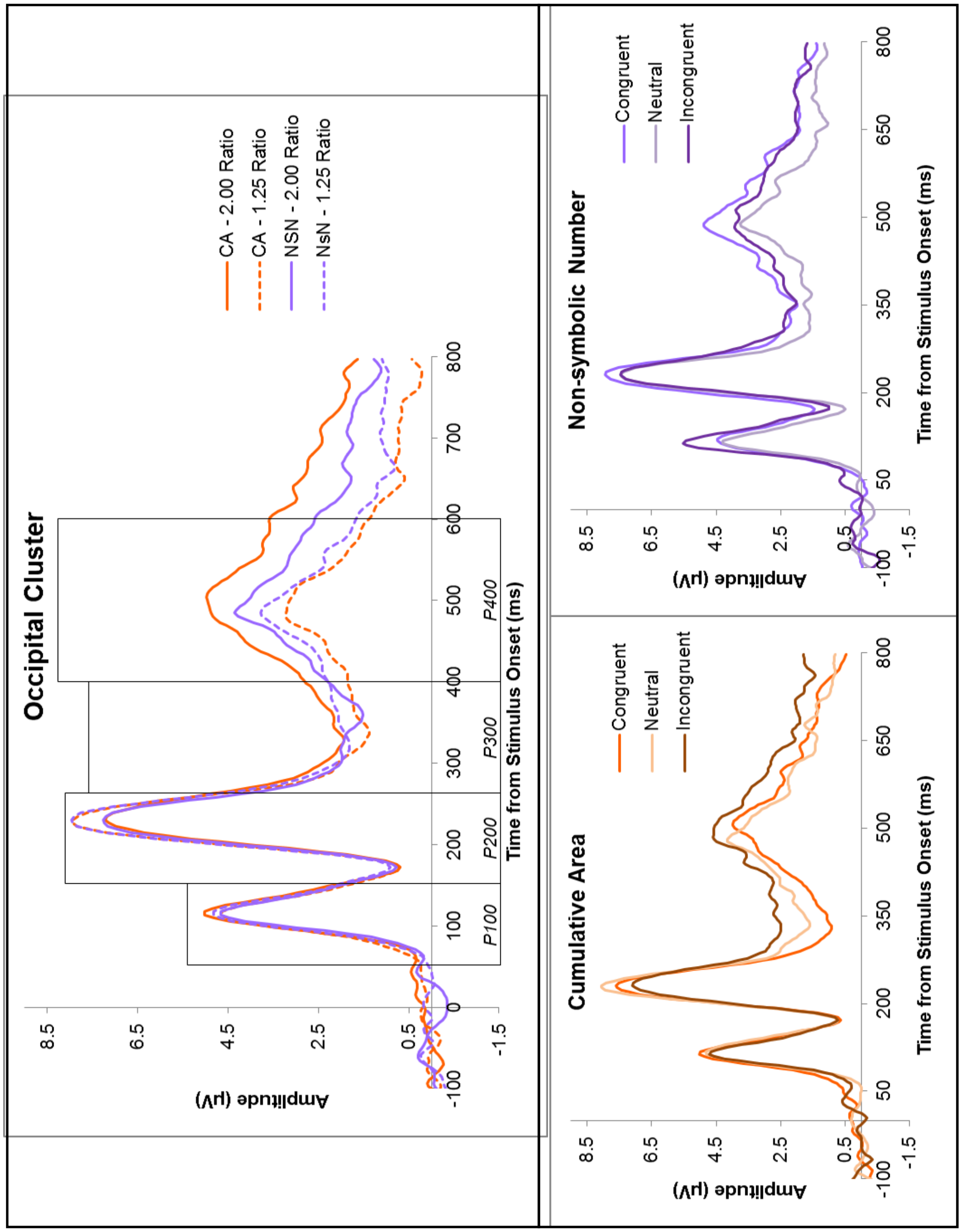


Figure 15. Waveforms for occipital cluster averaged across hemisphere and site. The top panel indicates the ratio conditions per magnitude and the bottom panels indicate the congruity conditions per magnitude.

Table 4

Summary of mean amplitude ratio and congruity F-effects with significant post-hoc comparisons in Experiment 2 for cumulative area (CA) and non-symbolic number (Number).

Window	Cluster	CA	Number
P100	Central	---	---
	Parietal	---	Magnitude x Ratio x Congruity x Site*
	Occipital	---	Magnitude x Congruity*
P200	Central	---	---
	Parietal	---	---
	Occipital	Ratio x Congruity**	Ratio x Congruity**
P300	Central	Magnitude x Ratio** Magnitude x Congruity x Site***	Magnitude x Congruity x Site***
	Parietal	Magnitude x Congruity x Site x Hemisphere*	Magnitude x Congruity x Site x Hemisphere*
	Occipital	Ratio x Congruity* Magnitude x Congruity*	Ratio x Congruity* Magnitude x Congruity*
P400	Central	Ratio*** Congruity*	Ratio*** Congruity*
	Parietal	Magnitude x Ratio x Congruity x Hemisphere x Site*	Magnitude x Ratio x Congruity x Hemisphere x Site*
	Occipital	Ratio** Magnitude x Congruity x Hemisphere**	Ratio** Magnitude x Congruity x Hemisphere**

Significance of F-effects: ***p < .001, **p < .01, *p < .05

P100 Mean Amplitude. At the central cluster, significant interactions for magnitude by ratio by congruity, $F(2, 46) = 4.737$, $p = .013$, $\eta_p^2 = .171$ (no significant post hoc comparisons were observed, *p*s > .05), and congruity by hemisphere by site, $F(4, 92) = 3.359$, $p = .013$, $\eta_p^2 = .127$, were observed. Post hoc analyses examining the congruity by hemisphere by site interaction revealed that there was no effect of congruity (*p*s > .05) and was not examined further.

At the parietal cluster, significant interactions for congruity by hemisphere, $F(2, 46) = 4.918$, $p = .012$, $\eta_p^2 = .176$ (no significant post hoc comparisons were observed, *p*s > .2), magnitude by ratio by congruity, $F(2, 46) = 4.157$, $p = .022$, $\eta_p^2 = .153$, as well as a magnitude by ratio by congruity by site, $F(2, 46) = 3.678$, $p = .033$, $\eta_p^2 = .138$, were observed. Post hoc analyses examining the four-way interaction revealed that the P7/P8 site pair was driving the effect with a magnitude by ratio by congruity interaction, $F(2, 46) = 6.127$, $p = .004$, $\eta_p^2 = .210$ (no other main effects or interactions observed nor at P3/P4 site pair, $p > .05$). Specifically, a ratio effect, $t(23) = 2.703$, $p = .013$, with higher MA for the 1.25 ($M = 3.64$ μV, $SD = 1.44$) than 2.00 ratio ($M = 3.07$ μV, $SD = 1.90$) was observed only for incongruent trials in the non-symbolic number condition (all other *p*s > .08; see Figure 16). Furthermore, a significant congruity effect was observed for non-symbolic number at the P7/P8 site pair with the MA for incongruent trials significantly higher than neutral trials ($p = .041$, Bonferroni corrected) and the MA for congruent trials in the 1.25 ratio for non-symbolic number were significantly higher than cumulative area ($p = .015$).

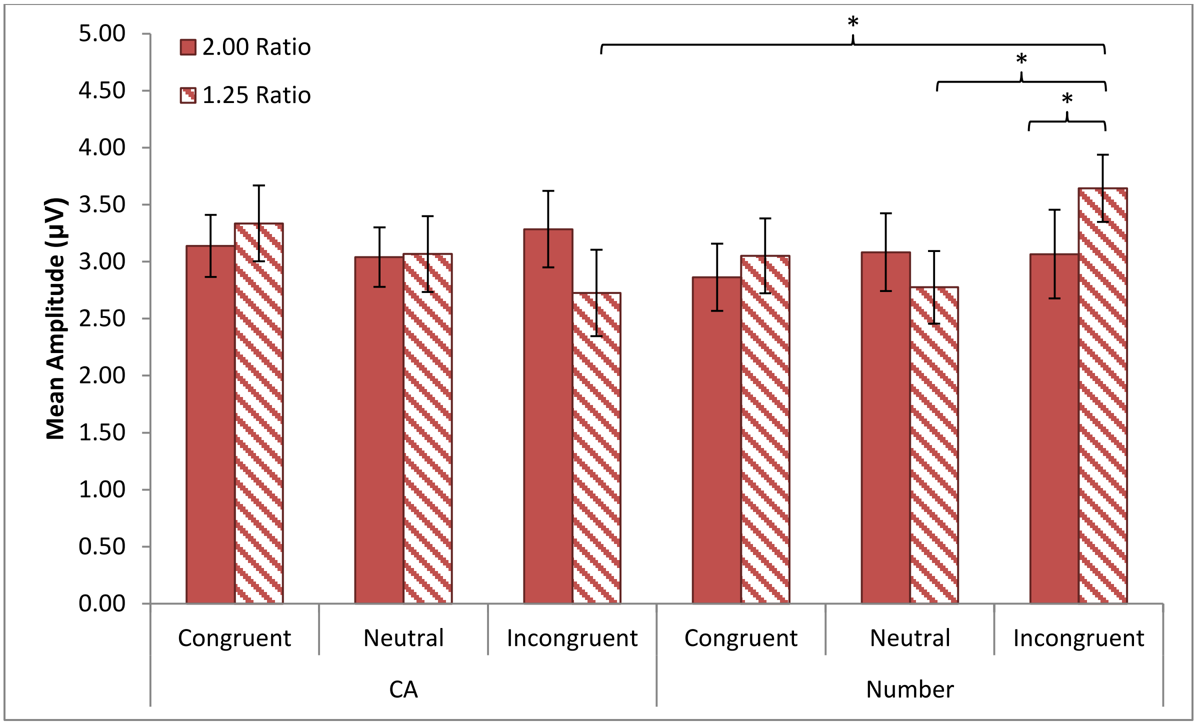


Figure 16. Mean amplitude of the P100 for magnitude (CA: cumulative area; Number: non-symbolic number) by congruity cells at the P7/P8 site pair in Experiment 2. A significant ratio effect was observed for only the incongruent by non-symbolic number condition. Error bars reflect +/- 1 SEM. Asterisks indicate *p* values (**p* < .05).

At the occipital cluster, significant magnitude by congruity, $F(2, 46) = 3.229$, $p = .049$, $\eta_p^2 = .135$, and congruity by hemisphere, $F(2, 46) = 5.229$, $p = .009$, $\eta_p^2 = .185$ (no significant post hoc comparisons were observed, *p*s > .08), interactions were observed. The magnitude by congruity interaction was driven by a significant congruity effect only for non-symbolic number, $F(2, 46) = 3.567$, $p = .036$, with significantly higher MA for the incongruent versus neutral trials ($p = .045$, Bonferroni corrected).

P100 Latency to Peak. At the central cluster, significant ratio by site, $F(1.54, 35.34) = 4.197$, $p = .032$, $\eta_p^2 = .154$, congruity by hemisphere by site, $F(2.17, 50.01) = 4.570$, $p = .013$, $\eta_p^2 = .166$, and ratio by congruity by hemisphere by site, $F(2.92, 67.06) = 4.370$, $p = .008$, $\eta_p^2 = .160$, interactions were observed. Follow up analyses on the four-way interaction revealed that the congruity by hemisphere interaction for the C3 and C4 sites in the 1.25 ratio was driving the effect, $F(2, 46) = 5.449$, $p = .008$. Specifically, latencies were shorter for the C3 site than C4 site only for the congruent condition, $t(23) = -2.105$, $p = .046$ (all other *p*s > .1).

At the parietal cluster, a main effect of magnitude was observed, $F(1, 23) = 6.066$, $p = .022$, $\eta_p^2 = .209$, with shorter latencies for non-symbolic number ($M = 116.35$ ms, $SD = 8.32$) than cumulative area ($M = 117.94$ ms, $SD = 7.46$).

At the occipital cluster, a significant ratio by congruity by hemisphere interaction was observed, $F(1.55, 35.62) = 3.891$, $p = .039$, $\eta_p^2 = .145$. Follow up analyses revealed that the interaction was driven by a ratio by hemisphere effect on the neutral condition, $F(1, 23) = 7.207$, $p = .013$. Specifically, a ratio effect with shorter latencies for the 2.00 ratio ($M = 102.01$ ms, $SD = 27.70$) than the 1.25 ratio ($M = 113.65$ ms, $SD = 20.13$), $t(23)$

= -2.357, p = .027, was observed, but only for the right hemisphere. No significant congruity effects were observed at the occipital cluster (ps > .05).

P100 Summary. The first mean amplitude ratio effect was observed in parietal cluster electrodes, but only for non-symbolic number. Furthermore, the first mean amplitude congruity effect was observed in the parietal and occipital clusters, but only for non-symbolic number. Interestingly, when ratio and congruity effects emerged in mean amplitude, they interacted and were dependent on one other (except for the occipital cluster). The first ratio effect for latency to peak was also observed for both magnitudes in the occipital cluster, but was dependent on congruity. These effects emerged earlier than what has been typically observed in previous research examining numerical ratio effects (Dehaene, 1996; Libertus et al., 2007) and substantially earlier than what has been reported with congruity effects (Cohen Kadosh et al., 2007; Gebuis et al., 2010; Schwarz & Heinze, 1998). Taken together, the mean amplitude and latency to peak results indicate that there may be magnitude differences as to when initial ratio effects emerge, but that information from both magnitudes are interacting when it occurs.

P200 Mean Amplitude. At the central cluster, a significant magnitude by congruity by site interaction was observed, $F(2.93, 67.33) = 5.138$, $p = .003$, $\eta_p^2 = .183$. This three-way interaction was driven by a significant two-way interaction between magnitude and congruity at the CP1/CP2 site pair, $F(2, 46) = 3.631$, $p = .034$. Specifically, the MA for cumulative area was significantly higher (M = 5.20 μV, SD = 2.72) than non-symbolic number (M = 4.38 μV, SD = 2.53), but only for the neutral condition (all other ps > .2).

At the occipital cluster, a significant ratio by congruity interaction was observed, $F(2, 46) = 5.844$, $p = .005$, $\eta_p^2 = .203$. Post hoc analyses revealed a significant congruity effect limited to the 2.00 ratio with lower MA for incongruent versus neutral conditions ($p = .021$, Bonferroni corrected), as well as a significant ratio effect for the incongruent condition with higher MA for the 1.25 ratio ($M = 4.813$ μV, $SD = 4.52$) than 2.00 ratio ($M = 3.82$ μV, $SD = 4.19$), $t(23) = 3.990$, $p = .001$ (see Figure 17).

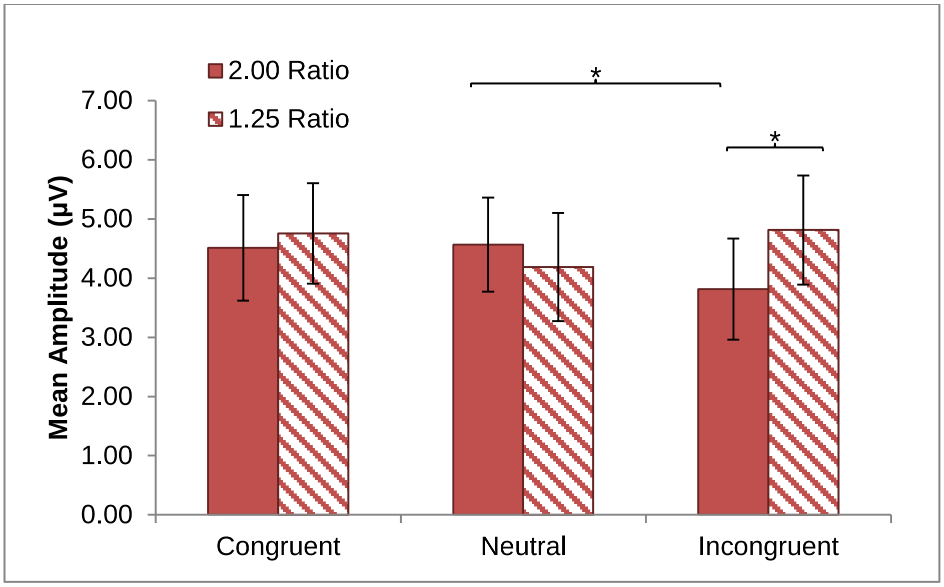


Figure 17. Mean amplitude of the P200 for ratio by congruity cells at the occipital cluster in Experiment 2. A significant congruity effect was observed for the 2.00 ratio and a ratio effect was observed for only the incongruent condition. Error bars reflect +/- 1 SEM. Asterisks indicate *p* values (*p < .05).

P200 Latency to Peak. At the central cluster, significant interactions for magnitude by hemisphere by site, $F(1.59, 36.64) = 3.582$, $p = .047$, $\eta_p^2 = .135$, and magnitude by ratio by congruity by hemisphere by site, $F(4, 92) = 2.543$, $p = .045$, $\eta_p^2 = .100$ (no significant post hoc comparisons were observed, *p*s > .05), were observed. Post hoc analyses on the magnitude by hemisphere by site interaction indicated that the effect was driven by significantly shorter latencies at CP5 ($M = 230.06$ ms, $SD = 20.14$) versus CP6 ($M = 237.76$ ms, $SD = 17.65$), $t(23) = -2.796$, $p = .010$ (all other *p*s > .1), only for non-symbolic number.

At the parietal cluster, significant interactions for ratio by congruity by site, $F(2, 46) = 8.132$, $p = .001$, $\eta_p^2 = .261$, and magnitude by ratio by congruity by hemisphere, $F(2, 46) = 5.689$, $p = .006$, $\eta_p^2 = .198$, were observed. The ratio by congruity by site interaction was driven by an interaction between ratio and congruity at the P7/P8 site pair, $F(2, 46) = 4.872$, $p = .012$. Specifically, there was a significant congruity effect at the P7/P8 site pair, but only for the 1.25 ratio, with shorter latencies for the neutral ($M = 231.40$ ms, $SD = 15.29$) than incongruent ($M = 239.75$ ms, $SD = 13.32$) conditions ($p = .009$, Bonferroni corrected, all other *p*s > .1). Post hoc analyses examining the four-way interaction revealed that it was driven by a significant ratio by congruity interaction for the non-symbolic number condition, $F(2, 46) = 4.687$, $p = .014$, on the right hemisphere. Specifically, there was a significant congruity effect for the 1.25 ratio; at this ratio, there were shorter latencies for the neutral ($M = 227.96$ ms, $SD = 19.23$) than the congruent ($M = 237.92$ ms, $SD = 20.60$) conditions ($p = .044$, Bonferroni corrected, all other *p*s > .3). Furthermore, a significant ratio effect was observed for the same hemisphere and magnitude, but only for the neutral condition, $t(23) = -2.261$, $p = .034$ (all other *p*s > .05), with shorter latencies for the 1.25 ratio (*M* = 227.96 ms, *SD* = 19.23) than the 2.00 ratio (*M* = 234.91 ms, *SD* = 21.57).

At the occipital cluster, a significant ratio by congruity by hemisphere interaction, $F(2, 46) = 4.603$, $p = .015$, $\eta_p^2 = .167$, was observed. The interaction was driven by a hemispheric difference in the incongruent condition for the 2.00 ratio, with significantly shorter latencies on the right hemisphere (*M* = 220.74 ms, *SD* = 15.81) than left (*M* = 231.85 ms, *SD* = 13.36), $t(23) = -3.398$, $p = .002$.

P200 Summary. Congruity and ratio effects persisted for mean amplitude, although now located at the occipital cluster. A mean amplitude ratio effect (difference between 2.00 and 1.25 ratio) was observed for both magnitudes in the occipital cluster and was dependent on congruity. These results are similar to what was observed for cumulative area in Experiment 1, although in more posterior sites. The presence of a occipital mean amplitude and parietal latency to peak ratio effects for non-symbolic number in the P200 is different than Experiment 1, but similar to previous research (Libertus et al., 2007).

P300 Mean Amplitude. At the central cluster, significant main effects of ratio, $F(1, 23) = 7.428$, $p = .012$, $\eta_p^2 = .244$, and congruity, $F(2, 46) = 3.365$, $p = .043$, $\eta_p^2 = .128$, as well as magnitude by ratio, $F(1, 23) = 7.802$, $p = .010$, $\eta_p^2 = .253$, and magnitude by congruity by site, $F(4, 92) = 5.985$, $p < .001$, $\eta_p^2 = .206$, interactions were observed. Post hoc analyses indicated that the magnitude by ratio interaction was driven by a significant ratio effect for cumulative area with higher MA for the 2.00 ratio (*M* = 5.55 μV, *SD* = 2.97) than 1.25 ratio (*M* = 4.64 μV, *SD* = 2.35), $t(23) = 3.651$, $p = .001$, and that the 1.25 ratio of cumulative area was significantly higher than non-symbolic number

(p = .018). Post hoc analyses indicated the three-way interaction was driven by a main effect of congruity across magnitude at the CP5/CP6 site pair, $F(2, 46) = 4.232$, $p = .021$, and an interaction between magnitude and congruity at the CP1/CP2 site pair, $F(2, 46) = 3.612$, $p = .035$. The congruity effect at CP5/CP6 was driven by lower MA for the neutral condition than incongruent condition ($p = .047$, Bonferroni corrected, other ps > .05). The post hoc interaction at the CP1/CP2 site pair was driven by a congruity effect for only non-symbolic number with the neutral condition having lower MA than the congruent and incongruent conditions (ps = .042, Bonferroni corrected).

At the parietal cluster, a significant main effect of congruity, $F(2, 46) = 4.004$, $p = .025$, $\eta_p^2 = .148$, and a magnitude by congruity by hemisphere by site interaction, $F(2, 46) = 4.099$, $p = .023$, $\eta_p^2 = .151$, were observed. Post hoc ANOVAs with magnitude and congruity as factors at each electrode site indicated that whereas there were no effects at P7 or P8 (ps > .05), there was a significant congruity effect at the P3 site pair, $F(2, 46) = 5.353$, $p = .008$ (incongruent MA higher than both neutral and congruent, ps < .04, Bonferroni corrected) and a significant main effect of congruity as well as an interaction, $F(2, 46) = 3.718$, $p = .032$, at the P4 site, suggesting that it was driving the initial four-way interaction. Specifically, at the P4 site, there was a significant congruity effect only for the non-symbolic number condition with lower MA for the neutral than both congruent and incongruent conditions (ps < .05, Bonferroni corrected), and significantly higher MA for non-symbolic number than cumulative area at for the congruent condition, $t(23) = 2.715$, $p = .012$ (see Figure 18). Upon further inspection, it appeared that the pattern of the congruity effect differed substantially for cumulative area and non-symbolic number, as indicated by the difference in MA for the congruent condition. To further examine the congruity effect pattern for each magnitude, two types of contrasts were used to determine if there was indeed a significantly different pattern of congruity at the P4 site. For each magnitude, a linear and quadratic contrast was used to determine if there was a specific pattern. For cumulative area, the linear contrast was significant, $F(1, 23) = 4.925$, $p = .037$, indicating MA was progressively higher when moving from congruent to incongruent conditions, but not the quadratic contrast ($p = .650$). However, for non-symbolic number, the quadratic contrast was significant, $F(1, 23) = 9.467$, $p = .005$, indicating similar MA for congruent and incongruent conditions and lower MA for the neutral condition, but not the linear contrast ($p = .682$). These analyses suggest that the magnitude by congruity interaction at P4 was driven by a difference in the pattern of the congruity effects for cumulative area and non-symbolic number.

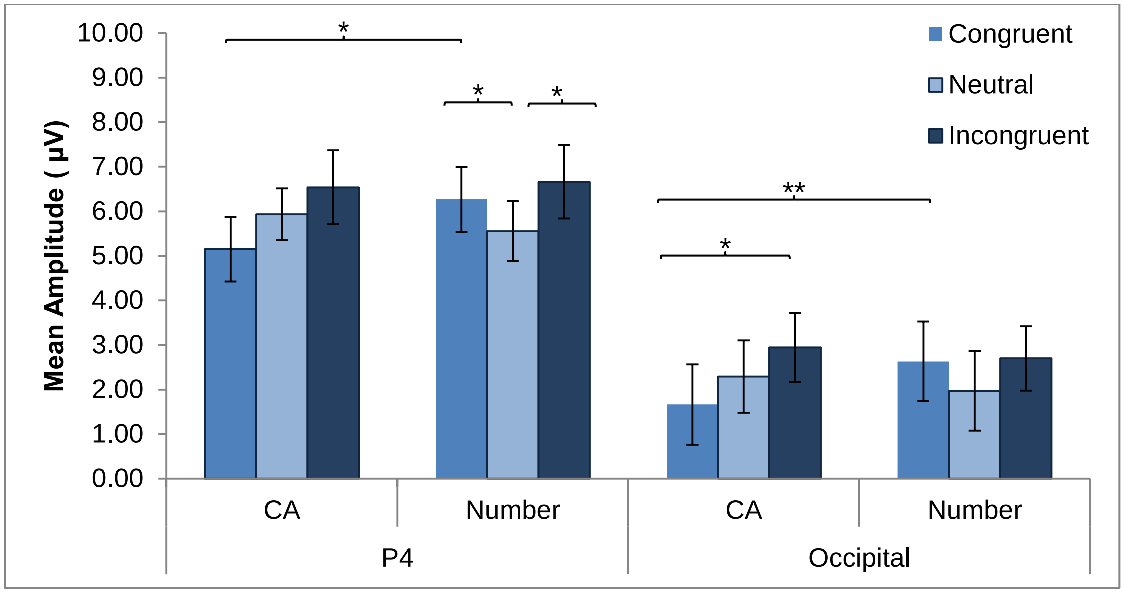


Figure 18. Mean amplitude of the P300 for magnitude (CA: cumulative area; Number: non-symbolic number) by congruity cells at the P4 site and occipital cluster in Experiment 2. Pairwise comparisons (Bonferroni corrected) revealed congruity effects for non-symbolic number at P4 and cumulative area at occipital sites. Error bars reflect +/- 1 SEM. Asterisks indicate *p* values (***p* < .01, **p* < .05).

At the occipital cluster, a significant main effect of congruity, $F(2, 46) = 4.697$, $p = .014$, $\eta_p^2 = .170$, as well as magnitude by congruity, $F(2, 46) = 4.674$, $p = .014$, $\eta_p^2 = .169$, and ratio by congruity, $F(2, 46) = 4.548$, $p = .016$, $\eta_p^2 = .165$, interactions were observed. Post hoc analyses for the magnitude by congruity interaction indicated the effect was driven by a congruity effect only for the cumulative area condition. Specifically, the incongruent condition had higher MA than the congruent condition ($p = .025$, Bonferroni corrected) and that the difference between the two magnitudes was driven by significantly higher MA for the non-symbolic number condition on congruent trials, $t(23) = 2.898$, $p = .008$ (see Figure 18). However, similar to P4, the pattern of the congruity effect appeared to differ for each magnitude, as indicated by the difference in MA for the congruent condition, and was further examined using linear and quadratic contrasts. For cumulative area, the linear contrast was significant, $F(1, 23) = 8.284$, $p = .008$, but not the quadratic contrast ($p = .962$). However, for non-symbolic number, the quadratic contrast was significant, $F(1, 23) = 6.652$, $p = .017$, but not the linear contrast ($p = .838$). Similar to P4, these results indicate that a different pattern of congruity effects drove the magnitude by congruity interaction. Post hoc analyses indicated that for the ratio by congruity interaction there were significant congruity effects for both ratios, though the patterns were different. Pairwise comparisons for the 2.00 ratio did not reach significance (ps > .05, Bonferroni corrected). Significant pairwise comparisons for the 1.25 ratio revealed that the neutral condition had lower MA than both the congruent and incongruent conditions (ps < .05, Bonferroni corrected). Follow up comparisons indicated that a significant ratio effect was only observed at the neutral condition with a significantly higher MA for the 2.00 ratio (*M* = 2.66 μV, *SD* = 3.95) than 1.25 ratio (*M* = 1.60 μV, *SD* = 4.43), *t*(23) = 2.987, *p* = .007.

P300 Latency to Peak. At the central cluster, a significant interaction between magnitude and congruity, *F*(2, 46) = 3.257, *p* = .048, η_p^2 = .124, was observed. Post hoc comparisons indicated that the interaction was driven by significantly shorter latencies for non-symbolic number (*M* = 320.30 ms, *SD* = 30.00) than cumulative area (*M* = 311.00 ms, *SD* = 36.44) for neutral trials, *t*(23) = -2.075, *p* = .049.

At the parietal cluster, a significant ratio by congruity by hemisphere by site interaction, *F*(1.56, 35.78) = 4.216, *p* = .031, η_p^2 = .155, was observed. Post hoc analyses indicated the interaction was driven by a difference in the P3/P4 site pair, specifically, the presence of a ratio by congruity interaction at the P4 site, *F*(2, 46) = 5.685, *p* = .006 (all other *p*s > .05). At the P4 site, there was a congruity effect for the 2.00 ratio, with shorter latencies for congruent (*M* = 300.78, *SD* = 29.80) than incongruent trials (*M* = 326.05, *SD* = 35.73; *p* = .010, Bonferroni corrected). Additionally, in the congruent condition there was a significant ratio effect with shorter latencies for the 2.00 ratio than 1.25 ratio (*M* = 324.34, *SD* = 36.32), *t*(23) = -2.764, *p* = .011.

P300 Summary. There continued to be similar ratio effects for both magnitudes in mean amplitude at the occipital cluster. In the central cluster a ratio effect in mean amplitude was only observed for cumulative area. The presence of ratio effects replicated previous research examining non-symbolic number at posterior sites (Libertus et al., 2007) and central sites for spatial information (Andreassi & Juszczak, 1984; Hagen et al., 2006; Proverbio et al., 2002). In contrast to those of earlier windows, the ratio effect had a pattern with higher mean amplitudes for the 2.00 than 1.25 ratios. Although this pattern was observed in later waveforms for cumulative area in Experiment 1 and has been observed in previous research (Hagen et al., 2006; Paulsen & Neville, 2008), it suggests there is a transition in processing between earlier and later waveforms. Although there continued to be congruity effects at all site clusters, the congruity patterns were not consistent between magnitudes. The congruity effect for cumulative area was best fit by a linear contrast whereas non-symbolic number was best fit by a quadratic contrast. The presence of a main effect of congruity in the P300 replicates previous non-symbolic number research (Gebuis et al., 2010) and extends this finding to cumulative area. For latency to peak, magnitude by congruity interactions continued at the central cluster. At the parietal cluster, congruity effects continued for both magnitudes and a similar ratio effect was also observed for both magnitudes, the first instance of which for cumulative area at this cluster. However, unlike the previous window the non-symbolic number ratio effect was reversed for the parietal cluster.

P400 Mean Amplitude. At the central cluster, a main effect of ratio, $F(1, 23) = 16.782$, $p < .001$, $\eta_p^2 = .422$, as well as magnitude by ratio, $F(1, 23) = 8.707$, $p = .007$, $\eta_p^2 = .275$ (no significant post hoc comparisons were observed, *p*s > .08), ratio by congruity, $F(1.58, 36.27) = 4.419$, $p = .027$, $\eta_p^2 = .161$, ratio by site, $F(1.46, 33.58) = 4.065$, $p = .038$, $\eta_p^2 = .150$ (no significant post hoc comparisons were observed, *p*s > .8), congruity by site, $F(2.82, 64.90) = 4.654$, $p = .002$, $\eta_p^2 = .200$, and magnitude by congruity by site, $F(3.22, 74.07) = 4.776$, $p = .003$, $\eta_p^2 = .172$ (no significant post hoc comparisons were observed, *p*s > .1), interactions were observed. Post hoc analyses indicated the ratio by congruity interaction was driven by a significant congruity effect limited to the 2.00 ratio with higher MA for the incongruent ($M = 7.03$ μV, $SD = 2.84$) than congruent trials ($M =$

6.15 μV, *SD* = 2.77; $p = .027$, Bonferroni corrected) as well as a significant ratio effect limited to the incongruent condition with higher MA for the 2.00 ratio than the 1.25 ratio (*M* = 5.23 μV, *SD* = 2.63), $t(23) = 4.161$, $p < .001$.

At the parietal cluster, main effects of ratio, $F(1, 23) = 26.810$, $p < .001$, $\eta_p^2 = .538$, and congruity, $F(2, 46) = 5.142$, $p = .010$, $\eta_p^2 = .183$, as well as magnitude by ratio, $F(1, 23) = 6.597$, $p = .017$, $\eta_p^2 = .223$, ratio by congruity, $F(1.61, 37.10) = 3.811$, $p = .040$, $\eta_p^2 = .142$, ratio by site, $F(1, 23) = 4.720$, $p = .040$, $\eta_p^2 = .170$, and magnitude by ratio by congruity by hemisphere by site, $F(2, 46) = 3.300$, $p = .046$, $\eta_p^2 = .125$, interactions were observed. Post hoc ANOVAs for each parietal site examining the five-way interaction revealed that it was driven by a difference in the ratio effect for P7 compared to other parietal sites. Specifically, for P3, P4, and P8, significant main effects for ratio were observed across congruity and magnitude with higher MA for the 2.00 than 1.25 ratio (*p*s < .001). Furthermore, significant pairwise comparisons revealed a significant main effect of congruity at P8, with higher MA for incongruent versus both neutral and congruent trials (*p*s < .05). For P7, a significant main effect of ratio, $F(1, 23) = 14.328$, $p = .001$, and a magnitude by ratio by congruity interaction, $F(2, 46) = 3.950$, $p = .026$, were observed. Further analyses examining the interaction at P7 found the interaction was driven by a main effect of ratio ($p < .001$) as well as interaction between ration and congruity for cumulative area ($p = .004$), and main effects of ratio ($p = .012$; 2.00 ratio < 1.25 ratio) and congruity ($p = .009$; neutral less than both congruent and incongruent, *p*s < .05, Bonferroni corrected) for non-symbolic number. The interaction for cumulative area was driven by a significant congruity effect for only the 2.00 ratio (incongruent > congruent, p = .042, Bonferroni corrected) and a significant ratio effect limited to the incongruent condition (p < .001, 2.00 ratio > 1.25 ratio).

At the occipital cluster, main effects of ratio, $F(1, 23) = 32.572$, $p < .001$, $\eta_p^2 = .586$, and congruity, $F(2, 46) = 4.549$, $p = .016$, $\eta_p^2 = .165$, as well as significant magnitude by congruity, $F(2, 46) = 3.775$, $p = .030$, $\eta_p^2 = .141$, and magnitude by congruity by hemisphere, $F(2, 46) = 6.250$, $p = .004$, $\eta_p^2 = .214$, interactions were observed. Post hoc ANOVAs for each hemisphere examining the three-way interaction indicated that whereas there was only an effect of congruity for the right hemisphere, with higher MA for incongruent versus congruent trials (p = .017, Bonferroni corrected), there was an interaction between magnitude and congruity for the left hemisphere in addition to the main effect of congruity. The left hemisphere interaction was driven by a congruity effect limited to the non-symbolic number condition with lower MA for neutral trials than both congruent and incongruent trials (ps < .01, Bonferroni corrected).

P400 Latency to Peak. At the central cluster, a main effect of ratio, $F(1, 23) = 13.305$, $p = .001$, $\eta_p^2 = .366$, and a significant congruity by hemisphere interaction, $F(2, 46) = 5.703$, $p = .006$, $\eta_p^2 = .199$, were observed. Latencies were faster for the 1.25 ratio (M = 514.56 ms, SD = 23.48) than the 2.00 ratio (M = 529.73 ms, SD = 21.34). Post hoc analyses examining the congruity by hemisphere interaction revealed a hemispheric difference limited to the congruent condition with shorter latencies in the left versus right hemisphere, $t(23) = -2.147$, $p = .043$.

At the parietal cluster, a significant main effect of ratio, $F(1, 23) = 43.813$, $p < .001$, $\eta_p^2 = .656$, as well as a magnitude by ratio by site interaction, $F(1, 23) = 7.967$, $p = .010$, $\eta_p^2 = .257$, were observed. Post hoc ANOVA analyses conducted at each site with magnitude and ratio as factors to examine the three-way interaction revealed that whereas there was only a main effect of ratio at the P7/P8 site pair ($p < .001$; 2.00 ratio: 504.46 ms; 1.25 ratio: 489.93 ms), there was an interaction between magnitude and ratio at the P3/P4 site pair ($p = .016$) as well as a main effect of ratio ($p < .001$). Follow-up analyses examining the P3/P4 interaction revealed that whereas there were significant ratio effects for both cumulative area (2.00 ratio: 522.92 ms; 1.25 ratio: 509.93 ms) and non-symbolic number (2.00 ratio: 528.00 ms; 1.25 ratio: 492.89 ms; *p*s < .03), the interaction was driven by significantly slower latencies for cumulative area than non-symbolic number on the 1.25 ratio, $t(23) = 2.275$, $p = .033$.

For the occipital cluster, a significant main effect of ratio was observed, $F(1, 23) = 5.713$, $p = .025$, $\eta_p^2 = .199$. Latencies were shorter for the 1.25 ratio ($M = 488.87$ ms, $SD = 30.97$) than the 2.00 ratio ($M = 503.15$ ms, $SD = 33.09$).

P400 Summary. For mean amplitude, ratio and congruity effects continued for both magnitudes at all clusters indicating that these effects were stable across later windows. The ratio effect continued the pattern of the P300 window, with higher mean amplitudes for the 2.00 ratio compared to the 1.25 ratio. Besides one instance, the ratio effect was similar between cumulative area and non-symbolic number, as well as across congruity conditions. The presence of ratio effects for non-symbolic number in the P400 replicates previous research (Paulsen & Neville, 2008; Paulsen et al., 2010) and extends the effect to cumulative area. The congruity effect was relatively comparable for both cumulative area and non-symbolic number, with an exception at the occipital cluster. For latency to peak, ratio effects continued for all clusters; however, there were no direct differences between congruity conditions (only the presence of a hemispheric difference within congruent trials at the central cluster) during this window. Similar to the previous window, latencies were shorter for the 1.25 than 2.00 ratio. Unlike mean amplitude, there were no differences in ratio effects due to magnitude.

Discussion

Experiment 2 is the first electrophysiological study to demonstrate congruity effects when cumulative area and non-symbolic number information are directly pitted against each other. Similar to previous research (Cohen Kadosh et al., 2007; Gebuis, Cohen Kadosh, et al., 2009; Gebuis et al., 2010; Henik & Tzelgov, 1982), ratio and congruity effects were observed in behavioral performance for both non-symbolic number as well as cumulative area. Unlike Experiment 1, a ratio effect was detected in the mean amplitude of the P100 for the P7/P8 site pair, but was limited to non-symbolic number. Interestingly, the early emergence of the ratio effect in the P100 for non-symbolic number interacted with congruity, indicating that although there was no ratio effect for cumulative area, the information still influenced numerical processing. In addition to mean amplitude, the latency to peak of the P100 yielded a ratio effect for both magnitudes in the occipital cluster and, similar to mean amplitude, interacted with congruity (see General Discussion for further interpretation of P100 effects). Outside the P100, the earliest ratio effect for mean amplitude was observed for both cumulative area and non-symbolic in the P200 at the occipital cluster and interacted with congruity. That there were no magnitude differences observed in this ratio effect makes this the strongest evidence of overlapping mechanisms for cumulative area and non-symbolic number processing. In contrast to mean amplitude, the P200 ratio effect in the latency to peak of the parietal cluster contained magnitude differences. Unlike non-symbolic number, which contained a ratio effect specific to the neutral condition at right parietal sites, there were no ratio effects for cumulative area in the latency of the P200. The results of the P200, combined with those from the P100, indicate that although there may be similar ratio effects for each magnitude, the onset of the effect differs for each magnitude. This suggests that there is partial overlap in the representations underlying cumulative area and non-symbolic number.

Evidence suggesting there are magnitudes representations that overlap to some extent but are also somewhat dissociable for cumulative area and non-symbolic number continued during the P300 and P400 waveforms. Some of the results in these components suggested shared magnitude representations were used during the task. Similar ratio and congruity effects were observed for both magnitudes in the latency of the P300 in the parietal cluster as well as the mean amplitude and latency of the P400 at central sites. In contrast, there were also results that indicated specificity in the underlying representations of cumulative area and non-symbolic number. There were differences in congruity effects in the P300 at all clusters and P400 at parietal sites. Furthermore, there were magnitude differences in the ratio effects in the P300 at central sites and the P400 at parietal and central sites. The lack of consistent results concerning the specificity of cumulative area and non-symbolic number representations suggests that, instead of shared or specific, there are partially overlapping mental magnitudes.

One of the best examples of evidence in favor of partial overlap in magnitude representations are the mean amplitude congruity effects of the P300. Although P300 congruity effects were observed for cumulative area and non-symbolic number, the pattern of the effect differed by magnitude. At the P4 electrode, as well as the occipital cluster, the congruity effect for cumulative area displayed a linear increase in mean amplitude when going from congruent to incongruent. In contrast, the congruity effect for non-symbolic number was characterized by a quadratic shape with higher mean amplitudes for congruent and incongruent trials versus neutral trials. Interestingly, and strikingly, these two congruity effect patterns were driven by the congruent condition. Mean amplitude of the P300 in the congruent condition was higher for non-symbolic number than cumulative area, even though the actual stimuli in this congruity condition were perceptually identical for both magnitudes. This suggests that despite the presence of ratio effects as well as congruity effects, which suggest interacting representations, there is still specificity as indicated by the different patterns. In summary, the presence of a congruity effect at the initial onset of the ratio effect for each magnitude, combined with continued congruity effects of common and distinct patterns of activation throughout the epoch, indicate the partial overlap in the representations underlying cumulative area and non-symbolic number.

General Discussion

In the present study, we examined the neural processing of mental magnitude information as it was used during a comparison task. Using ERPs, across two experiments we compared the electrophysiological response to cumulative area and non-symbolic number judgments when the magnitudes were presented independently (Experiment 1) as well as simultaneously (Experiment 2). We used the onset and shape of the ERP ratio effect to indicate the formation of a mental magnitude as well as a means to compare how cumulative area and non-symbolic number representations are created. Furthermore, the congruity effect was used as an indicator of the interaction between the underlying magnitude representations as well as an additional means to examine the specificity of the associated neural processes. The results of both experiments replicated and expanded on existing research. First, we replicated the presence of a ratio effect over parietal sites as well as a congruity effect over central sites for non-symbolic number (Cohen Kadosh et al., 2007; Dehaene, 1996; Gebuis et al., 2010; Libertus et al., 2007; Temple & Posner, 1998). Second, we expanded upon previous research by providing evidence of a ratio and congruity effect for cumulative area in an ERP paradigm. Additionally, we used a novel method for defining the period of early interaction for the congruity effect, using the initial onset of the ratio effect as an indicator. Overall, the results of both experiments build upon previous research that has examined the specificity of magnitude representations by providing evidence of partial overlap between cumulative area and non-symbolic number representations.

Comparison of Experiment 1 and 2 Results

Across both experiments, there were important differences in the behavioral and electrophysiological results. Magnitude differences in behavioral performance varied by experiment. Although there was no difference in overall accuracy between magnitudes in Experiment 1, non-symbolic number accuracy was significantly higher in Experiment 2. A slightly different pattern of results was observed for overall reaction time. In Experiment 1, there were significantly faster times for cumulative area than non-symbolic number, but no difference in Experiment 2. This pattern of results is likely due to the type of cumulative area stimuli in Experiment 1 and the inclusion of the congruity manipulation in Experiment 2. The use of amorphous cumulative area in Experiment 1 likely reduced, or even eliminated, any numerical information that may have interfered with performance. This is in contrast to Experiment 2 where both magnitudes were present to interfere with performance across trials. The level of interference as the primary factor driving the different patterns of performance across experiments is also supported by the overall accuracy correlations in each experiment. Unlike overall reaction times for each magnitude, which were significantly correlated for both experiments, there was only a significant correlation between accuracy measures for Experiment 2. Although the correlation for overall accuracy was of moderate size in Experiment 1, it did not reach significance and was of smaller strength than the correlation in Experiment 2. In combination with the different patterns in overall accuracy, these results suggest that the correlation between overall accuracy measures in Experiment 2 was likely due to interference between magnitude representations, as indicated by the congruity effect, and that the interference was reduced by the use of amorphous cumulative area in Experiment 1. These results indicate that, at least at a behavioral level, the use of different types of stimuli can modulate the level of interaction between magnitude representations.

One of the largest differences between the two experiments was the presence of an early ratio effect for non-symbolic number in Experiment 2. In the P100 window, a ratio effect specific to non-symbolic number was observed for mean amplitude at the P7/P8 site pair. However, in the P200 waveform, there is no significant ratio effect for either magnitude in the parietal cluster. A further ratio effect for latency to peak of the

P100 waveform was observed for both magnitudes over the O2 electrode. In all cases, the P100 ratio effects interacted with congruity. In contrast, in Experiment 1 the only P100 effects observed were magnitude effects. What is particularly striking about the presence of these early ratio effects in Experiment 2 is the similarity in the stimuli for both magnitudes. In fact, the stimuli were perceptually identical for cumulative area and non-symbolic number for the congruent and incongruent conditions, with differences only present in the neutral condition. Despite this similarity, there were mean amplitude ratio effects in the P100 for number in the congruent condition (central sites) as well as the incongruent condition (P7/P8).

The presence of early ratio effects raises the question as to whether this was the result of rapidly emerging magnitude representations or continued perceptual processing. The ratio effect has typically been assumed to be an indicator of mental representations of magnitude, whether in behavior (Cordes et al., 2001; Dehaene, 1992; Moyer & Landauer, 1967) or neuroimaging data (Dehaene, 1996; Nieder & Dehaene, 2009; Piazza et al., 2004; Pinel et al., 2004; Temple & Posner, 1998). It also has been argued in the numerical magnitude literature that there are separate perceptual and representational stages during the processing of numerical magnitude (Dehaene & Changeux, 1993; Verguts & Fias, 2004). As indicated by previous research, subtle changes in the perceptual properties of stimuli can lead to differences in early ERP waveforms [e.g., luminance (Johannes, Münte, Heinze, & Mangun, 1995); contour (Proverbio & Zani, 2002)]. When observed in number comparison tasks, main effects of stimulus type (e.g., number words versus Arabic numerals) that emerge early in the epoch during number judgment tasks have similarly been argued to be due to differences in perceptual properties, rather than the underlying representations (Dehaene, 1996; Temple & Posner, 1998). There have also been cases in which early emerging ratio effects have been attributed to perceptual properties of the stimuli rather than magnitude representations. For example, in one ERP study using non-symbolic number, a ratio effect observed in the amplitude in an early emerging component (138 – 172 ms) was argued to be due to differences in stimulus properties, specifically the overall number of objects across arrays, rather than the ratio difference between the arrays (Libertus et al., 2007). Furthermore, in a second experiment in which these differences were controlled for, the effect was absent (Libertus et al., 2007). Other ERP studies have shown similar effects of stimulus properties on non-symbolic number processing in early waveform components (Gebuis & Reynvoet, 2011; Hyde & Spelke, 2009). This suggests that the presence of an early ratio effect, especially if the onset is soon after stimulus presentation, may not be sufficient evidence for a fully formed magnitude representation and that it may be due to perceptual differences in the stimuli. In light of this previous research, as well as the relatively short duration of the observed effects, we believe it is likely that the ratio effects present in the P100 in Experiment 2 reflect continued perceptual processing rather than fully-formed magnitude representations. The numerical ratio effect in the mean amplitude of the P7/P8 site pair was only present for the P100 waveform, with no ratio effect in the P200 window at the same site. Furthermore, the ratio effect in the latency of the P100 at the O2 site was also only present for that waveform, with no ratio effect in the P200. In contrast to the P100 ratio effects, the presence of ratio effects in the mean amplitude of the P200 at the occipital sites and the latency to peak in the parietal sites continued through the P300 and P400, indicating a sustained effect that was more likely due to mental magnitudes.

Instead of indicating a formed magnitude representation, the presence of a ratio effect for non-symbolic number, but not cumulative area, in the P100 supports the view that there may be an inherent bias for numerical information in regard to perceptual processing of discrete arrays of objects (Cordes & Brannon, 2008a, 2009). In addition to the presence of a ratio effect in the mean amplitude of the parietal cluster, the latency to peak was slower for cumulative area (118 ms) than non-symbolic number (116 ms). Although the difference was small, it was of a moderate effect size, and is further evidence in line with the view that the perception of non-symbolic number is faster than cumulative area in discrete arrays of objects. In contrast, in Experiment 1 there were mixed effects in the latency to peak of the P100 with shorter latencies for amorphous cumulative area (86 vs. 109 ms; averaged) at some central sites and shorter latencies for non-symbolic number in the occipital cluster (100 vs. 121 ms). These results suggest that, at the very least, the use of amorphous stimuli affects the speed of perceptual processing of cumulative area information when compared to non-symbolic number.

Differences between experiments in the electrophysiological ratio effects suggest that the process of forming mental magnitudes is sensitive to stimulus properties. Specifically, the temporal and spatial location of the initial onset of the ratio effect for the magnitude conditions varied across experiments. For the cumulative area condition, an initial ratio effect was observed in the P200 over parietal and central cites in Experiment 1. In contrast, in Experiment 2, an initial ratio effect was observed over occipital sites in the P200. For the non-symbolic number condition, in Experiment 1 an initial ratio effect was observed in the P400 over all clusters, whereas in Experiment 2 multiple ratio effects were observed across the P100 and P200 as well as multiple sites. These differences in the ERP waveform indicate that both cumulative area and non-symbolic number processes are sensitive to stimulus properties. In the case of cumulative area, the influence of conflicting as well as congruent numerical information shifted the initial onset of the ratio effect to more posterior sites. For non-symbolic number, the inclusion of conflicting and congruent spatial information led to a more widespread and early presentation of ratio effects. These results are in conflict to the view that numerical magnitude representations are impervious to the influence of other magnitude information (Butterworth, 2010; Dehaene & Changeux, 1993). The presence of a congruity effect for non-symbolic number at every time window suggests that cumulative area information is not stripped away from numerical magnitude representations. Similarly, this suggests that numerical information is not stripped away from cumulative area magnitude representations. The results of both experiments indicate that magnitude representations are sensitive to stimulus properties and that other quantitative information is present in the resulting mental magnitudes.

Congruity Effect: Evidence of Early Interaction

The results of the present study support the early interaction view of the congruity effect. Previous ERP research has examined whether the congruity effect emerges early or late in processing and has provided mixed results, with some evidence of early interaction (Gebuis et al., 2010; Schwarz & Heinze, 1998), late interaction (Cohen Kadosh et al., 2007; Santens & Verguts, 2011), or both (Cohen Kadosh et al., 2007;

Szucs & Soltész, 2007, 2008). In Experiment 2, we demonstrate that, for either magnitude domain, the initial onset of a ratio effect is matched with a congruity effect, which is clear support for the early interaction view. Together with previous research, these results suggest that the congruity effect is due to the interaction of magnitude representations as they are being formed. Furthermore, unlike some previous research (Cohen Kadosh et al., 2007), the presence of a congruity effect was not restricted to the more difficult ratio. When congruity effects were dependent on ratio, they were not restricted to the 1.25 ratio. In fact, of the instances when the factors of congruity and ratio interacted, only for a subset was the congruity effect restricted to the 1.25 ratio. The presence of congruity effects at both ratios suggests that the interaction of magnitude representations does not only occur when quantities are difficult to discriminate. The present study combined with previous ERP research examining symbolic (Schwarz & Heinze, 1998) and non-symbolic (Gebuis et al., 2010) number supports the view that congruity effects are the result of an early interaction between magnitude representations.

Flip in Ratio Effect between Early and Late Components

A pattern in the ratio effect emerged across the ERP epoch for both experiments, where mean amplitude was higher for the 1.25 ratio in early components whereas it was higher for the 2.00 ratio in later components. Specifically, in Experiment 1, the flip in ratio effect occurred for cumulative area between the P200 in parietal and central sites and the P400 for all clusters. Since there was no significant mean amplitude ratio effect for non-symbolic number in early components, it was unclear whether there was a similar shift in the ratio effect pattern. However, the same ratio effect pattern was observed for non-symbolic number in the P400 as cumulative area. In Experiment 2, the flip in mean amplitude ratio effects was observed for both experiments between the P100 as well as P200 and the P300 and P400 in various sites across clusters. Since most of the previous ERP research examining non-symbolic number has not observed a shift in ratio effects (Paulsen & Neville, 2008; Paulsen et al., 2010), the source of the shift in pattern is unclear. One study that did observe a similar flip in ratio effect between P200 and P300 in non-symbolic number judgments suggested that it might be due to participants' low confidence in the accuracy of their judgments (Libertus et al., 2007). An alternative possibility that comes from conflict processing ERP research is that the shift in later components may be due to the suppression of irrelevant or conflicting information and enhancement of target information. In ERP studies that have examined the impact conflicting information has on the electrophysiological signal during visual judgment tasks, a large deflection in the waveform has been observed around 300 ms after stimulus onset in posterior sites (Mao & Wang, 2008; H. Wang, Wang, & Kong, 2001; Y. Wang, Kong, Tang, Zhuang, & Li, 2000). Specifically, in these experiments participants made judgments about occasionally presented target stimuli across trials intermixed with irrelevant but conflicting, stimuli [e.g., (Rugg, Milner, Lines, & Phalp, 1987)]. During these studies it has been observed that the deflection of the waveform around 300 ms after stimulus onset is modulated by the presence of target and conflicting stimuli (Rugg et al., 1987; Y. Wang, Wang, Cui, Tian, & Zhang, 2002) and has been argued to be due to both active suppression and enhancement processes (Hickey, Lollo, & McDonald, 2009). A similar set of processes may have been in play during the present experiments. As suggested by the shift in ratio effect patterns between early and late components, after magnitude representations were created there may have been active processes to enhance magnitude information from the target domain and suppress information from the irrelevant domain. This could explain why mean amplitude was higher for the 2.00 ratio in the later components as conflicting information is more salient for larger differences between arrays, especially in the incongruent condition in Experiment 2. This would also account for the shift in pattern occurring in the P400 in Experiment 1 and the slightly earlier P300 in Experiment 2 as there were fully congruent and incongruent trials in Experiment 2. If the flip in ratio effect patterns between early and late components is due to processes reducing the conflict between the target and non-target magnitude in mental magnitudes, this suggests that the creation and comparison of mental magnitudes is a dynamic and continuous rather than stage-like process. The potential role for conflict processes creating a shift in ratio effect patterns during magnitude judgments should be further explored in future research.

Shared or Specific Magnitude Systems?

Connected to the discussion of the early interaction account of the congruity effect is whether there is a general magnitude system for quantity representation. Theories that propose a general magnitude system hold that all quantities are represented using a common, shared representation (Bueti & Walsh, 2009; Walsh, 2003). In contrast, theories that propose specific magnitude systems hold that each quantity is represented using distinct, non-overlapping representations (Dehaene, 2011; Odic et al., 2012). The results of the present study support neither the general nor specific magnitude views. Rather, the results suggest that there are partially overlapping magnitude representations

(Lourenco et al., 2012; Lourenco & Longo, 2010). In Experiment 1, we observed a differential onset of a ratio effect for cumulative area and non-symbolic number. Although the stimuli were designed to independently present either magnitude, the strongest general magnitude view would still have predicted identical ratio effects. In Experiment 2, we observed partial overlap in the onset and distribution of ratio effects. Even though both magnitudes were presented simultaneously, the strongest specific magnitude view would have predicted no overlap in the ratio effects. Perhaps the strongest evidence of a partially overlapping magnitude system was the presence of congruity effects in the mean amplitude of the P300 that differed in their pattern for cumulative area and non-symbolic number. The presence of any congruity effect for either magnitude suggests that there is an interaction in the underlying representations, and is support for the general magnitude view. However, the distinct patterns observed in the congruity effect, with a linear pattern for cumulative area and quadratic pattern for non-symbolic number indicates the interaction of magnitudes affected the representations differently. This difference in the pattern of congruity effects for each magnitude indicates that asymmetries still remain in the representations of cumulative area and non-symbolic number.

Future Directions

The present study examined the ratio and congruity effects of cumulative area, using amorphous and discrete arrays, as well as non-symbolic number during an explicit judgment task. Although the results of the present study are in line with some previous research (Gebuis et al., 2010; Schwarz & Heinze, 1998), they are also in conflict with other studies (Cohen Kadosh et al., 2007; Dehaene, 1996; Temple & Posner, 1998). Two of the major differences in the present study and conflicting previous studies is the presentation of both stimuli that are to be compared and the use of non-symbolic magnitudes. Some of the previous research suggesting that numerical magnitude representations are abstracted away from other quantitative information have used tasks where the participant is presented with a number and then has to compare it to an absent reference number [e.g., presented with '4' and asked whether it is larger than five; (Dehaene, 1996; Temple & Posner, 1998)]. Currently, it is unknown how the absence or presence of one of the pair of numerical stimuli may affect the electrophysiological response during the judgment task. Although the accumulation of similar results using both types of tasks (Dehaene, 1996; Piazza et al., 2007) suggests the presentation method does not affect the presence of a ratio effect, this is also confounded with the use of symbolic numerical stimuli. The format of the magnitude information is another difference in the present study compared to previous research examining the congruity effect. Studies that have found evidence of a late interaction for a congruity effect have used symbolic number stimuli (Cohen Kadosh et al., 2007; Szucs & Soltész, 2007, 2008). Although there is some ERP evidence that the use of symbolic and non-symbolic number stimuli does not affect the onset of the congruity effect (Libertus et al., 2007; Temple & Posner, 1998), it is still to be seen whether, when using the operational definition of an early interaction proposed by the present study, if an effect of stimulus type is observed.

In summary, we examined the onset of the ratio and congruity effects for non-symbolic cumulative area and number. In Experiment 1, we found evidence of a difference in the onset of the ratio effect for amorphous cumulative area and non-symbolic number when presented independently. In Experiment 2, we found evidence of early interaction between magnitude representations of cumulative area and non-symbolic number when presented simultaneously. The results of both experiments indicate there are partially overlapping representations for non-symbolic magnitudes.

Discussion of Study 2

In Study 2, I examined the specificity of the mental magnitudes underlying non-symbolic cumulative area and number judgments using ERP. The presence of a ratio effect for non-symbolic number over parietal sites in Experiment 1 replicates previous research (Hyde & Spelke, 2009; Libertus et al., 2007; Temple & Posner, 1998). The presence of a ratio effect for cumulative area in the P200 over central and parietal sites in Experiment 1 builds upon previous research that has examined the electrophysiological response during judgments of spatial extent and extends this to cumulative area (Andreassi & Juszczak, 1984; Hagen et al., 2006; Proverbio et al., 2002). The results of Experiment 2 both extend and build upon previous research examining the congruity effect in symbolic and non-symbolic number and extending this to cumulative area (Cohen Kadosh et al., 2007; Gebuis et al., 2010; Schwarz & Heinze, 1998). Congruity and ratio effects were observed for both non-symbolic number and cumulative area over parietal and occipital sites. Taken together, the experiments of Study 2 indicate that ratio and congruity effects can be observed with cumulative area and non-symbolic number in electrophysiological activity during judgment tasks.

The results of the two ERP experiments suggest there is at least some specificity in magnitude representations. In Experiment 1, ratio effects were observed for both amorphous cumulative area and non-symbolic number, but in different spatial and temporal positions. Different results for the ratio effect were observed in Experiment 2. Specifically starting with the P200 component, ratio and congruity effects were observed for both magnitudes when they were presented simultaneously. Although the initial ratio effects for each magnitude were matched by the presence of a congruity effect, suggesting an interaction between representations, the pattern of the congruity effect varied for each magnitude, especially in the P300, indicating some specificity. These results are in conflict with strong views of general and specific magnitude systems (Dehaene, 2011; Walsh, 2003), and are in line with previous research suggesting a system of partial, not full, overlap (Lourenco et al., 2012).

Evidence for partially overlapping representations was found across Studies 1 and 2. In Study 1, where adults and children judged which of two arrays were larger in non-symbolic number and cumulative area across different spatial arrangement contexts, there were similarities in performance across magnitudes when presented in spatially intermixed displays. However, when arranged as spatially separated displays, cumulative area and non-symbolic number performance varied. Although spatial arrangement was not examined in Study 2, there was still evidence of partially overlapping representations as indicated by similarities and differences in the onset of ratio effects as well as the presence of early congruity effects, the patterns of which differed for each magnitude. The evidence of partial overlap for magnitude representations came from the stimulus manipulations in both studies. In Study 1, it was the spatial arrangement manipulation whereas in Study 2 it was the presentation of cumulative area and non-symbolic number independently and simultaneously. This suggests that the amount of overlap in magnitude representations, at least for cumulative area and non-symbolic number depends on the ways in which they are presented.

Dissertation General Discussion

Taken together, the results of this dissertation are strongly suggestive of magnitude representations that partially overlap. This is in line with previous research that similarly found evidence of a partially overlapping magnitude system in the patterns of behavioral performance and correlations between individual differences in magnitude precision and tests of symbolic math skills (Lourenco et al., 2012). However, what a partially overlapping magnitude system looks like has yet to be fully specified. Theoretically, it falls somewhere between strong general and specific magnitude system views, but this still does not provide much of a description of how a partially overlapping system could be implemented. In an attempt to provide an explanation for such a system, I will first examine what it is not by discussing specific and general magnitude systems in their strongest forms. I will then provide a hypothesis for how a partially overlapping magnitude system may be structurally, as well as functionally, implemented in the mind, and, how this hypothesis fits with the present dissertation.

Theories that have argued for specificity of magnitude representations have focused on numerical magnitude and how it is representationally different from any other mental magnitude. In these theories, it has been proposed that even when numerical information is presented as non-symbolic number displays, a modular perceptual mechanism is used to process and generate a mental magnitude, both of which are unique to number (Dehaene, 1992). An influential model proposed by Dehaene and Changeux (1993) argues that a numerosity detector module is the perceptual mechanism by which a purely numerical representation is first extracted from an array of objects and then represented using an analog magnitude. The numerosity detector was proposed to operate by taking input from the retina and subsequently registering the location of each object while simultaneously removing any spatial information by normalizing the size of each object. After non-numerical information is removed, the numerosity detector sums together each normalized object, yielding an analog number representation that is devoid of other magnitude information and available for mental operations. A similar model has been proposed for symbolic number stimuli with the analog number representation being identical and the main difference being the lack of the normalization process (Verguts & Fias, 2004). The evidence from the present dissertation is in conflict with the numerosity detector, and thus specific magnitude system view in two ways. First, the differences in number performance due to the spatial manipulation in Study 1 suggest that properties of the stimulus influence the resulting number representation. Second, the presence of a congruity effect at the initial onset of the numerical ratio effect in Study 2 - Experiment 2 provides evidence that spatial information can at least influence the perceptual processing of number.

Theories of a general magnitude system have proposed a common magnitude representation for all types of quantities. In these theories, it is typically accepted that there is some specificity in perceptual mechanisms that register quantities [e.g., speed vs. size; (Walsh, 2003)], although there are cases in which shared perceptual mechanisms are proposed [e.g., time and sequential number; (Meck & Church, 1983)]. Regardless of whether there are specific or shared mechanisms for registering perceptual information, it is proposed that there is a common mental magnitude used for all quantities (Bueti & Walsh, 2009; Walsh, 2003). Since there are common representations for all magnitudes, there should be comparable effects: if one quantity is affected by an experimental manipulation, other magnitudes should be affected in a similar manner. The results of the dissertation studies conflict with this general magnitude view in two main ways. First, there are some dissociations in the effects experimental manipulations had on each magnitude. In Study 1, the spatial arrangement manipulation only modulated performance on the non-symbolic number task. Furthermore, the simultaneous presentation of magnitudes in the Study 2 - Experiment 2 hampered behavioral performance on the cumulative area task more than the non-symbolic number task. The second way in which the dissertation results conflict with the general magnitude view is the different pattern of congruity effects present in the mean amplitude of the P300 in the second ERP experiment. Although the presence of a congruity effect in the P300, as well as earlier components, indicated that there was an interaction between representations of cumulative area and non-symbolic number, the different pattern in the congruity effect indicates that the interaction of magnitude representations influenced cumulative area and non-symbolic number differently. This suggests that in the present dissertation studies there was not a completely overlapping mental magnitude used to represent all types of quantitative information.

Hypothesis for a Partially Overlapping Magnitude System

My hypothesis for a partially overlapping magnitude system fills the gap between specific and general theories of magnitude by assuming mental magnitudes are multifaceted. What I mean by multifaceted is that magnitude representations are composed of pieces of magnitude information integrated from multiple dimensions. The hypothesis makes use of the body of literature examining the nature of cross-modal perception. The debate between specific versus overlapping magnitude systems is similar to the debate in cross-modal perception as to whether there are modality specific versus general perceptual representations.

The discussions that have, and still are, occurring concerning the specificity in perceptual knowledge are similar to those discussing the specificity in magnitude representation. The history of the debate of modality specific versus general perceptual knowledge dates back to Aristotle (Aristotle, 350BCE) and centers on whether representations generated for one sensory modality are the same representations used by a different sensory modality (Barsalou, 1999; Gallese & Lakoff, 2005; Stoffregen & Bardy, 2001). Cross-modal perception refers to the ability to transfer information registered in one sensory modality to a different sensory modality [e.g., (Jack & Thurlow, 1973)]. Behavioral evidence of cross-modal perception comes from a variety of studies, including across developmental groups [e.g., infants (Kuhl & Meltzoff, 1982; Meltzoff & Borton, 1979); adults (Jack & Thurlow, 1973; McGurk & MacDonald, 1976; Spence, 2011); developmental review (Lewkowicz, 2000)]. Much of the debate has centered on whether cross-modal perception is due to the use of general representations to encode sensory information, or the rapid integration of initially distinct perceptual representations into a multimodal representation [e.g., (Lewkowicz, 2000)]. The two views entail markedly different representational systems. According to the general view, all perceptual information is represented using a common representation that is shared by all sensory modalities (Ettlinger & Wilson, 1990; Marks, 1987; Meltzoff, 1990). In contrast, according to the multimodal view perceptual information is initially registered using distinct representations but is then quickly integrated into partially overlapping representations (Lewkowicz, 2000; Stein & Meredith, 1990).[5] Further evidence for partially overlapping, or integrated, perceptual representations comes from neuroimaging research examining cross-modal interactions in perception.

Neuroimaging research has examined how neural activity in particular regions reacts to uni- and multi-modal stimuli. Single-cell recording studies in cats have found evidence of topographic maps for neurons sensitive to visual, auditory, and somatosensory in the superior colliculus (Stein & Meredith, 1990). Interestingly, it was found that the topographic fields for each modality partially overlap, with neurons sensitive to multiple modalities. The neural activity of these multimodal neurons suggested that a particular combination of perceptual information could lead to enhancement effects, indicated by higher activity when two modalities were presented, as well as depressant effects, indicated by reduced activity when two modalities were presented (Stein & Meredith, 1990). This research suggests that after perceptual information is registered by sense organs, that information is integrated into a multimodal representation. Neuroimaging research in humans indicates partially overlapping representations as well. For example, the IPS is believed to be a integration area of perceptual information given that activity in that region is modulated during object recognition tasks when multimodal stimuli contain visual and somatosensory information (Amedi, Von Kriegstein, Van Atteveldt, Beauchamp, & Naumer, 2005; Grefkes, Weiss, Zilles, & Fink, 2002) as well as visual and auditory information (Calvert, 2001).

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[5] There are ongoing discussions in concept theory about whether multimodal perceptual representations are actually supramodal representations. Two views of supramodal representations have been discussed in the literature. In one proposal, supramodal representations are viewed as being shared representations that are tied to the perceptual stimulus (Barsalou, 1999). This view is similar to what is described as the general view of cross-modal perception. A different view of supramodality is that there are distinct representations that are integrated via association areas (Gallese & Lakoff, 2005). Given these different views, in the present dissertation, I avoided the use of the term supramodal to avoid ambiguity.

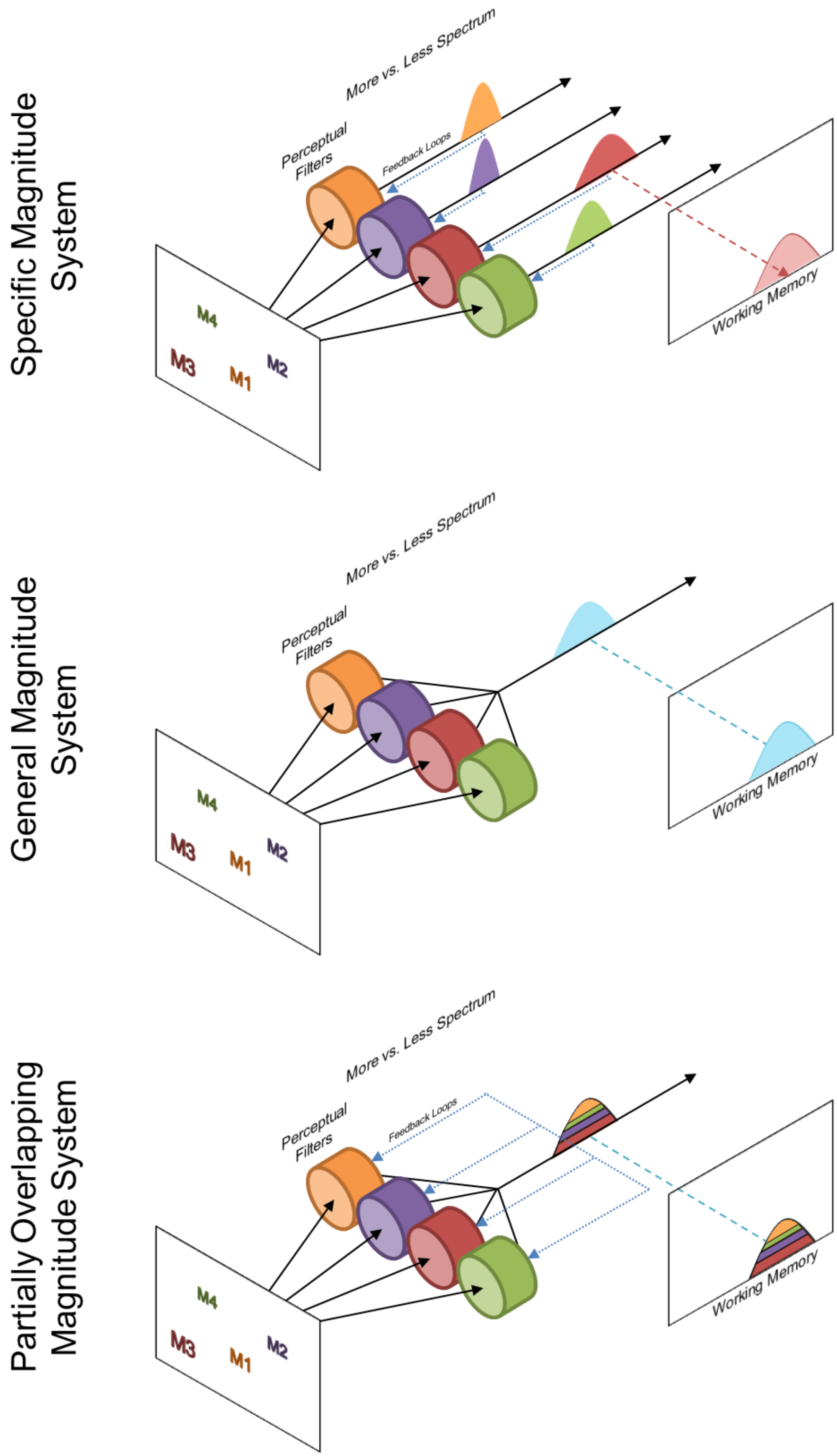
Furthermore, ERP research using dense electrode arrays and source modeling has found evidence that cross-modal integration of auditory and visual information occurs very early in processing (around 150 to 250 ms after stimulus onset) in posterior regions, suggesting that cross-modal integration occurs rapidly during decision making (McDonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2003; Störmer, McDonald, & Hillyard, 2009; Teder-Sälejärvi, Di Russo, McDonald, & Hillyard, 2005). Interestingly, even though this research suggests cross-modal integration occurs rapidly after stimuli are registered, top-down effects on cross-modal perception have been observed, suggesting that the actual integration of multimodal information is dynamic and can be affected via feedback loops (Macaluso, 2006; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Given the multiple parallels between the theoretical discussions and empirical evidence examining cross-modal integration, I have used some of the same arguments in the literature to develop a new hypothesis to account for partial overlap in mental magnitudes.

Combing the theories that have been discussed in the cross-modal perception literature, I modified specific mental magnitude models to account for a partially overlapping magnitude system. In the environment, magnitude information can come from multiple dimensions (e.g., time, size, number, etc.) and, similar to cross-modal perception, different sensory modalities (e.g., vision, audition, etc.). Even within a single dimension and sensory modality, magnitudes can be presented in different ways. For example, numerical information can be visually presented sequentially [e.g., number of visual dots that appear in a sequence; (Meck & Church, 1983)] or, similar to the present studies, in parallel [e.g., array of visual dots in an image, (Dehaene & Changeux, 1993).

My proposal for a partial magnitude system takes into account the multiple ways that magnitude information can be presented by proposing that mental magnitudes are multifaceted, such that they are the product of integrated multiple types of magnitude information. The key difference between my model and previous ones is that mental magnitudes are proposed to be the product of cross-magnitude integration. Similar to the multimodal view of cross-modal perception, mental magnitudes are not a uniform entity; rather they are constructed by integrating all magnitude information present in a stimulus into a single multifaceted representation.

My partially overlapping magnitude system (POMS) hypothesis proposes three features concerning the representation of magnitude information. First, similar to the specific magnitude theory, POMS proposes that there are many magnitude-specific perceptual filters for detecting quantitative information. Evidence for magnitude-specific perceptual mechanisms, although still debated, has been presented for non-symbolic quantities such as number arrays [e.g., (Dehaene & Changeux, 1993; Verguts & Fias, 2004)] and average size of a set of objects [e.g., (Alvarez, 2011; Chong & Treisman, 2005; Im & Halberda, 2013)] and luminance [e.g., (Burr & Ross, 2008)]. Similar to the numerosity detector and perceptual mechanisms proposed for other domains, the perceptual filters in POMS would register a particular type of magnitude information. However, they would differ from the numerosity detector in that they do not create a specialized magnitude representation. Instead, the output of the perceptual filters, reflecting the relative amount of a quantity is present in a stimulus, would be fed directly into a multifaceted representation. These perceptual filters would operate in parallel and there could be multiple types of filters for any particular type of quantity. For example, multiple perceptual mechanisms have been proposed for non-symbolic number (Dehaene & Changeux, 1993; Gallistel & Gelman, 1992; Meck & Church, 1983) as well as temporal duration (Eagleman, 2008).

A second feature of the POMS hypothesis is that mental magnitudes are the sum of the output of the perceptual filters (see Figure D1). Instead of there being a specific representation for each magnitude (specificity) or a unitary common representation for all magnitudes (shared), the magnitude representation proposed by POMS is multifaceted as it is the integration of the perceptual filter outputs. This proposal entails that there is no abstraction away from the stimulus information such that all quantitative information present in the stimulus is reflected in the multifaceted magnitude representation. Similar to evidence observed during multimodal perception (Amedi et al., 2005; Barsalou, 1999; Grefkes et al., 2002; Talsma et al., 2010) the summation of the perceptual filter output would occur in association areas of the cortex, such as the parietal lobe, and would then held in working memory until no longer required for decision making. Evidence from previous research as well as models supports the view that working memory serves as the vessel in which mental magnitudes are held for further mental operations (Alvarez, 2011; Brady, Konkle, & Alvarez, 2011; Halberda, Sires, & Feigenson, 2006; Hyde & Wood, 2011).


Specific Magnitude System
More vs. Less Spectrum
Perceptual Filters
Feedback Loops
M4
M3
M1
M2
Working Memory
General Magnitude System
More vs. Less Spectrum
Perceptual Filters
M4
M3
M1
M2
Working Memory
Partially Overlapping Magnitude System
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M2
Working Memory

Figure D1. Diagrams of the magnitude systems proposed by the specific (top) general (middle) and partial (bottom) views. A sample stimulus that contains four magnitudes (M1 to M4) is presented and the task is to represent the magnitude of M3. The way in which this is accomplished varies for each magnitude system. When a stimulus that contains magnitude information is encountered, the information is initially registered by magnitude-specific perceptual filters. In the specific magnitude view (top), each perceptual filter produces a specific mental magnitude that is then represented in working memory. In the general magnitude view (middle), all perceptual filters produce the same mental magnitude that is then represented in working memory. In the POMS view (bottom), the output of the perceptual filters is summed together to create an integrated mental magnitude that is represented in working memory. Both the specific and partial magnitude views offer feedback pathways from the mental magnitude to the perceptual filters such that the activity of the filters can be modulated by top-down processes. As the mental magnitude in the general magnitude view is not specific to any perceptual filter, there are no feedback pathways to specific perceptual filters.

A third feature of the POMS hypothesis is the presence of continuous feedback between the integrated mental magnitude in working memory and perceptual filters. The connections between the magnitude representation and perceptual filters would allow particular connections to be weighed more heavily than others via top-down processing. For example, if the goal for a task was to discriminate a particular type of quantitative information, the corresponding perceptual filter would be given more weight such that it composed a larger proportion of the summed representation. This would make the integrated magnitude representation a stronger reflection of the required quantitative information than others. Evidence for a similar effect of top-down goals and intentions have been found in cross-modal perception (Talsma et al., 2010). Feedback between mental representations and perceptual mechanisms has also been incorporated into computational models in number processing. When creating an analog representation of number, several models have built in back propagation as a way to adjust the weight of connections in order to settle on a numerosity (Dehaene & Cohen, 1995; Verguts & Fias, 2004). With these proposals, the POMS hypothesis allows for mental magnitudes that contain information from multiple magnitudes and allows these representations to be dynamic based on the stimulus presented as well as the action or decision to be made.

The POMS Hypothesis and Present Studies

The results of the present dissertation studies provide support for the POMS hypothesis as well as identify aspects of the proposals that should be investigated in future research. Across both studies, there was evidence in support of the feature of specific perceptual filters. Combined with the results of previous research (Barth, 2008;

Cordes & Brannon, 2008a), the dissociation in performance as the result of spatial arrangement in Study 1 as well as the early magnitude differences in Study 2 – Experiment 1 suggest that there are different perceptual mechanisms for registering cumulative area and non-symbolic number. Furthermore, despite some evidence of a congruity effect with non-symbolic number in Study 2 – Experiment 2 in the P100, this was not present for cumulative area. This is additional evidence that there is a specific perceptual filter for cumulative area, but also highlights an ongoing discussion about non-symbolic number. In light of multiple models of modular perceptual mechanisms for non-symbolic number, it has been suggested that numerical magnitude representations may not be directly created from visual stimuli (Dakin et al., 2011; Durgin, 1995; Tibber et al., 2012). Based on the results of these studies it has been proposed that representations of non-symbolic number are secondary calculations based on density (Dakin et al., 2011; Durgin, 2008). This suggests, along with the results of the present studies, that non-symbolic number perceptual mechanisms are not distinctly numerical. If so, this does not go against the POMS hypothesis in that it would be evidence that there is a perceptual filter for density and that there may not be as many perceptual filters within the domain of number as previously believed. Future research will need to further examine whether magnitude representations of density are mistaken for non-symbolic number.

The results of Study 2 are in support of the proposal that mental magnitudes are integrated in association areas. In Study 2, the use of ERP does not allow for the specific source of the neural signal to be localized. However, in previous research that combined ERP and fMRI paradigms during magnitude comparison tasks provided evidence that ratio effects recorded in the ERP signal at parietal sites in the P200 were coming from the IPS (Cohen Kadosh et al., 2007; Pinel et al., 2001). Although there were numerous task differences in Study 2, the results of previous studies suggest that the P200 ratio effect reflects neural activity of the parietal lobe. This is in line with the proposal that magnitude representations are integrated in association areas in the cortex.

The results of Study 2 are in support for the feedback loop feature of the POMS hypothesis. The presence of a flip in the mean amplitude ratio effect pattern between early and later components suggested that there may be top-down processes influencing mental magnitudes. Support for this interpretation can be found in the modulation of the ERP signal around 300 ms after stimulus onset during conflict processing during visual comparison (Hickey et al., 2009; Rugg et al., 1987; Wang et al., 2002). As discussed in Study 2, the flip in the ratio effect pattern may be indicative of top-down processes modulating mental magnitudes to resolve conflicting cumulative area and non-symbolic number information. When applied using the POMS hypothesis, this may suggest that the integrated magnitude representation is being modified to better represent the targeted magnitude information given the type of trial. Future research using tasks designed to detect top-down processing will have to be conducted to determine whether top-down processes are enhancing target information, suppressing conflicting information, or both.

POMS Hypothesis and Development

The structure of the POMS hypothesis offers some developmental predictions concerning age-related changes in mental magnitudes. Similar to previous research, in Study 1, performance on the judgment tasks increased with older age groups (Halberda &

Feigenson, 2008; Odic et al., 2012). As discussed previously, this improvement has been attributed to an increase in the precision of mental magnitudes and is a result of general maturation processes [e.g., neural efficiency; (Halberda et al., 2012)]. The POMS framework identifies specific components that may undergo developmental changes that, in addition to general maturation, lead to increasing precision in magnitude representations; specifically, perceptual filters and feedback loops. With experience, perceptual filters may become better able to encode magnitude information from the environment, especially when the salience of the information is low. Similar developmental improvements in the strength of representations have been observed in various aspects of perception [e.g., (Aslin & Smith, 1988)]. Age-related experience may also affect the feedback connections between top-down processes and perceptual filters. The level of flexibility in representations proposed by POMS may lead to imprecision in mental magnitudes early in development. When a particular perceptual filter is required to complete a task, infants and children may not be able to selectively enhance the signal from the target filter while reducing the signal from other magnitudes, leading to competition and more variability. In other areas of cognitive development, the use of top-down processes during decision making has been shown to undergo significant improvements during childhood [e.g., (Garon, Bryson, & Smith, 2008)]. Overall, the POMS hypothesis offers ways in which developmental changes affect the formation of mental magnitudes. Future research should further examine these proposals to determine which specific components in the hypothesis change over development.

Dissertation Summary

Across two studies, I examined the specificity of mental magnitudes by comparing cumulative area and non-symbolic number judgments across multiple contexts. In Study 1, I examined whether performance on discrimination tasks for each magnitude differed to a similar degree across different developmental and spatial arrangement contexts. The results of Study 1 suggested that representations of cumulative area and non-symbolic number undergo similar changes across development, but are differentially impacted by the spatial arrangement of stimuli. In Study 2, I examined the onset of ratio and congruity effects for cumulative area and non-symbolic number when they were presented independently or simultaneously using an ERP paradigm. The results of Study 2 indicated that the onset of ratio effects were similar for each magnitude when presented simultaneously, but differed when presented independently. Additionally, congruity effects were present at the initial ratio effects for each magnitude, suggesting the effect was due to an interaction between mental magnitudes. Overall, the results of both studies support the view that mental magnitudes are produced by a partially overlapping magnitude system. I propose a framework for such a system, the POMS hypothesis, which holds that there are distinct perceptual mechanisms, the output of which are summed together to create multifaceted mental magnitudes.

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