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THEORETICAL REVIEW

Number, time, and space are not singularly represented: Evidence against a common magnitude system beyond early childhood

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Abstract
Our ability to represent temporal, spatial, and numerical information is critical for understanding the world around us. Given the prominence of quantitative representations in the natural world, numerous cognitive, neurobiological, and developmental models have been proposed as a means of describing how we track quantity. One prominent theory posits that time, space, and number are represented by a common magnitude system, or a common neural locus (i.e., Bonn & Cantlon in *Cognitive Neuropsychology*, *29*(1/2), 149–173, 2012; Cantlon, Platt, & Brannon in *Trends in Cognitive Sciences*, *13*(2), 83–91, 2009; Meck & Church in *Animal Behavior Processes*, *9*(3), 320, 1983; Walsh in *Trends in Cognitive Sciences*, *7*(11), 483–488, 2003). Despite numerous similarities in representations of time, space, and number, an increasing body of literature reveals striking dissociations in how each quantity is processed, particularly later in development. These findings have led many researchers to consider the possibility that separate systems may be responsible for processing each quantity. This review will analyze evidence in favor of a common magnitude system, particularly in infancy, which will be tempered by counter evidence, the majority of which comes from experiments with children and adult participants. After reviewing the current data, we argue that although the common magnitude system may account for quantity representations in infancy, the data do not provide support for this system throughout the life span. We also identify future directions for the field and discuss the likelihood of the developmental divergence model of quantity representation, like that of Newcombe (*Ecological Psychology, 2,* 147–157, 2014), as a more plausible account of quantity development.

Keywords Nonsymbolic quantity processing · Temporal precision · Spatial processing · Numerical acuity

Our lives are inundated with temporal, spatial, and numerical information. Given the fundamental nature of quantity processing, it may not be surprising that infants, children, adults, and even nonhuman species rely on quantity information to navigate the world. The ability to track quantities is vital for basic learning processes such as foraging (e.g., Levey, 1988; Loiselle & Blake, 1991; Osborne et al., 1999; Shettleworth, Krebs, Stephens, & Gibbon, 1988), language acquisition (through the tracking of statistical information; Conway, Bauernschmidt, Huang, & Pisoni, 2010; Romberg & Saffran, 2010; Saffran, Aslin, & Newport, 1996), and decision-making (see Hyde, Porter, Flom, & Stone, 2013; Lusardi, 2012; Peters et al., 2006; Reyna, Nelson, Han, & Dieckmann, 2009), to name a few. Further emphasizing the pervasiveness of quantity processing is evidence that basic quantitative abilities may underlie formal academic achievement in humans (time, space, and number: Skagerlund & Träff, 2016; space: Bonny & Lourenco, 2015; number: Holloway & Ansari, 2009; Mazzocco, Feigenson, & Halberda, 2011; space and number: Geary & vanMarle, 2016; number and time: Odic et al., 2016). Given the ubiquity and importance of quantity representation, it is essential to understand how basic quantitative processing occurs.

Theories of quantity representation

Several theories have been put forth to describe how quantities are represented. The most prominent, and the focus of this article, is that of the common magnitude system. Through experiments in which rats were able to generalize rules in one domain (e.g., time) to another domain (e.g., number),

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Meck and Church (1983) were the first to suggest that a single, shared cognitive system (the analog magnitude system, or AMS), located within a specific neural locus, was responsible for processing time and number. Expanding this theory to include spatial magnitudes, Walsh (2003) offered a theory of magnitude (ATOM), positing that time, space, and number are represented by a common magnitude system in which quantities are specifically linked via a common metric for action. That is, Walsh (2003) argues that processing quantities using a single system facilitates sensorimotor actions. Although Bonn and Cantlon (2012, 2017) agree that quantities are represented in a similar fashion, they believe the common currency to be ratio calculations rather than actions. According to this view, comparisons between two of the same quantities (number vs. number) or two different quantities (number vs. time) rely on tracking the ratios between them, rather than attending to the actual quantities themselves.[1]

Despite much support for a common system representing all or at least some quantity representations throughout part of the life span, others have suggested that distinct modules are responsible for quantity processing. That is, the idea is that although there are similarities in the way that time, number, and space are represented, there are distinct cognitive/neural loci responsible for tracking each of these quantities, undermining claims of a single common magnitude system. For example, some have proposed a single system for tracking number alone—the approximate number system (ANS)—thought to be an innate, domain-specific structure that allows for the representation of number (Dehaene, 1997; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Odic & Starr, 2018). Other researchers have focused exclusively on interval timing abilities (e.g., Buhusi & Meck, 2009) or spatial abilities (e.g., Vasilyeva & Lourenco, 2012), considering these domains to be distinct from each other.

A plethora of research identifying commonalities in how we track temporal, numerical, and spatial information has provided support for claims of a common magnitude system (e.g., time, space, and number: Crollen, Grade, Pesenti, & Dormal, 2013; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Lourenco & Longo, 2010; number and space: Dehaene, Bossini, & Giraux, 1993; DeWind & Brannon, 2012; number and time: Dormal, Dormal, Joassin, & Pesenti, 2012; Meck & Church, 1983; space and time: Bottini & Casasanto, 2013; Vallesi, Binns, & Shallice, 2008). Despite this, research explicitly exploring predictions of a common magnitude system has also revealed numerous inconsistencies across spatial, temporal, and numerical processing, particularly later in development (e.g., time, space, and number: Agrillo, Piffer, & Adriano, 2013; Droit-Volet, Clément, & Fayol, 2008; Odic, 2018; Skagerlund & Träff, 2016; time and number: Baker, Rodzon, & Jordan, 2013; Hamamouche, Keefe, Jordan, & Cordes, 2018; Lewis, Zax, & Cordes, 2017; Young & Cordes, 2013; space and number: Geary & Vanmarle, 2016; Odic et al., 2013). In response to these inconsistencies, Newcombe (2014) proposed the developmental divergence account, which serves as a compromise between these two theories. She suggested that although a common magnitude system is present in infancy, representations for each quantity diverge over the course of development. Newcombe, Levine, and Mix (2015) offer support for this theory by highlighting evidence supporting the idea that at least space and number representations are first represented by a single system. The signal clarity hypothesis, which suggests that in infancy all quantities are seen as a single dimension, and thus the confounded nature of quantity facilitates infants' understanding of quantity, is also consistent with the developmental divergence model (Cantrell & Smith, 2013; Cantrell, Boyer, Cordes, & Smith, 2015). In this article, we review the evidence for and against a common magnitude system and conclude that, while not conclusive, the data provide the strongest support for the developmental divergence model (Newcombe, 2014).

Implications of a common magnitude system

Determining whether or not a common magnitude system exists throughout development is important for several reasons. First and foremost, investigating the likelihood of this system will inform current cognitive models of quantity processing, guiding research in this important domain. Much of the research in the field over the past several decades has been motivated by the proposal of the common magnitude system. Thus, by fine-tuning our understanding of how time, space, and number are represented, we can refine the questions we address regarding how these quantity representations shape our understanding of the world. Moreover, the common magnitude account has shaped research into educational interventions (e.g., Siegler & Ramani, 2009). Siegler and Ramani (2009), for instance, show that drawing children's attention to the spatial representation of number through linear board games facilitates children's understanding of number. As such, a more complete understanding of quantity representation may be critical for creating more advanced interventions. More broadly, understanding the likelihood of a common

[1] Recently, Leibovich and colleagues argued that a single system represents all quantities, but over development, number processing separates from continuous quantities, such as time and space ("sense of magnitude theory"). Because numerosity is often confounded with other continuous dimensions (e.g., a larger number of items also takes more space), supporters of the sense of magnitude theory assert that numerical representations are simply an artifact of representations of continuous quantities (Leibovich, Katzin, Harel, & Henik, 2017). According to this view, early in development, infants are unable to track number—they are only able to represent continuous quantity dimensions. Over time, as children develop language, they become able to discriminate number from (e.g., space). Key to this theory is the idea that numerical information is not readily trackable early in development—that our ability to track number only emerges over the course of development as children come to understand that quantity information is highly correlated in the environment.

magnitude system may also facilitate neurobiological investigations in mapping of the human brain, which may be particularly important for furthering our knowledge of cognitive disorders, such as Turner syndrome and attention-deficit/hyperactivity disorder (ADHD), which typically involve comorbid quantity processing deficits.

Predictions of a common magnitude system

Although there is reason to believe the relation between number and space is stronger than the connections between number and time or time and space, the common magnitude account predicts all quantities to be represented by a single system. That is, the same cognitive system is used to represent the duration of a sound, the number of clouds in the sky, or the distance between two points. As such, we will review literature across the three domains of time, number, and space. Although the specific predictions of a common magnitude system have not been clearly outlined, we investigate six distinct pieces of behavioral and neural evidence that have been offered in favor of this account.

First, according to this account, temporal, spatial, and numerical precision should adhere to similar behavioral signatures, including comparable (1) *discrimination precision* among quantities, as measured by adherence to Weber's law. In addition to adhering to Weber's law, discrimination precision is predicted to be comparable across development, and within individuals. That is, temporal, spatial, and numerical acuity should become more precise at a comparable rate across development, *and* temporal, numerical, and spatial magnitude acuity should be identical, or at least correlated, within the same individuals.

If a single system were responsible for processing all quantity information, one would also expect frequent (2) *interactions across quantity representations*. A common magnitude system implies that temporal, numerical, and spatial magnitudes are represented via a common mental currency; and as such, it is likely that representations of one quantity may be confused with representations of another, leading to biased responding (e.g., Meck & Church, 1983). Thus, it would be highly likely that, for example, spatial magnitude information would interfere with and/or bias, for example, numerical judgments (herein referred to as quantity interference). Relatedly, if quantitative information was transformed into a common currency, one would expect rules learned in one quantitative domain to be spontaneously generalized to the other domains (i.e., cross-domain transfer), resulting in the mapping of one quantity onto another (e.g., number being mapped to space; cross-domain mapping).

The common magnitude account would also predict identical (3) *response biases in identical contexts*. Although investigations of quantity representation often take place in controlled lab settings, quantity processing in the real world occurs in variable contexts. For instance, we may need to judge the distance between a speeding car and the crosswalk where we stand, or the number of seconds it will take for the car to reach the intersection. These real-world contexts introduce emotional responses and/or limitations on cognitive processing that may take away from our ability to make accurate quantitative judgments. Importantly, if time, space, and number were represented by the same mental magnitudes via a single system, one would expect these external factors to affect quantity processing identically.

Moreover, this account also anticipates temporal, numerical, and spatial processing to have identical relations to (4) *formal learning*, specifically, math achievement (e.g., calculation, problem solving). Although the relation between numerical acuity and math abilities should be straightforward—mathematical abilities rely on an understanding of basic numerical concepts—it is less clear why a relation between temporal and/or spatial processing and mathematical abilities should exist. Although research has supported ties between basic timing and math, and, separately, between spatial processing and math, a common magnitude would suggest that these relations should be identical—that is, temporal, numerical, and spatial abilities should predict the same aspects of mathematical processing.

In addition to comparable behavioral patterns, a common magnitude system, presumably located at a common neural locus, predicts overlapping (5) *neural activation* to occur during temporal, numerical, and spatial tasks. That is, temporal, numerical, and spatial processing should not only invoke identical brain activation patterns but finer grain analyses at the neuronal level should also reveal a common representational code. Relatedly, because quantity processing should be tied to a single neural locus, any impairments to this quantity processing system should result in identical temporal, numerical, and spatial deficits. Thus, (6) *clinical investigations* should reveal similar quantity processing impairments. In particular, the comorbidity of temporal, numerical, and spatial processing impairments should be very high.

We review existing data addressing a common magnitude system, focusing in particular on these six assumptions. Our review reveals strong support for a common magnitude system early in development; however, we conclude that the current evidence does not support the presence of the common magnitude system throughout the life span. Instead, we argue, data reveal, at least by midchildhood, that time, space, and number are more likely represented by three distinct magnitude systems. Although more data are needed to address a developmental account, we end by discussing the possibility of a developmental divergence model like that of Newcombe (2014), in which a single locus may be present at birth but quickly diverges into three separate systems over early childhood.

Behavioral signatures

Research demonstrating remarkable similarities in the behavioral signatures of temporal, numerical, and spatial processing has frequently been offered as evidence in favor of a common magnitude system (e.g., time, space, and number: Agrillo et al., 2013; Dormal & Pesenti, 2013; Gallistel, 1990; space and number: de Hevia, Vanderslice, & Spelke, 2012; time and number: Meck & Church, 1983). Although there are many similarities, there are also many striking inconsistencies in the behavioral data of children and adults, which cast doubt on the likelihood of the common magnitude system supporting quantity representations throughout all of development.

Discrimination precision

A myriad of studies reveal that temporal, numerical, and spatial magnitude (i.e., length or area) discriminations follow Weber's law; that is, the speed and accuracy with which two values are discriminated is dictated by the ratio between them, not their absolute difference (Stevens, 1957). Importantly, this pattern is present across species, and across human development (nonhuman animals: e.g., Jordan & Brannon, 2006; Meck & Church, 1983; Tudusciuc & Nieder, 2010; see Gallistel, 1990, for a review; human development: Brannon, Lutz, & Cordes, 2006; Brannon, Suanda, & Libertus, 2007; Cantlon & Brannon, 2007; Droit-Volet et al., 2008; Feigenson, 2007; Halberda & Feigenson, 2008; Izard, Sann, Spelke, & Streri, 2009; Odic, 2018; Odic et al., 2013; Provasi, Rattat, & Droit-Volet, 2011), suggesting that this is not a learned pattern of responding, but instead reflects something inherent in the way we represent these quantities.

Although we are able to discriminate magnitudes early in development, this ability becomes more precise with age (e.g., Droit-Volet et al., 2008; Halberda & Feigenson, 2008; Odic et al., 2013), with the most dramatic changes occurring in infancy (see Feigenson, 2007, for a review). Proponents of a common magnitude system have emphasized findings of comparable developmental trajectories for spatial, temporal, and numerical discriminations in infancy. These data demonstrate that infants as young as 6 months of age consistently discriminate changes involving a 1:2 ratio change in number (Xu & Spelke, 2000), duration (VanMarle & Wynn, 2006), and surface area (i.e., spatial magnitude; Brannon et al., 2006), but consistently fail to detect a 2:3 ratio change for these same quantities. Following the same trajectory, 10-month-old infants successfully discriminate a 2:3, but not a 3:4 ratio change for time (Brannon et al., 2007) and number (Xu & Spelke, 2000; see Cordes & Brannon, 2008, for a review), although no published studies have assessed area discriminations at this age.

Although similar levels of precision at varying points of development in infancy have been reported, the data are less consistent with regard to the acuity of quantity representations in children and adults. Spatial and numerical acuity differ in childhood (Geary & Van marle, 2016; Odic et al., 2013), although the direction of the difference has varied across reports. Moreover, 2-year-olds to 12-year-olds' performance on temporal, spatial, and numerical discrimination tasks reveal distinct, independent developmental trajectories for each quantity (Odic, 2018). Specifically, despite spatial discriminations (both area and length) maturing to adult-like levels of performance in adolescence, temporal discriminations continue improving throughout early adulthood. Numerical abilities peak after spatial dimensions, but before temporal ones. Differences in discrimination precision have also been reported in adulthood, such that adults reliably discriminate an 8:9 ratio difference of number, but a finer 9:10 ratio of area (Odic et al., 2013). Temporal acuity remains lower than spatial or numerical acuity in both children and adults (Droit-Volet et al., 2008, Experiment 1).

Although there is overwhelming evidence to suggest that comparable developmental trajectories exist in infancy, but not later on, some have argued that differences in stimulus format may account for distinct discrimination precision. Whereas numerical and spatial stimuli can be presented in either a simultaneous manner (i.e., an array of items or a particular line length presented for a brief period) or a sequential manner (i.e., the number of dots displayed one at a time, or the length of space an item travels), time is inherently incremental (accumulating over time, i.e., sequential). Critically, this means that the mode of presentation of temporal stimuli is typically distinct from that of numerical and spatial stimuli, potentially undermining our ability to make a fair comparison of acuity levels for these distinct quantities. Few studies have consciously controlled the presentation mode of quantitative stimuli when investigating similarities in quantity processing. In one of the few studies to do so, Droit-Volet et al. (2008) systematically controlled for presentation format by presenting temporal, numerical, and spatial stimuli in a sequential format. The authors found that only when presentation format was similar, acuity across the three quantities was comparable in children and adults. These findings suggest that differences in acuity—at least between that of timing and the other quantities—may, in fact, be driven primarily by differences in presentation format. That is, time, space, and number may be more similar when all three quantities are presented visually and/or sequentially (Droit-Volet et al., 2008; see also Cai & Connell, 2015, for space and time). Importantly, however, differences in acuity across number and space, reported from studies in which both quantities are tested using a simultaneous presentation, cannot be explained away by differences in presentation format (e.g., Droit-Volet et al., 2008; Geary & Vanmarle, 2016; Odic, 2018; Odic et al., 2013). Future work will be critical in determining the role of presentation format in quantity discrimination across the life span.

Although a common magnitude system would not be discounted by subtle differences in the discriminability of each quantity, the finding of consistent, unique developmental trajectories in quantity acuity undermine predictions of a single quantity processing system throughout the entire life span. In particular, the fact that numerical and spatial acuity—both of which are typically presented simultaneously—continue to differ throughout development undermines the common magnitude account. Despite this, the consistency of the acuity with which infants discriminate quantities supports the possibility that a common magnitude system may be present early in development.

Individual differences If temporal, numerical, and spatial magnitudes are represented by a single common currency, then we should also expect similar levels of acuity for these three quantities within the same individual—that is, one's ability to detect changes in number should track with their ability to detect changes in time and space. There is mixed evidence regarding how well representational acuity of these three quantities correlates within the same individuals (e.g., time, space, and number: Agrillo et al., 2013; De Visscher, Noël, Pesenti, & Dormal, 2017; Odic, 2018; number and space: Geary & Vanmarle, 2016; Odic et al., 2013; time and number: Hamamouche et al., 2018; Odic et al., 2016; Young & Cordes, 2013). Although some studies have revealed similar representational acuity of these distinct quantities (DeWind & Brannon, 2012; Jang & Cho, 2016; Lourenco & Bonny, 2017), others have not found a correlation between tasks (e.g., Agrillo et al., 2013;[2] Hamamouche et al., 2018; Odic et al., 2016). Although the ratios used in each task should not affect the likelihood of a correlation between tasks, it should be noted that those studies showing correlations tend to use the same ratios across quantities (see DeWind & Brannon, 2012; Jang & Cho, 2016; Lourenco & Bonny, 2017; but see Young & Cordes, 2013). Importantly, if the ratio is indeed affecting the likelihood of a correlation between quantities, this would indicate that it is the method of measurement, not necessarily the underlying quantity representations that are resulting in the lack of a correlation.

Although these variations in quantity discrimination undermine claims of a common magnitude system in childhood and adulthood, the absence of a correlation is not necessarily grounds for discounting the possibility of such a system. One possible explanation for this is low reliability between the tasks (see Norris & Castronovo, 2016). Supporting this possibility are data showing no correlation between comparable numerical discrimination tasks when the dot arrays were created using different methods (Clayton, Gilmore, & Inglis, 2015; see also DeWind & Brannon, 2016). Additionally, there are many challenges in interpreting correlational data, and thus we must be cautious when considering correlations. Although the absence of a correlation between tasks is not enough evidence to completely discount the common magnitude account, it adds to the list of counterevidence of such a system post-infancy. Importantly, because of limitations on the number of tasks that can be administered to a single infant, no work to date has explored whether individual acuity measures for time, number, or space correlate within infant participants.

[2] In this study, the same ratios were used for the temporal and spatial tasks, but different ratios were employed on the numerical task. None of the correlations reached significance.

Interactions across representations of time, number, and space

Evidence of a common magnitude system has also been drawn from notable interactions between representations of time, space, and number. Here, we review evidence of these interactions, while also providing alternative explanations for such interactions. Namely, we posit that findings of quantity interactions may instead be accounted for by domain-general processes such as analogical reasoning, not necessarily by the existence of a common magnitude system. Importantly, although domain-general processes may explain the findings of cross-domain interactions in childhood and adulthood, these capacities are not fully developed in infancy, thus leaving open the possibility of a common magnitude system early on.

Interference across domains Quantity interference between numerical, spatial, and temporal judgments has been demonstrated in children, adults, and even nonhuman primates (e.g., time and number: Agrillo, Ranpura, & Butterworth, 2010; Dormal, Seron, & Pesenti, 2006; Droit-Volet, Clément, & Fayol, 2003; time and space: Bottini & Casasanto, 2013; Merritt, Casasanto, & Brannon, 2010; number and space: Clayton & Gilmore, 2015; Nys & Content, 2012). In general, interference is defined as the disruption of quantity processing by irrelevant quantitative information, particularly from a different domain (i.e., differences in item size biasing judgments of the number of items). For example, when participants are instructed to select the more numerous of two arrays, in which half of the trials are congruent in spatial quantity (i.e., the more numerous array also has a greater cumulative surface area) and the other trials are incongruent in spatial quantity (i.e., cumulative area is the same in both arrays, such that the more numerous array contains smaller individual elements), responses are slower and less accurate on incongruent trials relative to congruent trials (e.g., Clayton & Gilmore, 2015; DeWind & Brannon, 2012; Gilmore et al., 2013; Hurewitz, Gelman, & Schnitzer, 2006; Nys & Content, 2012). That is, when making a numerical judgment, participants are unable to ignore the spatial extent of the arrays, leading to biased responses. Mirroring these findings, similar experiments exploring the impact of numerical information on spatial judgments have revealed the reverse pattern, such that participants are less precise in judging relative spatial extent when the array with the greater cumulative area has fewer items (e.g., Barth, 2008; Hurewitz et al., 2006; Nys & Content, 2012).

Temporal judgments also interact with spatial and/or numerical information; however, studies have revealed an asymmetrical pattern of interference. That is, numerical and spatial information have been found to bias temporal judgments, but temporal information does not alter numeric or spatial judgments in either children (space: Bottini & Casasanto, 2013; Casasanto, Fotakopoulou, & Boroditsky, 2010; number: Droit-Volet et al., 2003) or adults (space: Casasanto & Boroditsky, 2008; Merritt et al., 2010; Xuan, Zhang, He, & Chen, 2007, but see Cai & Connell, 2015; number: Dormal et al., 2006, but see Agrillo et al., 2010). In one study, children watched two animals move across a computer screen. The animals traveled either (1) different distances over differing periods of time; (2) different distances, but over the same amount of time; or (3) the same distance, but over a different amount of time. After watching the animals, children were asked questions regarding the distance and/or duration of the animal's movement. Results revealed that competing spatial information (traveling different distances) drastically reduced accuracy on temporal questions ("Did the two snails stop *at the same time*?"), but competing temporal information (traveling for different amounts of time) did not affect spatial judgments ("Did the two snails stop *at the same place*?"; Bottini & Casasanto, 2013). Although results of this work indicate that more numerous and physically larger stimuli are judged as lasting longer (e.g., Xuan et al., 2007), some work suggests that this does not mean the stimuli are actually *perceived* as lasting longer, but instead that the spatial information biases decisions about time (Yates, Loetscher, & Nicholls, 2012).

Two studies concurrently pitted all three quantities against each other, resulting in conflicting findings (Dormal & Pesenti, 2013; Lambrechts, Walsh, & van Wassenhove, 2013). Dormal and Pesenti (2013) instructed participants to judge which of two sequentially presented arrays was (1) more numerous, (2) physically longer, or (3) presented for the longer duration. Importantly, each array varied in numerosity (the number of dots), spatial extent (the length of the dot array), and presentation duration. Results were consistent with previous findings revealing asymmetry, such that both numerical and spatial cues interfered with temporal judgments, but temporal cues did not affect numerical or spatial ones (Dormal & Pesenti, 2013). On the other hand, Lambrechts et al. (2013) also asked participants to judge the numerosity, spatial extent, or duration of displays; however, their paradigm differed in two critical ways. First, the arrays were presented simultaneously. That is, the dots were displayed all at once rather than one at a time. Secondly, half of the participants were told which quantity to judge before seeing the stimuli (prospective judgment condition), whereas the other half of the participants were told which judgment to make after seeing the stimuli (retrospective judgment condition). Performance was comparable regardless of condition (prospective vs. retrospective judgment); however, the results indicated the reverse pattern of interference: Temporal judgments were not affected by space or number, yet temporal cues affected both numerical and spatial judgments. Thus, although there is clear evidence for quantity interference, there is some inconsistency in the reported direction of the phenomenon.

Another form of quantity interference has been shown using a cross-domain adaptation paradigm. In this work, participants are first shown a spatial prime of two circles that vary in size. After a specified duration, the circles disappear and are replaced with dot arrays. Participants are then asked to select which dot array is more numerous. When comparing large numerosities, judgments are biased by the previously presented spatial display, such that participants were more likely to select the more numerous of two arrays when the choice was preceded by a larger circle (Zimmermann & Fink, 2016; see also Burr & Ross, 2008). These data provide further evidence that spatial information can bias numerical judgments.

What accounts for this interference? Proponents of the common magnitude system posit that if time, number, and space are represented by a common mental currency, then it would be reasonable to expect different quantity representations to interfere with our ability to make quantity judgments—that is, magnitude representations of one quantity may be indistinguishable with magnitude representations of another quantity, leading to biased responding.

On the other hand, these interference effects may occur because quantity judgments were based upon encoding magnitude information via linguistically mediated generic concepts such as "more," "less," "a lot," "big," and so on. Interference among quantities may also occur at the response stage when choosing which array contained, for example, "more." Thus, using the same linguistic term is used to describe numerical, spatial, and temporal quantities may lead to biases, at either the encoding or response stage (see Kadosh, Kadosh, Linden, Gevers, Berger, & Henik, 2007; Odic & Starr, 2018). Given that English speakers often use spatial language to talk about time, but they do not use temporal language to refer to space (Lakoff & Johnson, 1980), one might expect spatial information to bias temporal judgments, but spatial judgments to be unaffected by temporal information. In fact, several studies have found support for this asymmetrical relationship in both children (Bottini & Casasanto, 2013; Cassasanto, Fotakopoulou, & Boroditisy, 2010) and adults (Casasanto & Boroditsky, 2008; Merritt et al., 2010; Xuan et al., 2007). Despite this, one recent study undermines this linguistic account by revealing cross-domain interference occurring even when linguistic cues cannot be used at the encoding or response stage. In this study, participants' spatial judgments were biased even when Arabic numerals were presented subliminally and thus language was unlikely to be invoked to encode or respond to quantity information (Lourenco, Ayzenberg, & Lyu, 2016).

Although a linguistic encoding account is not supported, many critics of the common magnitude account still argue that interference across quantity representations should not be taken as definitive evidence for a single, representational system. Interactions across quantity representation may be predicted even in the absence of a common magnitude system. That is, one would still predict interactions between quantities if separate, but parallel quantity systems were simultaneously activated when making quantitative judgments (see Odic & Starr, 2018, for a similar argument). Given that response biases are found in quantitative processing in the context of stimuli not posited to be represented in the common magnitude system (e.g., emotional stimuli result in temporal overestimation and numerical underestimation: Young & Cordes, 2013; filled intervals are perceived as lasting longer than empty intervals: Wearden, Norton, Martin, & Montford-Bebb, 2007), these interactions may not necessarily be driven by a common system. Moreover, symmetrical cross-domain interference is a requisite of a common magnitude system. Thus, the finding of asymmetrical patterns of interference, particularly in the case of time, similarly undermine claims of a common magnitude system. In sum, findings of interference among quantity representations are neither conclusive proof of nor clear evidence against a common system.

Cross-domain transfer Another behavioral phenomenon provided as support for a common magnitude system is that of cross-domain transfer, in which rules learned within one quantitative domain are applied to a different quantitative domain, either through explicit instruction or via spontaneous transfer. Meck and Church (1983), the first to posit a single AMS for tracking time and number, provided some of the first evidence of spontaneous cross-domain transfer. In their study, rats were trained to press one lever when a stimulus was presented for 2 seconds and another lever when a stimulus was presented for 8 seconds. Then, during the testing phase, ambiguous stimuli that did not vary in duration (always lasted 4 seconds), but varied in numerosity, were presented. Results revealed that numerical stimuli were classified according to the previously learned temporal rules, suggesting that the rats spontaneously transferred the temporal rule to the domain of number (Meck & Church, 1983; see also Roberts, Coughlin, & Roberts, 2000).

Spontaneous cross-domain transfer has also been reported in human infants (e.g., de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Lourenco & Longo, 2010). For example, when habituated to arrays of dots that are increasing in number (e.g., four items—eight items—16 items), infants subsequently looked longer when presented with a series of lines decreasing in length (a novel ordinal direction), compared with lines increasing in length, suggesting infants spontaneously generalized an "increasing" rule from number to spatial extent and thus looked longer to the stimuli violating that rule (de Hevia et al., 2014; de Hevia & Spelke, 2010; Lourenco & Longo, 2010; space and time: Srinivasan & Carey, 2010). Similarly, other work has found infants to generalize "increasing" or "decreasing" rules between number and time, time and spatial extent, and spatial extent and number (de Hevia et al., 2014; Lourenco & Longo, 2010). These findings have prompted researchers to propose that infants may perceive temporal, spatial, and numerical quantitative information as falling within a single magnitude continuum.

Children also show cross-domain transfer (e.g., de Hevia etal., 2012). In one study, preschoolers' watched as an experimenter matched cards that varied in either numerosity, length, or brightness. For example, the experimenter may match a card with a specific line length to a card containing a specific number. After only three examples, the child was presented with a card with a specific line length and was asked to choose which of two cards varying in numerosity was the best match. Children easily mapped number onto space (and vice versa) and for space onto brightness (although less robustly). Notably, however, children were unable to map numerosity onto brightness (de Hevia et al., 2012). In line with findings with human infants, these findings reveal children are capable of making cross-domain mappings.

Other evidence of domain transfer comes from work involving the mental number line. Some researchers suggest there is a mapping between number and space (referred to as a mental number line), with smaller numerical values falling in the left side of space and larger values falling on the right side of space. Evidence in favor of this has shown that children (Siegler & Opfer, 2003), as well as literate and illiterate adults (Dehaene, Izard, Spelke, & Pica, 2008; Seigler & Booth, 2004), readily map numbers onto explicit number lines without extensive instruction providing support for a relation between number and space. Stronger evidence of a mental number line is derived from work involving the spatial–numerical association of responses codes (SNARC) effect. The SNARC effect is the phenomenon that individuals from Western cultures are faster to associate small numerical values with the left side of space and larger numerical values with the right side of space, consistent with reference to a mental number line running from left to right (e.g., infants & children: de Hevia, Veggiotti, Streri, & Bonn, 2017; Patro & Haman, 2012; van Galen & Reitsma, 2008; Yang et al., 2014; adults: Dehaene et al., 1993). For instance, when participants judge the parity (odd/even) of numbers, participants are faster to respond with their left hand when the digit corresponds with a small value and with their right hand when the digit is a larger value (Dehaene et al., 1993). Similarly, in implicit priming tasks, adults are faster to detect items in the left visual field after priming with a small-valued number and faster to detect items in the right visual field when primed with larger numbers (Fischer, Castel, Dodd, & Pratt, 2003). These findings indicate that both children and adults may encode number according to a mental number line with smaller values associated with the left side of space and larger values on the right.

Early accounts of the SNARC effect suggested that the imposition of number along a spatial continuum may be a function of cultural reading conventions. In support of this claim, cross-cultural work has shown that the direction of the SNARC effect tracks with the reading direction of the culture, such that individuals in cultures that read from right to left exhibit a "reverse" (i.e., right-to-left) SNARC effect (Dehaene et al., 1993). However, more recent findings have undermined claims that this phenomenon is solely a function of culture, by demonstrating the SNARC effect in nonhuman animals (Rugani, Vallortigara, Priftis, & Regolin, 2015). Newborn chicks were trained to locate food behind a panel on which five dots were displayed. During critical test trials, however, chicks saw two side-by-side panels, both of which contained a novel but identical number of dots (e.g., eight dots on each). Consistent with a left-to-right mapping of number in space, chicks were more likely to retrieve food from behind the left panel when the number of dots at test was *smaller* than the trained value, and from the right panel when the number of dots was *larger* than the trained value. Evidence for a similar left-to-right mapping has also been found in 55-hour-old human infants (Rugani et al., 2017). These data have led Rugani et al. (2015) to suggest that humans, and other animals, may be evolutionarily predisposed to represent numbers from left-to-right in space—an orientation that could be the result of asymmetrical brain maturation in which the right hemisphere (which processes the left visual field) develops more rapidly than the left hemisphere during early development (Rugani et al., 2017). If this is the case, then the left-to-right orientation may be available early in life, but still subject to cultural influences later in life.

Time seems to be similarly mapped onto space (the mental timeline; Santiago, Lupáñez, Pérez, & Funes, 2007; see Bonato, Zorzi, & Umiltà, 2012, for a review). Much like work asking individuals to place numbers onto a spatial number line, several studies have asked individuals to order images of items, people, or plants at different stages of time (i.e., images of a seed, a sprout, and a full-grown flower) on a spatial timeline. These investigations have revealed both children and adults consistently place events in a systematic spatial representation (Boroditsky & Gaby, 2010; Fuhrman & Boroditsky, 2007; Tversky, Kugelmass, & Winter, 1991). Like the number line, the direction of the mental timeline depends on language and culture. Individuals from cultures who read left to right represent the past on the left and the future on the right (e.g., Boroditsky, 2001, 2008; Boroditsky, Fuhrman, & McCormick, 2011; Fuhrman & Boroditsky, 2007); Mandarin speakers process the mental timeline in a vertical fashion, with earlier events being above later events (Boroditsky, 2001; Boroditsky et al., 2011); Hebrew speakers process time as moving right to left (Fuhrman & Boroditsky, 2007); and individuals of the Pormpuraaw community envision time as moving east to west (Boroditsky & Gaby, 2010).

Mirroring the SNARC effect, individuals from Western cultures are also more likely to associate short durations with the left side of space and long durations with the right side (Conson, Cinque, Barbarulo, & Trojano, 2008; Vallesi et al., 2008). That is, individuals are quicker at responding to short durations with their left hand and longer durations with their right, an effect coined the spatial–temporal association of response codes (STARC; Vallesi et al., 2008). Relatedly, participants are quicker at judging words that are associated with the past (e.g., *before, yesterday, previously*) with their left hand and words that are associated with the future (e.g., *after, tomorrow, subsequently*) with their right (Santiago et al., 2007). The STARC effect also varies by culture, such that individuals who read right to left exhibit a reverse STARC effect (Ouellet, Santiago, Israeli, & Gabay, 2010). Work with preverbal infants indicates that unlike the SNARC effect, the STARC effect does not hold this early in life (de Hevia et al., 2017), which casts some doubt on the likelihood of time, space, and number being indistinguishable at first. To date, no work has demonstrated the STARC effect in nonhuman animals.

Although cross-domain mappings provide some evidence in favor of the common magnitude account, some of these mapping tasks specifically instruct adults and children to map the quantity onto space, leaving it unclear whether individuals naturally map information in this way or are simply following task instructions. In this case, it is likely that participants invoke analogical reasoning abilities to perform cross-domain mappings. It should be noted that young children are not only capable of forming analogies but that this ability is relatively stable in early childhood (Alexander et al., 1989; Crisafi & Brown, 1986; Goswami & Brown, 1990). For example, when placing numbers on a number line, children or adults may decide where the number falls proportionally between the end points and thus place the number proportionally along the line (e.g., we know that 10 is halfway between 1 and 20, so it must be located at the midpoint of the line). Notably, this explicit analogical reasoning across domains is found for non-quantitative ordinal sequences as well. There is substantial evidence that individuals who read left to right tend to map any ordered information (e.g., the alphabet, days of the week, months of the year) in a left-to-right pattern (Gevers, Reynvoet, & Fias, 2003, 2004; Hurst, Leigh Monahan, Heller, & Cordes, 2014; Previtali, de Hevia, & Girelli, 2010). Again, these sequences (letters, days of the week, etc.) are not likely part of the common magnitude system, suggesting that these findings of explicit cross-domain mappings may not be indicative of a common magnitude system, but instead a general propensity to map *any* ordinal information in space.[3] Thus, it is possible that cross-domain mapping in children and adults is not indicative of a common magnitude system, but instead a tendency to map any ordered information in a consistent fashion.

Animals and human infants, however, do not receive (or understand) explicit instructions on these types of mapping tasks; thus, cross-domain mappings in these populations suggest strong evidence of a common magnitude system. Thus, it seems less likely that analogical reasoning may account for evidence of spontaneous cross-domain transfer. Why? First, because there are not explicit instructions on how to perform the task, it seems unlikely that participants reveal a consistent pattern of responding without a consistent mental model of how quantities may map onto each other. And, second, given that most evidence of spontaneous transfer is found in data from human infants, and the earliest evidence of analogy use reported is at 13 months of age (Chen, Sanchez, & Campbell, 1997), it seems unlikely that cross-domain transfer in infancy is a function of analogy use. Although cross-domain interference in infancy has been shown to predict comparable interference in preschool children, even when controlling for analogical reasoning abilities (Aulet & Lourenco, 2018), future work will be important for determining whether spontaneous cross-domain transfer is found in later childhood and adulthood.

Response biases identical contexts

If time, number, and space were represented by a common magnitude system, then we would predict identical contexts to result in comparable quantitative biases. However, several studies reporting unique quantitative biases in comparable situations contradict this prediction. For example, an extant literature reveals that emotional content affects our ability to process time (for reviews, see Droit-Volet, Fayolle, Lamotte, & Gil, 2013; Droit-Volet & Meck, 2007), such that children and adults *overestimate* time in the presence of angry faces, in particular, relative to neutral or happy ones (Doi & Shinohara, 2009; Droit-Volet, Brunot, & Niedenthal, 2004; Gil & Droit-Volet, 2012; Gil, Niedenthal, & Droit-Volet, 2007; Tipples, 2008; Young & Cordes, 2013; see also Bar-Haim, Kerem, Lamy, & Zakay, 2010; Tipples, 2011). More recently, however, work has revealed that *the same* emotional faces result in the *underestimation* of number (Baker et al., 2013; Doi & Shinohara, 2016; Hamamouche, Hurst, & Cordes, 2016; Lewis et al., 2017; Young & Cordes, 2013; see also Ashkenazi, 2018; Hamamouche, Niemi, & Cordes, 2017). That is, children and adults underestimate number in the context of happy and angry faces relative to neutral ones, whereas they overestimate time in the context of angry faces. Not only is the direction of impact on temporal and numerical judgments opposite (overestimation in the case of time, underestimation in the case of number), the particular emotional stimuli provoking these reactions differ across quantities (angry faces uniquely affect temporal processing, whereas both happy and angry faces affect numerical processing).

As another example, the imposition of cognitive load (remembering and alphabetizing letters while making temporal or numerical judgments) leads to a similar pattern of opposing biases: underestimation of number, and marginal overestimation of time (Hamamouche et al., 2018; but see Block, Hancock, & Zakay, 2010; Brown, 1997, for temporal underestimation during cognitive load). Although it is unknown how early in development these biases occur, the opposing patterns of bias found for temporal and numerical processing under cognitive load and emotional stimuli in childhood and adulthood provide strong evidence against a common magnitude system at this point in development.

Although unique temporal and numerical processing biases occur in the presence of emotional content and cognitive load, it is unknown how spatial extent is affected by external stimuli. Although this work has provided evidence against a common magnitude system, future work is necessary to determine if emotion and/or cognitive load lead to spatial overestimation or underestimation. The findings of this research may unveil important information regarding the cognitive mechanism(s) responsible for these quantitative biases, while also addressing claims of a common magnitude system. Additionally, this work has been limited in the types of external stimuli used. Future work investigating whether there are other contexts that reveal further dissociations, may also guide investigations of quantity representation.

Relation to formal learning

Interestingly, numerical, spatial, *and* temporal processing have each been shown to relate to mathematics achievement, suggesting a common link among these representations. However, upon further inspection, the data point to the fact that specific quantities (e.g., spatial processing) are more closely linked to math topics that share similarities in content (e.g., geometry), further discounting the common magnitude theory.

Numerical acuity The relation between numerical acuity (the precision with which an individual can discriminate between two sets on the basis of their numerosity) and formal math has been well-established across numerous mathematical tasks and ages ranges (e.g., Bonny & Lourenco, 2013; Halberda,

[3] Although this is a strong alternative account, some have argued that unique processes may be involved in mapping ordered sequences (e.g., number) in space and mapping two quantities (e.g., brightness and number) onto one another (e.g., de Hevia & Spelke, 2013).

Mazzocco, & Feigenson, 2008; Mazzocco et al., 2011; Starr, Libertus, & Brannon, 2013; for a review, see Feigenson, Libertus, & Halberda, 2013). For example, numerical acuity at 6 months is predictive of performance on a standardized math assessment at age 3 (Starr et al., 2013), and preschoolers' approximate sense of number has been shown to predict their math abilities at age 6 (Mazzocco et al., 2011). A correlation between our approximate sense of number and formal math abilities is also present in adulthood; Libertus, Odic, and Halberda (2012) discovered a significant relation between undergraduates' approximate sense of number and their math SAT scores. Further, the predictive relation between numerical acuity and math achievement appears to be stable over time—formal math abilities in kindergarten predict numerical acuity at 14 years of age (see Feigenson et al., 2013).

More recent training studies have suggested the possibility of a causal relation between our approximate number and formal math abilities (e.g., Hyde, Khanum, & Spelke, 2014; Khanum, Hanif, Spelke, Berteletti, & Hyde, 2016; Park, Bermudez, Roberts, & Brannon, 2016; Park & Brannon, 2013; Wang, Odic, Halberda, & Feigenson, 2016). In one study, children's performance on a symbolic math task was improved following nonsymbolic addition and nonsymbolic numerical comparison training. Importantly, training in line length addition (i.e., spatial magnitude training) or in brightness comparison, however, did not improve symbolic math performance. Moreover, this improvement was specific to mathematics, as children's performance on a verbal task did not improve with training (Hyde et al., 2014; however, see Park & Brannon, 2014, for an alternative account in adults).

Although the relation between numerical acuity and math achievement is well documented, newer work has doubted the strength of the relation (e.g., Gilmore et al., 2013; Inglis, Attridge, Batchelor, & Gilmore, 2011; Price, Palmer, Battista, & Ansari, 2012; Skagerlund & Träff, 2014). For instance, some have argued that inhibitory control (Fuhs & McNeil, 2013; Gilmore et al., 2013), an ability to order quantities (Lyons & Beilock, 2011; Price & Fuchs, 2016), or symbolic understanding of number (Göbel, Watson, Lervåg, & Hulme, 2014) facilitates this relation. Moreover, this relation appears to hold in childhood, but it is less consistent in adulthood (see Inglis et al., 2011; Price et al., 2012). Nuances in the casual nature of this relation are also important to note. For instance, while training nonsymbolic number appears to improve math performance, training math skills does not lead to enhanced numerical acuity (Lindskog, Winman, & Poom, 2016), and adults' math abilities appear to improve only when the nonsymbolic number training involves manipulating approximate quantities, rather than just comparing them (Park & Brannon, 2014). Importantly, this relation would still be likely if a domain-specific module, such as the ANS, were responsible for numerical processing.

Spatial acuity The relation between spatial abilities and mathematics may be driven by a common ability to perform mental manipulations (e.g., mental rotation, arithmetic decomposition [which requires breaking down a number into different components, such as 12 = 10 + 2]; see Mix & Cheng, 2012, for review). Importantly, though, mental manipulation is not the same as representing spatial magnitude (i.e., the size or length of an item), which is purportedly supported by a common magnitude system. Very few studies have explored the relation between spatial magnitude acuity (e.g., area or length discrimination), which is directly relevant to a common magnitude system, and formal math abilities.[4] This work has reported a relation between area discrimination (i.e., judging spatial magnitude) and geometry and calculation abilities (Bonny & Lourenco, 2015; Geary & Van marle, 2016; Lourenco, Bonny, Fernandez, & Rao, 2012). In one study, preschoolers' abilities to decide which of two shapes contained a larger surface area were related to their ability to solve geometry questions as well as their ability to engage in simple numerical calculations (Bonny & Lourenco, 2015). In another study, area discrimination acuity predicted preschoolers' math abilities (as assessed by a standardized math test including different mathematical competencies). However, this relation did not hold above and beyond other nonsymbolic, numerical abilities, such as nonverbal calculation and ordinal number comparison (Geary & Van marle, 2016), consistent with the idea of a common mechanism underlying both numerical and spatial abilities. In adults, area acuity uniquely accounts for a significant amount of variance in geometry performance and calculation abilities (Lourenco et al., 2012). Thus, spatial acuity appears to be specifically linked to geometry and calculation abilities.

Temporal acuity There is also a relation between temporal acuity and formal math (e.g., Odic et al., 2016; Skagerlund & Träff, 2016); however, the reasoning for this relation is less obvious. Some have argued that a unique relation between temporal and spatial abilities may mediate the relation between time and math (Kramer, Bressan, & Grassi, 2011), whereas others have suggested that the ability to manipulate ordered magnitude, which is important for both numerical and temporal processing, may be key in understanding the relation between temporal processing and mathematics (Skagerlund & Träff, 2016).

Evidence in support of this relation has reported that children at risk for developing dyscalculia (a developmental

[4] Although some studies have explored the relation between spatial scaling abilities (the ability to locate where an item should be located along a line when the line increases or decreases in size) and the ability to indicate proportional information along a line (e.g., Möhring, Frick, & Newcombe, 2018), overt similarities between the two tasks make it likely that these tasks are gauging the same underlying proportional abilities, not necessarily the relation between spatial skills and mathematical abilities.

mathematics disorder) tend to experience impoverished timing abilities early on (Tobia, Rinaldi, & Marzocchi, 2016). In another study, elementary school students completed a battery of symbolic (e.g., arithmetic, symbolic ordinal judgments) and nonsymbolic quantity tasks (numerical discrimination, temporal discrimination). Results revealed that both numerical acuity and temporal acuity correlated with math abilities, and these relations held after controlling for acuity in the other domain and working memory (Odic et al., 2016). That is, although both timing and numerical abilities were related to math abilities, they each offered unique predictive value, undercutting the idea that they were tapping into similar representations by a common magnitude system.

Although links between formal mathematics achievement and temporal, spatial, and numerical abilities have been established, the fact that temporal and spatial acuity predict distinct aspects of math achievement, whereas numerical acuity predicts several aspects of mathematics, undercuts claims of a single magnitude system. For instance, spatial abilities appear closely linked to geometry and calculation (Lourenco et al., 2012), whereas timing abilities appear to be specifically related to multidigit calculation abilities (Skagerlund & Träff, 2016). Explorations of these relations in infancy and childhood also demonstrate unique relations between nonsymbolic acuity and formal math. Starr et al. (2013), for example, found a significant relation between infant numerical acuity, but not area acuity, and math abilities at age 3. Moreover, under the premise of a common magnitude system, one would predict the relation between quantity processing (e.g., time) and math to disappear when controlling for performance on another quantity (e.g., number). However, reports indicate quantity processing in one domain (i.e., time) continues to significantly predict mathematics when controlling for quantity processing in another domain (i.e., number; Odic et al., 2016). Overall, the relations between quantity processing and mathematics do not provide substantial support for the existence of a common magnitude system.

Neural signatures

The work discussed thus far has concerned similarities and differences among behavioral data across quantity representations; however, parallels in neural and clinical investigations have also provided insight into the plausibility of a common magnitude system. Although neural and clinical evidence point to some commonalities in quantity processing, we argue that the data are not nearly robust enough to support the existence of a single system. In particular, distinct topographic organizations for number and space (Harvey, Fracasso, Petridou, & Dumoulin, 2015) indicate that separate neural networks are likely responsible for quantity processing. Moreover, comorbid processing deficits seem linked to clinical disorders that emerge early in development, as opposed to later in life.

Patterns of neural activation

Neurobiological investigations give pause to claims of the existence of a common locus of activation for quantitative processing. Although some evidence of comparable neural activation during quantity processing has been offered in support of the common magnitude account (space and number: Dormal, Andres, & Pesenti, 2012; time and number: Dormal, Dormal, et al., 2012), several studies have revealed unique brain activation patterns during quantity processing, specifically during timing tasks (e.g., Gooch, Wiener, Hamilton, & Coslett, 2011; Mattell & Meck, 2004; Vuokko, Niemivirta, & Helenius, 2013). The general consensus is that the intraparietal sulcus (IPS) is active during numerical and spatial processing; in contrast, subcortical areas have been identified as the primary locus of timing. Importantly, the common magnitude system would predict not only common brain activation patterns but also a common representational code across quantities. Despite some evidence for similar neural activation patterns when processing these distinct quantities, there is no evidence for a common representational code for both quantities—at least in respect to space and number (Borghesani et al., 2018). Given that timing appears less connected to both space and number, it is unlikely that a common representational code exists between space and timing or number and timing.

Number A substantial literature suggests that the IPS is activated during numerical processing. For instance, IPS activation has been reported when individuals make numerical judgments (i.e., which array of dots is more numerous; Castelli, Glaser, & Butterworth, 2006; Dormal & Pesenti, 2012; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pesenti, Thioux, Seron, & De Volder, 2000; Piazza, Mechelli, Butterworth, & Price, 2002; Venkatraman, Ansari, & Chee, 2005).[5]

[5] Although the IPS has been identified as the neural locus of numerical processing, it is important to note that a network of brain regions—not solely the IPS—is responsible for this process. In addition to the IPS, the right middle and inferior frontal gyri and the right supplementary motor area appear to be activated during numerical processing (Dormal, Dormal, Joassin, & Pesenti, 2012). Moreover, a meta-analysis conducted by Sokolowski, Fias, Mousa, and Ansari (2017) revealed activation in the frontoparietal network, specifically, the bilateral parietal and frontal cortex, and the bilateral middle occipital gyri during nonsymbolic number processing. The parietal cortex, more broadly, has also been implicated in numerical processing. In particular, Harvey, Klein, Petridou, and Dumoulin (2013) determined the topographic organization of numerosity within the parietal cortex. Importantly, number-specific neural models best predict numerosity judgments compared with other nonnumerical features (e.g., convex hull, density) that might vary with numerosity, indicating that this mapping is unique to number (Harvey & Dumoulin, 2017).

This pattern of activation, which is seen throughout development (Cantlon, Brannon, Carter, & Pelphrey, 2006), becomes more localized with age (Ansari & Dhital, 2006). Further emphasizing the role of the IPS in numerical processing are data revealing that children who suffer from dyscalculia, a number-processing disorder, have weaker activation in the IPS when engaging in numerical tasks compared with typically developing peers (Mussolin et al., 2010; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007).

Although patterns of activation give some insight into the neural locus of quantity processing, the most stringent test occurs when a specific brain region is deactivated. This work has revealed that applying transcranial magnetic stimulation (TMS, a process that uses magnetic fields to activate, or render inactive, specific brain regions) to the left IPS, but not adjacent brain regions, leads to impaired numerical processing (Cappelletti, Barth, Fregni, Spelke, & Pascual-Leone, 2007). Comparable findings have been reported when applying TMS to the right IPS (Dormal, Andres, & Pesenti, 2012). Together, this evidence suggests that the IPS is critical in numerical processing.

Space Spatial processing also appears to rely heavily on the IPS (Dormal, Andres, et al., 2012; Fias et al., 2003; but see Cantlon et al., 2006). For example, IPS activation occurs in adults when they judge which of two discrete, linearly arranged arrays of dots or two rectangles are physically longer (Dormal & Pesenti, 2009). Moreover, when processing spatial locations, adults show activation in the right posterior parietal cortex and IPS. TMS studies also emphasize the role of the IPS in spatial processing—deactivating the IPS (Bjoertomt, Cowey, & Walsh, 2002; Dormal, Andres, et al., 2012) or the posterior parietal cortex (Göbel, Calabria, Farne, & Rossetti, 2006) through the use of TMS also disrupts spatial abilities.

Despite evidence supporting the role of the IPS in both numerical and spatial processing, direct comparisons of numerical and spatial tasks within the same individuals indicates that the patterns of brain activation are not completely overlapping. For example, one study instructed children and adults to make judgments about either the number of items on the screen (number), the orientation of the items (space), or the color of the items (control) and found both age-specific and task-specific neural activations. Although both numerical and spatial judgments elicited activation in adults' right posterior superior parietal lobe, nonoverlapping activations occurred in the right angular gyrus and the right IPS for numerical judgments and in the superior and inferior parietal lobe regions for spatial ones. Children, on the other hand, showed no overlapping activations during numerical and spatial tasks (Kaufmann et al., 2008). In another experiment, adults showed similar activations in the right posterior parietal cortex and IPS when processing spatial (locations on a screen) and numerical (Arabic numerals) stimuli, yet contrasts also revealed unique activations in regions solely associated with spatial or numerical processing (Coull & Frith, 1998). It should be noted that the majority of these studies involve spatial tasks that do not require spatial magnitude judgments, thus a lack of neural overlap may not completely undermine a common magnitude account. However, Harvey et al. (2015) investigated topographic mappings of object size (spatial magnitude) and numerosity. Although data revealed some overlap in the topographic organization of both number and object size tuning, the properties of the mappings were largely distinct, further indicating differences in spatial and numerical representations (Harvey et al., 2015). Thus, although the IPS may be activated in both spatial and numerical processing, each quantity recruits a unique network of brain regions, making it unlikely that a common magnitude system fully underlies quantity processing.

Time Support for IPS involvement in the case of timing, however, is less clear. Some studies have reported IPS activation during timing tasks (see Coull, Vidal, Nazarian, & Macar, 2004; Pouthas et al., 2005) and impaired timing abilities when TMS is applied to the IPS (Walsh & Pascual-Leone, 2003). And, a few studies have found overlapping activation in the IPS, precentral, middle, and superior frontal gyri (Dormal, Dormal et al., 2012) or the inferior frontal gyrus and right intraparietal cortex (Hayashi et al., 2013, Experiment 1) during both temporal and numerical processing.

Despite some comparable findings, there are many reasons to believe the IPS is not central to timing. First, participants were slower at making numerical, but not temporal judgments, after TMS was applied to the left and right IPS (Dormal, Andres, & Pesenti, 2008). Moreover, it has been argued that the activation of the IPS during timing tasks may be attributed to attentional factors rather than specifically to making temporal judgments (e.g., Casini & Ivry, 1999; Harrington, Haaland, & Knight, 1998; Meck, Church, Wenk, & Olton, 1987). Extensive work with humans and rodents points to the cerebellum and basal ganglia as the center of temporal processing (see Mattell & Meck, 2004; Rammsayer & Classen, 1997), with cortico-striatal circuits within the basal ganglia being particularly important during suprasecond (>1 second) timing (Buhusi & Meck, 2009; Coull et al., 2004; Hinton & Meck, 2004; Meck, Penney, & Pouthas, 2008). The fact that the cerebellum and the basal ganglia are involved in timing, but less so during numerical or spatial tasks, points to distinct neural loci for temporal magnitude judgments compared with numerical and spatial ones. It should be noted, however, that these brain regions (specifically the cerebellum) are also involved in visual and auditory perception (Baumann et al., 2015), and so its involvement in timing may reflect a more general perceptual processing function, rather than a unique role in timing. Still, the general consensus seems to be that neurobiological studies do not support the existence of a common neural locus for temporal, numerical, and spatial processing—that is, they do not support a common magnitude system.

Clinical investigations

Evidence in support of a common magnitude system, however, is derived from clinical investigations revealing comorbid quantity processing deficits (see Vicario, Yates, & Nicholls, 2013, for a review), primarily in developmental disorders. For example, patients with genetic disorders such as Turner syndrome exhibit deficits in both spatial and temporal processing, in addition to poorer math abilities, compared with their IQ-matched peers (Silbert, Wolff, & Lilienthal 1977). Similarly, children with chromosome 22q11.2 deletion syndrome show difficulties in mathematics, spatiotemporal processing (Simon, 2008), and numerical processing (Simon, Bearden, Mc-Ginn, & Zackai, 2005; Simon et al., 2008). Children with ADHD suffer from compromised numerical (Kaufmann & Nuerk, 2008) and temporal processing abilities (Smith, Taylor, Rogers, Newman, & Rubia, 2002). Relatedly, children with dyscalculia also endure impaired numerical, temporal, and spatial abilities (Skagerlund & Träff, 2014; time only: Tobia et al., 2016; Vicario, Rappo, Pepi, Pavan, & Martino, 2012). Moreover, estimating spatial (e.g., Irving-Bell, Small, & Cowey, 1999), temporal (e.g., Basso, Nichelli, Frassinetti, & di Pellegrino, 1996; Danckert et al., 2007), and numerical (e.g., Cappelletti, Freeman, & Cipolotti, 2007; Zorzi, Priftis, & Umiltà, 2002) magnitudes is difficult for patients who experience hemispatial neglect (i.e., the lack of awareness of one side of space) after brain trauma.

Although the comorbidity of quantity processing deficits hint at the possibility of a common magnitude system, it is important to note that these individuals often also experience domain-general processing difficulties. Thus, the overlapping deficits may be indicative of an overall processing deficit rather than a common neural mechanism for quantity processing. For instance, children with ADHD (Kuntsi, Oosterlaan, & Stevenson, 2001; Mariani & Barkley, 1997; Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004) and Turner syndrome (e.g., Hart, Davenport, Hooper, & Belger, 2006) experience working memory difficulties in addition to quantity processing deficits. Thus, comorbid difficulties processing quantity in clinical populations may reflect overall processing deficits rather than damage to a common neural locus.

Moreover, clinical populations in which quantity processing deficits present as independent of each other hint at a possible dissociation between temporal, numerical, and spatial processing in the brain (time, space, and number: Cappelletti, Freeman, & Cipolotti, 2009; time and number: Cappelletti, Freeman, & Cipolotti, 2011). For instance, individuals suffering from Parkinson's disease are documented as having impaired timing abilities, but process number similarly to healthy, age-matched peers (Dormal, Grade, Mormont, & Pesenti, 2012). Moreover, patients who experience brain trauma do not always experience simultaneous impairments in all quantity processing. In a case study, a patient with a right hemisphere lesion displayed temporal processing deficits but was able to process numerical and spatial information normally (Cappelletti, Freeman, & Cipolotti, 2009). A related study revealed numerical, but not temporal, deficits in a patient with a left hemispheric lesion, and temporal, but not numerical, deficits in a different patient with a right hemispheric lesion (Cappelletti, Freeman, & Cipolotti, 2011).

Importantly, the clinical data suggest that simultaneous spatial, numerical, and temporal deficits are typically found in developmental disorders, presenting from early in development, such as in the case of ADHD or learning disabilities. Disorders and/or brain injuries occurring later in life, however, appear to result in distinct quantity processing deficits (although hemispatial neglect is an exception). Thus, these findings provide support for the developmental divergence model in which a common magnitude system may be present early in development, but it quickly diverges into separate systems over time.

The developmental divergence model

Despite some evidence in favor of a common magnitude system throughout development, strong counter evidence suggests that a single quantity-processing system does not exist across the entire life span. How are quantities represented if not by a common magnitude system? Although more research is needed to fully understand potential variations to the common magnitude account, we next discuss the developmental divergence model, like that of Newcombe (2014), as what we consider to be a more plausible model of quantity representation.

A somewhat complementary account to the common magnitude theory, the developmental divergence model suggests that we may be innately endowed with a single representational system for quantity processing, yet over the course of development, the system divides into several separable systems (Newcombe, 2014). For example, sometime during early development, the ANS may emerge from the common magnitude system to represent number whereas a specific spatial system may develop to represent space. Unlike the sense of magnitude account, which suggests that number separates from continuous representations of quantity such as spatial dimensions over development (Leibovich et al., 2017), the developmental divergence model suggests that all three quantities—continuous and discrete alike—diverge from one another over time. According to both accounts, quantity representations may follow a similar pattern early in development because infants are born with a generalized system for representing magnitude. There are many ways in which a common magnitude system may work in infancy. For instance, infants may be unable to distinguish between time, space, and number and instead simply consider "quantity" in the world around them. Being regularly inundated with new information may be particularly taxing for young infants' working memory and attention, making it difficult to accurately differentiate between stimuli in the environment. The natural correlations that exist amongst quantities (i.e., more apples take up more space and take longer to eat) may similarly make it harder for infants to distinguish among these quantities early on. Regardless, early in development, a common magnitude system may be a particularly useful way to efficiently use limited cognitive resources. The evidence of similar developmental trajectories (space: Brannon et al., 2006; time: Brannon et al., 2007; number: Xu & Spelke, 2000) and cross-domain transfer in infancy (e.g., de Hevia et al., 2014; Lourenco & Longo, 2010), but not necessarily during later childhood (e.g., Odic, 2018) support the possibility that a common magnitude system is present early in development.

Contrary to the commonalities observed across representations of quantity in infancy, a growing body of evidence indicates remarkable differences in the ways these quantities are represented in older individuals. Both children and adults discriminate temporal, numerical, and spatial magnitudes with differing levels of precision (see Droit-Volet et al., 2008; Odic, 2018), and temporal, numerical, and spatial information do not equally bias quantity judgments in another domain (e.g., Dormal & Pesenti, 2013). Further, data from children and adults indicate unique brain activation patterns when processing these quantities (e.g., space and number: Dormal, Andres, et al., 2012; time and number: Dormal, Dormal, et al., 2012), and distinct quantitative biases in the presence of emotionally laden stimuli when processing time and number (e.g., Young & Cordes, 2013). Evidence such as this suggests that the likelihood of a single system accounting for representations of time, number, and space later in children and adults is low. Unlike infants, children and adults have better developed cognitive capacities and are better able to quickly process information. For example, young children's language abilities improve drastically as demonstrated by an ability to rapidly learn words (e.g., Goldfield & Reznick, 1990; Schafer & Plunkett, 1998; Woodward, Markman, & Fitzsimmons, 1994). Moreover, cognitive control, executive functioning, and working memory abilities become exceedingly advanced in infancy and early childhood (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Diamond & Doar, 1989; Diamond, Towle, & Boyer, 1994; see Bunge & Wright, 2007, for a review). And, information processing speed becomes significantly better over the first year of life (Rose, Feldman, & Jankowski, 2002). These broad cognitive developments make children and adults better equipped to use several, unique systems to represent quantity, and emphasize the need for a common magnitude system in infancy.

Support for the divergence model is furthered by evidence revealing broad synaptic pruning leading to localization of brain functions in early to middle childhood (e.g., Giedd et al., 1996; Thompson et al., 2000; van der Knaap et al., 1990). Studies across several domains, including language (Mills, Coffey-Corina, & Neville, 1997; Minagawa-Kawai, Mori, Naoi, & Kojima, 2007; Perani et al., 2011) and facial recognition (de Haan, Pascalis, & Johnson, 2002; Halit, de Haan, & Johnson, 2003) have found early general activation followed by later neural localization of function. As such, it is conceivable that quantity representations may follow a similar pattern: in infancy a single, neural locus may be responsible for all quantitative information; however, over the course of development, specific brain regions may become specialized to uniquely support temporal, numerical, and spatial capacities.

Substantially more work is needed to address the many open questions regarding the proposed divergence model. Of particular importance is determining what might provoke divergence across development. One possibility is that over development, children gain a great deal of experience with quantitative information, which likely helps them differentiate time, space, and number. Related to this idea is work by Gibson and Gibson (1955), revealing differentiation of stimuli with practice. According to this work, space, time, and number may be indistinguishable at first, but increased exposure and developing expertise of quantitative information over time may be at the root of the proposed developmental divergence. A second, nonmutually exclusive possibility is that formal education provides children with distinct symbols to measure temporal, spatial, and numerical quantities (e.g., centimeters for space, seconds for time, and number words for number). Learning these formal labels might also shape our nonsymbolic representations of quantity, leading to an enhanced ability to distinguish between quantitative information and thereby causing these representations to diverge. If so, we would expect number to diverge first (since number words are acquired during early childhood, whereas spatial and temporal words are not learned until later); however, the current evidence suggests that spatial representations may be the first to diverge (Odic, 2018). Thus, more work is needed to determine what specifically instigates this divergence. Other factors, including but not limited to burgeoning linguistic abilities and/or developing domain-general capacities, may also prompt the divergence of a common magnitude system throughout the course of development and warrant further investigation.

If a developmental divergence model provides the best account of quantity representation, other open questions, such as the specific time at which the divergence occurs, also exist. Although 3-year-olds have comparable spatial and numerical acuity, performance on spatial and numerical tasks begins to deviate around age 4 (time, space, and number: Odic, 2018; space and number: Geary & Vanmarle, 2016; Odic et al., 2013), indicating that the third year of life may mark an important transition for quantity representations. Temporal discriminations may also separate around this time, as 4-year-olds' accuracy on temporal tasks is much lower than on spatial tasks, and by age 5, performance on temporal and numerical tasks begins to differ (Odic, 2018).

Another unresolved question is whether or not the developmental divergence model is limited to time, space, and number, or if it may encompass a broader set of quantities to include speed, loudness, brightness, and so on. Given that discrimination of speed (e.g., Möhring, Libertus, & Bertin, 2012) and brightness (e.g., Starr & Brannon, 2015) also adhere to Weber's law, one might think that the same system should represent all quantities. However, other evidence has been provided to suggest that some quantities may align more readily than others. De Hevia and Spelke (2013), for instance, found that infants less readily mapped number onto brightness than they mapped number onto space, suggesting a more privileged relationship between the latter quantities. In related work, de Hevia, Vanderslice, and Spelke (2012) found that children also struggled with mapping number onto brightness, and Srinivasan and Carey (2010) showed that adults had difficulty mapping loudness onto space. Future work must investigate not only the development of temporal, spatial, and numerical magnitudes but also explore how other quantity dimensions such as loudness and brightness may be integrated (or not) in this early system.

Developmental designs and consistent paradigms will be necessary for assessing the plausibility of the developmental divergence model. Critically, few studies have explored spatial, temporal, and numerical processing between 10 months and 3 years of age, and even fewer have assessed the development of all three quantities in children using the same paradigm (although see Droit-Volet et al., 2008; Odic, 2018). Better understanding of the development of spatial and temporal representations during late infancy will be necessary for assessing the plausibility of the divergence model, specifically, to determine at what point these quantities are no longer represented by a common metric (see Odic, 2018). Longitudinal research may also shed light on the format of quantity representations.

Implications of the developmental divergence model

Although data in favor of a common magnitude system has shaped numerous educational interventions (e.g., Siegler & Ramani, 2009), it is important to consider the implications of separate quantity processing systems—particularly for children and adults. For instance, treating individuals with comorbid quantity-processing deficits may be less straightforward in the presence of separate quantity-processing systems after infancy. Thus, rather than treating all quantity deficits by gaining experience with a single quantity (e.g., number), separate experiences with each quantity may be necessary. Knowing that separate systems may be responsible for quantity processing may also guide future neurobiological investigations by allowing for a clear identification of the location of each of these systems in the brain.

Limitations of the developmental divergence model

Although this model seems plausible, there are several alternative explanations that must be seriously considered. For instance, although common developmental trajectories have been put forth as evidence in favor of a common magnitude system in infancy, it is possible that similar acuity emerges not because infants are using a common magnitude system, but instead because of their limited abilities early on. For example, infants have limited working memory (e.g., Reznick, Morrow, Goldman, & Snyder, 2004; Ross-Sheehy, Oakes, & Luck, 2003) and poor visual acuity (e.g., Harter & Suitt, 1970) among many other domain-general limitations. Therefore, any of these limits on domain-general abilities may hinder their ability to perform standard discrimination tasks unless there are very large changes in quantity, which attract their attention. Although this may explain comparable developmental trajectories in infancy, but not in childhood or adulthood, it would not align with a common magnitude system, and these possibilities must be explored to fully understand the plausibility of a common magnitude system in infancy.

One might also wonder how quantity processing in nonhuman animals fits into the developmental divergence model. Indeed, much of the animal literature supports the common magnitude account. For instance, animals show comparable temporal and numerical discrimination abilities (Meck & Church, 1983) and they, too, map number onto space (Rugani et al., 2017; Rugani et al., 2015). Much like infants, animals are not equipped with language faculties, and thus having a common magnitude system may be a more accessible way to represent quantities. On the other hand, many animals have advanced cognitive capacities, such as working memory (e.g., in pigeons: Honig, 2018; in rats: Beatty & Shavalia, 1980), which may support unique quantity-processing systems. Thus, one might expect animals to be able to manage separate quantity processing systems, like children and adults. In fact, research shows that spatial discriminations are comparable in adult humans and nonhuman primates (humans and monkeys: Tudusciuc & Nieder, 2010; humans, monkeys, and apes: Schmitt, Kröger, Zinner, Call, & Fischer, 2013), which hints at the possibility that adult humans and nonhuman primates may use a distinct spatial processing mechanism. If animals use unique quantity-processing systems, whether these systems develop in parallel, or diverge over the course of development, remains unclear. While we predict that language and/or increased experience with each unique quantity might promote the divergence of quantity processing systems in children, it is unlikely that either of these situations causes a divergence in animals. Future research with animal models will be crucial for determining (1) whether or not animals employ a single quantity processing system throughout development and (2) if the systems diverge, what causes this divergence.

Conclusions

Space, time, and number are necessary for understanding the world around us. Not only are these quantitative processes important for basic learning, they also facilitate daily activities, such as language acquisition and foraging (e.g., see Gallistel, 1990, for review). Although the common magnitude system (Cantlon et al., 2009; Meck & Church, 1983; Walsh, 2003) has been the dominant theory for several decades, a growing body of literature has doubted such a system. Throughout this review, evidence in favor of a common magnitude system was contrasted with strong counter evidence. We contend that a common magnitude system is not present throughout the life span given the current data. As such, we have suggested the developmental divergence model as an alternative model for quantity representation.

Although the common magnitude system is a parsimonious account, it requires a stringent examination of the data. Certain pieces of evidence certainly favor a common magnitude system, such as adherence to Weber's law (e.g., space: Brannon et al., 2006; number: Izard et al., 2009; time: Provasi et al., 2011) and similar developmental trajectories in infancy (see Feigenson, 2007, for a review). Despite some data in favor of this account, it still remains unclear exactly *how* and *why* these quantities may be processed by a single system. Cantlon et al. (2009) identifies the potential evolution of the common magnitude system by stating that "the common algorithms and neural processes underlying magnitude judgments may instead derive from a shared evolutionary heritage." (p. 89). Yet, even if a common magnitude system has evolved over time, what benefit does this system offer? It is possible that a single cognitive structure may have evolved for tracking quantity to account for the fact that the different forms of quantitative information is highly correlated in the natural world. By using a single structure to process quantity, other cognitive resources would be free for other processing purposes. Thus, representing all quantities via a common magnitude system might facilitate or increase the ease with which quantities are processed in our everyday lives (see Gallistel, 1990).

Despite this, there are numerous examples in which the basic premises of the common magnitude system are undermined. Unique neural activations occur when processing each quantity (number: Ansari, Lyons, Ivan Eimeren, & Xu, 2006; Vuokko et al., 2013 time: Gooch et al., 2011; Mattell & Meck, 2004; space: Dormal & Pesenti, 2009), distinct biases arise when making temporal and numerical judgments in the presence of emotional content (Young & Cordes, 2013), and nonsymbolic temporal, spatial, and numerical judgments predict unique aspects of formal mathematics (e.g., Skagerlund & Träff, 2016). Although the evidence makes it unlikely that a common magnitude system exists throughout the entire life span, the current data are consistent with the possibility that a common system may exist in infancy, which quickly diverges into separable, specialized systems across development. The common magnitude system may facilitate processing in young infants by freeing up other limited cognitive resources. Moreover, neural systems specializing over development is not uncommon (see de Haan et al., 2002; Mills et al., 1997), and thus it is likely that quantity representations follow a similar path.

Understanding the format of nonsymbolic quantity representations is critical, as basic quantitative processing consumes our everyday lives. Research on quantity representations will be especially important for assessing the suggested variation to the common magnitude account. What is the plausibility of a divergence model? At what point in development does the system diverge? What prompts this divergence? In assessing the developmental divergence model, research will need to carefully control for inherent differences across quantities, such as input modality and presentation format. Regardless of the outcome, future work will shed light on the representational formats of each quantity, allowing for better evaluation of the systems used for quantity representation more broadly.

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