CHAPTER

15

Origins and Development of Generalized Magnitude Representation

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Summary

Among the most fundamental of mental capacities is the ability to represent magnitude information such as physical size, numerosity, and duration. Accumulating evidence suggests that such cues are processed as part of a general magnitude system with shared *more vs less* representational structure. Here we review recent research with young children and preverbal infants suggesting that this system is operational from early in human life and may be far more general than currently believed. We present data suggesting that from early in development, the representation of magnitude extends across sensory modalities (e.g., vision and audition) and beyond the "big three" dimensions of spatial extent, number, and time. We also speculate about particular properties of the general magnitude system, including the potentially special role of space in grounding magnitude information.

Philosophers and scientists have long been interested in the human capacity to process magnitude. Questions such as "Which piece of pie is largest?" "How many guests are coming to the wedding?" and "Will my taxes take longer than two hours to finish?" illustrate the diversity of decisions that rest on the ability to represent magnitude in its many forms, among them being the dimensions of spatial extent, number, and time. Despite common empirical origins in psychophysical experiments [1–3], much research on the representation of magnitude exists in separate literatures, with claims of domain specificity prevalent in each (e.g., [4]). Debates on the nature and origins of quantitative reasoning reflect this approach. Some

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investigators argue that infants discriminate sets of objects or sequences of events and perform simple arithmetic calculations such as addition and subtraction using number [5–9], whereas others suggest that these abilities are supported instead by spatial and/or temporal cues such as cumulative surface area (or contour length) and duration [10–14].

In other work, increasing attention has been paid to the psychological links among space, number, and time, and to the proposed existence of a *general magnitude system*, which processes magnitude information regardless of the specific dimension. This idea, as formalized by Walsh [15] and suggested previously by others [16,17], maintains that representations of different quantitative cues (e.g., physical size, numerosity, and duration) are, to some extent, undifferentiated and processed in a common code as generalized magnitude. The central characteristic of magnitude is the intrinsic "more than" *vs* "less than" structure of unequal stimulus values. Magnitude—whether it be the *size* of a piece of pie, the *number* of wedding attendees, or the *time* required to complete one's taxes—may be represented abstractly in terms of the more *vs* less relations or as some amount of "stuff." We would suggest that at the core of the general magnitude system is a (partly) shared currency of *more vs less stuff*. We use the notion of "stuff" to allow for inexactness in the representations, similar to that of the approximate number system [18] but applied more generally to both discrete and continuous quantities. While we do not distinguish in this review between discrete and continuous quantities, as both types involve magnitude, it is worth noting that there may be important differences between magnitude and other ordinal sequences. The more/less relations that characterize generalized magnitude information are inherently ordered. In contrast, ordinal sequences such as letters of the alphabet may exist without more/less relations, and, unless explicitly related to some dimension of magnitude (e.g., time), may not form part of this system (see below).

In the current review, we draw on recent behavioral research with children and infants to shed insight on the developmental origins of a general magnitude system. Much speculation has concerned these origins [15,19], but empirical data has only recently become available. We organize our review around three main issues, each treated in a separate section. In the first section, we focus on the associations among spatial extent, number, and time, as have been documented across early development. We refer to these dimensions as the "big three" because of their unambiguous more/less relations and their central importance in human cognition. In the second section, we turn to questions concerning the generality of a general magnitude system and its implications for development. Does this system extend to magnitudes beyond the big three, and across sensory modalities? In the third section, we turn to specific characteristics that may be fundamental to generalized magnitude representation, including the additional sense of space as location, as well as the development of its role in grounding and mentally organizing magnitude dimensions such as number and time.

THE BIG THREE: SPATIAL EXTENT, NUMBER, AND TIME

The notion of generalized magnitude representation has historical origins in philosophical writings [20–22]. Locke, for example, once argued for an intimate connection between space and time, suggesting that "expansion and duration do mutually embrace and comprehend each other… every part of space being in every part of duration, and every part of duration being in every part of expansion." Empirical support for such magnitude associations began emerging in the middle of the last century through the pioneering studies of Critchley [23] in neurology and

Piaget [24–26] in developmental psychology. Since then, accumulating evidence is suggestive of a shared representational code for at least the prototypical sources of magnitude information: spatial extent (e.g., physical size, length, height, and distance), number (whether symbolic or in non-symbolic form), and time (e.g., duration). In adult participants, cross-dimensional interactions between each pairing of space and number [27–29], space and time [30–32], and number and time [33,34] are now well documented (for reviews, see [15,35,36]).

As for so many cognitive domains, the developmental study of generalized magnitude representation begins with Piaget who observed that children often confused spatial extent with number [24] and time [25]. In the classic number conservation task, for example, Piaget asked children to judge the relative numerosity of two rows of objects that differed in length (see Fig. 15.1). Children between three and six years of age frequently judged longer rows as being greater in number, even when they actually had fewer (but, see [37]); they also claimed that the number of objects in a single row increased as the experimenter spread apart the objects. While such results have traditionally been taken as evidence for immature numerical

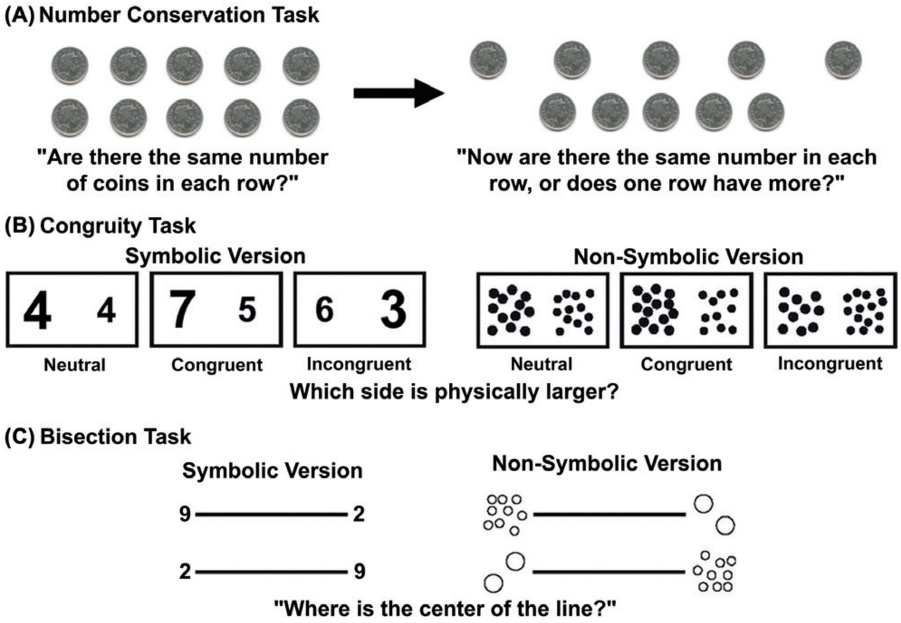


FIGURE 15.1 Three types of tasks (A: Number Conservation; B: Congruity; C: Bisection) used to show associations between space and number in children. (A) In the classic number conservation task, young children generally say that the longer row of coins is greater in numerical value (*right panel*), despite having previously answered that the two aligned rows contained an equal number of coins (*left panel*). (B) Symbolic (*left panel*) and non-symbolic (*right panel*) congruity tasks generally show interference and facilitation effects. When judging spatial extent, for example, numerical information both interferes with and facilitates spatial judgments. Relative to neutral conditions, participants (adults and children) are faster to respond in congruent conditions and slower in incongruent conditions. Reprinted with permission from [41]. (C) When asked to judge the perceived center of a physical line flanked by two numerical values, even children show systematic bias towards the larger value, whether numbers are presented symbolically (*left panel*) or in non-symbolic form (*right panel*), though effects are stronger for younger children in non-symbolic conditions. Such bisection tasks have been used to suggest that number affects the representation of length. Reprinted with permission from [43].

reasoning, several recent studies suggest instead that interference reflects a conceptual association between space and number, with bidirectional interactions. Indeed, both interference and facilitation effects have been reported in size congruity tasks with children as young as five to seven years, both with symbolic [38–40] and non-symbolic [41] stimuli (see Fig. 15.1). Other evidence for an association between space and number in childhood comes from bisection tasks. When flanked by numbers, adults' bisection judgments are systematically shifted towards the larger number [42]; five-year-olds, like older children and adults, judge the center of the line to be closer to the side of a larger numerical array [43] (see Fig. 15.1), suggesting that number affects the representation of length [44].

Since Piaget, others have focused on the association between space and time in school-aged children, with particular attention paid to the interactions between distance, duration, and speed [45–47]. The interactions with speed are particularly robust, perhaps not surprisingly given that calculations of speed, by definition, combine information about distance and duration. In a recent study, Casasanto and colleagues [48] examined distance and duration judgments by having children indicate which of two snails in a movie had traveled farther in space or longer in time. Clear cross-dimensional effects were observed, but they appeared to be stronger from space to time than *vice versa* (see below).

While less research has concerned the development of an association between number and time, evidence for such a connection has been reported in young children. In one study, numerical information interfered with five-year-olds' judgments of duration, even though they were explicitly told to ignore number [49]. Interestingly, despite more automatic access to number in both eight-year-olds and adults, numerical interference on temporal judgments decreased across development, suggesting that strategies such as explicit counting [49] may be effective in differentiating numerical and temporal magnitudes. There is also indirect evidence that temporal information may affect numerical reasoning. For example, preschoolers can detect numerical correspondence in audition and vision (e.g., three claps being equivalent to three objects), but only if rate and duration remain constant [50], suggesting that at least for young children, the processing of number is enhanced by temporal cues, as has been shown when spatial cues are congruent with numerical judgments (e.g., [12]).

Other research is consistent with a system of generalized magnitude representation that emerges as early as infancy. One line of evidence comes from comparisons of discrimination functions for spatial, numerical, and temporal stimuli. Discrimination sensitivity follows Weber's law, which holds that discriminability of unequal stimulus values varies as a function of the ratio difference. Using measures of reaction time and accuracy, discriminability of spatial extent (i.e. length and height), number, and duration [51–53] has been shown to increase in parallel from kindergarten into adulthood, even when accounting for developmental differences in processing speed [54]. Parallel discrimination functions have also been observed for these dimensions in the first year of life [7,55–58].

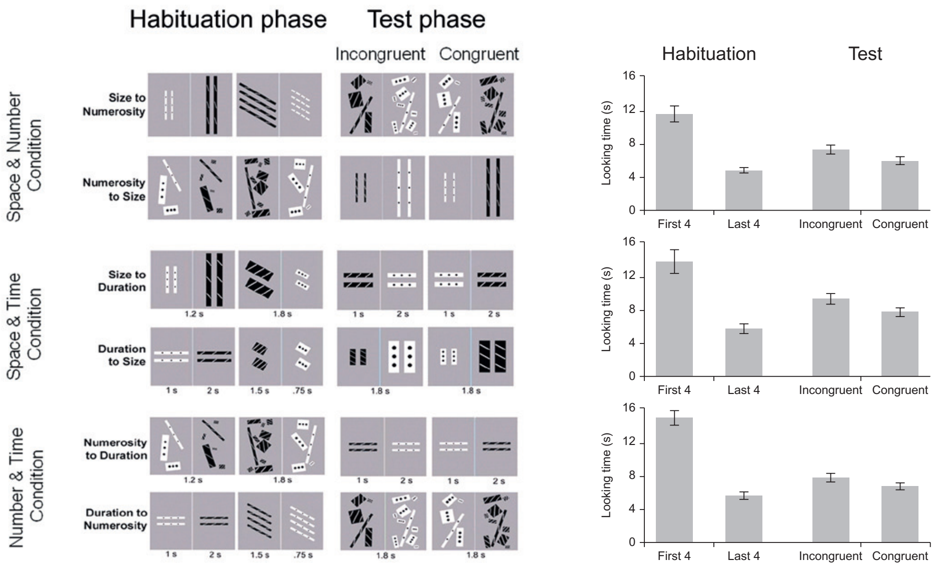
While parallel functions of discriminability are consistent with generalized magnitude representation, they can nevertheless be difficult to interpret. Greater discrimination sensitivity might be driven by developmental and experiential changes in, for example, perception, attention, and/or memory, none of which is specific to the general magnitude system. Consider changes in color discrimination and expertise effects on face processing. Over the first year of life, infants become sensitive to more colors because of maturation in the visual pathway [59], and with greater exposure to particular types of faces (e.g., gender and race), infants show increased sensitivity to faces with which they have greater expertise [60]. Increases in discriminablity for different stimuli can thus be driven by a variety of factors. In addition, discrimination functions for spatial extent, number, and time have only been observed for a restricted range of intensities, making it unclear whether parallel patterns of performance would generalize to non-tested intensities. Indeed, in the case of number, there are well-known range differences; infants, for example, have been shown to differentiate two *vs* three objects [61] but not eight *vs* twelve [7], despite identical ratios. In the case of temporal information, sub-second and supra-second ranges are even known to implicate distinct brain regions [62].

More direct evidence for the operation of a general magnitude system in infancy would involve showing *interactions* between different pairings of magnitude dimensions, as has been shown in adults (e.g., [27,30,33]) and older children (e.g., [24,26]). Recent studies have demonstrated such interactions, providing strong support for generalized magnitude representation by the end of the first year of life [63–65]. We conducted one of these studies [63], and our approach was modeled on the classic study of Meck and Church [17], in which rats were found to transfer associative learning from duration to number. We first taught nine-month-old infants that one magnitude (e.g., physical size) mapped systematically onto color/pattern cues; we then tested whether they generalized learning of these arbitrary mappings to other magnitudes (e.g., numerosity or duration). During habituation, infants might be shown, for example, that larger-sized rectangles were black with white stripes and that smaller rectangles were white with black dots (see Fig. 15.2). When subsequently tested with number, trials that maintained the mapping (i.e. congruent test trials) featured a larger numerical array with black/striped rectangles and a smaller numerical array with white/dotted rectangles; trials that violated the mapping (i.e. incongruent test trials) featured a larger numerical array with white/dotted rectangles and a smaller numerical array with black/striped rectangles (Fig. 15.2). The same logic was applied to duration (congruent test trials: longer-lasting objects as black/striped and shorter-lasting objects as white/dotted; incongruent test trials: longer-lasting objects as white/dotted and shorter-lasting objects as black/striped; Fig. 15.2). All combinations of size, numerosity, and duration were presented to infants, and for all, there was evidence of transfer across magnitude dimensions, as indicated by longer looking times to incongruent than congruent test trials (Fig. 15.2).

In another recent study, de Hevia and Spelke [65] tested the association between number and spatial extent in eight-month-old infants. Using a different procedure, they, too, showed transfer in infancy from one magnitude (i.e. numerosity) to another (i.e. length). Infants were visually habituated to continuous sequences of ascending or descending numerical values, and then during the test phase, presented with ascending and descending sequences of line lengths (see Fig. 15.2). Infants who habituated to ascending numbers, looked longer at descending lengths, and those who habituated to descending numbers, looked longer at ascending lengths (Fig. 15.2), suggesting that ordinal relations may have been coded with respect to more/less *generalized magnitude* (or *stuff*) rather than more/less *number*, which would allow for the observed generalization across visual stimuli. Srinivasan and Carey [64] have also provided converging evidence for an association between space and time in nine-month-olds, showing that congruent mappings between length and duration are easier to learn than incongruent ones.

Together, these findings suggest that generalized magnitude representation emerges by eight to nine months of age. In addition, they suggest that the associations among spatial extent, number, and time observed in the mature human organism are not mere

(A) Lourenco and Longo (2010)



(B) de Hevia and Spelke (2010)

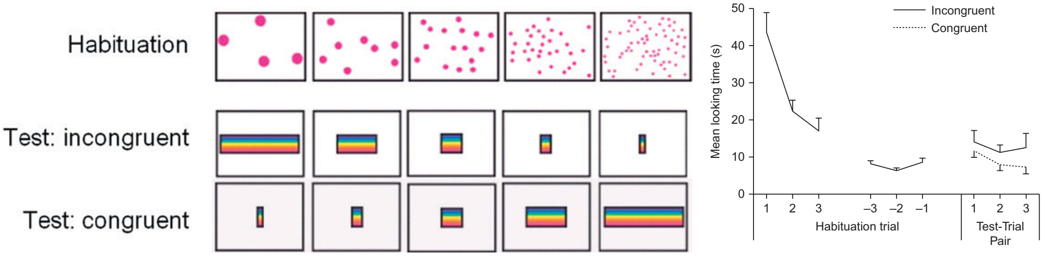


FIGURE 15.2 Two recent studies (A: Lourenco & Longo, 2010; B: de Hevia & Spelke, 2010) showing magnitude-related associations in preverbal infants. (A) Stimuli and results for each of the conditions in Lourenco and Longo (2010). Each condition included two groups (Space & Number condition: size-to-numerosity and numerosity-to-size; Space & Time condition: size-to-duration and duration-to-size; Number & Time condition: numerosity-to-duration and duration-to-numerosity). Examples of stimuli used in habituation and test phases are shown (*left panel*). The test phase included incongruent and congruent trials. Results for each condition involve mean looking times (in seconds) for both phases, collapsed across group in each condition (*right panel*). In all conditions, looking times were significantly greater during incongruent than congruent test trials. Reprinted with permission from [63]. (B) Examples of stimuli (*left panel*) and results (*right panel*) in de Hevia and Spelke (2010). The habituation trial shown involves a sequence of ascending numerical values. Test trials involve sequences of decreasing line lengths (incongruent) and increasing line lengths (congruent). Results show that the mean looking times during incongruent test trials were significantly greater than during congruent test trials. Reprinted with permission from [65].

epiphenomenon of stimulus- or response-related conflation, but rather may reflect a fundamental underpinning of human cognition [64,65]. Much remains to be understood, however, about the development and nature of the general magnitude system. Do early associations reflect, for example, developmental differentiation or enrichment (see Box 15.1)? Is this

BOX 15.1

DEVELOPMENTAL TRAJECTORY OF THE GENERAL MAGNITUDE SYSTEM AS DIFFERENTIATION *VS* ENRICHMENT

While we acknowledge below that the task of characterizing development of the general magnitude system is complicated by various factors, here we suggest a distinction between increasing differentiation and increasing integration among magnitude dimensions. On one view, humans might begin life with a completely undifferentiated ("one-bit") representation of magnitude, which, with development, would become separated into more discrete dimensions [15]. On another view, generalized magnitude representation might arise over the course of development with exposure to correlational structure in the physical environment; and such associative learning may be further maintained by particular linguistic experiences such as exposure to metaphors, which highlight specific associations [64,108,115,139]. These views reflect two classic approaches to perceptual learning [140]: as proceeding via differentiation from an initially monolithic representation *vs* enrichment in which initially disparate dimensions become increasingly integrated. These views make opposite predictions about the expected developmental trajectory of generalized magnitude representation, suggesting an important area for future research. On the differentiation view, conceptual associations as observed via, for example, cross-dimensional transfer should be strongest earlier in life, whereas on the enrichment view, these effects would increase in strength over development. Others have recently made similar distinctions concerning neural development. Cohen Kadosh and colleagues [35], for example, differentiate two types of neural change (see also [141]); one involves an increase in neural specialization with greater selectivity of activation and the other involves an increase in shared neural areas for highly similar dimensions, a type of neural economy.

Development is of course a highly complex process, and developmental accounts that emphasize either only increasing (conceptual or neural) differentiation or only increasing (conceptual or neural) integration are likely to be incomplete. Characterizing development of the general magnitude system is also likely to be complicated by the fact that the representation of *more vs less stuff* may constitute a distributed system with different classes of magnitude (stuff) which interact in complex ways (see [64] for a distinction between dimensions involving structural similarity *vs* functional overlap). Other complexities may emerge for associations and dissociations among magnitudes that occur at different stages of processing (see [36] for a distinction between input and comparison stages) and for different mental operations [35].

system limited to the big three magnitudes, or does it incorporate other dimensions such as pitch and luminance? Does cross-dimensional transfer operate primarily across visual stimuli, as used in recent studies, or does it extend across sensory modalities, as has been shown for number where infants match numerical value across vision and audition [66–68]? We turn to questions of generality in the next section.

BEYOND THE BIG THREE MAGNITUDES AND CROSS-MODAL TRANSFER

The defining feature of generalized magnitude representation is the more *vs* less ordering of unequal stimulus values. That is, for any pair of unequal values, one member of the pair always has more "stuff" and the other has less. It is this shared ordinal structure that serves as the mechanism by which magnitudes such as the big three are united and that may serve to support cross-dimensional comparisons from early in human life. Before considering how dimensions of magnitude beyond the big three might be represented by the general magnitude system, it is worth reiterating the distinction made above between magnitude and other ordinal sequences. While the more/less relations that characterize generalized magnitude representation are inherently ordered, ordinal structure can exist in the absence of magnitude. Indeed, magnitude and order are not synonymous and their relation is asymmetric, with magnitude implying order but order not implying magnitude, though this distinction can be complicated by contextual factors. Consider, for example, letters of the alphabet, for which there is a clear ordering from A to Z. Technically speaking, letters such as C and T are not characterized in terms of their more/less relations; that is, C is no more or less than T. And, yet, if considered in terms of their distances relative to some other letter (e.g., the distance between C and A is less than that between T and A) or in terms of temporal information (e.g., C comes earlier than T in the alphabet sequence), magnitude is clearly present. Existing evidence on the relation between magnitudes such as number and ordinal sequences such as letters are mixed [69–72], perhaps in part because it may be difficult to find ordinal sequences that are truly magnitude free (see Box 15.2). We thus discuss in this section only cases for which magnitude is more clearly delineated, even if the more and less ends of a continuum are not (see below).

Much of the recent research on magnitude representation has concentrated on *prothetic* dimensions [73]—those for which the polarity of more *vs* less is intrinsically determined. The big three magnitudes represent prothetic cues with a clear zero point, which marks where no magnitude exists and which may serve to unambiguously specify direction, namely, the more/less ends of a continuum. While there are countless other experiences that can be organized according to their magnitude (more/less) relations, many of these lack intrinsic polarity and have been referred to as *metathetic* dimensions [73,74]. Consider luminance—does darker or lighter gray represent the "more" end on the continuum? If luminance is defined with respect to black, the more end should be darker; if defined with respect to white, more is lighter (or "brighter"). Are such metathetic dimensions also represented by the general magnitude system? In a truly general system of magnitude representation, the lack of intrinsic polarity may have little functional impact, so long as one direction is operationally specified. Metathetic dimensions with arbitrarily imposed polarity may operate much like prothetic ones. But what about more complex stimuli for which magnitude is only one of many available cues? In this section, we distinguish between several classes of magnitude dimensions, and review recent research with adults, children, and infants demonstrating striking parallels in discriminability and cross-dimensional transfer regardless of class (see also [35,36,75]).

School-aged children (six to nine years of age) show distance effects when making judgments of relative luminosity [54], paralleling those observed in adulthood [76,77]. As with discrimination judgments of physical size, number, and duration (see above), reaction times

BOX 15.2

QUESTIONS FOR FUTURE RESEARCH

- Does language play a role in shaping the general magnitude system? There are at least two ways in which linguistic experience might affect generalized magnitude representation. One is that linguistic metaphors, which highlight directional associations (e.g., from space to time but not *vice versa*), may change initially symmetrical connections into asymmetrical ones [48]. Another possibility is that language may serve to delineate polarity for metathetic dimensions where more/less direction is not intrinsic [74,90].
- The more and less ends of the luminance continuum have been shown to vary across development; young children appear to represent darker as “more” and a significant proportion of adults represent lighter (or brighter) as “more” [74,78]. What might account for these developmental and individual differences? Does such variability extend to other metathetic dimensions?
- The dissociation between near and far space is well known [142–144], and recent research suggests that in adult humans, representations of number [145] and time [146] vary as a function of these relations. What are the developmental origins of the near/far space dissociation, and to what extent does it apply to other magnitude dimensions?
- In Western culture, the mental number line is oriented from left to right [110,111,147]. In speakers of Semitic languages such as Arabic and Hebrew, however, increasing numerical value is represented in the opposite direction, from right to left [130,148]. This variation has been tied to reading/writing direction as well as counting practices [110,130]. Does the spatial orientation of other magnitudes (e.g., duration and emotional expression) show similar cultural variation, and does the spatial grounding of magnitude dimensions depend on culture-specific experiences?
- Siegler and colleagues suggest that whereas young children appear to represent number along a compressive scale, older children and adults rely on a linear scale [149,150]. More recent evidence, however, suggests that adults in Western culture have access to both compressive and linear scales of number, switching flexibly between the two depending on task demands [151,152]. Do other dimensions of magnitude follow similar developmental, cultural, and task-related coordination of linear and compressive scales?
- Dyscalculia (known as a mathematical learning disability) is generally regarded as a developmental deficit of numerical processing [4,153,154]. To what extent are other magnitudes processed deficiently? Is the general magnitude system sufficiently malleable to withstand and compensate for deficits in one or more dimension?
- What is the relation between generalized magnitude representation and other, non-magnitude related, ordinal sequences? Existing evidence is mixed; for example, some studies show spatial organization and neural activation of letters similar to that for number [69,70], whereas others show differentiation [71,72]. What might

BOX 15.2 *(cont'd)*

account for the inconsistencies? Do similarities between letters and numbers, when they exist, reflect generalized magnitude representation? Do differences reflect unique characteristics for each stimulus type?

- How does generalized magnitude representation relate to other phenomena such as synesthesia [79,155] and sound symbolism [156–159]? Do synesthetic and sound-symbolic experiences involving magnitude dimensions implicate the general magnitude system, or do they reflect unique phenomena supported by distinct conceptual and neural mechanisms (cf. [90])?
- Walsh and colleagues [15,75] suggest that associations among spatial extent, number, and time are grounded in shared relevance for action, with convergence among these dimensions having evolved for the purpose of supporting sensory-motor transformations. In contrast, Cantlon and colleagues [36] have suggested that, rather than action, these dimensions share an evolutionarily "primitive" mechanism. These different, though not necessarily incompatible, views indicate the need for future research to investigate the developmental and evolutionary origins of generalized magnitude representation.

are shorter, and error rates lower, as luminosity differences between stimuli increase. In addition, direct interactions between luminance and size have been reported in younger children, with both preschoolers [78] and toddlers [74] associating larger objects with darker stimuli and smaller objects with lighter ones. Interestingly, whereas adults with synesthesia employ the same mapping as that of typically-developing children [79], the pattern for typical adults is less consistent, with a significant proportion mapping "lighter" or "brighter" onto larger size [74,80], greater number [81], and longer duration [82]. Importantly, however, there appears to be within-subject stability for these mappings [74,83], suggesting that while the processing of luminance may involve the general magnitude system, the exact manner in which it is incorporated may differ across individuals.

Pitch is another dimension lacking intrinsic polarity [84]. Yet, as with luminance, existing data suggest that pitch too may be treated as generalized magnitude information. In adults, clear distance effects are found for pitch discrimination [76,85], although nonlinear patterns of discrimination have been reported for complex (musical) tones [85]. Using measures such as heart rate, sucking, and head-turning, several older studies [86–88] reported distance effects for pitch in infants; and a recent experiment confirms sensitivity to ordinal relations of pitch by showing that at six months of age, infants treat relative pitch as more salient than absolute pitch in melodies [89].

Cross-dimensional interactions between pitch and other magnitude dimensions provide more direct evidence for generalization beyond the big three. Classic work by Marks and colleagues [77,90,91] demonstrated that adults associate higher pitch with brightness, light colors, and even sharp edges; sharpness, as discussed below, can be conceptualized with respect to more/less relations. More recent research also reveals a link between pitch and vertical height in space, with adults mapping higher pitch onto "up" spatial positions (i.e.

greater height) and lower pitch onto less vertical height [92]. Evidence of early developmental origins for these mappings comes from studies with young preschoolers; two-and-a-half-year-olds, for example, expect lighter and smaller objects to produce higher pitched sounds, although the association between pitch and size appears to be less robust than that between pitch and luminance [78].

A recent study [94] revealed that by three to four months of age, infants make associations between pitch and visuospatial height as well as between pitch and pointedness (see also [93]), with congruity effects that parallel those observed in adults. Preverbal infants preferred to look at mappings between higher frequency and greater height than between higher frequency and less height; they also spent more time looking at a mapping between higher frequency and greater pointedness than between higher frequency and less pointedness (i.e. smoother object). We suggest that these mappings may reflect generalized magnitude representation. With respect to pointedness, *pointed vs smooth* represent a natural polarity imposed by constraints in the physical world. For example, if object A is less pointy than object B, then A will also be smoother than B. This implication, however, is not symmetric; if A is less smooth than B, it is not necessarily pointier; it might be, for example, full of holes. Thus, on a continuum of pointedness, pointed reflects the *more* end and smooth the *less* end, with a perfectly smooth object perhaps even considered the zero point (between concave objects on the one hand and convex ones on the other).

That higher pitch is mapped onto greater visuospatial height and greater pointedness in both infants and adults suggests that higher pitch represents the *more* end of the pitch continuum and lower pitch the *less* end. However, higher pitch has also been shown to map onto smaller size [78], suggesting that there may be combinations in which lower pitch represents the *more* end and higher pitch the *less* end. Recent research with adults confirms that whereas higher pitch maps systematically onto “more” for both height and luminance, it maps systematically onto “less” for both physical size and number [95]. Yet, so long as polarity is somehow specified and there is internal consistency, more/less relations may align across dimensions (see also [36] who propose a distinction based on the stage of processing), allowing generalized magnitude representation to accommodate flexibly to developmental changes (as with luminance) and to variation depending on the combination of dimensions (as with pitch).

Other research suggests that more complex social stimuli may also involve some processing by the general magnitude system. In adults, comparisons of relative social status are accompanied by activation in posterior parietal cortex, particularly the intraparietal sulcus (IPS) [96]—a putative neural locus of the general magnitude system [15]—similar to that reported for prothetic dimensions [80,97–100], as well as for metathetic magnitudes such as luminance [80] and pitch [101]. In children (three, five, and eight years old), recent research points to associations between facial expression and temporal processing [102], with angry faces judged as lasting longer than neutral faces, as has also been observed in adulthood [103] and having been interpreted as reflecting acceleration of an internal clock in response to heightened arousal of negatively valenced stimuli. The temporal over-estimation of angry faces is reminiscent of recent data showing that larger numbers are judged as lasting longer than smaller numbers [33,82], and we would suggest that in addition to the difference in valence, angry faces involve more emotional expression than neutral faces [104]. The effect of emotion on duration judgments may thus reflect generalized magnitude representation, with more emotional expression associated with longer duration.

Much research has concentrated on the specific pairings of spatial extent, numerical value, and temporal information, with some investigators even arguing for privileged associations, such as between space and number [65,80], space and time [64], or number and time [17,58]. Given the multitude of associations, which include metathetic dimensions and social stimuli, we suggest that generalized magnitude representation may arise from a basic organizational structure of *more vs less*, widely applicable across a variety of magnitude dimensions and modalities (and perhaps relying on shared neural resources). Even when there is an arbitrary imposition of polarity and when magnitude exists alongside other cues, cross-dimensional transfer has been observed for different classes of dimensions and at different developmental time points, suggesting a general magnitude system that extends beyond the big three and across at least visual and auditory modalities from early in human life.

While various dimensions beyond the big three may form part of the general magnitude system, it is critical to note that not all more *vs* less relations are necessarily created equal or that there is a single code for representing amount of "stuff." While conceptual and behavioral implications of more/less ordering may be functionally similar for different classes of magnitude, there will likely be unique experiential and neural processes supporting distinctions among them. Indeed, development changes for pitch and luminance (described above) are suggestive of some fundamental distinctions. One important difference is that for dimensions such as pitch there may be a translation to *more vs less stuff* that occurs with reference, or in comparison, to some other dimension (e.g., one of the big three), rather than from the perception of the specific dimension itself (cf. [105,106]). In a recent review, Bueti and Walsh [75] suggested that generalized magnitude representation likely exists as a distributed system and not a single area in, for example, the IPS. Consistent with this possibility is neural evidence showing involvement of similar parietal and frontal regions for prothetic [80,97–100], metathetic [80,101], and more complex social dimensions [96]. Cohen Kadosh and colleagues [35] recently suggested a system of overlapping and distinct populations of neurons (see also [80]). Even within the big three, it is clear that whereas some neurons code for multiple magnitude dimensions (e.g., number and length), others do not [107].

PARTICULARS OF THE GENERAL MAGNITUDE SYSTEM

In this section, we address two questions that relate to specific properties characterizing generalized magnitude representation. The first concerns the extent to which magnitude associations are symmetric so as to produce bidirectional transfer. Recent research suggests that pairings between, for example, spatial extent and time, may be asymmetric, with cross-dimensional transfer applying more strongly from space to time than *vice versa* [48,108]. The second issue concerns whether the space dimension may have a special (foundational) role as the primary grounding of the general magnitude system (see [109] for a discussion of how space may structure numerical representations). In one sense, space exists as magnitude, and spatial extent has been shown to interact from early in life with other magnitude dimensions, including number [38–41,63], duration [25,48,63], luminance [78], and pitch [94]. In another sense, however, space provides location information and may serve to mentally organize magnitude cues such as numerical value in a reliable direction [109–111].

That spatial variables such as length and distance influence duration judgments more than the reverse has been reported across development, both in adults [108] and school-aged children [48]. Asymmetrical transfer has also been documented for spatial extent and number, with physical size and cumulative surface area having a greater influence on numerical judgments than *vice versa* [29,112]. Asymmetries are consistent with theories of conceptual metaphor [113,114], which argue that abstract concepts such as number and time are structured in terms of more concrete concepts such as space. People are consequently more likely to talk (and think) about number and time using spatial terms than the reverse [108,115].

Recent findings in preverbal infants reveal bidirectional associations among spatial, numerical, and temporal cues [63]. That these associations include transfer from more "abstract" (number and duration) to more "concrete" (spatial extent) information (e.g., [65]) argues against the exclusive role of conceptual metaphor (or linguistic conflation) in creating associations, asymmetric or otherwise. Of course, another possibility is that experience with metaphor shapes initially symmetrical associations to reflect directional relations highlighted in language or experience in the physical world. This possibility, however, is at odds with accumulating evidence of bidirectional interactions over development. For space and time, greater distances are associated with longer durations, with basically symmetrical transfer; perceived distance increases as a function of temporal separation for sequentially presented stimuli (known as the *Tau effect*) and perceived duration increases as function of spatial separation (known as the *Kappa effect*) [30–32]. Furthermore, the finding that number is more likely to influence duration judgments than *vice versa* in both adults [34] and children [49] is not predicted by theories based on metaphor, since number, like temporal information, is considered an abstract experience.

Asymmetrical effects could certainly be taken as evidence against generalized magnitude representation, since one might argue that shared representations of *more vs less stuff* should not differentially affect the specific dimensions involved. This type of logic, however, can be problematic, and we would urge that investigators use other approaches to address this issue (see [35] for one possibility concerning dissociations at the level of mental operations such as arithmetic). Asymmetries within the general magnitude system could easily arise from stimulus- or task-related factors, or differences in discriminability either within or across magnitude dimensions. In the case of spatial extent, for example, there is within dimension variability, with infants appearing more sensitive to individual element size [116] than to cumulative surface area [5,9] (but see [10,11]). There are also well known "size effects," which show that discrimination sensitivity depends on the magnitude of stimulus values; holding distance across stimulus values constant, discriminability decreases with increasing magnitude. At least some variation in discriminability may also reflect earlier developmental differences and differential experience with particular stimuli. In young children, acuity for duration is worse than that for spatial extent [40,51] and number [51]. And asymmetries between space and number in preschoolers may be largely due to inexperience with symbolic notation; when non-symbolic dot arrays (instead of Arabic numerals) are used, there are clear effects of numerical information on judgments of cumulative surface area [41]. These examples illustrate that asymmetrical transfer does not itself provide evidence against generalized magnitude representation, but, rather, may reflect dimensional properties and/or developmental differences in acuity.

Accumulating evidence suggests that space may be represented in two distinct ways in the general magnitude system, as information about *where* something is and as information about *how much* there is. The focus of the discussion above was on space as magnitude, with spatial extent cues such as physical size, height, length, and distance all referring to some amount of (i.e. how much) stuff. Here we discuss space as location, with spatial information serving to organize magnitude in a consistent manner. For number, it is well documented that Western adults mentally represent increasing numerical value from left to right, the so-called "mental number line." When making parity (odd/even) judgments, adults respond faster to smaller numbers (e.g., 1 and 2) on the left side of space and to larger numbers (e.g., 8 and 9) on the right, known as the SNARC (Spatial–Numerical Association of Response Codes) effect (e.g., [110,117,118]). Other evidence for the spatial organization of number comes from research showing that numerical value biases spatial attention, with adults detecting left- and right-side targets faster following small and large number primes, respectively [111,120–122].

Recent research on the representation of duration and emotional expression suggests that space may serve a fundamental organizational role, extending beyond number to magnitude information more generally. Western adults underestimate the amount of time that stimuli remain on screen when presented on the left side of space and overestimate when on the right [123]. They are also faster (and more accurate) when responding to shorter (or earlier) durations with their left hand and to longer (or later) durations with their right [124,125]. Similar left-to-right mental organization was recently shown for emotional expression, with Western adults responding faster to faces depicting greater emotion (whether happy or angry in expression) on the right side of space and to faces depicting less emotion on the left [104,126]. The magnitude of emotional expression was even found to bias spatial attention in leftward and rightward directions on a target detection task [127], as has been shown for number (e.g., [111]). Together, these data suggest that, like number, other magnitudes may be mentally organized in a consistent spatial direction, with increasing stimulus values oriented from left to right.

Studies with children suggest that the spatial organization of number and other magnitudes emerges over development with exposure to cultural conventions such as reading/writing direction [128–130] and counting practices [131,132]. Evidence for innate spatial organization of magnitude, as perhaps predicted by hemispheric-specific lateral biases [133,134], is lacking. Initial research designed to examine the development of the mental number line used parity judgments of Arabic numerals (as has been done with adults [110]) and found that children did not appear to represent number spatially until approximately nine years of age [135]. More recent studies confirm that younger children may not access numerical value in left-to-right orientation unless more/less relations are explicitly processed [136]. With explicit magnitude judgments (e.g., "Is the target number larger than 5?"), seven-year-olds show evidence of spatially oriented numerical representations, suggesting that spatial organization supports the instantiation of magnitude and may depend on direct access to the general magnitude system.

Other recent research provides evidence that the spatial orientation of number may emerge even earlier, following experience with the counting routine. By four to five years of age, American children reliably count arrays of objects from left to right and this strategy increases reliably over the school years [131,132]. Using a location task, Opfer and colleagues [131] found that preliterate preschoolers were more accurate at finding hidden objects when the locations were labeled using number words in a left-to-right *vs* right-to-left order, suggesting that the spatial organization of number may emerge, at least in part, from experience with counting in which common practice highlights a specific orientation. Other research has revealed that this orientation may be culture specific (e.g., left-to-right for English speakers and right-to-left for Arabic speakers) and may emerge in the school years for temporal information [128].

Taken together, these findings suggest that numerical magnitude is characterized by spatial organization, and at least in Western culture, involves left-to-right orientation. The specific orientation appears to emerge in the early preschool years with exposure to counting practices, and perhaps strengthened and extending to other magnitudes (e.g., time) with increasing exposure to more general spatial-attentional experiences such as reading/writing direction [110,128,129,135,136]. In this section, we distinguished between two senses of space—space as magnitude and space as location information. The latter sense should not be confused with the former, in which more/less structure is shared with other magnitudes such as number and time. As location, space may serve to organize various types of magnitude (e.g., number, time, and emotional expression), but is not itself magnitude per se. While direct evidence on the function of spatial organization is lacking, grounding magnitude dimensions in a common mental orientation may serve to further unite the dimensions, perhaps facilitating transfer across distinct forms of perceptual inputs.

CONCLUSIONS

Why might we represent magnitude in generalized form? And why might such a system emerge so early in development? One answer is that it makes adaptive sense. Many dimensions of magnitude, especially the big three, are highly correlated in the physical world. Bigger spaces tend to hold more objects than smaller spaces, and more objects usually take more time to put away. Representing different dimensions of magnitude with a partly shared vocabulary—more *vs* less stuff—might constitute a powerful learning mechanism, allowing information from one dimension to be used in making predictions about others. It is also the case that a system of generalized magnitude representation may be highly economical both with respect to conceptual and neural resources [137,138]. In this review, we presented evidence for early-developing associations among spatial extent, number, and time, as well as for generalized magnitude representation that extends beyond the big three. Such evidence provides reason to doubt strong claims of domain-specificity for dimensions such as number and has important implications for the debate on the origins of quantitative reasoning, which presupposes that at least the big three are conceptually dissociable. While the distinctions among magnitude dimensions may be salient to researchers, they may be less so in the mind of the young child. It is possible that any continuously varying stimulus dimension will naturally be conceptualized in terms of *more vs less stuff*, even if this involves a metaphorical leap or the arbitrary and idiosyncratic delineation of polarity. Given the myriad of magnitude dimensions, however, such a system would undoubtedly need limits and it will be up to future research to uncover whether these are imposed by developmental experiences or by various conceptual and neural constraints.

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