Research Reports

Developmental Continuity in the Link Between Sensitivity to Numerosity and Physical Size

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Abstract

Converging evidence suggests that representations of number, space, and other dimensions depend on a general representation of magnitude. However, it is unclear whether there exists a privileged relation between certain magnitude dimensions or if all continuous magnitudes are equivalently related. Four-year-old children and adults were tested with three magnitude comparison tasks – nonsymbolic number, line length, and luminance – to determine whether individual differences in sensitivity are stable across dimensions. A Weber fraction (w) was calculated for each participant in each stimulus dimension. For both children and adults, accuracy and w values for number and line length comparison were significantly correlated, whereas neither accuracy nor w was correlated for number and luminance comparison. However, although line length and luminance comparison performance were not correlated in children, there was a significant relation in adults. These results suggest that there is a privileged relation between number and line length that emerges early in development and that relations between other magnitude dimensions may be later constructed over the course of development.

Keywords: general magnitude representations, numerical cognition, approximate magnitude system, analog magnitude representations

The ability to represent and reason about magnitude emerges early in human development and is widespread throughout the animal kingdom. Quantities such as number, physical extent, and time can be expressed on a continuum of increasing amount, and representations of these quantities follow Weber's Law, suggesting that they share an analog magnitude format. Beyond sharing a common format, it has also been suggested that representations of different physical magnitudes may arise from a generalized magnitude system that is dependent on shared circuitry in the parietal cortex (Bueti & Walsh, 2009; Cantlon, Platt, & Brannon, 2009; Cohen Kadosh, Lammertyn, & Izard, 2008; Walsh, 2003). Magnitude dimensions that are structurally similar and automatically aligned with one another are said to be functionally overlapping (Srinivasan & Carey, 2010). However, it is unclear whether this functional overlap reflects a privileged relation between number, physical extent, and duration or whether it extends to all continuous dimensions (Bueti & Walsh, 2009; Cantlon et al., 2009; Lourenco & Longo, 2011; Walsh, 2003). Furthermore, the developmental origins of such an overlap remain unknown. One hypothesis is that infants are born with an undifferentiated sense of magnitude that becomes differentiated over the course of development through associative learning (Lourenco & Longo, 2010; Walsh, 2003). Alternatively, magnitude representations may initially be distinct in the infant brain, and relations between them may be constructed as a

result of maturation and experience. These hypotheses need not be entirely mutually exclusive; it is also possible that relations between some magnitude dimensions may be privileged early in development while others emerge later in life.

Early evidence for a functional overlap between magnitude dimensions comes from Meck and Church's (1983) seminal study demonstrating that rats spontaneously and simultaneously encode numerical and temporal information using a common mechanism. Additional supporting evidence comes from studies in humans demonstrating that irrelevant magnitude dimensions cause interference during magnitude comparison tasks. For example, judgments regarding the physical size of two Arabic digits are faster when the larger physical digit represents the larger numerical magnitude compared to when the physical and numerical magnitudes are incongruent (Tzelgov, Meyer, & Henik, 1992). This cross-dimensional interference suggests that not only are both numerical and physical magnitudes processed automatically, even when they are task irrelevant, but also that the irrelevant information interferes with the comparison process in the relevant dimension. Similar instances of interference also occur for judgments of number, size, duration, and luminance when the irrelevant dimensions are varied orthogonally to the target dimensions (Casasanto & Boroditsky, 2008; Cohen Kadosh & Henik, 2006; Dormal & Pesenti, 2013; Dormal, Seron, & Pesenti, 2006; Xuan, Zhang, He, & Chen, 2007). For instance, when judging the relative duration of two stimuli, greater stimuli (e.g., physically larger, more numerous, or more luminous) are judged to have longer durations than lesser stimuli (e.g., physically smaller, less numerous, or less luminous) (Xuan et al., 2007). Interestingly, the strength of this cross-dimensional interference is not always symmetrical. When making judgments regarding either the number of dots or their cumulative area, it appears that the influence of area on number is stronger than the reverse (Hurewitz, Gelman, & Schnitzer, 2006). However, when making judgments regarding either number or line length, number appears to influence line length more than the reverse (Dormal & Pesenti, 2013). These differential interference effects suggest that representations of number and spatial extent may not draw on entirely overlapping cognitive resources.

A functional overlap between number, physical extent, and duration appears to be present early in human development. Infants, like adults, spontaneously align representations of number, physical extent, and duration. For example, infants habituated to congruent pairs of lines and tones (e.g., long lines presented simultaneously with long tones) look longer at incongruent pairs (e.g., long lines paired with short tones) compared to congruent pairs at test (Srinivasan & Carey, 2010). Likewise, infants habituated to arbitrary color-magnitude pairings (e.g., large objects: black with stripes; small objects: white with dots) expect the color-pattern pairs to hold across the dimensions of size, number, and time (e.g., more numerous arrays and longer durations: black with stripes; less numerous arrays and shorter durations: white with dots), and look longer when the pattern is violated (e.g., less numerous arrays and shorter durations: black with stripes; more numerous arrays and longer durations: white with dots) (Lourenco & Longo, 2010). These results suggest that infants are sensitive to the relational congruence between large numerosities, large objects, and long durations in comparison to small numerosities, small objects, and short durations. Furthermore, these associations have recently been found in neonates just hours after birth (de Hevia, Izard, Coubart, Spelke, & Streri, 2014), suggesting that they are present even before infants have had a chance to experience correlations between these dimensions in the external world.

If representations of magnitude are functionally overlapping, then it follows that individual differences in magnitude comparison acuity should correlate across different dimensions. Recent studies probing this question, however, have provided conflicting answers. Some studies with adults have found correlations between acuity for number and line length or between number and the cumulative area of dot arrays (DeWind & Brannon, 2012; Lourenco,

Bonny, Fernandez, & Rao, 2012), whereas other studies have failed to find correlations in comparison performance between magnitude dimensions (Agrillo, Piffer, & Adriano, 2013; Cappelletti et al., 2014; Odic, Libertus, Feigenson, & Halberda, 2013). Although it can be difficult to interpret a null finding, differences in study design and sample size may have contributed to these conflicting results.

In addition to correlational designs, two recent studies have used training paradigms to address the relations between different magnitude dimensions. DeWind and Brannon (2012) found that while numerical comparison training resulted in an improvement in Weber fraction for the same numerosity task, the improvement did not transfer to a line length comparison task. A second study also failed to find a transfer effect from numerical comparison training to spatial discrimination performance. Interestingly, when numerical comparison training was coupled with transcranial random noise stimulation (tRNS) to the parietal lobe, however, improvements in numerical acuity did transfer to spatial acuity (Cappelletti et al., 2013). Therefore, transfer effects between magnitude comparison tasks may require cellular changes above and beyond those induced by behavioral training alone. Taken together, these previous studies suggest that representations of different magnitude dimensions may draw on a set of both common and unique cognitive resources. However, the degree to which these shared resources overlap, as well as the dimensions that rely on these shared resources, remains unclear.

There is also research suggesting that not all magnitude dimensions share the same level of functional overlap, particularly early in development. As described above, infants recognize congruity between numerosity and line length or numerosity and duration. However, infants do not readily form associations between line length and auditory volume (Srinivasan & Carey, 2010) or between numerosity and luminance (de Hevia & Spelke, 2013) when tested in the same paradigms. Likewise, preschool children perform better when mapping number to line length compared to mapping number to brightness or line length to brightness (de Hevia, Vanderslice, & Spelke, 2012). Furthermore, even adults do not spontaneously align auditory volume and line length when the task does not explicitly promote such a mapping (Srinivasan & Carey, 2010). These findings raise the question of whether the level of functional overlap found between representations of number, physical extent, and duration may be greater than the overlap exhibited by other magnitude dimensions.

The present study was designed to assess the relation between different magnitude representations over development. Although the infant studies reviewed above suggest that the relation between some dimensions may be privileged, studies with children and adults that have parametrically measured individual differences in acuity have only assessed acuity for spatial magnitudes (e.g., number and spatial extent) and have not included nonspatial dimensions such as loudness or luminance. Given the infant data, we predicted that acuity for line length and numerosity would be more closely linked to one another than to nonspatial dimensions. In addition, we hypothesized that if magnitude representations are initially undifferentiated, then acuity across magnitudes should be more closely linked in young children compared to adults. On the other hand, if magnitude associations are constructed over development, then adults may exhibit relations between magnitudes that are not present in young children. To investigate these hypotheses, we tested four-year-old children and adults with three magnitude comparison tasks: nonsymbolic number, line length, and luminance. We then compared performance across the three tasks to assess the strength of the relations between magnitude dimensions.

Methods

Participants

Data from 85 participants were included in the final analyses: 53 children (mean age: 3 years 11 months; range: 3 years 6 months to 4 years 5 months; 28 females) and 32 adults (mean age: 19 years 3 months, range 18 years 0 months to 21 years 7 months; 21 females). Seventeen additional children were excluded from all analyses due to failure to complete two or more of the three tasks and two additional adults were excluded due to chance-level performance on all tasks. Twelve of the 85 participants included in the final sample had incomplete data sets. Specifically, data from three children were excluded from analysis of the number task because they touched the stimulus with the largest individual dots exclusively, and data from one adult was excluded due to chance-level performance. Data from two children were excluded from analysis of the line length task due to computer error. Data from five children were excluded from analysis of the luminance task due to computer error and data from one adult was excluded due to chance-level performance. This resulted in 49 children and 31 adults in the number-line length correlation analyses, 49 children and 30 adults in the number-luminance correlation analyses, and 53 children and 31 adults in the line length-luminance correlation analyses of accuracy. Adult participants and parents of child participants gave written informed consent to a protocol approved by the local Institutional Review Board.

Stimuli and Design

Stimulus presentation and response collection were controlled using Psychophysics Toolbox Version 3 for Matlab (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007). In the number task, stimuli consisted of two arrays of colored dots surrounding a central cartoon image on a black background (Figure 1A).
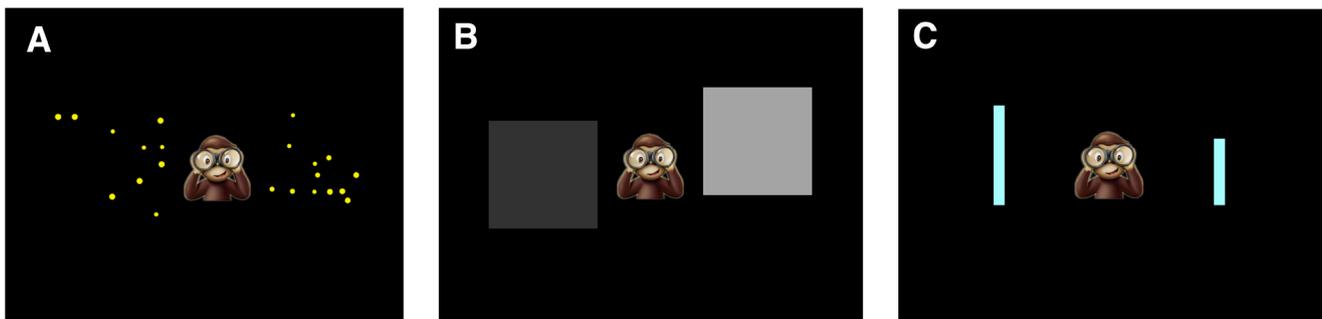

Figure 1. Example stimuli for the nonsymbolic number task (A), luminance task (B), and line length task (C).

The number of dots in each array ranged from 6 to 18. Five ratios were tested (larger number/smaller number): 3.0, 2.0, 1.5, 1.2, and 1.14. To control for non-numerical properties of the arrays, the average item size was equated in half of the trials, and cumulative surface area was equated in the other half of the trials. Therefore, in half of the trials the numerically larger had equally sized dots to the numerically smaller array, and in the other half the numerically larger array had smaller sized dots than the numerically smaller array. Dot arrays were drawn in real time before each trial such that each trial featured novel arrays. In the luminance task, stimuli consisted of two gray squares surrounding a central cartoon image on a black background (Figure 1B). The luminance of the squares ranged from 50 to 150 cd/m^2. The same five ratios were tested: 3.0, 2.0, 1.5, 1.2, and 1.14. A Spyder4Elite calibration system (Datacolor) was used to perform gamma correction and determine accurate luminance levels. In the line length task, stimuli consisted of two colored vertical lines surrounding a central cartoon image on a black background (Figure 1C). The lines lengths ranged in size from 108 to 216 pixels with a constant width of

20 pixels. The vertical position of the lines was jittered such that the distance between the endpoints of the line and the frame of the monitor could not be used as a reference. Five ratios were tested: 1.5, 1.2, 1.14, 1.11, and 1.1. Note that while the number and luminance tasks used the same ratios, more difficult ratios were used for the line length task after pilot testing indicated that some children performed at ceiling with the original ratios.

Procedure

Participants performed the number, line length, and luminance tasks in a counterbalanced order within a single experimental session lasting approximately 20 minutes. Participants were instructed to choose the array containing the "most dots", the "longest line", or the "brightest square." All ratios were presented in a randomized order.

In the child version of the experiment, each task was preceded by 3 practice trials to ensure that children understood how to play the game. Each task consisted of 50 test trials. On each trial, the stimuli appeared on the screen until the child made a response by touching one of the two stimuli. Immediately following the response, children received differential auditory feedback (a high tone for correct responses and a low tone for incorrect responses) and were given a small sticker for each correct response to maintain motivation throughout the session.

The adult version of the experiment consisted of 150 test trials for each task. On each trial, the stimuli were displayed for 500 ms followed by a 2500 ms response window. Adults pressed a button on the keyboard (F or J) to indicate their response. Because adults immediately understood the task and did not require external motivation to maintain focus, practice trials and feedback were not included. Cronbach's alpha was calculated for each task separately for children and adults, and reliability was high (.79, .80, and .67 for number, line length, and luminance respectively in children; .52, .76, and .85 in adults).

Modeling

We used a psychophysical modeling technique to calculate a Weber fraction (w) that served as an estimate for each participant's acuity in each of the three magnitude dimensions (e.g., Halberda & Feigenson, 2008). We modeled the error rate in the tasks as

$$\frac{1}{2} erfc\left(\frac{n_1 - n_2}{\sqrt{2}w\sqrt{n_1^2 + n_2^2}}\right),$$

where n_1 is the larger value, n_2 is the smaller value, w is a measure of variance in the internal representation, and *erfc* is the complementary error function. The resulting value of w represents the noise in each participant's internal magnitude representations, such that lower values of w correspond to less noise (i.e., higher acuity). Due to highly variable responses and performance at or below chance, the model was not always able to settle on a fit, and in those cases data from those participants for those conditions were excluded from further analyses involving w. This was the case for 15 children in the numerical task, one adult in the line length task, and one child in the luminance task.

Results

First we conducted an analysis of variance (ANOVA) investigating the effects of task and age group on magnitude comparison performance. This revealed a main effect of task ($F(2,234) = 8.02$, $p < .001$, $\eta^2 p = .06$), a main effect of age ($F(1,234) = 38.02$, $p < .001$, $\eta^2 p = .14$), and a significant task by age interaction ($F(2,234) = 7.06$, $p = .001$, $\eta^2 p = .06$).

Next we analyzed accuracy for each task using repeated-measures ANOVAs with ratio as a within-subjects factor and age group as a between-subjects factor (see Table 1 for descriptive statistics).

Table 1

Descriptive Statistics for Each Task

	Number				Line Length				Luminance			
	Accuracy		w		Accuracy		w		Accuracy		w	
	M	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*	*M*	*SEM*
Children	70.18	2.73	.50	.06	82.88	2.03	.12	.01	79.53	2.06	.31	.03
Adults	86.10	1.64	.20	.01	86.99	1.63	.10	.01	86.50	1.75	.21	.02

Note. w = Weber fraction.

In the nonsymbolic number task, there was a main effect of age group ($F(1,77) = 32.68$, $p < .001$, $\eta^2 p = .30$), indicating that adults were more accurate than children (Figure 2A). There was also a main effect of ratio ($F(4,308) = 37.78$, $p < .001$, $\eta^2 p = .33$), indicating that performance was more accurate for larger ratios. In addition, there was a significant age group by ratio interaction ($F(4,308) = 6.14$, $p < .005$, $\eta^2 p = .07$) indicating that the ratio effect was stronger in adults compared to children. In the line length task there was a marginal effect of age group ($F(1,79) = 3.46$ $p = .07$, $\eta^2 p = .04$), reflecting higher performance for adults compared to children (Figure 2B). There was also a main effect of ratio ($F(4,316) = 50.53$, $p < .001$, $\eta^2 p = .39$), reflecting that performance was better for larger ratios. The age group by ratio interaction was not significant ($p = .18$, $\eta^2 p = .02$). Finally, in the luminance task there was a main effect of age group ($F(1,78) = 6.69$, $p < .05$, $\eta^2 p = .08$), and a main effect of ratio ($F(4,312) = 86.08$, $p < .001$, $\eta^2 p = .53$), again reflecting better performance for adults and for larger ratios (Figure 2C). The age group by ratio interaction was not significant ($p > .8$, $\eta^2 p = .004$). Based on the observed effect sizes, it appears that ratio exerted a relatively large influence on all three tasks, as would be expected if participants' are engaging analogue magnitude representations to perform the comparison judgments. In addition, although the effect of age was large for the nonsymbolic number comparison task, it was relatively weaker for the line length and luminance comparison tasks.
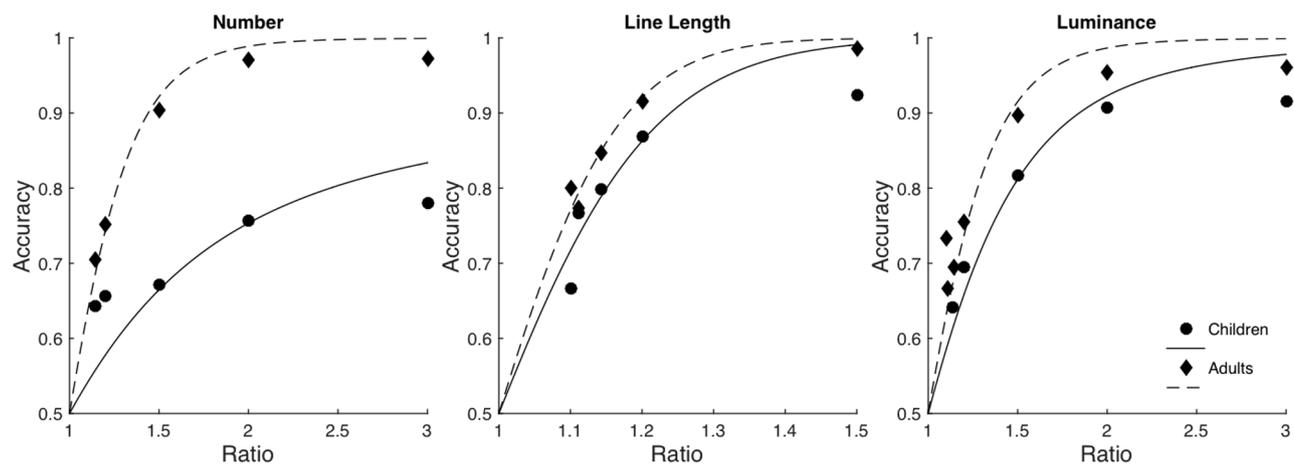

Figure 2. Mean performance in the nonsymbolic number task (A), line length task (B), and luminance task (C). Symbols indicate actual performance; lines indicate modeled best-fitting Weber function.

To determine the relation between acuity for different magnitudes, we performed correlational analyses between participants' accuracy in each of the three tasks using Pearson correlations (Figures 3 and 4) and compared the relative strength of the different correlation coefficients. The main finding was that number and line length were significantly correlated in both children ($r(47) = .58$, $p < .001$) and adults ($r(29) = .46$, $p < .01$). In contrast, neither children nor adults exhibited a significant correlation in performance between number and luminance (children: $r(47) = .26$, $p = .07$; adults: $r(28) = .20$, $p = .30$). Finally, performance in the line length and luminance tasks was not correlated in children ($r(51) = .21$, $p = .12$), but was significantly correlated in adults ($r(29) = .60$, $p < .001$).

The same analyses were repeated using Weber fractions (w) rather than accuracy for each participant. The w values for one child in the number task, two children in the line length task, and one child and one adult in the luminance task differed from the group means by more than three standard deviations, and these data were excluded from further analyses. The analyses based on w revealed the same pattern as those based on accuracy. The w values for number and line length were significantly correlated in children ($r(34) = .34$, $p < .05$) and in adults ($r(28) = .47$, $p < .01$). Number and luminance did not exhibit a significant correlation in either children ($r(31) = .19$, $p = .30$) or adults ($r(27) = -.07$, $p = .73$). There was again no correlation between line length and luminance in children ($r(42) = -.19$, $p = .21$), but the correlation was significant in adults ($r(27)= .40$, $p < .05$).

To compare the relative strengths of the correlations between task pairs, we used Lee and Preacher's method for comparing correlation strengths between dependent correlations (Lee & Preacher, 2013). This method involves converting the correlation coefficients into z-scores and then computing asymptotic covariance of the estimates (Steiger, 1980) for use in an asymptotic z-test to account for the samples being dependent rather than independent. Given that accuracy and w revealed the same pattern of correlations and accuracy allowed use of the full sample, we conducted the remaining analyses on accuracy. In children, the relation between number and line length was significantly greater than the relations between number and luminance or line length and luminance ($zs > 2.03$, $ps < .05$). In adults, there was a trend for the correlation between number and line length to be greater than that between number and luminance ($z = 1.68$, $p = .09$), and the correlation between line length and luminance was significantly greater than that between number and luminance ($z = 2.45$, $p < .05$). However, the correlation between number and line length was not significantly different than that between line length and luminance ($z = .77$, $p = .45$).

To address the possibility that domain-general processes common to all three types of magnitude comparison tasks may be influencing the correlations, we next performed correlations of comparison accuracy in which the variance of the third dimension was partialled out. These analyses showed the same pattern of results as the zero-order correlations. In children, the correlation between number and line length remained significant when luminance was controlled ($r_p(45) = .55$, $p < .001$), whereas the correlations between number and luminance and between line length and luminance still did not reach significance once the third dimension was controlled ($ps > .25$). In adults, the correlation between number and line length remained significant after controlling for luminance ($r_p(27) = .44$, $p = .02$), and the correlation between line length and luminance remained significant after controlling for number ($r_p(27) = .59$, $p = .001$), whereas the correlation between number and luminance once again did not reach significant after controlling for line length ($p = .55$).

A final analysis indicated that there was no statistical difference in the strength of the significant correlations between number and line length in children and adults ($z = .68$, $p = .50$), suggesting that the relation between

these dimensions remains stable between early childhood and adulthood. However, the correlation between line length and luminance was significantly stronger in adults than in children ($z = 2.02$, $p < .05$).
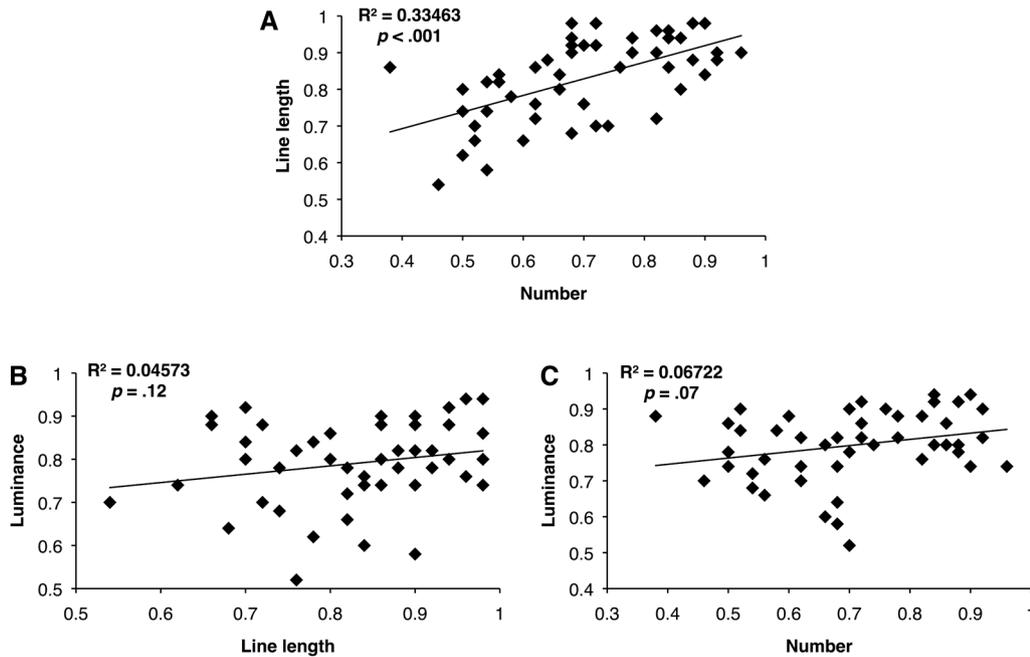

Figure 3. Correlational analyses illustrating the relation between children's performance in the different magnitude comparison tasks. Number and line length (A) are significantly correlated whereas line length and luminance (B) and number and luminance (C) do not exhibit a significant correlation.
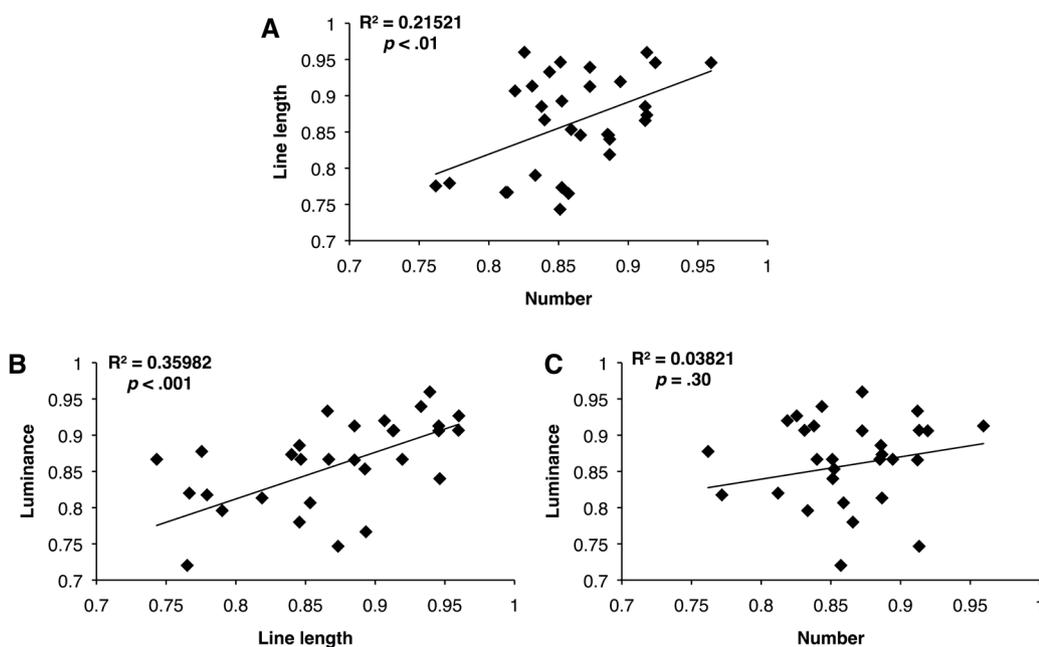

Figure 4. Correlational analyses illustrating the relation between adults' performance in the different magnitude comparison tasks. Number and line length (A) and line length and luminance (B) are significantly correlated whereas number and luminance (C) do not exhibit a significant correlation.

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Discussion

The primary goal of this research was to investigate the functional overlap between representations of different magnitude dimensions by assessing the relations between acuity for three types of magnitude: number, line length, and luminance. The study was designed to ask whether there is a privileged relation between number and line length compared to luminance and whether these relations change over development. Our first finding was that both children and adults exhibited a positive relation between acuity for number and line length, whereas number and luminance acuity were not significantly correlated in either age group. In contrast, we found age-related differences in the relation between line length and luminance acuity, in that acuity for these dimensions was correlated in adults but not in children. These results generally support the hypothesis that number shares a privileged relation with space that does not extend to all other magnitude dimensions. They are also consistent with research in adults demonstrating a correlation between numerical acuity and acuity for spatial extent (DeWind & Brannon, 2012; Lourenco et al., 2012), as well as with previous work demonstrating that infants and preschool children spontaneously form associations between representations of number and physical extent but fail to do so when relating these dimensions to luminance or volume (de Hevia & Spelke, 2010; de Hevia et al., 2012; de Hevia & Spelke, 2013; Lourenco & Longo, 2010; Srinivasan & Carey, 2010). One advance made by the present study with regards to previous research is the use of three magnitude dimensions rather than two (but see Agrillo et al., 2013). This enabled us rule out the influence of motivation or domain-general processes related to the comparison process by partialling out the variance attributed to the third dimension. Because the results of the partial correlation analyses are consistent with those from the zero-order correlations, it appears that the present results reflect true relations between individual differences in performance across the three magnitude comparison tasks.

Notably, although the relation between number and line length was comparable in four-year-old children and adults, the relation between line length and luminance appears to change over development. Whereas four-year-old children's acuity for line length and luminance were not correlated, by adulthood the correlation was significant. By one theory of generalized magnitude representations, infants enter the world with an undifferentiated sense of magnitude and come to segregate these representations into distinct magnitude dimensions over development (Walsh, 2003). This theory predicts that acuity for number, line length, and luminance would be more strongly correlated in young children and that the correlations may attenuate over development. Our results, however, reveal a different pattern and are more consistent with the idea that new relations between magnitudes can be constructed over the course of development.

Research measuring looking-time in infants has shown that in the first year of life infants are already sensitive to congruent pairings of number and physical size (de Hevia et al., 2014; de Hevia & Spelke, 2010; Lourenco & Longo, 2010) but do not recognize congruency for pairings of number and luminance (de Hevia & Spelke, 2013). Likewise, preschool children can explicitly form mappings between number and line length yet are unable to do so for number and luminance (de Hevia et al., 2012). Although adults can readily learn or form meaningful mappings across any ordered continuum (e.g., Stevens, 1957), the finding that this ability is not present early in development suggests that the relation between number and size may be primary to relations with nonspatial dimensions such as luminance.

If not all magnitude dimensions are related to one another in infancy, when and how do adults develop the ability to make vivid cross-dimensional associations? Future studies could examine this developmentally to assess when these relations becomes robust. However, two factors that may promote the formation of cross-dimensional relations

are analogical reasoning and the common language used across magnitude dimensions (e.g., ordinal terms such as more and less). In particular, the process of comparison may promote the recognition of the structural similarities between prothetic magnitude dimensions (Gentner & Medina, 1998). Older children, for example, readily match relational similarity (e.g., increasing monotonic order) both within and across perceptual dimensions, whereas younger children succeed only at same-dimension matches (Kotovsky & Gentner, 1996). However, when younger children are given practice with same-dimension matches before being asked to perform cross-dimension matches, they then succeed at making cross-dimension matches, suggesting that experience with same-dimension matches facilitates children's recognition of abstract relational rules that can be applied across perceptual dimensions. Practice therefore appears to encourage children to compare relations within and across dimensions, helping them to align representations of previously independent magnitude dimensions.

Common vocabulary used for different magnitude dimensions may also promote the formation of associations between previously independent dimensions (Gentner & Medina, 1998). For example, although infants do not spontaneously align representations of physical extent and loudness, children come to form associations between these dimensions by two to five years of age (Marks, 1978; Smith & Sera, 1992). One possibility is that the acquisition of words such as "loud," "quiet," and "more" underlies this developmental shift. When children grasp that "big" and "loud" are both words that represent "more," they may become able to recognize the structural similarity between physical extent and volume and form a congruent alignment between these dimensions (Smith & Sera, 1992). However, other research suggests that even though adults can consciously form mappings between volume and physical extent, this mapping does not always occur spontaneously (Srinivasan & Carey, 2010), which is consistent with the conclusion that associations between magnitude dimensions formed later in childhood may differ qualitatively from the cross-dimensional associations that exist early in development. As such, the relation between number and physical size may reflect an early-developing, privileged relation between these dimensions whereas the relation between size and luminance found in adults may reflect a relation that has been constructed through experience. Further work with children is needed to investigate the emergence of the relation between size and luminance and the possible contributions of analogy and language.

Another open question concerns the contribution of parietal cortex to cross-magnitude associations. The role of the parietal cortex in numerical representations has been well documented (see Nieder & Dehaene, 2009 for review). Parietal cortex, however, has also been implicated in the representation of many continuous magnitude dimensions. Comparison judgments for number, time, size, and luminance have all been found to engage neighboring or overlapping regions of parietal cortex, and cross-dimensional interference between these dimensions modulates parietal activity (Cohen Kadosh, Cohen Kadosh, & Henik, 2008; Cohen Kadosh et al., 2005; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel, Piazza, Le Bihan, & Dehaene, 2004). Furthermore, single-unit recording data from macaques indicates that individual neurons tuned to numerical, temporal, and spatial magnitudes co-exist in posterior parietal cortex (Leon & Shadlen, 2003; Onoe et al., 2001; Sawamura, Shima, & Tanji, 2002; Tudusciuc & Nieder, 2007). In addition, some of these neurons are even responsive to multiple quantity types, though these neurons exhibit dimension-specific response patterns (Tudusciuc & Nieder, 2007). Tudusciuc and Nieder (2007) trained monkeys to perform a delayed match-to-sample task using both numerical and line length stimuli while recording from neurons in the intraparietal sulcus. During the delay period, when the monkeys needed to maintain a quantity representation in working memory, 15% of the neurons were tuned to a specific numerosity or line length. In addition, 20% of these quantity-sensitive neurons responded to both number and length. However, none of the neurons that responded to both numerosity and length displayed an abstract magnitude preference (e.g., a preference for both larger numerosities and longer line lengths). This suggests that number and spatial

extent are represented by partly overlapping populations of neurons, with some neurons contributing to representations of both magnitude types. Together, these results suggest that the parietal lobe is a locus of magnitude representation and magnitude comparison. Furthermore, within the parietal lobe there exist both distributed and overlapping neural populations that contribute to magnitude judgment.

Conclusions

We investigated the relation between acuity for three magnitude dimensions in four-year-old children and adults to shed light on the question of whether number and size share a privileged relation. We found that in both young children and adults, numerical acuity was correlated with line length acuity. Furthermore, line length acuity was related to luminance acuity in adults but not in children. No relations between numerical and luminance acuity were found in either age group. Therefore, the present results support the idea that number and physical extent exhibit signs of a functional overlap early in human development and maintain a privileged relation throughout the lifespan. Other dimensions such as luminance may become integrated with a general sense of magnitude later in childhood but may never reach the same level of overlap.

Competing Interests

The authors have declared that no competing interests exist.

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