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Cross-magnitude Interactions across Development: Longitudinal Evidence for a General Magnitude System

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Abstract

There is general agreement that humans represent numerical, spatial, and temporal magnitudes from early in development. However, there is disagreement about whether different magnitudes converge within a general magnitude system and whether this system supports behavioral demonstrations of cross-magnitude interactions at different developmental time points. Using a longitudinal design, we found a relation between children's cross-magnitude interactions assessed at two developmental time points with different behavioral measures. More specifically, stronger cross-magnitude interactions in infancy ($M = 9.3$ months) predicted a stronger cross-magnitude congruity effect at preschool age ($M = 44.2$ months), even when controlling for performance on measures of inhibitory control, analogical reasoning, and verbal competence at preschool age. The results suggest a common mechanism for cross-magnitude interactions at different points in development as well as stability of the underlying individual differences. We argue that this mechanism reflects a nonverbal general magnitude system that is operational early in life and that displays continuity from infancy to preschool age.

INTRODUCTION

In his book entitled *Critique of Pure Reason*, Immanuel Kant famously argued that space and time provided “a priori intuitions” that structured how humans experience the physical environment (Kant, 1781/1929). Today, many researchers would add that intuitions of numerical magnitude play a similarly crucial role in structuring experience (e.g., Dehaene & Brannon, 2011), and evidence from studies with infants suggests that humans categorize stimuli according to spatial, temporal, and numerical magnitudes early in development (Brannon, Lutz, & Cordes, 2006; Feigenson, Dehaene, & Spelke, 2004; Lourenco & Huttenlocher, 2008; Newcombe, Huttenlocher, & Learmonth, 1999; VanMarle & Wynn, 2006; Xu & Spelke, 2000). Though there may be general consensus that humans are well equipped to process information related to different magnitudes from early in life, there is debate about the extent to which the underlying representations are related in the mind and brain. As described below, the current study adopted a longitudinal design to shed light on this debate.

On one side of the debate, there are those who argue that representations of space, time, and number converge within a general magnitude system (Walsh, 2003; see also, Bonn & Cantlon, 2017; Capelletti et al., 2013; Lourenco, Azyenberg, & Lyu, 2016). Though there remains ambiguity in this literature about the precise nature of the convergence, we suggest that the core feature is a direct link between magnitude representations. According to Walsh and colleagues (Bueti & Walsh, 2009; Walsh, 2003), these links are rooted in the need to coordinate multiple magnitudes (e.g., space and time) relevant for action. Over evolution, numerical representations came to overlap with other magnitudes (space and time) in posterior parietal cortex where there is common analog format (Gallistel & Gelman, 2000), thereby providing a unified metric for action (Andres, Davare, Pesenti, Olivier, & Seron, 2004). Another possibility is that the convergence reflects perceptual integration such that number and other magnitudes are represented in holistic fashion as integral dimensions (Garner, 1974; Garner & Felfoldy, 1970; Persichetti, Aulet, Dilks, & Lourenco, 2017). These types of representations might involve a composite of the cues related to different magnitudes, such as a low dimensional summary of the correlated cues (Bonn & Cantlon, 2012; Jones & Goldstone, 2013).

On the other side of the debate, there are those who argue against the convergence of space, time, and number, such that different magnitudes are exclusively represented independently of one another (Hyde, Khanum, & Spelke, 2014; Odic, Libertus, Feigenson, & Halberda, 2013; Van Opstal & Verguts, 2013). As an example of this perspective, there is the Approximate Number System (ANS) in which number is differentiated from other magnitudes by normalizing over non-numerical cues (e.g., Dehaene & Changeux, 1993; for review, see Anobile, Cicchini, & Burr, 2016). The claim that follows from this perspective is that any ‘cross-talk’ between magnitudes, as when different magnitudes interact with one another to affect behavior, does not occur vis-à-vis overlapping representations within a general magnitude system. On this view, any interactions reflect the influence of other, non-magnitude mechanisms (discussed below).

Neuroimaging data have been used as evidence to support a general magnitude system. In humans, there is overlapping activation, as measured by BOLD in fMRI, for different magnitudes in and around the intraparietal sulcus (IPS) (Harvey, Fracasso, Petridou, & Dumoulin, 2015; for meta-analysis, see Sokolowski, Fias, Ononye, & Ansari, 2017). Behavioral findings of cognitive interactions for different combinations of magnitude dimensions have also been taken as evidence for a general magnitude system. For example, the so-called ‘size congruity effect’ reflects the influence of the physical size of Arabic numerals on participants’ judgments of numerical value (Henik & Tzelgov, 1982). Such congruity effects are also observed with non-symbolic displays in humans at different developmental stages (adults: Hurewitz, Gelman, & Schnitzer, 2006; children: Rousselle, Palmers, & Noël, 2004) and with nonhuman animals (Merritt, Casasanto, & Brannon, 2010). In humans, behavioral demonstrations of cross-magnitude interactions at different developmental time points are suggestive of a general magnitude system that is functional and stable across development. However, an alternative possibility is that these cross-magnitude effects reflect different mechanisms across development, each of which may be unrelated to a general magnitude system. For example, among linguistic individuals, associations between different magnitudes could be supported by language, not a general

magnitude system (Casasanto, Fotakopoulou, & Boroditsky, 2010; Winter, Marghetis, & Matlock, 2015). In this case, there would be no functional overlap between magnitudes. Instead, common words such as “more” and “less” could mediate the interactions between different magnitudes that exist exclusively as independent representations. Indeed, it has been suggested that the prevalence of particular magnitude words leads to asymmetric patterns of interactions between magnitudes (e.g., Bottini & Casasanto, 2013; but see, Bonn & Cantlon, 2012; Buetti & Walsh, 2009; Lourenco & Longo, 2011). Mediation by way of a linguistic system is a possible mechanism for cross-magnitude interactions documented in adults and older children, but not in prelinguistic children and nonhuman animals in whom cross-magnitude interactions have also been reported (de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Lourenco & Longo, 2010; Meck & Church, 1983; Merritt et al., 2010; Srinivasan & Carey, 2010). In prelinguistic children, synesthesia has been proposed as a mechanism that could account for associations between magnitudes, but such a mechanism is unlikely in older children and adults because of the putative neural pruning later in development (Cantlon, 2012; cf. Cohen Kadosh & Gertner, 2011). Thus, it is an open question whether the magnitude associations in infants are supported by the same mechanism as those in older children and adults. In particular, it is unclear whether the cross-magnitude interactions that have been observed at different points in development reflect continuity of a general magnitude system or, rather, different mechanisms at different developmental time points such as synesthesia in infancy and linguistic mediation in older individuals.

The goals of the present study were two-fold. First, we sought a test of the developmental stability of cross-magnitude associations. Although cross-magnitude associations have been reported at different ages, no study to our knowledge has examined time-to-time reliability of these effects. A longitudinal assessment of this type not only provides a unique test of the robustness of the cross-magnitude associations, but it also places constraints on the potential mechanism(s) that may underlie these effects. Accordingly, our second goal was to provide a test of the general magnitude system within a longitudinal context across two disparate time points. The data from the first time point are reported in Lourenco and Longo (2010) where cross-magnitude congruity effects were assessed with a visual attention paradigm in 9-month-olds who were mostly preverbal and, thus, had little or no knowledge of words for magnitude. In the present study, we examined the extent to which inter-individual variability related to these effects remained stable when children were tested at 3.5 years of age on a forced choice magnitude judgment task. As the test of developmental stability, we assessed whether individual differences in the strength of the cross-magnitude associations in infancy predicted the strength of the cross-magnitude associations at preschool age. We also tested whether this relation held when accounting for the effects of other, non-magnitude cognitive abilities, including inhibitory control, analogical reasoning, and verbal competence. Our approach allowed us to rule out the effects of language and other cognitive abilities, namely analogical reasoning and inhibitory control, as explanations for the stability of cross-magnitude associations between infancy and preschool age. Given this design, we take evidence of longitudinal stability as support for a general magnitude system during early development.

METHOD

Participants

Of the 72 children who participated in the original study of Lourenco and Longo (2010), 36 returned to the laboratory at approximately 3.5 years of age ($M_{\text{age}} = 44.21$ months; $\text{range} = 40.28 - 47.23$ months; 17 girls). Parents or legal guardians provided written informed consent on behalf of their children at both time points. All children were given a gift for their participation at the completion of each visit. Experimental procedures were approved by the local Institutional Review Board (IRB).

Design and Procedure

At the first time point, children were presented with a visual attention paradigm that tested for cross-magnitude associations by assessing congruity between different magnitudes. Children were tested in one of three conditions (“space & number”, “space & time”, and “number & time”; see Lourenco & Longo [2010] for details). During the habituation phase of this paradigm, children were presented with stimuli that depicted a systematic mapping between relative magnitude and pattern. For example, in the “space & number” condition, half of the children were habituated to a mapping for area such that they observed trials in which the larger-sized objects were striped and the smaller-sized objects were dotted (the other half were habituated to a mapping for number). In the test trials that followed, children were presented with a different magnitude that mapped to pattern in congruent or incongruent fashion depending on the mapping during habituation. For example, in the “space & number” example just described, children observed congruent trials in which the larger numerical array was striped and the smaller numerical array was dotted. The incongruent test trials in this example consisted of a larger numerical array that was dotted and a smaller numerical array that was striped. In Lourenco and Longo (2010), congruity effects were observed in all conditions, such that children looked significantly longer on incongruent than congruent trials, as would be predicted given that it was the incongruent trials that violated the expectation established during the habituation phase.

At the second time point, children returned to the laboratory for testing. They participated in a single testing session during which they were administered three tasks in the following order: Magnitude Judgment (similar to Bonny & Lourenco, 2013; also, Rousselle et al., 2004), Day-Night Stroop (Gerstadt, Hong, & Diamond, 1994), Analogical Reasoning (Kotovsky & Gentner, 1996), and the PPVT (Peabody Picture Vocabulary Test, 4th edition, Dunn & Dunn, 2007). Except for the PPVT, each of the tasks was administered on a Dell Vostro laptop with an external touchscreen (34 × 21 cm; MagicTouch, Keytec) used for recording children’s responses. Children sat approximately 40 cm from the screen. The PPVT was administered with the use of a freestanding booklet of printed color images using the standard protocol. Children were given a selection of stickers after completing each task.

Magnitude Judgment.—Each trial of the Magnitude Judgment task involved the presentation of two arrays of two-dimensional objects (e.g., an array of 4 squares and an array of 8 squares). Each array appeared in front of a Sesame Street character (Bert and Ernie; see Figure 1A). With the arrays presented side-by-side, children were asked to judge

which array was larger in number (“Who has more things?”). The arrays remained onscreen until children made a response but they were discouraged from explicitly counting the items in the arrays so as to ensure reliance on approximate numerosity; if they attempted to count, they were immediately discouraged from doing so by being told that it was not a counting game. Number pairs differed by a 1:2 ratio. Given that small numerosities may recruit different quantification processes than larger numerosities (Feigenson et al., 2004; Trick & Pylyshyn, 1994), only numerosities above the subitizing range (i.e., larger than 3) were included in this task (i.e., 4 vs. 8, 6 vs. 12, and 8 vs. 16). Half of the trials were congruent with spatial properties, namely cumulative area and individual element size. The other half were incongruent with these spatial properties. Because we wanted to ensure that trials were clearly congruent or incongruent, we created displays with homogenous sets of elements in which cumulative area and individual element size were both either congruent or incongruent with number (see Figure 1A). Congruity varied from 2-fold to 6-fold differences. These differences were determined for both cumulative area and individual element size. Each number pair was presented as sets of squares or circles (half of each type).

Children received two training trials with corrective feedback to ensure that they understood the task instructions, which was to select the array with the larger number of items. Twenty-four test trials followed (randomly ordered); no corrective feedback was provided on these trials. The side of the correct answer was counterbalanced across trials. Congruity scores were used in the analyses below and were calculated for each child as the difference in the number of errors for congruent and incongruent trials ($\text{congruity score} = \text{incongruent}_{\text{errors}} - \text{congruent}_{\text{errors}}$), with higher scores indicating a greater congruity effect between number and spatial magnitudes.

Day-Night Stroop.—The Day-Night Stroop task included two types of trials (Gerstadt et al., 1994). On the naming trials, children were instructed to say “day” when shown the picture of a yellow sun in a light sky and to say “night” when shown the picture of a white moon in a dark sky (see Figure 1B). On the interference trials, the instructions were the opposite (i.e., “day” to moon, “night” to sun).

Children were given a total of 16 test trials (no corrective feedback). Following previous research (Gerstadt et al., 1994), trials were blocked by type, with the naming trials administered prior to the interference trials. Order of trials within block was randomized, with the constraint that the same picture never appeared on more than two consecutive trials. Inhibition scores were calculated for each child as the difference between the number of correct responses on the naming and interference trials ($\text{inhibition score} = \text{naming}_{\text{correct}} - \text{interference}_{\text{correct}}$), with higher scores indicating greater inhibitory control.

Analogical Reasoning.—The Analogical Reasoning task used in the current study was adapted from Kotovsky and Gentner (1996). On each trial, children were shown a target card and two choice cards. Both the target and choices consisted of three items each, with one of the choices matching the relation depicted in the target. The choice card that matched the target either matched in a symmetrical (e.g., target card of the form “XOX” and choice card of the form “OXO”) or directional (e.g., target card of the form “OOX” and choice card of

the form “XXO”) relation (half of each type). Non-matching choice cards were always of the opposite relation (e.g., if the matching card was based on a symmetrical relation then the non-matching card was directional). The matching cards could involve relations between color and shape (see Figure 1C), color and size, size and shape (equal number of trials each). On each trial, children were instructed to select the choice card that matched the target by selecting the one that “goes with” the target. Children received six practice trials in which they were provided with corrective feedback. This was followed by 12 test trials with no corrective feedback. For each child, we calculated accuracy as the proportion of total correct responses on the test trials. The side of the correct response was counterbalanced across trials.

PPVT.—On each trial of the PPVT (Dunn & Dunn, 2007), children were read a word and asked to select from one of four pictures the one that corresponded in meaning. This task is a normed measure of receptive vocabulary of standard American English. Scores reported in the results are age-standardized.

RESULTS

Preliminary analyses revealed that scores on all of the tasks were normally distributed, with skewness and kurtosis statistics for all tasks within the acceptable range of -1 to 1 (Tabachnik & Fidell, 2001). Internal consistency was analyzed for the preschool measures using a split-half correlation (Spearman-Brown formula)¹. All preschool measures yielded acceptable reliability (Magnitude Judgment: $r = .64$; Day-Night Stroop: $r = .78$; Analogical Reasoning: $r = .55$). Reported reliability is high for the PPVT ($r = .94$, split-half correlation; Dunn & Dunn, 2007).

Analyses of children’s performance at the first time point on the visual attention paradigm revealed that the sample who participated in the current study showed cross-magnitude interactions that were comparable to those of the larger sample (Lourenco & Longo, 2010). In particular, children included in the current study looked longer to incongruent than congruent trials (incongruent – congruent: $M = 2.11$ s, $SD = 2.04$ s; 95% CI [1.42, 2.80]), $t(35) = 6.21$, $p < .001$, $d = 0.78$, with no significant effect of condition, $F(2, 33) = 0.68$, $p = .51$. To ensure that the congruity effect on this task could not be explained by individual differences in attention during the test trials, we also analyzed children’s performance using a proportion score that accounted for their total looking times on congruent and incongruent trials (i.e., incongruent / [incongruent + congruent]). Proportional looking times to the incongruent trials were then compared to the chance level of 0.50. This analysis revealed that infants looked significantly longer to incongruent trials ($M = 0.57$, $SD = 0.08$), $t(35) = 5.53$, $p < .001$, $d = 0.92$, 95% CI [0.54, 0.60], demonstrating reliably greater looking by infants towards incongruent than congruent trials that was not simply the result of differences in overall attention across the test trials.

We also analyzed children’s performance on each task administered at the second time point. On the Magnitude Judgment task, children showed the expected congruity effect. That is,

¹The design of the infant measure did not permit an assessment of internal consistency.

they were less accurate at judging which array was larger in numerosity when spatial cues were incongruent with number ($M = 7.56$, $SD = 1.81$) compared to when the spatial cues were congruent ($M = 9.06$, $SD = 2.00$). Indeed, an analysis of children's congruity scores (incongruent_{errors} – congruent_{errors}: $M = 1.50$, $SD = 2.27$, 95% CI [0.73, 2.27]) revealed a significant effect, $t(35) = 3.96$, $p < .001$, $d = 0.79$. A separate analysis of children's overall accuracy on this task revealed above-chance performance, $t(35) = 9.03$, $p < .001$, $d = 1.51$ (see Table 1 for descriptive statistics of all tasks administered at the second time point). Importantly, a zero-order correlation analysis between accuracy and congruity scores revealed no relation ($p > .55$), confirming that children's congruity scores were not simply a reflection of accuracy, but rather, an index of the influence of spatial magnitude on their numerical judgments. On the Day-Night Stroop task, children's performance also yielded the expected effect. That is, their inhibition scores (naming_{correct} – interference_{correct}: $M = 2.72$, $SD = 1.34$, 95% CI [2.26, 3.17]) differed significantly from zero, $t(35) = 12.15$, $p < .001$, $d = 2.03$, such that there was greater accuracy on naming than interference trials. On the Analogical Reasoning task, the analyses revealed that children's accuracy ($M = 0.54$, $SD = 0.12$, 95% CI [0.50, 0.58]) was significantly above chance (0.50), $t(35) = 2.11$, $p = .04$, $d = 0.35$. Children's scores on the PPVT were above average ($M = 116.39$) and consistent with the normative range of variability ($SD = 12.49$).

Of particular interest to the current study was the potential link between the magnitude tasks administered at the two time points. Thus, in subsequent linear regression analyses we examined whether cross-magnitude associations tested in infancy predicted cross-magnitude associations at preschool age. In a first analysis, we tested whether performance on the infant visual attention paradigm was a significant predictor of children's performance on the Magnitude Judgment task when controlling for age at each of the time points. A magnitude congruity effect at the first time point was assessed as proportional looking time to the incongruent trials (incongruent / [incongruent + congruent]), collapsing across condition (i.e., "space & number", "space & time", and "number & time"), because, as indicated above, infants' performance did not vary by condition. At both time points, age-residualized congruity scores were obtained by regressing congruity scores on age at the respective time point. This analysis revealed that performance at time point 1 significantly predicted performance at time point 2, $F(1, 34) = 7.08$, $R^2 = .17$, $p = .01$, $BF_{10} = 4.42$ (see Figure 2 for scatterplot), suggesting stability from infancy to preschool age in children's cross-magnitude associations.

In subsequent analyses, we examined whether this longitudinal effect could be due to cognitive factors not related to a general magnitude system. In separate hierarchical regression analyses, we tested whether children's performance on the infant visual attention paradigm predicted performance on the Magnitude Judgment task administered at preschool age when accounting for children's performance on the Day-Night Stroop task, the Analogical Reasoning task, and the PPVT. Age-residualized scores were obtained for all tasks except the PPVT, which was already age-standardized, by regressing scores on age at the respective time point. Given the sample size ($n = 36$), we conducted separate regression analyses to maximize the power of detecting effects of the different variables on children's performance on the Magnitude Judgment task. These analyses revealed that only children's performance at time point 1 was a significant predictor of the magnitude congruity effect at

time point 2 (see Table 2 for the regression coefficients of each model). No other predictor (i.e., children's performance on the Day-Night Stroop task, the Analogical Reasoning task, or the PPVT) reached statistical significance². Taken together, these analyses demonstrate a relation between infant and preschool measures of magnitude congruity, not accounted for by inhibitory control, analogical reasoning, or verbal competence.

DISCUSSION

By showing that individual differences in cross-magnitude interactions in infancy predicted variability in the relation between number and spatial magnitude at preschool age, we provide the first evidence of developmental stability in the associations between representations of different magnitudes. Children who showed stronger magnitude associations within the first year of life also showed a stronger association between number and area at 3.5 years of age. That this predictive relation held even when we accounted for inter-individual variability in inhibitory control, analogical reasoning, and verbal competence provides support for a general magnitude system in which there is convergence between different magnitudes (e.g., Walsh, 2003; see also, Cappelletti et al., 2013; Harvey et al., 2015; Lourenco, 2015).

Other researchers, however, have suggested that cross-magnitude interactions do not reflect a general magnitude system. From this perspective, magnitude associations could instead reflect independent representations of magnitude that communicate by way of other systems. As described in the Introduction, one possibility is that a linguistic system could provide mediation between magnitude representations because different magnitudes are referred to by the same words (e.g., "larger," "greater," or "more"). That we found continuity between infant and preschool time points on our measures of magnitude associations argues against a language account because the children tested at the first time point were mostly prelinguistic. If language mediated the link between representations of different magnitudes, it is unclear how individual differences in infancy would have predicted individual differences in verbal children in whom the interactions could have been linguistically mediated. Moreover, we found that the relation between the two time points held when accounting for verbal competence at preschool age, suggesting further that a linguistic mechanism is unlikely to account for the interactions between magnitudes.

But could individual differences in other general cognitive capacities account for the developmental continuity in our data? One possibility is that analogical reasoning might support alignment and comparison across different magnitudes (Srinivasan & Carey, 2010). If such an alignment and comparison process occurred across development, then it would provide an alternative account to the longitudinal effect in the present study. To address this possibility, we assessed children's analogical reasoning ability using a task that required

²At the first time point, 6 children showed a congruity effect less than or equal to .50, reflecting equal or greater looking to congruent than incongruent trials on the visual attention paradigm. At the second time point, 5 children showed a congruity effect less than or equal to zero, reflecting equal or greater accuracy on incongruent than congruent trials on the Magnitude Judgment task. Because there may be debate about how to interpret the data from these children, we conducted supplemental analyses with these children excluded. As in the full data set, we found that children's performance at time point 1 significantly predicted their performance at time point 2 (age-residualized scores), $F(1, 23) = 7.06$, $R^2 = .24$, $p = .01$, $BF_{10} = 4.23$. Furthermore, this effect held when accounting for inhibitory control, analogical reasoning, and verbal competence ($ps < .05$; see Table S1), as reported in the main text.

alignment and comparison. Importantly, we found that the longitudinal effect between the measures of cross-magnitude associations at the two time points held even when accounting for children's ability to engage in analogical reasoning at 3.5 years of age, providing support against an alternative account based on analogical reasoning. Yet another possibility is that the observed longitudinal effect in the present study reflected inhibitory control. In this case, the cross-magnitude associations at the different time points could be the result of weak inhibition. However, our finding that the longitudinal relation of magnitude associations held in spite of individual differences in inhibitory control when assessed at preschool age suggests that inhibition is not responsible for the stability in magnitude associations.

We argue that the longitudinal cross-magnitude associations observed in the current study reflect a general magnitude system in which there is convergence across representations of different magnitudes. In the Introduction, we suggested two views of convergence within such a system. Walsh (2003) originally proposed that different magnitudes map to a common (analog) metric. Another take on convergence is that representations are integral in nature such that they are perceived, at least to some extent, holistically, as in the case of integral dimensions in the classic work of Garner (1974)³. Studies using single cell recordings with monkeys have revealed conjoint coding of number and spatial extent (i.e., line length) in the intraparietal sulcus (IPS; Tudusciuc & Nieder, 2007, 2009), though questions exist about the directional alignment of these neurons. In particular, it has been found that a portion of neurons in IPS are tuned to both number and line length, though individual neurons tuned to a larger numerical value are not consistently tuned to a larger line length. Importantly, however, neuroimaging with humans demonstrates overlapping topographic representations of number and area that capture a shared directional organization, such that voxels displaying greater activation for larger numerosities also display greater activation for items that are larger in area (Harvey et al., 2015). Such convergence in the neural code demonstrates a common analog organization and captures the correlation between magnitudes. These features of convergence could account for the behavioral cross-magnitude associations observed across development, including the detection of correspondences between different magnitudes when each is presented sequentially (as in our visual attention paradigm presented to infants) and contributing to congruity effects when dimensions are presented simultaneously (as in our Magnitude Judgment task presented to children at preschool age).

A question that arises from the current findings is how to interpret children's performance on the Magnitude Judgment task in which they responded reliably on the basis of number (as indicated by their above-chance performance when they were asked to select the larger numerosity) while also showing a magnitude congruity effect between number and area. One way in which to explain these effects is that the convergence of number and area within a general magnitude system reflects a differential weighting of the inputs such that the inputs of each dimension are not combined equally. It has been suggested that such weighting occurs via Bayesian cue combination with more reliable dimensions receiving more weight

³Integral representations can be considered distinct from the phenomenon of synesthesia where the processing of one type of information automatically elicits that of another (Cytowic, 2002) but where the individual sources of information are separable (e.g., letters and color) (Sagiv, 2005).

(Lambrechts, Walsh, & Wassenhove, 2013; see also, Jones & Goldstone, 2013). Given evidence for greater discriminability of number compared to dimensions such as spatial extent in displays of discrete arrays (e.g., Cordes & Brannon, 2008), it would follow that number is weighted more heavily than area in a composite representation that either reflects a mapping to a common metric for the purpose of action (Walsh, 2003; Buetti & Walsh, 2009) or integral dimensions formed during perception (Garner, 1974; Kemler Nelson, 1993). Another possibility is that integral dimensions exist along a continuum from separable to integral, such that some separability is possible with selective attention (Jones & Goldstone, 2013; Kemler Nelson, 1993; Lockhead, 1972). The Magnitude Judgment task emphasized a number, not area, judgment (i.e., children were asked to select the array using the count noun “things” which children interpret as a question about numerosity) so that children were more likely to attend to the dimension of number, potentially supporting the use of number on this task, though not full separation from spatial magnitude.

Nevertheless, an important qualification of the current findings is that the existence of a general magnitude system does not preclude the existence of separate, independent representations of number, as proposed by proponents of the ANS (e.g., Feigenson et al., 2004; Halberda, Mazzocco, & Feigenson, 2008). Such independent representations could exist prior to a mapping to common analog format in the general magnitude system or in parallel with integral representations of magnitude. Although there is debate about the computational mechanisms that support independent number representations within an ANS (Dakin et al., 2011; Dehaene & Cohen, 1995; Gebuis & Reynvoet, 2012; Leibovich, Katzin, Harel, & Henik, 2017; Stoianov & Zorzi, 2012), data from single cell recordings with monkeys (Nieder & Miller, 2004) and neuroimaging with humans (Park, DeWind, Woldorff, & Brannon, 2016) suggest conditions in which number is dissociated from and, thus, independent of other magnitudes. For example, using event-related potentials (ERPs), Park et al. (2016) argued that number is encoded early in the visual processing stream and that these representations can be tracked independent of sensitivity to other visual properties such as area. It is possible that access to such number representations could have facilitated children’s performance on the Magnitude Judgment task. Moreover, it is possible that such number representations interact with other magnitudes to produce congruity effects separate from those supported by a general magnitude system. As we have already noted, it has been suggested that cross-magnitude interactions may occur on independent, non-overlapping representations of magnitude vis-à-vis non-magnitude systems such as analogical reasoning or metaphor (e.g., Winter et al., 2015)⁴. Although we have argued that the longitudinal effects reported in the current study are not likely supported by such systems, we acknowledge that there may be different types of cross-magnitude interactions, some of which are not supported by a general magnitude system. Cross-magnitude interactions that are supported by analogical processes or metaphor may be prevalent in linguistic individuals

⁴It has been suggested that, at least in older children and adults, magnitude congruity effects depend on inhibitory control (e.g., Cappelletti, Didino, Stoianov, & Zorzi, 2014; Gilmore et al., 2013; Nys & Content, 2012). Such a proposal is consistent with independent representations of magnitude (e.g., number and area) that are separable by inhibition. In the present study, correlation analyses among the tasks administered at time point 2 (see Table S2) revealed no relation between the strength of the magnitude congruity effect (as measured by the Magnitude Judgment task) and children’s inhibitory control (as measured by the Day-Night Stroop task). The lack of a correlation at this age is consistent with overlapping representations of number and area, not separable by inhibitory control. However, additional research is clearly needed to examine such correlations at different times in development and with comparable measures at different ages.

who compare and combine magnitudes flexibly, including non-prothetic (i.e., “metathetic”) dimensions such as pitch (e.g., Marks, 1987; Mondloch & Mauer, 2004). An important area for future research will be to determine the potentially pluralistic mechanisms that underlie different types of cross-magnitude interactions.

We conclude by acknowledging some limitations of the current research. First, although neither inhibitory control, nor analogical reasoning, nor verbal competence, affected the developmental stability of the cross-magnitude associations, the individual differences approach adopted in this study does not rule out that minimal competence in either of these abilities could account for the longitudinal effect. For example, if most children met a lower threshold of analogical reasoning, this minimal competency could be sufficient to support the cross-magnitude associations observed at the different ages. Moreover, we only assessed these abilities at preschool age, and although we have no reason to predict that our findings would differ if we had, instead, used analogical reasoning or inhibitory control earlier in development, future research will be needed to address this possibility. Future research should also consider directly manipulating the mediating variables of interest (e.g., analogical reasoning and inhibitory control) to determine the extent to which they may, or may not, be implicated in the cross-magnitude associations. Finally, the small sample in this study necessitates the need for additional research that replicates our findings. Although longitudinal research is logistically challenging, we urge future research to adopt longitudinal designs because of their strength in addressing questions on the nature and development of magnitude representations.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References

- Andres M, Davare M, Pesenti M, Olivier E, & Seron X (2004). Number magnitude and grip aperture interaction. *Neuroreport*, 15, 2773–2777. [PubMed: 15597052]
- Anobile G, Cicchini GM, & Burr DC (2016). Number as a primary perceptual attribute: A review. *Perception*, 45, 5–31. [PubMed: 26562858]
- Bonn C, & Cantlon JF (2012). The origins and structure of quantitative concepts. *Cognitive Neuropsychology*, 29, 149–173. [PubMed: 22966853]
- Bonn CD, & Cantlon JF (2017). Spontaneous, modality-general abstraction of a ratio scale. *Cognition*, 169, 36–45. [PubMed: 28806722]
- Bonny JW, & Lourengo SF (2013). The approximate number system and its relation to early math achievement: Evidence from the preschool years. *Journal of Experimental Child Psychology*, 114, 375–388. [PubMed: 23201156]
- Bottini R, & Casasanto D (2013). Space and time in the child’s mind: Metaphoric or ATOMIC? *Frontiers in Psychology*, 4, 1–9. [PubMed: 23382719]
- Brannon EM, Lutz D, & Cordes S (2006). The development of area discrimination and its implications for number representation in infancy. *Developmental Science*, 9, F59–F64. [PubMed: 17059447]
- Bueti D & Walsh V (2009). The parietal cortex and the representations of time, space, number, and other magnitudes. *Philosophical Transactions of the Royal Society B.*, 364, 1831–1840.
- Cantlon JF (2012). Math, monkeys, and the developing brain. *Proceedings of the National Academy of Sciences*, 109, 10725–10732.

- Cappelletti M, Didino D, Stoianov I, & Zorzi M (2014). Number skills are maintained in healthy ageing. *Cognitive Psychology*, 69, 25–45. [PubMed: 24423632]
- Cappelletti M, Gessaroli E, Hithersay R, Mitolo M, Didino D, Kanai R, Cohen Kadosh R, & Walsh V (2013). Transfer of cognitive training across magnitude dimensions achieved with concurrent brain stimulation of the parietal lobe. *Journal of Neuroscience*, 33, 14899–14907. [PubMed: 24027289]
- Casasanto D, Fotakopoulou O, & Boroditsky L (2010). Space and time in the child's mind: Evidence for a cross-dimensional asymmetry. *Cognitive Science*, 34, 387–405. [PubMed: 21564218]
- Cohen Kadosh R & Gertner L (2011). Synesthesia: gluing together time, number and space In M Brannon E & Dehaene S (Eds.), *Space, time, and number in the brain: Searching for the foundations of mathematical thought* (123–132). London: Elsevier Academic Press.
- Cordes S, & Brannon EM (2008). The difficulties of representing continuous extent in infancy: Using number is just easier. *Child Development*, 79, 476–489. [PubMed: 18366435]
- Cytowic RE (2002). *Synesthesia: A union of the senses*. MIT press.
- Dakin SC, Tibber MS, Greenwood JA, Kingdom FA, & Morgan MJ (2011). A common visual metric for approximate number and density. *Proceedings of the National Academy of Sciences*, 108, 19552–19557.
- de Hevia MD, Izard V, Coubart A, Spelke E, & Streri A (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences*, 111, 4809–4813.
- Dehaene S, & Brannon EM (2011). *Space, time, and number in the brain: Searching for the foundations of mathematical thought*. London: Elsevier Academic Press.
- Dehaene S, & Changeux J-P. (1993). Development of elementary numerical abilities: A neuronal model. *Journal of Cognitive Neuroscience*, 5, 390–407. [PubMed: 23964915]
- Dehaene S, & Cohen L (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition*, 1, 83–120.
- Dunn LM, & Dunn DM (2007). *The Peabody picture vocabulary test* (4th ed.). Circle Pines, MN: American Guidance Service.
- Feigenson L, Dehaene S, & Spelke E (2004). Core systems of number. *Trends in Cognitive Sciences*, 8, 307–314. [PubMed: 15242690]
- Garner WR (1974). *The processing of information and structure*. Potomac, MD: Lawrence Erlbaum Associates.
- Garner WR, & Felfoldy GL (1970). Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology*, 1, 225–241.
- Gallistel CR, & Gelman R (2000). Non-verbal numerical cognition: From reals to integers. *Trends in Cognitive Sciences*, 4, 59–65. [PubMed: 10652523]
- Gebuis T, & Reynvoet B (2012). The interplay between nonsymbolic number and its continuous visual properties. *Journal of Experimental Psychology: General*, 141, 642–648. [PubMed: 22082115]
- Gerstadt CL, Hong YJ, & Diamond A (1994). The relationship between cognition and action: Performance of children 3 ½–7 years old on a stroop-like day-night test. *Cognition*, 53, 129–153. [PubMed: 7805351]
- Gilmore C, Attridge N, Clayton S, Cragg L, Johnson S, Marlow N, ... & Inglis M (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PloS One*, 8, e67374. [PubMed: 23785521]
- Halberda J, Mazocco MM, & Feigenson L (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, 455, 665. [PubMed: 18776888]
- Harvey BM, Fracasso A, Petridou N, & Dumoulin SO (2015). Topographic representations of object size and relationships with numerosity reveal generalized quantity processing in human parietal cortex. *Proceedings of the National Academy of Sciences*, 112, 13525–13530.
- Henik A, & Tzelgov J (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory & Cognition*, 10, 389–395. [PubMed: 7132716]
- Hurewitz F, Gelman R, & Schnitzer B (2006). Sometimes area counts more than number. *Proceedings of the National Academy of Sciences*, 103, 19599–19604.

- Hyde DC, Khanum S, & Spelke ES (2014). Brief non-symbolic, approximate number practice enhances subsequent exact symbolic arithmetic in children. *Cognition*, 131, 92–107. [PubMed: 24462713]
- Jeffreys H (1998). *The theory of probability*. OUP Oxford.
- Jones M, & Goldstone RL (2013). The structure of integral dimensions: Contrasting topological and Cartesian representations. *Journal of Experimental Psychology: Human Perception and Performance*, 39, 111. [PubMed: 22799263]
- Kant I (1781/1929). *Critique of pure reason*. London: Macmillan.
- Kemler Nelson DG (1993). Processing integral dimensions: the whole view. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 1105–1113. [PubMed: 8228842]
- Kotovsky L, & Gentner D (1996). Comparison and categorization in the development of relational similarity. *Child Development*, 67, 2797–2822.
- Lambrechts A, Walsh V, & van Wassenhove V (2013). Evidence Accumulation in the Magnitude System. *PLoS ONE*, 8, e82122. [PubMed: 24339998]
- Leibovich T, Katzin N, Harel M, & Henik A (2017). From “sense of number” to “sense of magnitude”: The role of continuous magnitudes in numerical cognition. *Behavioral and Brain Sciences*, 40.
- Lockhead GR (1972). Processing dimensional stimuli: A note. *Psychological Review*, 79, 410. [PubMed: 5076869]
- Lourengo SF (2015). On the relation between numerical and non-numerical magnitudes: Evidence for a general magnitude system In Geary DC, Berch DB, & Koepke KM (Eds.), *Evolutionary origins and early development of number processing* (pp. 145–174). London: Elsevier Academic Press.
- Lourengo SF, & Huttenlocher J (2008). The representation of geometric cues in infancy. *Infancy*, 13, 103–127.
- Lourengo SF, & Longo MR (2010). General magnitude representation in human infants. *Psychological Science*, 21, 873–881. [PubMed: 20431048]
- Lourengo SF, & Longo MR (2011). Origins and development of generalized magnitude representation In Dehaene S & Brannon EM (Eds.), *Space, time and number in the brain: Searching for the foundations of mathematical thought* (pp. 225–244). London: Elsevier.
- Lourengo SF, Azyenberg V, & Lyu J (2016). A general magnitude system in human adults: Evidence from a subliminal priming paradigm. *Cortex*, 81, 93–103. [PubMed: 27179917]
- Marks LE (1987). On cross-modal similarity: Auditory–visual interactions in speeded discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 384. [PubMed: 2958587]
- Meck WH, & Church RM (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology: Animal Behavior Processes*, 9, 320–334. [PubMed: 6886634]
- Merritt DJ, Casasanto D, & Brannon EM (2010). Do monkeys think in metaphors? Representations of space and time in monkeys and humans. *Cognition*, 117, 191–202. [PubMed: 20846645]
- Mondloch C, & Maurer D (2004). Do small white balls squeak? Pitch-object correspondences in young children. *Cognitive, Affective, and Behavioral Neuroscience*, 4, 133–136.
- Nieder A, & Miller EK (2004). A parieto-frontal network for visual numerical information in the monkey. *Proceedings of the National Academy of Sciences*, 101, 7457–7462.
- Newcombe N, Huttenlocher J, & Learmonth A (1999). Infants’ coding of location in continuous space. *Infant Behavior and Development*, 22, 483–510.
- Nys J, & Content A (2012). Judgement of discrete and continuous quantity in adults: Number counts!. *Quarterly Journal of Experimental Psychology*, 65, 675–690.
- Odic D, Libertus ME, Feigenson L, & Halberda J (2013). Developmental change in the acuity of approximate number and area representations. *Developmental Psychology*, 49, 1103–1112. [PubMed: 22889394]
- Park J, DeWind NK, Woldorff MG, & Brannon EM (2015). Rapid and direct encoding of numerosity in the visual stream. *Cerebral Cortex*, 26, 748–763. [PubMed: 25715283]
- Persichetti AS, Aulet LS, Dilks DD, & Lourengo SF (2017). Conjoint and independent representation of numerosity and area in human intraparietal cortex. *Journal of Vision*, 17, 174.

- Rousselle L, Palmers E, & Noël M-P (2004). Magnitude comparison in preschoolers: What counts? Influence of perceptual variables. *Journal of Experimental Child Psychology*, 87, 57–84. [PubMed: 14698689]
- Sagiv N (2005). Synesthesia in perspective. *Synesthesia: Perspectives from cognitive neuroscience*, 3–10.
- Sokolowski HM, Fias W, Ononye CB, & Ansari D (2017). Are numbers grounded in a general magnitude processing system? A functional neuroimaging meta-analysis. *Neuropsychologia*, 105, 50–69. [PubMed: 28119003]
- Srinivasan M & Carey S (2010). The long and the short of it: On the nature and origin of functional overlap between representations of space and time. *Cognition*, 116, 217–241. [PubMed: 20537324]
- Stoianov I, & Zorzi M (2012). Emergence of a ‘visual number sense’ in hierarchical generative models. *Nature Neuroscience*, 15, 194–196. [PubMed: 22231428]
- Tabachnik BG, & Fidell LS (2001). *Using multivariate statistics* (4th ed.). Boston, MA: Allyn & Bacon.
- Trick L, & Pylyshyn ZW (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review*, 101, 80–102. [PubMed: 8121961]
- Tudusciuc O, & Neider A (2007). Neuronal population coding of continuous and discrete quantity in the primate posterior parietal cortex. *Proceedings of the National Academy of Sciences*, 104, 14513–14518.
- Tudusciuc O, & Neider A (2009). Contributions of primate prefrontal and posterior cortices to length and numerosity representations. *Journal of Neurophysiology*, 101, 2984–2994. [PubMed: 19321641]
- Van Opstal F, & Verguts T (2013). Is there a generalized magnitude system in the brain? Behavioral, neuroimaging, and computational evidence. *Frontiers in Psychology*, 4, 435. [PubMed: 23874319]
- VanMarle K, & Wynn K (2006). Six-month-old infants use analog magnitudes to represent duration. *Developmental Science*, 9, F41–F49. [PubMed: 16911436]
- Walsh V (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, 7, 483–488. [PubMed: 14585444]
- Wetzels R, & Wagenmakers EJ (2012). A default Bayesian hypothesis test for correlations and partial correlations. *Psychonomic Bulletin & Review*, 19, 1057–1064.
- Winter B, Marghetis T, & Matlock T (2015). Of magnitudes and metaphors: Explaining cognitive interactions between space, time, and number. *Cortex*, 64, 209–224. [PubMed: 25437376]
- Xu F, & Spelke ES (2000). Large number discrimination in 6-month-old infants. *Cognition*, 74, B1–B11. [PubMed: 10594312]

HIGHLIGHTS

- Number and other magnitudes interact to produce cognitive congruity effects, but the potential mechanisms underlying these effects are debated
- Cross-magnitude interactions in infancy predicted a congruity effect between numerical and spatial magnitudes at preschool age
- The longitudinal result was not due to individual differences in non-magnitude cognitive abilities—namely, verbal competence, analogical reasoning, or inhibitory control
- We suggest that longitudinal cross-magnitude interactions are supported by a nonverbal general magnitude system that exhibits stability from infancy to preschool age

Figure 1.

Examples of trials from Magnitude Judgment (A), Day-Night Stroop (B) and Analogical Reasoning (C) tasks administered to children at the second testing point (preschool age) in this study. **A:** Congruent and incongruent examples are shown for the Magnitude Judgment task. Children were asked to judge which character (Bert or Ernie) had the larger numerosity. In the congruent trial, the array with the larger numerosity was also larger in cumulative area and item size. In the incongruent trial, the array with the larger numerosity was smaller in cumulative area and item size. **B:** Sun and moon pictures from the Day-Night Stroop task. On the naming trials, children were instructed to say “day” to the sun image and “night” to the moon image. On the interference trials, children were instructed to do the opposite—that is, to say “day” to the moon image and “night” to the sun image. On each trial, children were presented with single images centrally onscreen. **C:** A trial from the Analogical Reasoning task with a symmetrical target card (top). The matching card represents a matching symmetrical relation (bottom, left); the non-match is directional (bottom, right).

Scatterplot relating age-residualized cross-magnitude congruity effects at the first (infant) and second (preschool) testing points. Performance in infancy was assessed as their looking time during the incongruent trials relative to their total looking time on the visual attention paradigm. Performance at preschool age was assessed as the difference between errors on incongruent and congruent trials ($\text{incongruent}_{\text{errors}} - \text{congruent}_{\text{errors}}$) of the Magnitude Judgment task. Children's performance in infancy significantly predicted their performance at preschool age. The scatterplot includes the best-fitting regression line and the 95% CI (shaded area).

Table 1.

Descriptive data for the experimental tasks (Magnitude Judgment, Day-Night Stroop, and Analogical Reasoning) administered at the second testing point (preschool age). PPVT data are not included in this table.

Task	Mean accuracy (%)	Range (%)	Number of children exhibiting above-chance performance
Magnitude Judgment			
Total	69.21	41.67 – 100	33
Congruent	75.46	41.67 – 100	32
Incongruent	62.96	33.33 – 100	28
Day-Night Stroop			
Total	78.70	66.67 – 100	36
Naming	90.05	75.00 – 100	36
Interference	67.36	41.67 – 100	30
Analogical Reasoning	54.17	25.00 – 75.00	19

On all tasks, mean accuracy was significantly above chance. Children performed above chance whether analyzed as total performance (see Total for Magnitude Judgment and Day-Night Stroop, and the individual score for Analogical Reasoning), all $ps < .05$, or by trial type (see Congruent and Incongruent trials for Magnitude Judgment, and Naming and Interference trials for Day-Night Stroop), all $ps < .05$.

Table 2.

Summary of the regression models with the preschool magnitude congruity effect (Magnitude Judgment task) as the outcome variable ($n = 36$). β = Standardized regression coefficient. BF_{10} = (log₁₀ Bayes factor). 95% CIs are provided for respective β s. R^2 is included for each model comparison. Only the infant magnitude congruity effect significantly predicted the preschool magnitude congruity effect, with the BF indicating substantial evidence for the alternative hypothesis (Jeffreys, 1998; Wetzels & Wagenmakers, 2012). Models including a second predictor did not produce additional explained variance.

Model	Measures	β	95% CI (Lower, Upper)	BF_{10}	Model Comparisons (R^2 ; p value)
1	Infant Magnitude Congruity Effect	.415 *	.098, .732	4.42	
2	Infant Magnitude Congruity Effect	.397 *	.066, .728	4.42	2 vs. 1 (.002; .656)
	Day-Night Stroop (Inhibitory Control)	.073	-.404, .258	0.40	
3	Infant Magnitude Congruity Effect	.404 *	.055, .753	4.42	3 vs. 1 (.001; .863)
	Analogical Reasoning	-.030	-.379, .319	0.50	
4	Infant Magnitude Congruity Effect	.386 *	.065, .707	4.42	4 vs. 1 (.03; .271)
	PPVT (Verbal Competence) [†]	-.176	-.497, .144	0.71	

* $p < .05$

[†] non-residualized measure.

All other measures represent residualized scores after controlling for age at the respective time points.