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Encoding "10ness" Improves First-Graders' Estimation of Numerical Magnitudes

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Abstract

Understanding numerical magnitudes is a foundational skill that significantly impacts later learning of mathematics concepts. The current study tested the idea that encoding of "10ness" is crucial to improving children's estimation of two-digit number magnitudes. We used commercially available base-10 blocks for this purpose. The children in the experimental condition were asked to construct two-digit numbers by laying down the precise combinations of 10- and 1-blocks horizontally (e.g., three 10-blocks and seven 1-blocks for 37). Two control conditions were also included. In one control condition, children used 1-blocks only. In another control condition, children used one 10-block and as many 1-blocks as necessary. After working with the experimenter for only 15 minutes twice, the children in the experimental condition were significantly more accurate on the estimation task than those in the control conditions. The findings confirmed the importance of encoding 10ness as a unit in making accurate estimates of two-digit number magnitudes. The importance of encoding other units in the base-10 system is discussed.

Keywords: numerical magnitudes, numerical estimation, numerical board games, numerical cognition, numerical language, place value, base-10

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Early acquisition of numerical magnitudes has been identified as a significant predictor of later mathematics learning (Fazio, Bailey, Thompson, & Siegler, 2014). Children from middle-income backgrounds typically develop this understanding for small numbers during preschool years (White & Szucs, 2012), and for two-digit numbers during early primary school years (e.g., Case & Okamoto, 1996; Siegler & Booth, 2004). Not all children, however, reach this developmental milestone at the same rate. To remedy this problem, several attempts have been made to date (Ginsburg, Lee, & Boyd, 2008; Griffin, 2004; Starkey, Klein, & Wakeley, 2004).

Of particular relevance to the present study are interventions in which numerical board games were used to strengthen the association between Arabic numerals and their magnitudes. The board game for numbers 1 to 10 had the numerals written in the squares of equal size from left to right (Ramani & Siegler, 2008). The board game for numbers 1 to 100 was presented in a 10 x 10 matrix with a 1-to-10 row at the bottom and a 91-to-100 row at the top (Laski & Siegler, 2014). Siegler and colleagues reported that after playing these games for a brief period of time, preschoolers and kindergartners made significant gains on the estimation of numerical magnitudes of single-digit numbers (Ramani & Siegler, 2008) and two-digit numbers (Laski & Siegler, 2014), respectively.

In both these games, one critical feature is how children were instructed to count as they moved their token. Unlike conventional games, children playing these board games were asked to *count on from* the number where the token was located. For example, if the token was on the position labeled 3 and the child drew a 2, she moved the token two spaces as she counted "three, four" not "one, two." This counting method was presumed to help children generate a linear ruler representation. By connecting numerals to their corresponding magnitudes, children were said to encode the magnitudes of numbers (Laski & Siegler, 2014). The importance of linearity in numerical board games was also evident in Siegler and Ramani's (2009) study in which preschoolers playing the linear board game outperformed those playing a circular board game on the numerical magnitude tasks.

As important as a linear ruler representation may be, encoding numerical magnitudes by an increment of one alone may not be sufficient in encoding magnitudes of larger numbers. We thus speculated that children would need to encode "10ness" in order to develop an accurate linear representation of numerical magnitudes for two-digit numbers. Our idea was inspired by Miura and colleagues' cross-cultural studies (e.g., Miura, 1987; Miura & Okamoto, 1989, 2003). Their thesis was that variations in numerical language characteristics might influence the way children mentally represent two-digit numbers. They explained that characteristics of spoken languages (i.e., counting systems) differ from one language group to another. Those that have roots in ancient Chinese, for example, have counting systems that follow the rules of base-10. That is, once children memorize the base-sequence of number names for 1 to 10, the rest can be generated applying the rules of base-10. For example, eleven and twelve are spoken as "ten one" and "ten two" in these Asian languages. Teen numbers in English have single and ten number words in the reverse order as in "thirteen." In contrast, it is "ten three" in these Asian languages. Two-digit numbers beyond 19 also show different characteristics. Instead of twenty-five in English, for example, East Asian speakers say "two-tens five." Miura and colleagues found large differences in cognitive representations of number between East Asian-speaking children and English-, French-, and Swedish-speaking children and attributed the results to differences in counting systems (Miura, Okamoto, Kim, Steere, & Fayol, 1993).

Although Miura and colleagues did not test to see if these two groups of children would show similar or different performance on the numerical estimation task, Dowker and Roberts (2015) examined this question with Welsh- and English-speaking children. The Welsh counting system is transparent like the Chinese one in that two-digit numbers follow the rules of base-10. Although Welsh- and English-speaking children did not differ in general arithmetic abilities, Dowker and Roberts found that Welsh children were more accurate in the numerical estimation tasks than their English counterparts. They also noted that performance differences were more pronounced on the 0-100 number line than on the 0-20 number line. Similar findings were reported between German- and Italian-speaking children (Helmreich et al., 2011). The German counting system includes inversion properties (e.g., 48 is spoken as "eight and forty) whereas no such properties appear in Italian. Controlling for general cognitive abilities, Italian-speaking children were found to be more accurate in the number line estimation than their German-speaking counterparts.

Based on these findings, we inferred that transparent counting systems influenced the way children mentally organized two-digit numbers, which, in turn, helped to develop accurate two-digit number magnitudes. The goal of the current study, however, was not to verify this hypothesis between English- and East Asian-speaking children. Rather, we wanted to test the hypothesis that English-speaking children could benefit from instruction that focused on encoding "10ness." We reasoned that the irregular counting system of English might make it difficult for young children to map between spoken words and their magnitudes. However, training to represent two-digit numbers like the way Chinese-, Japanese-, Korean-, and Welsh-speaking children naturally do in everyday life might

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strengthen English-speaking children's mental representations of two-digit numbers and their understanding of numerical magnitudes. When given a 0-100 number line, English-speaking kindergartners' estimates of numerical magnitudes were better described as logarithmic (i.e., overestimating smaller numbers and underestimating larger numbers). It was not until second grade that English-speaking showed a linear pattern of estimation (Siegler & Booth, 2004). It is important to mention that Siegler and Mu (2008) found that the estimation pattern of Chinese-speaking kindergartners was remarkably similar to that of English-speaking second graders.

Thus, it is plausible to predict that teaching English-speaking children to encode 10ness using base-10 blocks horizontally would help them to form a linear representation of numerical magnitudes. In proposing a two-linear model of magnitude representations (one for single-digit numbers and another for two-digit numbers), Moeller, Pixner, Kaufmann, and Nuerk (2009) stated that children's estimation of two-digit magnitudes becomes more linear as they integrate tens and ones. Laski and Siegler (2014) also suggested that their 10 x 10 board game was presumed to convey the physical realization of the base-10 system. Although Moeller et al. and Laski and Siegler differ in their theoretical positions, both groups of researchers suggested that the acquisition of the base-10 system – the system of tens and ones – would improve children's estimation of two-digit number magnitudes.

Our study differs from Laski and Siegler's (2014) in several ways. The most important is how two-digit numbers were counted. In Laski and Siegler's study, children counted each number, for example, "sixty-two, sixty-three" to move the token two spaces. This suggests to us that children encoded each number as a "collection" of ones, not a combination of tens and ones (e.g., Miura & Okamoto, 1989). In contrast, we focused on both tens and ones. To show 63, for example, we instructed children in the experimental condition to lay down six 10-blocks and three 1-blocks horizontally as they counted "one ten, two tens, …, six tens, one, two, three, [pause], sixty-three" (Multiple 10 condition). We designed two comparison conditions. Children in one of the control conditions were instructed to use 1-blocks only (Multiple 1 condition). Children in another control condition were instructed to use one 10-block and as many 1-blocks as necessary to make each number (Single 10 condition). We predicted that the Multiple-10 condition, not the Multiple-1 condition, would show improved representations from logarithmic to linear. As for the Single-10 condition, our prediction was that the exposure to a magnitude of 10 would help overcome the problem of overestimating numbers under 20. We did not, however, expect that the Single-10 condition would extend much beyond 20.

Method

Participants

Participants were 31 first-graders (12 boys and 19 girls, M_{age} = 7 years 1 month, age range: 6 years - 8 years 6 months) recruited from an after-school program of a public elementary school and a parochial language school, both of which were located in the same Central Coast city of California. These schools served children from predominantly low to lower-middle income families. All participating children received free or reduced meals. The ethnic composition of the public school was 55% Latino/Hispanic, 32% Asian, and 13% Caucasian.

Materials

For the pretest and posttest, we used a closed number-line task (e.g., Siegler & Booth, 2004). Similar to the previous studies, a 25-cm line was drawn on each sheet with "0" just below the left end and "100" just below the right end of the number line. No other marks appeared on the sheet. This type of number line is also referred to as a

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bounded (as opposed to unbounded) number line. As for training, commercially available base-10 blocks were used. Each 1-block was 1 cm × 1 cm × 1 cm in size and each10-block was 10 cm × 1 cm × 1 cm in size.

Procedures

Placement of students to conditions did not follow a random assignment procedure due to classroom activities in which students were engaged at a time. At the pretest, teachers brought one student at a time and the students were assigned to conditions as they were brought in.

All participants met with the experimenter individually for the pre- and posttest sessions. The training sessions were conducted in a small group of three students. Teachers brought in three students deemed available at a time. Three students were not always the same over the two training sessions but the teachers made sure to bring in the students who were assigned to the same condition. Each of the four-phases of the study (i.e., pretest, Training 1, Training 2, and posttest) was completed within the same week over the four-week period in the same school year. That is, all participants completed each session in the same week. All sessions were held in either their classroom or an unoccupied room nearby.

Pre- and Posttests

The number-line estimation task required children to estimate where a particular number should be located on a 0-100 number line. The experimenter showed each child a sheet of paper with the closed number line drawn on it as well as an index card with a numeral written on it. The experimenter then pointed to the 0 and 100 positions and said, "if this is where 0 goes and this is where 100 goes, where will *N* go?" No feedback was provided. Children worked on 26 estimation problems presented in a random order. The numbers used were identical to those used in Booth and Siegler's (2008) study: 2, 3, 6, 7, 11, 14, 15, 19, 21, 23, 24, 28, 32, 36, 44, 47, 51, 58, 63, 69, 72, 76, 84, 87, 91, and 98. As described in their study, the numbers below 30 were oversampled to ensure that we would be able to discriminate between logarithmic and linear estimation patterns. The same numbers were used at pretest and posttest. The experimenter measured children's estimates using a ruler and rounded each estimate to one decimal place. A graduate student, blind to the study, also measured all of the children's estimates to confirm the accuracy of the initial measurements. There was 100% agreement.

Children's estimates were fitted to a linear function (*i.e.,* $y = ax + b$) as well as a logarithmic function (*i.e.,* $y = \ln x + b$). Coefficient R^2 was used to measure linearity. If R^2_{Lin} is larger than R^2_{Log}, it means that estimates are more linear than logarithmic (Siegler, Thompson, & Opfer, 2009). The reverse shows that estimates are better described as logarithmic.

Training Sessions

Multiple 10 Condition

The children in this condition were provided with multiple 10-blocks and multiple 1-blocks. The experimenter first demonstrated how to "show" (construct) 37 using base-10 blocks (see Figure 1-a). She did so by placing three 10-blocks and seven 1-blocks horizontally without any space between any two adjacent blocks, as she counted "one ten, two tens, three tens (pause), one, two, three, …, seven (pause), thirty-seven." During the next phase, children saw a card with 44 written on it and another with 15 written on it. Children first saw a card with 44 and were asked to say how many tens and ones are in 44. If they were correct, they were then asked to select the correct number of 10- and 1-blocks and place them horizontally. At any point during this phase, coaching was provided, including the experimenter demonstrating the correct procedure. During the final phase, children were

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asked to construct the following five numbers: 16, 22, 33, 41, and 56 (not used in the number-line estimation task). They were encouraged to use the method practiced earlier. If children selected an incorrect number of 10- or 1-blocks, they were asked how many tens or ones were in a particular number. No further coaching was provided during this phase. If children had difficulty with a particular number, the experimenter moved on and presented a new number. Each session lasted a maximum of 15 minutes.

Single 10 Condition

The children in this condition were provided with a single 10-block and multiple 1-blocks. The demonstration and training were identical to the Multiple 10 condition, except that only one 10-block and multiple 1-blocks were used. Thus, for the demonstration of constructing 37, the experimenter first placed a 10-block and then 27 1-blocks horizontally as she counted “ten (pause), one, two, three, …, twenty-seven, (pause), thirty-seven” (Figure 1-b). When constructing the five target numbers, children always started with one 10-block and continued with as many 1-blocks as they thought necessary. Again, children were encouraged to make a straight line without any space between the blocks.

Multiple 1 Condition

The children in this condition were provided with 1-blocks only. The demonstration and training were identical to the other conditions, except that only 1-blocks were used. For the demonstration of constructing 37, the experimenter placed 37 1-blocks horizontally as she counted “one, two, three, …, thirty-seven” (Figure 1-c).

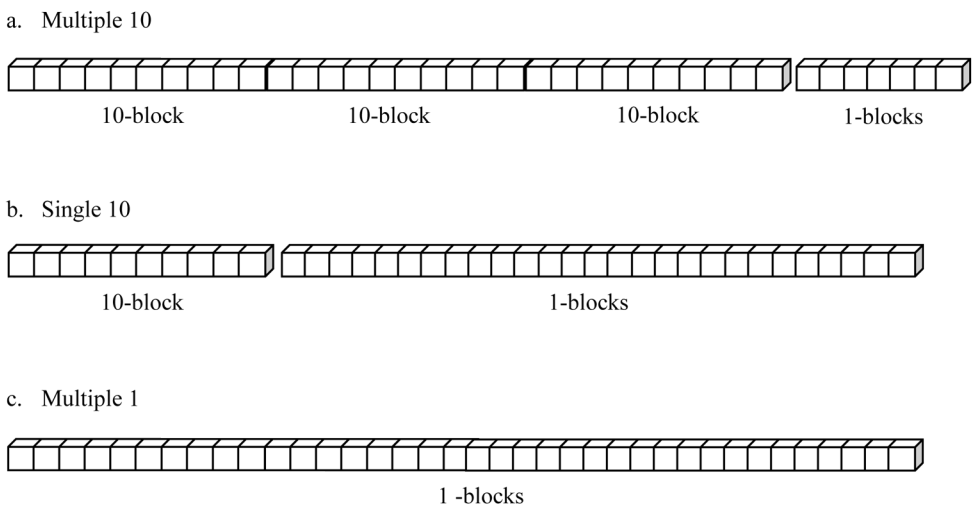

Figure 1. How 37 was represented using base-10 blocks for the Multiple 10 (a), Single 10 (b), and Multiple 1 (c) conditions.

Note. Although the visuals in this figure show spaces to distinguish 10- and 1-blocks, children were encouraged to leave no space between any two adjacent blocks.

Results

A preliminary analysis of linearity found no statistically significant gender differences at the pretest, $F(1, 30) = 2.02$, $p = .166$. The average R^2_{Lin} for girls was 47.68%, which was comparable to the boys’ average of 43.67%.

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Ethnicity was also non-significant at the pretest, $F(2, 30) = 1.088$, $p = .350$. The average R^2_{Lin}s were 49.19%, 44.82%, and 44.25%, for Asian-, Latino-, and Caucasian-American children respectively. Therefore, the data from girls and boys, as well as thee ethnic groups, were combined for subsequent analyses.

Because random assignment was not used to place children into the three conditions, we next compared the pretest scores of the children in the three conditions. The results showed no statistically significant differences among the conditions, $F(2, 30) = .855$, $p = .436$.

Effects of Training

A repeated-measures ANOVA was carried out to examine if training had differential effects on the children in the three conditions. The results showed statistically significant differences among the conditions, $F(2, 28) = 58.44$, $p < .001$, $\eta^2_p = .81$. The effect size was substantially large. Further analyses showed that the gains made by children in the Multiple 10 condition were significantly greater than those in the Single 10 block or Multiple 1 condition, both at $p < .001$. Pair-wise comparisons of the posttest performance on R^2_{Lin} showed that the Multiple 10 condition outperformed the Single 10 condition $t(19) = 7.44$, $p < .001$, $d = 3.17$ as well as the Multiple 1 condition, $t(19) = 27.11$, $p < .001$, $d = 11.60$.

When each condition was examined separately, both the Multiple 10 and Single 10 conditions made significant gains from pre- to posttests whereas the Multiple 1 condition did not (see Table 1). The mean R^2_{Lin} for the Multiple 10 condition improved from 52% at pretest to 98% at posttest, $t(10) = 13.81$, $p < .001$, $d = 4.17$. The improvement or the Single 10 condition was from 48% to 63%, $t(9) = 5.83$, $p < .001$, $d = 1.85$. The effect sizes for these two groups were large. In particular, the Multiple 10 condition's effect size of 4.17 was considerably larger than that of 1.85 for the Single 10 condition. In contract, there was a minimal gain for the Multiple 1 condition: 43% at pretest and 45% at posttest, $t(9)= 1.53$, $p = .162$, $d = .48$.

Table 1

Linearity (R^2_{Lin}) at Pretest and Posttest for Each Condition

	***M* (*SD*)**				
Variable	**Pretest**	**Posttest**	***t***	***p***	**Cohen's *d***
Multiple 10	.52 (.11)	.98 (.02)	13.81	<.001	4.17
Single 10	.48 (.06)	.63 (.11)	5.83	<.001	1.85
Multiple 1	.43 (.02)	.45 (.06)	1.53	.162	0.48

Figure 2 shows the median estimates of numerical magnitudes at pre- and posttests for each group. As should be clear, the Multiple 10 condition's median estimates at the posttest resembled a linear estimation.

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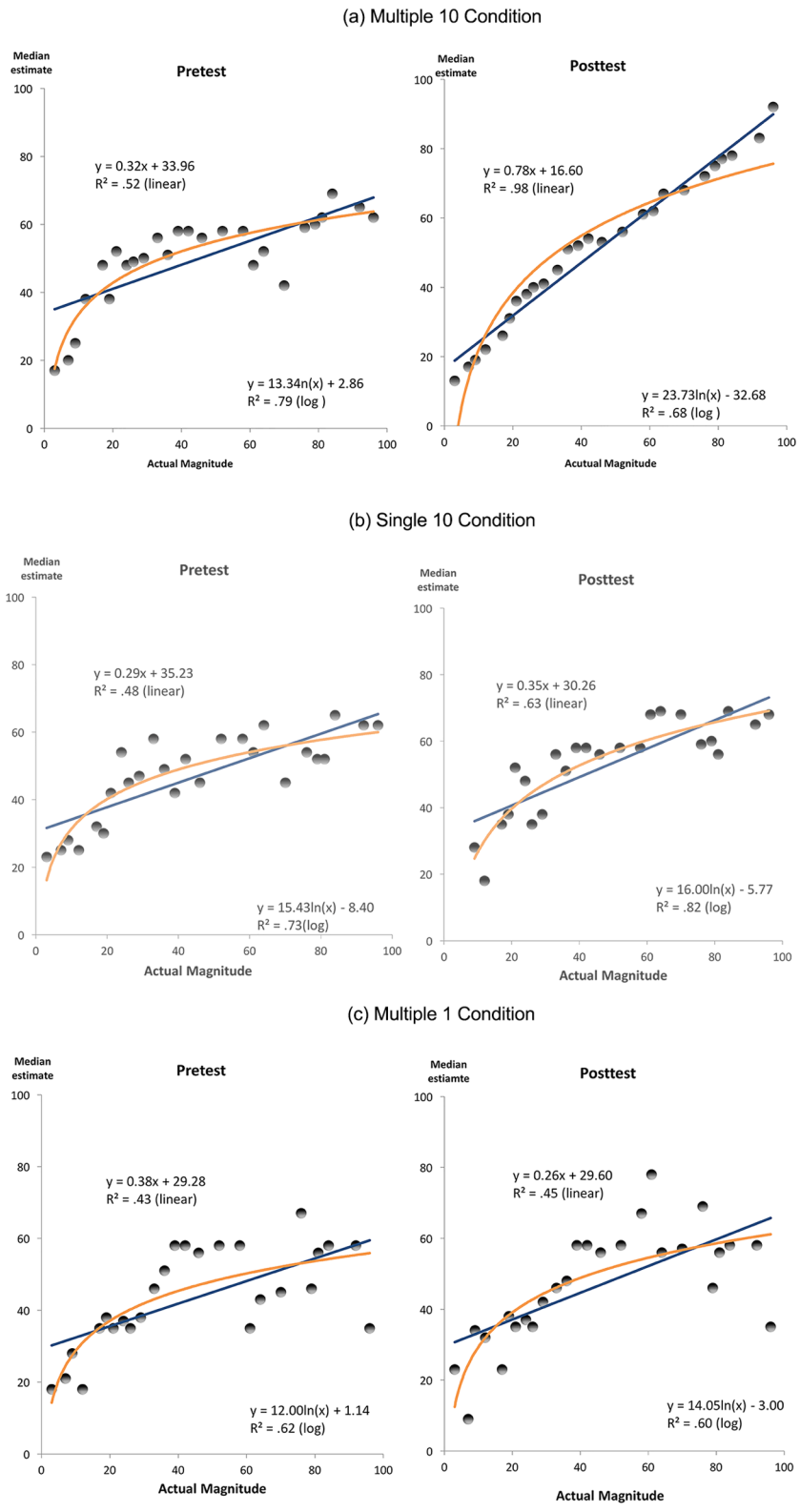

Figure 2. Median estimates of numerical magnitudes at pre- and posttests for the Multiple 10 (a), Single 10 (b), and Multiple 1 (c) conditions.

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In fact, children's estimates at the posttest were best fitted by the linear function, R^2_{Lin} = .98, as opposed to the logarithmic function, R^2_{Log} = .68. Taking into account that at the pretest these children's estimates were more logarithmic (R^2_{Log} = .79) than the linear function (R^2_{Lin} = .52), it showed a clear trend from log to linear for this condition. This was not the case for the other two conditions. The median estimates made by children in the Single 10 and Multiple 1 conditions were best described as logarithmic both at the pre- and posttests.

Range of Estimation

Although descriptive, we were interested in visually inspecting if children's estimates differed at the posttest depending on the numbers they estimated. We reasoned that training provided for children in the Multiple 10 condition should show linearity regardless of number. Training provided in the Single 10 condition should help make more accurate estimates for numbers between 10 and 19. We did not expect any particular pattern for the Multiple 1 condition. It is possible that children in the Multiple 1 condition, only practicing to count by ones, would show estimates in line with (1) overestimation of smaller numbers and underestimation of larger numbers; (2) a two-linear model (Moeller, Pixner, Kaufmann, & Nuerk, 2009); or (3) the use of landmarks such as midpoints (Ashcraft & Moore, 2012).

As shown in Figure 3, children's estimates in the Multiple 10 condition were relatively linear. However, larger numbers tended to be underestimated. This could be attributed to the fact that almost all numbers used in the training were smaller, with 56 being the largest (16, 22, 33, 41, and 56). As for the Single 10 condition, as expected, they showed relatively accurate estimates for numbers up to 20 but for the rest of the numbers accuracy declined. Finally, children's estimates for the Multiple 1 condition were better described as overestimating smaller numbers and underestimating larger numbers. Their tendency to overestimate numbers was observed as early as the single-digit numbers and continued to almost 50.

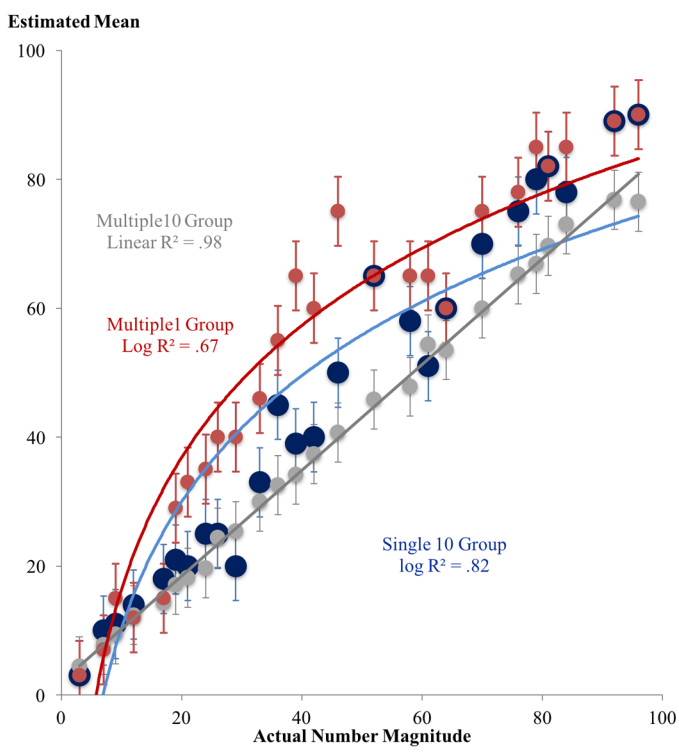

Figure 3. Range of estimation for each number at posttest by conditions.

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Effects on Individual Participants

Thus far, our analyses focused on median estimates at the group level. We next considered individual estimates at the posttest to determine if the results obtained earlier would hold up at the individual level as well.

The results for the Multiple 10 condition showed that all of the 11 children's individual estimates were better described as linear. As for the Single 10 condition, only one child's estimates were linear and all of the children's estimates for the Multiple 1 condition were logarithmic.

Discussion

The primary goal of the present study was to examine if teaching children "10ness" by asking them to place 10-blocks horizontally would improve their estimation of numerical magnitudes. Our rationale was that children using base-10 counting systems show earlier mastery of place value (e.g., Miura, Okamoto, Kim, Steere, & Fayol, 1993) and more accurate numerical estimation (e.g., Dowker & Roberts, 2015) than those who speak irregular counting systems. The results showed that English-speaking first graders from low-income families who learned to show numbers using 10- and 1-blocks horizontally changed their estimation from logarithmic to linear in just two training sessions. The estimation patterns of their counterparts who were taught to use only 1-blocks, however, remained logarithmic.

Laski and Siegler (2014) also obtained similar results by using a 10 x10 board game. Children who played this game improved their estimation accuracy when they were taught to move their token by counting on (e.g., count "sixty-seven, sixty-eight" to move the token from 66). Those who were taught to move the token by counting from 1 (e.g., count "one, two" to move the token 66 to 68) did not. What their study showed is the importance of encoding the numerical magnitudes in the physical layout of a 10 x 10 board game. Our experimental manipulation also intended to help children encode two-digit numbers. Both approaches proved successful. We speculate that embedded in the 10 x 10 board game is a "10ness" in each row. That is, the spatial layout of the game board implicitly taught them chunks of 10. In both these studies, children were likely to develop spatial representations of number (Link, Huber, Nuerk, & Moeller, 2014). In Laski and Siegler's game, each row could be thought of as showing a bounded number line segmented into 10 equal parts. Children in our intervention, on the other hand, were not given any end point. Once they understood the magnitude of 10, they were able to apply this understanding to a 0-100 number line of any length. It is likely that they developed 10 as a reference point (Link et al., 2014).

Children who were taught to use only single 10-block and multiple 1-blocks in the present study made significant gains. However, their median estimates at the posttest were better described as logarithmic than linear. Inspecting individual performance, we found only one child's estimation was linear in the Single 10 condition. Having just one 10-block appeared to have helped children to form relatively accurate magnitudes of numbers smaller than 20. But their understanding of one 10 did not transfer to larger two-digit numbers.

Although replications to confirm the current findings are in order, we emphasize the fact that the significant improvements resulted from working with children over two brief sessions, constructing just five numbers each. In replicating the current study, it is essential to recruit many more participants. Having about 10 children in each condition limited our ability carry out more detailed analyses.

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We also note that we only used a closed number line as our outcome measure. As Link, Huber, Nuerk, and Moeller (2014) found, it is important to administer both closed (or bounded) and unbounded number lines to observe children's strategies for estimating numerical magnitudes. Future studies should consider videotaping or use systematic rubrics to record children's strategies. Although our findings show that children who learned to put down the precise numbers of 10- and 1-blocks improved their estimation accuracy, we have no way of knowing what strategies they used nor would they perform differently on bounded and unbounded number lines.

As mentioned earlier, our study was designed based on the prior findings showing that children who use regular counting systems develop base-10 like representations of number and master place value earlier than those who use irregular counting systems. The literature on the relation between numerical language and mathematics performance, however, provides counter evidence as well. For example, Towse and colleagues (e.g., Muldoon, Simms, Towse, Menzies, & Yue, 2011; Towse, Muldoon, & Simms, 2015) and Laski and Yu (2014) provided evidence that differences in numerical language alone could not explain children's understanding of number and other mathematics performance. For example, in the study by Muldoon et al. (2011), Chinese and Scottish children's numerical estimation and other indicators of mathematics performance were examined. One of the findings is that Chinese children's earlier mastery of linearity of numbers was associated with counting *proficiency*, not counting words themselves. When Chinese and Scottish children were matched in their mathematics ability rather than their chronological age, differences between the two groups disappeared (Towse et al., 2015). In comparing Chinese and Chinese-American children's number line estimation, Laski and Yu (2014) found that Chinese children's number line estimation was 1 to 2 years ahead of their Chinese-American counterparts, even though both groups of children were fluent in Chinese. Similar to Towse and colleagues, Laski and Yu (2014) thus concluded that the development of linearity could not be explained by differences in the counting systems alone.

As should be apparent from above, there are more questions than answers in regards to the relation among numerical language, numerical estimation, and mathematics abilities. The current study at the very least reconfirmed the importance of children making connections between Arabic numerals and their magnitudes. As foundational as encoding the unit of one is to single-digit numbers, the unit of ten is crucial to understanding two-digit numerical magnitudes. Likewise, we speculate encoding the unit of 100 is as essential to comprehending three-digit magnitudes as the unit of .1 is to the decimal numbers in the tenths place. These units might play an important role in developing a complete sense of numerical magnitudes. If our speculation proves to be correct, it has significant implications for how we help children expand their understanding of the number system. Use of number lines, focusing on different units of measure, is likely to help children encode numerical magnitudes of not just whole numbers but also rational numbers.

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Competing Interests

The authors have declared that no competing interests exist.

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