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Reexamining the language account of cross-national differences in base-10 number representations

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East Asian students consistently outperform students from other nations in mathematics. One explanation for this advantage is a language account; East Asian languages, unlike most Western languages, provide cues about the base-10 structure of multi-digit numbers, facilitating the development of base-10 number representations. To test this view, the current study examined how kindergartners represented two-digit numbers using single unit-blocks and ten-blocks. The participants ($N = 272$) were from four language groups (Korean, Mandarin, English, and Russian) that vary in the extent of "transparency" of the base-10 structure. In contrast to previous findings with older children, kindergartners showed no cross-language variability in the frequency of producing base-10 representations. Furthermore, they showed a pattern of within-language variability that was not consistent with the language account and was likely attributable to experiential factors. These findings suggest that language might not play as critical a role in the development of base-10 representations as suggested in earlier research.

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Introduction

Cross-national studies reveal persistent differences in mathematics; American school students are outperformed by counterparts from some Asian and European countries, including those with fewer educational resources (Gonzales, Williams, Jocelyn, Roey, Kastberg, & Brenwald, 2008; Mullis, Martin, Foy, & Arora, 2012; Stevenson, Chen, & Lee, 1993). For example, the latest large-scale mathematics assessment showed that eighth graders from South Korea and Russia scored higher than their American peers even though the United States spends twice as much money per pupil as South Korea and nearly four times as much as Russia (Mullis et al., 2012). Understanding the sources of these differences is critical to America's ability to compete during a time of accelerating progress in science and technology.

Although a variety of factors, including parental values and instructional approaches, have been identified as potential sources of such differences (cf. Göbel, Shaki, & Fischer, 2011; Ng & Rao, 2010), the role of language has become a prominent account in psychological and popular literature discussing cross-national differences in mathematics (Gladwell, 2008; Krulwich, 2011). Based on this account, the roots of Asian students' mathematics advantage can be traced to the period of development when children acquire basic linguistic and conceptual knowledge of numbers prior to extensive exposure to formal schooling. The current study offers new evidence about the extent to which linguistic factors may account for differences in foundational mathematics concepts, particularly children's understanding of the base-10 structure of numbers.

The language account

Acquiring numeric language plays a significant role in the development of mathematical thinking. For example, language provides a means of forming exact representations of large quantities (Dehaene, Izard, Spelke, & Pica, 2008). It has been further suggested that the linguistic structure of counting systems might facilitate or impede numerical development. Specifically, several Asian languages use number naming systems that can be characterized as "transparent," whereby the names of multi-digit numbers explicitly reflect their base-10 structure. For example, the Chinese word for 12 is "ten-two," the word for 34 is "three-ten four," and so forth. Conversely, English does not provide equally transparent information about the base-10 structure. In fact, the first two-digit numbers that English-speaking children learn, "eleven" and "twelve," have arbitrary labels with no clues about number composition. Words beyond 12 are organized more systematically, but phonetic modifications complicate the extraction of the tens and ones. Such linguistic differences may lead to differences in numeric thinking. In particular, children's mental representation of numbers might vary as a function of support available for the base-10 structure in their language (Helmreich, Zuber, Pixner, Kaufmann, Nuerk, & Moeller, 2011).

Early empirical evidence for this idea came from studies examining performance on a number representation block task (Miura, 1987; Miura, Kim, Chang, & Okamoto, 1988). In this task, children needed to show two-digit numbers using blocks that included small cubes representing single units and bars representing ten units. Asian first graders tended to produce base-10 representations (combinations of ten-bars and single units), whereas American first graders tended to use only single-unit cubes to represent the same numbers. For example, when shown the number 34, Japanese children typically represented it with three ten-bars and four single units, whereas American children used 34 single units (Miura & Okamoto, 1989).

In addition to findings implicating the transparency of counting words in children's understanding of the base-10 number structure, it has been suggested that language may, in part, account for cross-national variability in other math skills. For instance, researchers have shown that children with different linguistic systems demonstrate differences in counting skills (Miller & Stigler, 1987; Song & Ginsburg, 1988), mental arithmetic (Dowker, Bala, & Lloyd, 2008; Geary, Bow-Thomas, Liu, & Siegler, 1996), place-value understanding (Fuson, 1992), and numerical estimation (Laski & Yu, 2014; Siegler & Mu, 2008). In this literature, investigators discuss how diverse aspects of language, including the length of the count words, the number of unique count words that must be learned, and the transparency of multi-digit numbers, might influence mathematical learning.

In the current study, we were interested specifically in the relationship between the transparency of the number system and children's representation of the base-10 number structure. Cross-national differences in the early ability to represent the base-10 structure may have important consequences throughout mathematical learning. For example, thinking about double-digit numbers as combinations of tens and ones may be beneficial for comparing numeric magnitudes and using effective computational strategies. Indeed, several studies have reported that early knowledge of base-10 structure is related to subsequent mathematical learning (Fuson & Briars, 1990; Geary, Hoard, Nugent, & Bailey, 2013; Valeras & Becker, 1997). Recent evidence suggests that the link between the ability to represent the base-10 structure and later mathematical performance may be mediated by the use of base-10 decomposition strategies. In particular, the frequency of base-10 representations in kindergartners has been linked to the use of base-10 decomposition strategies (Laski, Ermakova, & Vasilyeva, in press); such strategies, in turn, lead to better performance on computation tasks involving multi-digit numbers (Carr, Steiner, Kyser, & Biddlecomb, 2008; Geary, Hoard, Byrd-Craven, & DeSoto, 2004).

Questions about the language account

Despite the strength of the logical argument and empirical evidence of the relation between language and children's understanding of the base-10 structure, it is hard to disentangle the role of linguistic factors from the role of other cultural and educational factors. The differences between linguistic systems are impressive, but the differences between the corresponding educational contexts are equally striking. Across educational contexts, there are structural differences (e.g., whole class instruction vs. work in small groups), quantitative differences in the amount of work that students are expected to complete in class and at home, and substantial variability in the instructional approaches to mathematics (Fuson & Li, 2009; Newman et al., 2007; Perry, 2000; Schleppenbach, Perry, Miller, Sims, & Fang, 2007; Stigler & Stevenson, 1992). For example, Chinese and Taiwanese elementary math curricula place a greater emphasis on the use of base-10 decomposition for computation, whereas in American curricula it is typically introduced as one of many available strategies and, as a result, children practice base-10 decomposition less (e.g., Fuson & Li, 2009). Thus, even though a language-based account may offer a plausible explanation of cross-national differences, alternative interpretations cannot be excluded.

One alternative interpretation of Miura's (1987) findings was explored by Saxton and Towse (1998), who hypothesized that differences in experience lead children to particular patterns of responses on a number representation task. Namely, American students' tendency to use single units in Miura's study may have been reinforced by practice trials in which the experimenter represented single-digit numbers with unit cubes. Having less experience with numbers, American children may be less confident than their Asian peers and, therefore, more reliant on the experimenter's cues. Indeed, adding a practice trial, in which the experimenter showed a double-digit number with ten-bars and unit cubes, increased the use of base-10 representations among English-speaking first graders, eliminating cross-national differences. This finding contrasted with the single-digit practice condition in which Asian students showed more frequent use of base-10 representations. Saxton and Towse argued that if English-speaking children lacked a conceptual understanding of base-10 structure, one practice trial with a double-digit number would probably not have had such a substantial effect on their responses. The possibility remains, however, that Asian children frequently used base-10 representations even when only single-digit numbers were shown at practice because they had a more robust knowledge of base-10 number structure than American students due to linguistic differences.

The current study

Given the foundational importance of the base-10 number concept, the prominence of the language account, and the largely overlooked evidence raising questions about the account, we aimed to gain new insights into the nature of cross-national differences in base-10 number representations. As a basis for our investigation, we took Miura's (1987) task in which children were asked to represent two-digit numbers with single unit-blocks and ten-blocks. Half of the students were tested in the single-digit practice condition, and the other half were tested in the mixed-digit practice condition, as in Saxton and Towse (1998).

The study included two related tasks. In Task 1, students were allowed to show the number with blocks any way they chose. This task provided a window into how children spontaneously think about two-digit numbers—namely, whether the first type of representation that comes to their minds involves a combination of tens and ones or a collection of single units. In Task 2, students were shown the representation they had constructed in Task 1 and were asked to show the same number in a different way. This task tested the depth and flexibility of children's number representations—that is, their ability to switch between single-unit and base-10 representations. Together, the two tasks provided a broad picture of children's representations of base-10 numeric structure.

Unlike previous cross-national studies that examined number representations in first graders, we tested kindergartners. Our choice of this age group provided a means of minimizing effects of instructional differences across countries in order to better isolate the role of language. Participants' languages were chosen so that they varied in the explicitness of the base-10 structure from highly transparent (Mandarin and Korean) to much less transparent (English and Russian). In this context, we addressed the following research questions concerning the nature of the relation between children's language and their base-10 number representations.

Is the language advantage present in kindergartners?

Performance on number representation tasks by first graders and older students is likely to reflect, at least in part, effects of instruction. This view is supported by a study of Japanese students that showed increased use of base-10 representations in first graders compared with same-age kindergartners (Naito & Miura, 2001). Examining kindergartners, rather than first graders, provides a way of reducing the influence of instruction. Kindergartners are proficient speakers of their language, and their numeric vocabulary extends beyond the first 10 numbers; yet, their exposure to math instruction is fairly limited. In fact, our interviews with teachers in all participating countries indicated that by the time of the study, kindergartners were familiar with two-digit numbers but only in the context of rote counting and number naming. They had no computational practice with two-digit numbers and, critically, no activities involving materials or tasks similar to those in the current study.

If the tendency to use base-10 representations is largely driven by the features of language, then we should expect Asian kindergartners to show this tendency, similar to prior findings with first graders. Even though younger children may be less accurate than first graders in reading numbers or counting blocks, the use of base-10 representations should still be higher in kindergartners speaking more transparent languages. If, on the other hand, math instruction plays a key role in promoting children's understanding of base-10, then kindergartners, having limited relevant instruction, may show little or no cross-national variability on the number representation task.

Is performance related to the degree of number word transparency?

For a more nuanced analysis of the influence of language on base-10 number representations, we examined children's performance both across and within languages. Not only are English and Russian less transparent than Korean and Mandarin, but the degree of their transparency varies across numbers. In English, for example, the smallest two-digit numbers (11 and 12) are the least transparent. In Russian, phonetic modifications complicate the extraction of tens and ones for numbers up to 50, after which they become more transparent. If transparency is the key factor helping children to recognize base-10 structure, then English- and Russian-speaking children should be more likely to generate a base-10 representation on more transparent targets (e.g., "sixty one" vs. "twelve"). If, on the other hand, base-10 representations are largely shaped by mathematical experience, then one would expect a different pattern. Because children tend to have more experience with smaller numbers, they should have a better idea about "12" as a quantity composed of one ten and two single units and should be more likely to produce base-10 representations for smaller, rather than larger, numbers.

Are kindergartners from different language groups equally susceptible to variations in task instructions?

Saxton and Towse (1998) argued that English-speaking first graders had less experience with two-digit numbers than their Asian peers and, therefore, were more sensitive to the experimenter's demonstration (single digit vs. two digit). If experience with numbers is a factor in performance on the block task, then all kindergartners, given their limited instruction related to two-digit numbers, may be similarly affected by the type of demonstration they observe. In contrast, if a transparent language provides an early advantage for representing base-10, irrespective of instructional experience, then kindergartners from Asian countries should generate more base-10 representations than American and Russian kindergartners even when only a single-digit number is demonstrated.

Can kindergartners represent numbers in multiple ways, and does this flexibility vary with language structure?

An important aspect of understanding the structure of multi-digit numbers is the ability to recognize the equivalence between multiple representations of the same number (e.g., 28 single units = 2 tens and 8 ones = 1 ten and 18 ones). Such flexibility in thinking about numeric structure indicates that children understand the underlying relation between ones and tens (and, later, the relation among tens, hundreds, thousands, etc.) and the various ways the numeric units can be combined to form a number. It is akin to understanding the fact families for single-digit numbers (i.e., 5 = 4 + 1 or 5 = 3 + 2). Some researchers compare representing numbers in different ways to measuring quantities with different units such as grams and kilograms (e.g., Sophian, 2007). This understanding may facilitate multi-digit computation, which often involves switching between and combining different units. In other words, a child who can simultaneously think of a number as both a collection of units and a collection of tens and units may have an advantage in selecting and using strategies that involve parsing numbers into tens and ones over a child who cannot.

To examine the flexibility of children's thinking about numeric structure, we compared their performance on Tasks 1 and 2. We aimed to determine whether children who initially produced single-unit representations were able to generate base-10 representations when asked to show the number in a different way. If so, it would suggest that kindergartners possess greater base-10 knowledge than is captured by their Task 1 performance. This is particularly important to explore for children who received only single-digit practice in Task 1 given that they may have produced single-unit representations because they were following the experimenter's example. Furthermore, Task 2 provided an additional test of the language account. If the transparency of the counting system facilitates a base-10 representation, then Asian children who used a single-unit representation in Task 1 should be more likely to switch to a base-10 representation in Task 2 compared with American and Russian children.

Method

Participants

The study consisted of 272 kindergartners. Table 1 presents the breakdown by country. Participants were recruited from comparable social backgrounds—namely, from well-educated professional families. This selection criterion was used (a) to facilitate comparison with previous studies (Miura, 1987; Miura et al., 1988) that involved children from similar backgrounds and (b) to increase the likelihood that children had high levels of language skills. In the United States, children were from schools where 75% of adults had a bachelor's or higher degree (based on publicly available school-level information). In the other countries, where demographic data were not publicly available, we relied on information about families' professional backgrounds provided by local education officials. This information indicated that participating schools served families in which parents held high-status and well-paid jobs (e.g., academics, physicians).

Materials

The plastic blocks used in the study included small cubes (single unit-blocks) and longer bars (ten-blocks) with the 10 single-unit segments marked. One ten-block was equivalent to 10 unit-blocks. Numerals used in the study were printed on individual cards. Two numbers were used during practice

Table 1
Sample characteristics.

Country	Number of students	Mean age in months (range)	% Female students
USA (Massachusetts)	90	73 (61–84)	57
Russia (Moscow)	60	81 (68–89)	50
Taiwan (Taipei)	62	76 (68–81)	47
Korea (Seoul)	60	73 (67–80)	50

trials (2 and 7 or 2 and 14, depending on condition), and five numbers were used during test trials (12, 16, 28, 34, and 61). These numbers were selected because they represented a range of tens and ones and because they varied in the explicitness of the base-10 structure (Table 2).

Procedure

At the start of the study, 100 unit-blocks and 20 ten-blocks were placed in separate trays. Children were told that these blocks could be used to show numbers. The tester stressed the equivalence between the long block and 10 small ones by taking 10 unit-blocks and lining them up against the ten-block. During two practice trials, the tester presented children with a number card, saying, "I'll show you how we can make this number using the blocks." Children were randomly assigned to either the single-digit or mixed-digit practice condition. In the single-digit condition, children were shown the numbers 2 and 7 that the tester constructed using unit-blocks. In the mixed-digit condition, children were shown the numbers 2 and 14. To represent "14," the tester used one ten-block and four unit-blocks.

The practice was followed by Task 1, which consisted of five test trials. On each trial, children were given a number card and asked to name the number and show it using the blocks. Children produced each number representation on a separate tray, and when they were done the tray was put aside and retained for Task 2. When Task 1 was completed, the tester introduced Task 2, which also included five trials. On each trial, the tester presented children with a number card and the corresponding tray showing the number representation created in Task 1, saying, "This is how you showed this number last time. Now I want you to show the same number but in a different way." On both Tasks 1 and 2, number cards were presented in random order.

Responses on each trial were documented on an answer sheet; the tester recorded how many unit-blocks and ten-blocks children used to represent a given number. The tester also wrote comments to describe particular features of children's responses (e.g., whether children arranged blocks in a certain shape or made comments that could be helpful in coding). Responses were later categorized based on the coding scheme described in Table 3. The first three categories can be used to correctly represent any double-digit number, whereas the last three categories reflect misconceptions about base-10 numeric structure and/or a lack of task understanding.

Table 2
Target numbers.

	12	16	28	34	61
Mandarin	Shi-er (ten-two)	Shi-liu (ten-six)	Er-shi-ba (two-ten-eight)	San-shi-si (three-ten-four)	Liu-shi-yi (six-ten-one)
Korean	Ship-yi (ten-two)	Ship-yook (ten-six)	Yi-ship-pal (two-ten-eight)	Sam-ship-sa (three-ten-four)	Yook-ship-il (six-ten-one)
Russian[a]	Dve-na-dzat (two-on-*dzat*)	Shest-na-dzat (six-on-*dzat*)	Dva-dzat vosem (two-*dzat*-eight)	Tri-dzat chetyre (three-*dzat*-four)	Shest-desyat odin (six-ten-one)
English	Twelve	Six-*teen*	Twen-*ty* eight	Thir-*ty* four	Six-*ty* one

[a] In Russian number words up to 40, tens are indicated by an archaic word "dzat," which in the distant past meant "ten" but has not been used in modern language as a separate word.

Table 3
Categories of number representations.

Category	Description	Example
Canonical base-10	Using the largest possible number of ten-blocks to represent tens and unit-blocks to represent ones	34 = 3 ten-blocks + 4 unit-blocks
Non-canonical base-10	Using some ten-blocks and more than nine unit-blocks	34 = 2 ten-blocks + 14 unit-blocks
Single-unit collection	Using only single-unit blocks	34 = 34 unit-blocks
Unit confusion	Using ten-blocks to represent ones and/or unit-blocks to represent tens	34 = 20 ten-blocks blocks + 14 unit-blocks
Shape-based representation	Depicting the shape of the numeral rather than representing quantity	34 = 20 unit-blocks (to "draw" the shapes of 3 and 4)
Other	Guessing, no response, and rare strategies that did not fit into other categories	Grabbing a random number of blocks and placing them on the tray without counting

Results

Prior to analyzing the types of number representations children generated, which was the main focus of our study, we determined whether children were able to accurately name the target number shown on the card and represent the quantity corresponding to that number using the blocks. This analysis served to ensure that participants were familiar with two-digit numbers and understood the relation between written numerals and corresponding quantities. Next, we examined the types of representations produced by students in Task 1. To address our key research questions, we analyzed the use of base-10 representations across languages as a function of practice condition and target number. Finally, we analyzed performance on Task 2 to determine whether children could represent the same number in more than one way and whether their ability to switch from single-unit to base-10 representations varied across languages.

Task 1: Accuracy of number representations

On each trial, children's response received two accuracy scores: (a) naming accuracy that reflected whether the target number was identified correctly and (b) representational accuracy that reflected whether the value of the blocks used by children added up to the target number. Across countries, naming accuracy was very high (95%); representational accuracy was somewhat lower (83%). Looking at the representational errors, we found that 20% of them were due to inaccurate counting (e.g., double-counting blocks and, as a result, representing "61" with 59 unit-blocks). Other errors reflected conceptual difficulties with the task such as when children chose inappropriate representational strategies (e.g., using unit-blocks to represent tens).

To compare accuracy across countries, we conducted a multivariate analysis of variance (MANOVA) with country as the independent variable and with two accuracy scores as dependent variables: (a) the percentage of trials on which children named the target number correctly and (b) the percentage of trials on which children correctly represented the number with blocks. The results showed that neither score varied significantly by country ($ps > .05$).

Task 1: Types of number representations

On the majority of trials in Task 1, children represented target numbers in conceptually appropriate ways; the two most common types of representations were base-10 canonical and single unit (53% and 26% of all responses, respectively). Erroneous approaches, such as reproducing the shape of the number and using ten-blocks as single units, were also observed, albeit less frequently (14% of all responses). An analysis of individual students' performance provided further evidence that a base-10 representation was the most common approach used by kindergartners across countries. More than a third of participants (36%) always produced canonical base-10 representations, whereas fewer

Table 4
Percentages of different types of representation (out of all responses in Task 1).

	Canonical base-10	Non-canonical base-10	Single unit collection	Unit confusion	Shape-based representation	Other
USA	48	8	29	2	9	4
Russia	56	7	28	2	3	4
Taiwan	57	7	20	6	3	7
Korea	53	4	27	7	3	6

than a fifth of participants (18%) always produced single-unit representations. The remaining participants either used a mix of representations (39% of children) or always used an incorrect representation (7% of children). This kind of variability among children was seen within each country sample. Although there were differences in the pattern of individual responses within countries, the group averages for the frequency of particular types of representations were very similar across countries (see Table 4).

To address our research questions, we examined children's use of canonical base-10 representations. Two sets of analyses were conducted; one included responses on all trials, and the other included only those trials where children accurately named and represented the numbers. The pattern of findings was identical in both. In the analyses reported below, the dependent variable is the percentage of canonical base-10 representations out of all trials.

Use of base-10 representations as a function of practice condition

To determine whether the practice condition (single digit vs. mixed digit) affected children's use of base-10 representations and whether this effect varied across languages (English, Russian, Korean, and Mandarin), we conducted a 2 (Condition) × 4 (Language) analysis of variance (ANOVA) with the percentage of canonical base-10 representations as the dependent variable. The results showed a main effect of condition, $F(1,582) = 155.10$, $p < .001$, $\eta_p^2 = .21$, but no effect of language and no interaction. The effect of condition reflected more frequent use of base-10 representations after the mixed-digit practice (68%) compared with the single-digit practice (39%). As indicated by the lack of interaction between condition and language, this pattern was observed across languages (see Fig. 1).

Use of base-10 representations as a function of target number

To determine whether the target number (12, 16, 28, 34, or 61) affected children's use of base-10 representations and whether this effect varied across languages, we conducted a 5 (Number) × 4 (Language) ANOVA with the percentage of canonical base-10 representations as the dependent variable. It showed a main effect of number, $F(4,590) = 18.40$, $p < .001$, $\eta_p^2 = .03$, but no effect of language and no interaction. Children's use of base-10 representations was inversely related to the numerical magnitude (see Fig. 2). Pairwise LSD (least significant difference) comparisons indicated that the use of

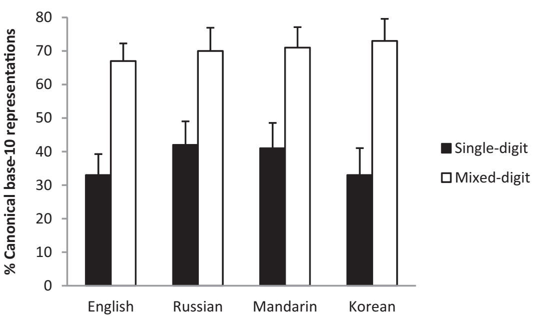

Fig. 1. Effect of practice condition across languages.

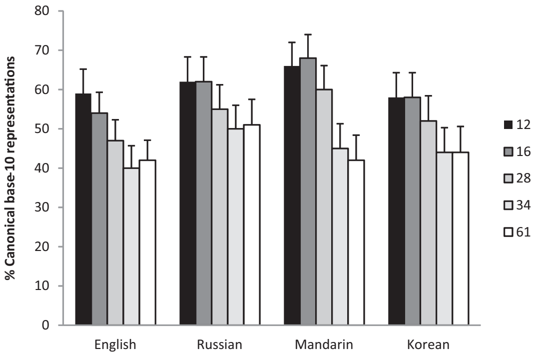

Fig. 2. Effect of target number across languages.

base-10 representations did not differ for "12" and "16", as well as for "34" and "61", but all other pairwise comparisons were significant (*p*s < .05).

We considered the possibility that kindergartners used base-10 representations less frequently with large numbers, such as 61, because some of them were unable to meaningfully represent corresponding quantities. In this case, they may simply place a random collection of blocks on the tray or resort to strategies such as reproducing the shape of the numeral. To address this possibility, we examined the performance of a subset of participants who accurately named and represented all five target numbers. The subset consisted of 152 children (56% of the whole sample), 49 of whom were from the United States, 36 from Russia, 37 from Taiwan, and 30 from Korea (which represented 54%, 60%, 60%, and 50% of each country's sample, respectively). We conducted a 5 (Number) × 4 (Language) ANOVA on this subset of students with the percentage of canonical base-10 representations as the dependent variable. The results showed a main effect of number, $F(4,148) = 5.40$, $p < .001$, $\eta_p^2 = .07$—a finding parallel to that with the whole sample. Again, neither language nor its interaction with number was significant (*p*s > .05).

Task 2: Accuracy of alternative representations

The key questions concerning Task 2 performance were whether children were able to produce alternative representations of double-digit numbers and whether this ability varied by language. To be coded as "alternative," the representation constructed in Task 2 needed to be from a different category than the one in Task 1 (e.g., base-10 canonical vs. base-10 non-canonical or single-unit collection; see Table 3). When students produced non-canonical representations in both tasks but used a different combination of blocks (e.g., 2 ten-blocks + 14 units vs. 1 ten-block + 24 units), their Task 2 response was also coded as an alternative representation. Some children used the same blocks as in Task 1 but arranged them in a spatially different way (e.g., a circle rather than a line of 12 single units); they did not get credit for this superficial change.

Overall, kindergartners produced alternative representations on 75% of trials, and 69% of these representations were accurate. An ANOVA with the percentage of accurate alternative representations (out of all Task 2 trials) as the dependent variable and with language as the independent variable showed a main effect of language, $F(3,271) = 5.57$, $p < .05$, $\eta_p^2 = .03$. Pairwise LSD comparisons indicated that this effect was not driven by the difference between transparent and non-transparent languages. There were no statistical differences in the percentage of accurate alternative representations produced by American, Russian, and Taiwanese students (53%, 57%, and 59%, respectively). The only significant difference among all pairwise comparisons was between Taiwanese children and their Korean peers, who produced accurate alternative representations on 45% of trials. A closer examination indicated that it was largely due to the fact that Korean students were more likely than Taiwanese students to report that they could not show the number in a different way.

Task 2: Changes in representations

As in Task 1, children produced conceptually appropriate representations of numbers on the majority of trials in Task 2; however, the distribution of the two most common types of representations (base-10 canonical and single unit (22% and 39% of all trials, respectively) was the inverse of Task 1. This is not surprising given that children's goal was to produce representations that were different from the initial ones. An analysis of individuals' patterns of performance found that in contrast to Task 1, where the majority of children consistently used either base-10 canonical or single-unit representations, in Task 2 the majority of children (64%) used a mix of representation types across the five trials. The finding that children were less consistent in their use of a representational strategy in Task 2 indicated that many of them did not have one obvious alternative numeric representation.

To examine this further, we analyzed how children's number representations in Task 2 compared with those in Task 1 on a trial-by-trial basis. As indicated earlier, on most trials in Task 1, kindergartners used two types of representations: base-10 canonical or single-unit collections. In the current analysis, we examined representations generated on the corresponding trials in Task 2. We found that following the initial use of canonical base-10 representations, children generated an appropriate alternative representation (single digit or non-canonical base-10) on 68% of Task 2 trials. On the remaining trials, they either produced an inappropriate alternative representation, such as shape based (12%), or did not create an alternative representation (20%). Following the initial use of single-unit collections, children switched to a base-10 representation (canonical or non-canonical) on 54% of corresponding Task 2 trials. On the remaining trials, they either produced an inappropriate alternative representation (25%) or did not create an alternative representation (20%). Thus, roughly half of the children who produced a single-unit representation in Task 1 were able to produce a base-10 representation to show the same number in Task 2.

We conducted a one-way ANOVA to examine whether the frequency of switching from a single-unit representation to a base-10 representation varied as a function of language. To compute the dependent variable for this analysis, we identified all of the trials on which children used single-unit representations in Task 1 and calculated the percentage of these trials on which they switched to a base-10 representation in Task 2. The results showed no effect of language on the frequency of switching from single-unit to base-10 representations, $F(3,99) = 0.38$, $p = .77$, $\eta_p^2 = .01$.

Discussion

The idea that linguistic differences in counting systems contribute to cross-national differences in mathematics achievement has become widely accepted in the general media, with popular books and Internet blogs presenting the argument as fact (Bellos, 2010; Gladwell, 2008; Krulwich, 2011). This view, resonating with a more general Whorfian idea that language differences may lead to differences in thinking, traces back to early studies of children's base-10 number representations conducted by Miura and colleagues (e.g., Miura, 1987). It is possible, however, that the previous studies examining cross-national differences in base-10 representations confounded language and educational experience by testing first graders. The current study examined cross-national differences in performance on Miura's block task but focused on kindergartners rather than first graders. Because kindergartners have mastery of their numeric language but more limited practice with two-digit numbers than first graders, this approach reduces confounding between language and experience. The results provide insights into children's understanding of the base-10 numeric structure in relation to the linguistic structure of their counting system.

Kindergartners' use of base-10 representations

Our findings indicated that kindergartners from all four countries had similar levels of familiarity with two-digit numbers. They were highly accurate (>90%) in naming target numerals and also quite accurate (>80%) and comparable in representing corresponding quantities using either ten-blocks or unit-blocks. Furthermore, and more important, we found no language-related differences in kindergartners' representations of the number structure; regardless of language, they were equally likely to represent two-digit numbers using ten-blocks. The lack of differences cannot be explained by floor effects given that kindergartners produced base-10 representations on roughly half of the trials. Furthermore, within each language group, the frequency of base-10 representations varied systematically as a function of target number and practice condition. Together, these findings suggest that children's performance was not based on chance or a lack of task understanding. Rather, the similarity in performance may be attributable to a comparable level of knowledge about the base-10 structure of two-digit numbers, likely derived from experience rather than language.

The effect of target number was consistent with this interpretation. Kindergartners from all four language groups used base-10 representations more frequently with smaller numbers than with larger numbers. Yet, in two languages (Mandarin and Korean) numbers do not vary in the degree of transparency, and in the other two languages (English and Russian) larger numbers actually have a more transparent base-10 structure. Although the observed pattern of performance was not consistent with linguistic factors, it corresponded to the frequency of particular numbers in the environment and, thus, children's likely experience with them (Dehaene & Mehler, 1992).

The effect of practice condition provided further evidence relevant to the evaluation of the language account. If a transparent counting system provides an advantage for representing base-10, then kindergartners from Asian countries should produce more base-10 representations than other students when only a single-digit number is demonstrated. Yet, this was not the case. There were no statistical differences among children across the four linguistic groups in both practice conditions. Overall, kindergartners used more base-10 representations when the experimenter demonstrated the task with a double-digit number rather than a single-digit number. In part, this pattern could be due to children following the experimenter's example; however, it was not simply a mechanical imitation of the practice trial because the experimental trials required using different combinations of ten-blocks and unit-blocks than was demonstrated. Most children who created base-10 representations did so in a meaningful way, choosing the number of ten-blocks that reflected the base-10 structure of the target number.

Children's performance on Task 2, in which they were asked to produce an alternative number representation, served as an additional check of their ability to generate base-10 representations of double-digit numbers. The practice effects observed across language groups raised the possibility that some kindergartners produced single-unit collections after single-digit practice because they were following the experimenter's demonstration. In other words, their Task 1 performance did not reveal their true ability to generate a base-10 representation, whereas Task 2 allowed them to do so. Indeed, on nearly half of the trials in which children initially produced single-unit representations, they switched to a base-10 representation when asked to show the number in a different way. Critically, the likelihood of this switch did not vary as a function of language.

The results of the two tasks show substantial individual variability in children's performance. Although there were children in each country who did not produce any type of appropriate representation, the majority of kindergartners were able to show double-digit numbers with blocks using an appropriate representational strategy. Some of the participants generated base-10 representations in Task 1, others initially produced single-unit representations but switched to base-10 in Task 2, and yet others appeared to be unable to make this switch. The percentages of children in each of these categories were comparable across languages that varied in terms of transparency of their counting systems, which is in contrast to the findings of earlier work with older students.

Conclusions and future directions

The current results suggest that language might not play as critical a role in the early ability to represent the base-10 numeric structure as suggested by earlier research. Prior to formal instruction, kindergartners from different language backgrounds demonstrate a similar pattern of responses on the number representation block task. Although null findings (with respect to language effects) do not lend themselves to definitive interpretations, the effects of task instruction and target number provide convergent evidence for this interpretation. These effects captured systematic within-language variability. Critically, they were similar across language groups, possibly reflecting parallel experiential processes (e.g., prevalence of smaller two-digit numbers in kindergartners' experience).

These results add to a growing base of research questioning the language account in explaining cross-national differences observed on a wide range of math tasks (Cankaya, LeFevre, & Dunbar, 2014; LeFevre, Clarke, & Stringer, 2002). For example, Cankaya and colleagues (2014) showed that preschool children whose language has a more regular counting system than English learned number names more quickly; however, this advantage did not translate into better performance on numeracy tasks that required conceptual understanding of mathematical principles such as cardinality.

Our data suggest cross-national similarity in the development of number representations, with the base-10 knowledge developing in an incremental way. Initially, children may think of numbers predominantly as individual units based on practice enumerating small sets. Gradually, they develop base-10 representations of two-digit numbers, starting with numbers in the teens that they encounter more frequently. Early on, their nascent understanding of base-10 may be apparent only when the context supports or elicits it (e.g., through practice trials as in the current study). As children's experience expands and they accumulate diverse exemplars of two-digit numbers, they may be more likely to use base-10 representations spontaneously regardless of context. This developmental process aligns with the finding that English-speaking children as young as 4 years show a fledgling understanding of the structure of multi-digit number words but that age-related improvements occur through second grade (Mix, Prather, Smith, & Stockton, 2014).

Cross-cultural differences in base-10 representations may emerge later in development—as a function of instruction or its interaction with language features—when the link between the structure of number words and numeric concepts becomes more salient to children. This association may be strengthened through repeated practice with number words in the context of enumerating large sets. The link between linguistic structure and numeric concepts might also be communicated to children explicitly through instructional approaches that highlight the features of the numeric system captured by language. In other words, when children receive relevant instruction in school, the numeric information reflected in transparent number words may become more salient to them; thus, they may be better able to capitalize on the advantages of the transparency of number words.

It is likely that previous evidence of cross-national differences among first graders reflected differences in instruction about place value and computational strategies that highlighted the base-10 number structure such as base-10 decomposition (Fuson & Kwon, 1992; Ma, 1999; Miller, Kelly, & Zhou, 2005). In the case of kindergartners, however, analysis of math curriculum and interviews with teachers indicated that there were no substantial differences in the extent of classroom exposure to two-digit numbers across countries. Kindergartners were taught how to count and name numerals beyond 10, but other instructional activities involving these numbers (including place value and numeric representation tasks) were not introduced until first grade in all participating countries. Thus, similar levels of base-10 knowledge in kindergartners across countries are likely attributable to similar classroom experiences despite potential variability in parental input.

It is possible that greater differences in knowledge, both within and across language groups, may have been found if children from a wider range of socioeconomic levels had been included. Hypothetically, one could argue that high-SES (socioeconomic status) students are better suited to overcome language effects, whereas low-SES students may demonstrate such effects. We believe that this is unlikely because it implies that high-SES American and Russian kindergartners receive richer mathematical input than their high-SES counterparts from Taiwan and Korea to compensate for a language disadvantage. Nevertheless, this is an empirical question, and future research comparing cross-cultural patterns in high-SES versus low-SES groups may provide a better understanding of mathematical development in relation to language. For the purposes of the current study, the focus on high-SES participants made most sense because it facilitated comparisons with previous studies and provided the greatest control of linguistic and experiential factors. Across countries, high-SES children are likely to receive similarly rich mathematical experiences in school and at home; furthermore, they are likely to have comparably high levels of language proficiency, which may influence the extent to which the benefits of transparency are observed (Rasmussen, Ho, Nicoladis, Leung, & Bisanz, 2006).

In interpreting the current findings, it is important to note that our investigation did not aim to provide a general comparison of mathematical knowledge in kindergartners from participating countries. We examined one aspect of mathematics development, albeit the one that seems most likely to be influenced by transparency in the linguistic structure of count words—namely, the understanding of the base-10 numeric structure. There are numerous other concepts and skills that children must acquire during the course of mathematical learning. Cross-national differences in the development of many of these skills, such as numerical estimation and arithmetic strategies, have been found and associated with differences in the linguistic features of counting systems (e.g., Geary et al., 1996; Laski & Yu, 2014; Miller & Stigler, 1987; Siegler & Mu, 2008). The research trajectory delineated in the current study—(a) examining the role of language among younger children when instructional differences are least likely to be confounds and (b) conducting a fine-grained analysis of within-language differences—could lead to a better understanding of which numeric tasks do or do not show cross-national differences in early stages of math learning. This line of research may facilitate the identification of malleable experiential factors that can be used to optimize performance regardless of the extent of language support for mathematical learning.

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