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A cross-linguistic investigation on the acquisition of complex numerals

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Abstract

Complex numerals (e.g., four hundred) have a multiplicative structure (four hundred = 4 x 100). This paper investigates whether children are sensitive to the meaning of the multiplicative structure. We designed a novel word learning paradigm and taught 4- to 6-year-old children the meaning of a novel numeral phrase (e.g., 'one gobi houses' to mean a group of three houses). We then asked whether they could generalize it to a novel context (e.g., 'two gobi butterflies' to mean two groups of three). Experiment 1 showed that only English-speaking children who received multiplier syntax training were able to generalize. Experiment 2 extended findings from Experiment 1 to Cantonese-speaking children and found that they could also generalize a novel multiplier to novel contexts. These results suggest that children as young as 4 can create a mapping between the structure of complex numerals and a multiplicative meaning.

Keywords: complex numerals, digits, multipliers, syntax, semantics, preschoolers, cross-linguistic investigation

Introduction

Numerals are built using a compositional system, in which a set of individual numerals can be combined to form many different numerals. For example, to count to one hundred in English, we only need to remember 28 words: one through nineteen, twenty, thirty, forty, fifty, sixty, seventy, eighty, ninety, and hundred. Counting to one trillion, a number that is 10,000,000,000 times larger than 100 requires only four additional words: thousand, million, billion, and trillion. How numerals are combined to form complex numerals such as 'twenty-three' and 'two hundred' are governed by compositional rules (e.g., Hurford, 1975; Ionin & Matushansky, 2006). The current study investigates the developmental origins of the compositional rules of numerals, by examining the linguistic and conceptual building blocks of the system.

Linguists have long observed that there are two types of numerals based on which compositional rules apply: digits (two, five) and multipliers (hundred, thousand; Hurford, 1975; Ionin & Matushansky, 2006). Digits and multipliers have different syntactic properties. First, multipliers are similar to singular count nouns in English. They must be preceded by a numeral or a determiner – e.g., "A/one million people watched the game." In contrast, digits can be used in its bare form – e.g., "Three people watched the game." Second, multipliers in English such as hundred and million can be pluralized – e.g., "Vaccination could save millions" – but digits cannot – e.g., "Vaccination could save threes" is ungrammatical.

Across all natural languages with a numeral system, digits and multipliers can be combined in two ways to form complex numerals: conjunction and multiplication. Numerals can be combined via conjunction explicitly with the use of 'and' as in "one hundred *and* one" or implicitly as in "twenty-three." Moreover, similar to a determiner phrase in which a determiner is combined with a noun (e.g., "a" + "dog" → "a dog"), a digit and a multiplier can be combined to form a numeral phrase (e.g., "one" + "hundred" → "one hundred"). Each of these two types of combinations maps onto a unique arithmetic operation. Conjunctions map onto addition (e.g., twenty-three means 20 + 3), and numeral phrases map onto multiplication (e.g., two hundred means 2 x 100).

In this paper, we focus on the mapping between the structure of complex numeral phrases such as 'one hundred' and its multiplicative meaning as a first step to investigate the acquisition of the compositional nature of numerals.

Acquisition of compositional rules of numerals

How do children discover the compositional rules that govern the combination of digits and multipliers? On one view, children discover the rules of the numeral system on their own (e.g., Hurford, 1975; Siegler & Robinson, 1982). For example, after encountering numeral phrases in their language, children may discover a rule that maps the structure of complex numerals onto multiplication. They are then able to apply this rule to generate new numbers in the form of 'digit multiplier' and assign them a multiplicative meaning.

Alternatively, acquisition of complex numerals may be item-based. For example, after learning 'one hundred', children still have to separately learn numerals that are of a similar form – e.g., 'two hundred', 'three hundred', and 'four hundred'. In other words, children's learning is not initially rule-based, and only later do they learn the underlying compositional rules that govern numeral structure, perhaps via explicit instruction. Thus, children may learn complex numerals by rote memorization prior to decomposing them (Fuson, 1990).

Although no previous studies have examined the acquisition of multipliers, there is related, though indirect, evidence from studies on the acquisition of the count sequence and the place-value system that provide insights into how compositional rules for numerals may be acquired.

First, previous studies have demonstrated that children's counting experience is related to discovering the underlying structure of the count sequence. For example, Siegler and Robinson (1982) asked a group of 3- to 5-year-olds to repeatedly count from one over multiple sessions, and to count on from a particular number that was beyond their counting range. They found that children who counted between 20 and 99 always ended with 'nine' (twenty-nine, thirty-nine, etc), suggesting that they understood the within-decade structure but were limited by the knowledge of the next decade word. They also found that those who counted up to 100 understood the within-decade structure *and* showed some knowledge of the between-decade structure. Thus, a majority of children did not simply memorize up to an arbitrary number. Rather, children's counting reveals the different rules that they discover about the count sequence (e.g., the order of one to nine, the order of decade terms).

In addition, cross-linguistic studies have shown that the numeral structure of some languages may facilitate the rule discovery process (Miller, et al., 1995; Miller & Stigler, 1987). Numerals in Korean and Chinese follow a highly regular structure. For example, in Chinese, the numbers following ten (*shi*) are ten-one (*shi-yi*) and ten-two (*shi-er*), while the words for twenty and thirty are two-ten (*er-shi*), and three-ten (*san-shi*), respectively. This contrasts sharply with the irregularities in English (e.g., eleven, fourteen, twenty). Previous studies have found that 4-year-old children learning Chinese and Korean are able to count higher than their English counterparts (Miller et al., 1995), suggesting that the regularity of a language's numeral system may help children discover the count sequence structure.

Another piece of evidence comes from studies on children's understanding of the place-value system. Previous studies have found that when asked to represent 2-digit numerals (e.g., 11, 42) with blocks, children starting at around the age of 6 are able to use a combination of unit blocks and tens blocks. For example, children represent 42 using four blocks of 10 and two single blocks rather than 42 single blocks. Some have also documented cross-linguistic differences with children's place value understanding, showing that Japanese-speaking children are more likely to use a combination of tens and units blocks than English-speaking children (Miura, 1987; Miura, Kim, Chang, & Okamoto, 1988; but see Saxton & Towse, 1998; Vasilyeva et al., 2015). These results suggest that children are able to decompose complex numerals into its constituents. Nevertheless, children's understanding of the place-value system only reveals knowledge of *written* numerals and leaves open the question of what young children understand about the compositional nature of numerals *prior to* acquiring the place-value system.

The present experiments

To investigate whether and when children acquire the mapping between the compositional structure of complex numerals and their meaning, we designed a novel word learning paradigm. Specifically, in two experiments, we asked when children between the ages of 4 and 6½ recognize that a complex numeral in the form of 'digit multiplier' maps onto multiplication.

The general logic of our experiments was to teach children a novel noun phrase that described a set of three objects (e.g., the experimenter described a group of three houses as 'one gobi houses'). Then, we tested whether children have learned the meaning of the phrase (e.g., 'one gobi Xs' to refer to a group of three objects). Critically, we asked whether children can generalize the novel noun phrase to a novel context involving 'two' (e.g., Who has two gobi books?).

In Experiment 1, we provided one group of English-speaking children with informative multiplier syntax – i.e., the numeral 'one' followed by a novel multiplier 'gobi' (one gobi Xs), and another group with uninformative syntax, with only a novel word modifying the noun (gobi Xs). The two groups of children saw the same pictures but they heard verbal descriptions that differed only in the structure of the noun phrase (one gobi Xs vs. gobi Xs). We hypothesized that if children are sensitive to the mapping between complex numeral of the form 'digit multiplier' and its multiplicative meaning, then they should be more likely to generalize the learned novel numeral phrase to new contexts when they are presented with informative multiplier syntax than uninformative syntax.

In Experiment 2, we tested children learning Cantonese Chinese, which has a regular numeral structure, using the same paradigm. Cantonese Chinese, similar to Mandarin Chinese, has no irregularities in the naming of the numerals, and multiplier syntax occurs as early as 20 (*ji-sap*). We asked whether they would also demonstrate sensitivity to the multiplier syntax, and if so, whether they would show earlier knowledge of the multiplier structure than English-speaking children. To the extent that they do, we asked whether this was due to linguistic differences or other educational or cultural factors. Tests of general receptive vocabulary and mathematical competence were included as control measures. We also included a highest count measure to investigate if counting experience affects children's sensitivity to multiplier structure.

Experiment 1 – English-speaking children

We taught English-speaking children a novel numeral phrase with multiplier syntax – i.e., the numeral 'one' followed by a novel multiplier 'gobi' (one gobi Xs; Multiplier condition), and asked if they could generalize it to a novel context involving 'two'. For example, children heard 'one gobi houses' when shown a group of three houses, and they were then asked to choose which one of two sets contained 'two gobi books'. To investigate if children's understanding of multipliers is specific to multiplier syntax, we adopted a between-subjects design and presented another group of children with the same visual stimuli but with uninformative multiplier syntax. Specifically, the novel word ‘gobi’ was presented without the numeral ‘one,’ (gobi Xs; the No Digit condition). Thus, the only difference between the two conditions was in the syntactic structure of the noun phrase.

Method

Participants A total of 98 children between the ages of 4;2 and 6;6 participated. Sixty-eight of them were assigned to the Multiplier condition (M = 5;4), and 30 in the No Digit Condition (M = 5;4). They were recruited at daycare centres and schools in southwestern Ontario. All children spoke English as their primary language.

Design and Procedure

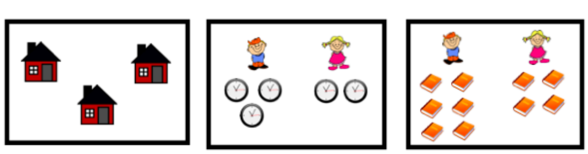
Highest count Children were asked to count as high as they can, and were stopped if they could count up to 100.

Novel Word Learning The novel word learning paradigm had two conditions: Multiplier and No Digit conditions, and each condition proceeded in three phases, including modelling, training, and generalization.

Multiplier Condition During modeling, children were told that they were going to learn a new word – gobi. They were shown sets of three objects that were labelled with a novel numeral phrase. Children in the Multiplier condition were provided with multiplier syntax, e.g., “This is one gobi houses” (see Figure 1a). There were a total of six trials. On the last modelling trial, children were shown groups of two, three, and four objects (e.g., two phones, three phones, four phones). They were told that the collection of three phones was ‘one gobi phones.’ Importantly, they were also told that the collection of two phones and that of four phones were *not* ‘one gobi phones.’

After the modelling phase, children proceeded to the training phase. During training, children were given a forced-choiced task. They were shown a boy and a girl, one of whom had three objects and the other had either four or two. Children were asked, “Who has one gobi clocks?” (Figure 1b). Children were corrected if they chose the wrong character and praised if they chose the right one. Children passed training if they correctly answered 4 trials in a row, with a maximum of 16 trials in the training phase.

After training, children were asked to generalize to a novel numeral phrase involving the numeral ‘two’. Children were shown the boy and the girl characters, and were asked, “Who has two gobi books?” (Figure 1c). Children who passed the training phase completed all generalization trials. Unlike the training phase, feedback was not provided.



a) Modelling b) Training c) Generalization

Figure 1a-c: A schematic illustration of the experimental set-up.

The forced-choice task in the generalization phase consisted of a character who had two groups of three or a group of six, and another character who had one of four different types of competitor sets: two individuals, a group of three, two groups of two, and four groups of three (see Figure 2). These competitor sets were designed to test the scope and the specificity of the acquired meaning of ‘digit multiplier’. We outlined our reasoning for including the four different competitor sets below:

(1) To test whether children interpreted the novel numeral phrase as one that refers to groups or to individuals (two individuals).
(2) To test whether children interpreted the novel numeral phrase as one that applies to two groups of any number (two groups of two).
(3) To test whether children interpreted ‘gobi’ to mean ‘three’ (a group of three).
(4) To ensure that children did not simply pick the more numerous set (four groups of three).

There were a total of 24 trials, four of each type. Children completed two blocks of 12 trials. The presentation of the competitor sets was pseudo-randomized in each block. The boy and the girl had an equal number of correct answers.

The task was presented on a laptop computer. A different kind of object was used for each trial. The stimuli set contained a total of 46 objects that were familiar to preschoolers (e.g., butterflies, houses, bags, cups).

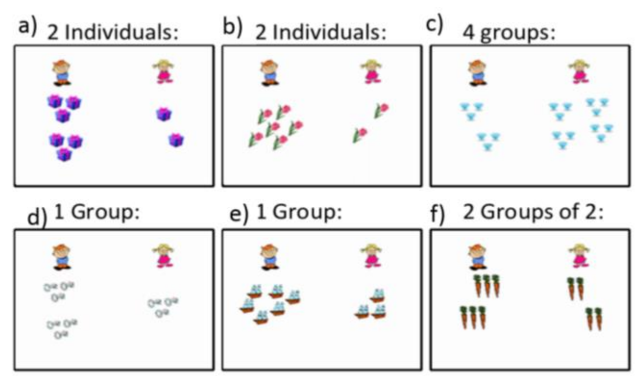


Figure 2: Six types of competitor sets. *a)* 2 groups of 3 vs. 2 individuals; *b)* a group of 6 vs. 2 individuals; *c)* 2 groups of 3 vs. 4 groups of 3; *d)* 2 groups of 3 vs. 1 group of 3; *e)* a group of 6 vs. a group of 3; *f)* 2 groups of 3 vs. 2 groups of 2

No Digit Condition Another group of children were presented with uninformative multiplier syntax in which the digit was removed from the numeral noun phrase. Specifically, children were modelled on ‘gobi Xs’ (e.g., This is gobi houses), trained on ‘gobi Xs’ (e.g., Who has gobi clocks?), and were asked to generalize to ‘two gobi Xs’ (Who has two gobi books?).

Control measures[1]

Receptive vocabulary We used the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2012) to measure children's receptive vocabulary. Children were asked to point to one of four pictures in response to a target word. They received one point for each correct answer, and a total score was computed for each child.

General mathematical competence We chose three subtests of the Test of Early Mathematics Ability (TEMA; Ginsburg & Baroody, 2003) as a measure of children's math skills: mental number line, verbal numerical comparison, and mental addition. Percent correct averaged across the three subtests was computed for each child.

Task Order Each testing sessions always began with a highest count task, followed by the novel word learning task. Children in the Multiplier condition also completed PPVT and TEMA.

Results and Discussion

Training phase A majority of children from the Multiplier condition (78%) passed training and were included in the analysis. Those who were included (*M* = 5;5) were on average five months older than those who did not pass training, $t(66) = 2.07$, $p = .042$. All children from the No Digit condition passed training and were included. Of those who passed the training phase, 85.9% of them did so within 4 to 6 trials.

Generalization phase We first examined how likely children in the Multiplier condition generalized to 'two gobi.' Children's scores in the generalization phase followed a bimodal distribution (see Figure 3). A Shapiro-Wilk test confirmed that the distribution of scores violated the normality assumption, W = .85, p < .001.

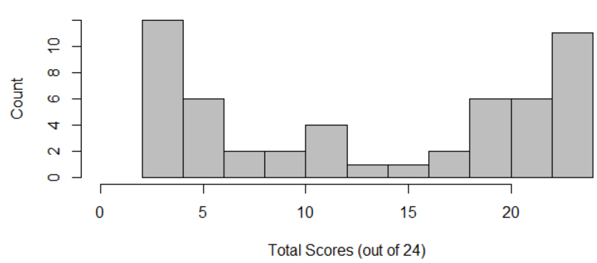


Figure 3: A histogram of children's scores in the generalization phase (Multiplier Condition).

As indicated in Figure 3, the distribution of scores formed two peaks, one at the highest end and another at the lowest end of the distribution, suggesting that some children were able to generalize from 'one gobi' to 'two gobi' consistently, and some were consistently unable to do so. To capture the dichotomous nature of children's responses and to investigate their performance in the generalization phase, we defined above chance performance as answering more than 16 out of 24 trials correct (binomial test, $p = .06$). Results showed that 25/53 (47.2%) of children scored at least 17 on the generalization task (*M* = 21.6, SD = 2.0); we labelled these children 'generalizers'. The remaining children scored on average 6.6 trials correct (SD = 3.7), and we labelled them 'non-generalizers'.

These results suggest that some children between the ages of 4 and 6 were able to generalize a novel numeral phrase 'one gobi Xs' to 'two gobi Xs'. This provides evidence that children are able to create a mapping between a numeral phrase in the form of 'digit multiplier' (e.g., one gobi) and a multiplicative meaning. Nevertheless, these results do not demonstrate that this mapping is unique. It is possible that the context of the training and generalization tasks allow some children to interpret any novel numeral phrase with a multiplicative structure, regardless of the actual form of the numeral phrase itself. To address this question, we analyzed how likely children in the No Digit condition generalized. We found that only 3 of them were 'generalizers', receiving a total score of 17 or higher, and a majority of them (n = 27) were 'non-generalizers'. Compared to those in the Multiplier condition, a significantly lower proportion of children in the No Digit condition generalized, $\chi^2(1) = 10.24$, $p = .001$. These results provide evidence that children who were provided with informative multiplier syntax were able to map the form 'digit multiplier' to multiplication.

Effect of age and highest count Next, we analyzed whether children's age or counting experience predicted the likelihood that they generalized in the Multiplier condition. We conducted a logistic regression with age in months and highest count as predictor variables. The dependent measure was children's status as a 'generalizer'. There was no effect of age, $\beta = .060$, $SE = .048$, $p = .21$, or counting, $\beta = .015$, $SE = .011$. $p = .17$. Nevertheless, the final model was significantly better than the constant-only model, $X^2(2) = 9.91$, $p < .001$.

Discussion

Results from Experiment 1 showed that 4 to 6½-year-old children who were trained to pair the novel numeral phrase 'one gobi' with sets of three were more likely than those in the No Digit condition to generalize to 'two gobi', suggesting that children in the Multiplier condition can create a mapping between a novel complex numeral in the form of 'digit multiplier' and a multiplicative meaning. This provides the first piece of evidence that children are sensitive to the multiplier syntax. In the following experiment, we extended this finding to another language group, and asked whether language structure affects children's sensitivity to the multiplier structure.

Experiment 2 – Cantonese-speaking children

Experiment 1 showed that English-speaking children between the ages of 4 and 6½ successfully generalized a novel numeral phrase 'one gobi' to novel contexts. We also

[1] Analyses on these control measures are reported in Experiment 2.

found that this knowledge was specific to complex numerals in the form of 'digit multiplier.' In Experiment 2, we asked whether children learning Cantonese, a language with transparent numeral system, would demonstrate earlier knowledge of the meaning of the multiplier structure. Cantonese belongs to the family of Chinese languages, and has a regular numeral structure. For example, numerals in the teens in Chinese are highly regular, unlike English – e.g., *eleven* is literally translated to 'ten one' (*sap jat*) in Cantonese Chinese, and *twelve* is 'ten two' (*sap ji*). Starting at the numeral *twenty* begins the multiplier structure – 'two ten' (*ji sap*), whereas in English, the multiplier structure appears at *one hundred*. Given these differences in numeral structure, we predicted that Cantonese-speaking children may demonstrate earlier sensitivity to the meaning of the multiplier structure.

To test this, we recruited a sample of Cantonese-speaking children and tested them using the same novel word learning paradigm as Experiment 1.

Method

Participants A total of 122 children between the ages of 4 and 6½ participated. Sixty-three children participated in the Multiplier condition (*M* = 5;3; range = 4;0 to 6;6), and 59 children participated in the No Digit condition (*M* = 5;3; range = 4;0 to 6;6). They were recruited at daycare centres in Hong Kong. All children spoke Cantonese as their primary language.

Design and Procedure The design of this experiment was identical to Experiment 1. Children were first modelled on a novel numeral phrase, followed by a training phase with feedback and a generalization phase without feedback.

Children were tested by a native Cantonese speaker. In the Multiplier condition, children were taught 'one gobi classifier Xs'. In the No Digit condition, children were trained on 'gobi classifier Xs'. All noun phrases were used with a general classifier (CL) – *goh*.[2]

Similar to Experiment 1, children also completed a highest count task, a receptive vocabulary test (PPVT) and a general mathematical competence test (TEMA).

Results

Training phase In the Multiplier condition, 90.5% of children passed the training phase (57/63 children), and among them, 94.7% of them did so within 4 to 6 trials. Children required an average of 4.72 trials (SD = 2.37 trials) to pass training. In the No Digit condition, a majority of children passed the training phase (89.8%; 53/59 children), and among them, 80.7% of them did so within 4 to 6 trials. Children required an average of 5.02 trials (SD = 2.30 trials) to pass training. Children who did not pass training were excluded (n = 6 in the Multiplier condition; n = 6 in the No-digit condition).

Generalization phase Similar to English-speaking children in Experiment 1, Cantonese-speaking children's responses in the generalization task followed a bimodal distribution (see Figure 4). A Shapiro-Wilk test confirmed that the normality assumption was violated, W = .80, p < .001.

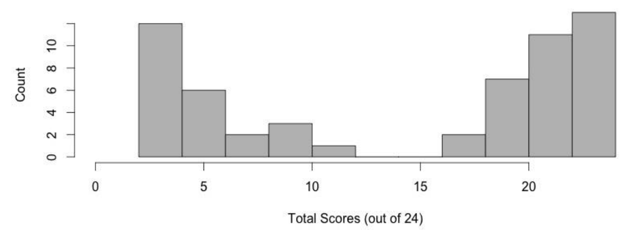


Figure 4: A histogram of children's scores in the generalization phase (Multiplier Condition).

Similar to Experiment 1, we defined above chance as answering more than 16 out of 24 trials correct (binomial test, *p* = .06). In the Multiplier condition, 33/57 children performed significantly above chance, *t*(32) = 16.97, *p* < .001 (*M*=21.7 trials, *SD*=1.9 trials), and were thus termed 'generalizers'. In contrast, the 'non-generalizers' scored on average 5.3 trials correct (SD = 2.4 trials).

In the No Digit condition, surprisingly, 26/53 children performed significantly above chance, *t*(25) = 12.11, *p* < .001 (*M*=20.7 trials, *SD*=12.0 trials), and the remaining children – 'non-generalizers' - scored on average 7.8 trials correct (SD=4.2 trials). This contrasts with the findings from Experiment 1. We discuss reasons for this diverging result in the Discussion section.

Effect of age and highest count We analyzed whether children's age or counting experience predicted the likelihood that they generalized in the Multiplier condition. We conducted a logistic regression with age in months and highest count as predictor variables. The dependent measure was children's status as a 'generalizer'. Results showed that there was no effect of age, β = .011, *SE* = .042, *p* = .78, but a marginal effect of highest count, β = .024, *SE* = .013, *p* = .064. The model with both predictors was significantly better than the constant-only model, $X^2(2) = 6.50$, *p* = .038.

Cross-linguistic comparison Next, to investigate whether there is a cross-linguistic difference in how likely children generalize the novel multiplier, we conducted a logistic regression with language (English, Chinese) as a predictor. We also included age in months, highest count and the two control measures – PPVT and TEMA – in the model. The dependent variable was children's status as a 'generalizer'. This analysis was performed for children in the Multiplier condition. We found no effect of language, β = -.26, *SE* =

[2] Cantonese is a classifier language in which nouns cannot co-occur directly with numerals, but require classifiers (CL). There is also no obligatory plural morphology. For example, 'three balls' is translated to 'three classifier ball'. In this experiment, we used the general classifier – *goh* – the most frequent classifier in Cantonese (Matthews & Yip, 1994).

.51. p = .61, suggesting that although proportionally more Chinese-speaking children were generalizers compared to English-speaking children, this difference was not reliable. None of the control measures were significant, all ps > .09.

Discussion

Experiment 2 extended the findings from Experiment 1 to children learning Cantonese, a language with regular numeral structure. We found that Cantonese-speaking children between the ages of 4 and 6½ could map complex numerals in the form 'digit multiplier' onto multiplication. We also found that some children in the No Digit condition demonstrated knowledge of the multiplier structure, which contrasts sharply with children learning English (Experiment 1). We speculate that this is due to the fact that in Cantonese, the numeral 'one' can often be dropped in conversations (Erbaugh, 2002; Matthews & Yip, 1994). This raises the possibility that even in absence of the word 'one' during modelling and training, children in the No Digit condition interpreted 'gobi CL Xs' as if it means 'one gobi CL Xs', and assigned it a multiplicative meaning. Another possibility is that the classifier may provide cues to Chinese speakers that 'gobi CL Xs' is a numeral phrase. We think that this explanation cannot fully explain the pattern of results because English-speaking children in the No Digit condition could identify a set of three objects as 'gobi Xs'. Their difficulty lies in generalizing it to novel contexts.

General Discussion

Two experiments explored whether and when children are able to map the multiplier structure, 'digit multiplier' (e.g., one hundred), onto multiplication. Using a novel word learning paradigm, we found that both English- and Cantonese-speaking children between the ages of 4 and 6½ who were taught the meaning of 'one gobi Xs' to refer to a group of three objects were able to generalize to 'two gobi Xs' as meaning two groups of three objects. We also found that knowledge of this mapping in complex numerals is specific to the form of 'digit multiplier' - when provided with uninformative syntax in which the digit was not presented, English-speaking children failed to generalize the novel noun phrase to a novel context. The current set of experiments are the first to investigate the acquisition of the multiplier syntax in children, and our results demonstrate that children as young as 4 can create a mapping between the multiplier structure – 'digit multiplier' – and a multiplicative meaning with minimal training.

Our findings provide some support for the rule-based learning account of the acquisition of complex numerals. With only six modelling trials, a majority of children learned that 'one gobi' refers to a group of three objects, and approximately half of those generalized to a novel context. Although not all children could generalize, our results indicate that even with very little input, children are able to map the syntax of multipliers to its semantics.

Nevertheless, the current study leaves open two questions. First, we found that Cantonese-speaking children in the No Digit condition were also able to generalize. Further studies are required to investigate whether Cantonese-speaking children would generalize the novel numeral phrase to novel contexts when presented with other uninformative syntactic structures. Second, we found that age, general vocabulary and mathematical skills, and the regularity of a language's numeral system did not predict how likely children generalized in the Multiplier condition. Counting experience was only marginally significant in the Chinese sample. It remains to be tested what may predict children's sensitivity to multiplier syntax.

In summary, the present results suggest that numeral syntax may provide a rich foundation for numeral learning. They also highlight the importance of investigating the linguistic aspects of the numeral system, and provide a fruitful avenue for examining the linguistic and conceptual building blocks of the acquisition of number.

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