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The Development of Ordinal Numerical Competence in Young Children

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Two experiments assessed ordinal numerical knowledge in 2- and 3-year-old children and investigated the relationship between ordinal and verbal numerical knowledge. Children were trained on a 1 vs 2 comparison and then tested with novel numerosities. Stimuli consisted of two trays, each containing a different number of boxes. In Experiment 1, box size was held constant. In Experiment 2, box size was varied such that cumulative surface area was unrelated to number. Results show children as young as 2 years of age make purely numerical discriminations and represent ordinal relations between numerosities as large as 6. Children who lacked any verbal numerical knowledge could not make ordinal judgments. However, once children possessed minimal verbal numerical competence, further knowledge was entirely unrelated to ordinal competence. Number may become a salient dimension as children begin to learn to count. An analog magnitude representation of number may underlie success on the ordinal task.

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INTRODUCTION

It is virtually impossible to escape number in our everyday interactions. We quantify and numerically compare entities ranging from the speed at which our computers run, to the points scored in a game of football, to the cost of a gallon of milk, to the size of our jeans. The importance of number is also evident in the widespread development across cultures of verbal and written systems of numerical notation. It is therefore not surprising that the phylogenetic and ontogenetic origins of numerical competence have become subjects of lively debate in cognitive science. Particularly provocative is the claim that number is a modular knowledge domain that is independent of linguistic ability or ‘‘general’’ intelligence (e.g., Dehaene, 1997; Dehaene, Dehaene-Lambertz, & Cohen, 1998). One source of evidence for such a claim is the finding that prelinguistic infants are sensitive to differences between and transformations of the cardinal values of sets of entities (e.g., Antell & Keating, 1983; Bijeljac-Babic, Bertoncini, & Mehler, 1991; Koechlin, Dehaene, & Mehler, 1998; Simon, Hespos, & Rochat, 1995; Starkey & Cooper, 1980; Strauss & Curtis, 1981; Treiber & Wilcox, 1984; Uller, Huntley-Fenner, Carey, & Klatt, 1999; van Loosbroek & Smitsman, 1990; Wynn, 1992a, 1996; Xu & Spelke, 2000). A second source of evidence comes from findings that nonhuman animals demonstrate some degree of numerical competence (see Gallistel & Gelman, 1992; and Dehaene, 1997 for reviews).

Full-fledged numerical concepts are multifaceted and complex. One essential aspect of number is that of cardinality—that is, the ability to represent the number of discrete entities in a set and to appreciate the numerical equivalence of all sets whose members can be placed into exact one-to-one correspondence. Another central aspect of number is the ability to represent ordinal relations between numbers—that is, the inherent ‘‘greater than’’ or ‘‘less than’’ relations between distinct numerosities. Without this ability, distinct numerosities such as ‘‘one’’ and ‘‘four’’ bear no more relation to one another than do cows and blenders. Together, however, these two aspects of number provide a rich concept that can be employed in contexts as diverse as determining the number of brides needed by seven brothers to assessing relative group size in order to predict the likelihood of winning a territorial dispute.

Both the cardinal property of numbers and the ordinal relations between cardinal numbers are inherent in verbal systems of counting. Linguistically, the cardinal aspect of number is captured in the fact that sets containing the same number of entities are labeled with the same number word (e.g., ‘‘three’’). Numerical ordinal relations are captured by the unique relative position of each number word in the counting sequence (e.g., ‘‘one,’’ ‘‘two,’’ and ‘‘three’’). The cardinal and ordinal properties of number in the counting sequence are related through the fact that each successive number word refers to the numerosity named by its predecessor plus one. Therefore, the verbal counting system presents a powerful tool through which to encode numerosity. Moreover, the ability to correctly employ the verbal counting system enables one to encode and compare numerosities with a high degree of accuracy. The fact that verbal counting is such a powerful, accurate tool for dealing with number and the fact that the use of such systems is culturally widespread raise the question of how it is related to nonverbal numerical knowledge. Indeed, explaining the specific nature of the relationship between the verbal counting system and the kind of nonverbal numerical abilities that infants possess is one of the biggest challenges facing students of numerical competence (Carey, 1998; Gelman, 1993). Addressing this question will require a clear specification of both the nature of nonverbal numerical competence and the ways in which the acquisition of the verbal counting system changes or augments these abilities. Important first steps toward understanding the relationship between basic numerical knowledge and verbal counting will be to document the range and limitations of nonverbal numerical abilities and to assess the changes and consistencies in these abilities as children learn the verbal counting system.

A substantial body of data currently suggests that prelinguistic human infants are sensitive to differences between the cardinal values of sets of entities (e.g., Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981; Uller et al., 1999; van Loosbroek & Smitsman, 1990; Wynn, 1996; Xu & Spelke, 2000). For example, following habituation to displays consisting of nonidentical sets of objects that share a common numerosity, infants then prefer a novel numerosity over a novel array of the same numerosity. Infants also appear to be sensitive to transformations of small numbers of objects (Koechlin et al., 1998; Simon et al., 1995; Wynn, 1992a). In these studies, infants are shown an array of objects, which is then occluded and a single object is either added or subtracted. Infants look longer at outcomes in which an incorrect number of objects is revealed than at outcomes with the correct number of objects.

Although children appear to possess some degree of appreciation of cardinality well before they learn the verbal counting system, these abilities are nonetheless quite limited early on and blossom as children learn to count. For example, with the exception of a single study, the research described above indicates that infants recognize cardinal distinctions only between sets ranging from 1 to about 3 or perhaps 4. This raises the intriguing possibility that the representations being tapped in these studies are not numerical at all, but rather reflect an inherently limited ability to keep track of individual entities (Leslie, Xu, Tremoulet, & Scholl, 1998; Scholl & Leslie, 1999; Simon, 1997; Uller et al., 1999). Currently, only Xu and Spelke's (2000) study suggests that infants' sensitivity may extend to much larger numbers. However, this ability too is limited in that it is highly approximate. Although infants in this study discriminate 8 from 16, they fail to discriminate 8 from 12. The limitations on human infants' nonverbal cardinal representations suggest that they are quite different from the representations encoded in the verbal counting sequence, which are neither restricted to small numbers nor imprecise.

Cardinal numerical abilities appear to improve rather dramatically as children undergo the lengthy process of mastering the verbal counting system. For example, Mix, Huttenlocher, and Levine (1996) demonstrated that only children with some verbal counting competence could compare the numerosity of a visually presented array with a sequentially presented auditory sequence of drumbeats. Children who had not yet learned to count were able to compare two visually presented arrays, but were at chance on the visual/auditory comparison. Similarly, before they understand the verbal counting system, children have great difficulty constructing sets consisting of a specific number of objects, even arrays as small as 2 or 3 (Schaeffer, Eggleston, & Scott, 1974; Sophian & Adams, 1987; Wynn, 1990, 1992b). Even after they have learned the verbal counting sequence, children appear to be unable to recognize how spatial transformations affect equivalence relations between two sets (Klahr & Wallace, 1976; Piaget, 1952; Saxe, 1979; Sophian, 1995). Indeed, children may learn that spatial transformations alone leave number unchanged at least partially by counting before and after such transformations (Klahr & Wallace, 1976). Thus it appears that learning the verbal counting sequence is a prerequisite for displaying explicit knowledge of some numerical concepts.

While a great deal of research has focused on the development of cardinal knowledge in both preverbal infants and in children in various stages of mastery of the verbal counting system, the development of ordinal knowledge has received much less attention. Currently, virtually nothing is known about ordinal knowledge in preverbal human infants (although see Cooper, 1984; and Strauss & Curtis 1984). Evidence from a different source nonetheless suggests that ordinal knowledge need not rely on verbal counting ability. Recent comparative research has shown that rhesus monkeys can detect ordinal relations between numerosities even when nonnumerical perceptual correlates such as cumulative surface area are randomized (Brannon & Terrace, 1998, 2000). In that research, monkeys trained to order the numerosities 1 to 4 were able to spontaneously order pairs of the novel numerosities 5 to 9. In another paradigm, Hauser, Carey, and Hauser (2000) tested free-ranging rhesus monkeys to see whether they would spontaneously choose a food collection with a greater number of successively visible items. The monkeys reliably chose the greater set for set sizes up to about 4. It is unclear why rhesus monkeys exhibit different levels of knowledge in these two different paradigms. However, the latter results are important because they demonstrate ordinal numerical knowledge without any experimental training. The findings with nonlinguistic primates suggest the possibility that humans too might represent such relations without the benefit of verbal counting knowledge.

Research on the ability of preschool- and kindergarten-aged children to make numerical ordinal comparisons, however, presents a somewhat less optimistic picture. Many studies on young children's ordinal numerical knowledge have focused on the ability to overcome misleading perceptual cues such as array length or density or on the relative order of acquisition of ordinal and cardinal concepts (e.g., Estes, 1976; McLaughlin, 1981; Michie, 1985; Siegel, 1971, 1972, 1974, 1977; Wohlwill, 1963). Children as young as 3 years of age have been shown to make relative magnitude discriminations between arrays as large as nine items when array length covaries with numerosity (Siegel, 1971, 1972, 1977). Under these circumstances, however, it is unclear whether children's judgments are in fact based on numerical differences between arrays. Indeed, in conditions in which array length or density was pitted against numerosity, even 4- to 6-year-old children have great difficulty basing their judgments on number (Piaget, 1952; McLaughlin, 1981; Siegel, 1972, 1974).

Mastery of the verbal counting system, although an extended process, typically begins to emerge around 3.5 to 4 years of age (Schaeffer et al., 1974; Wynn, 1990, 1992b). Therefore, the fact that children in or even beyond this age range have difficulty overlooking misleading perceptual correlates of number in making ordinal judgments raises the possibility that verbal counting is related to this ability. Indeed, given the paucity of data on preverbal ordinal competence, it is possible that verbal counting is strongly causally related to ordinal numerical competence. Children may come to appreciate ordinal relations only after they have learned how the words in the verbal counting sequence relate to numerosity. They may note the ordered position of the words in the count list and then come to understand that these ordered words encode specific ordered quantities in the real world. We will call this the ‘‘strong language hypothesis.’’ On this account, children should be entirely unable to make ordinal numerical comparisons until after they have achieved a relatively advanced degree of verbal counting competence. This hypothesis also predicts that the more number words children comprehend, the greater the range of ordinal comparisons they should be able to make.

A number of theorists have suggested a weaker relationship between verbal counting and numerical competence (e.g., Cooper, 1984; Hurford, 1987; Schaeffer et al., 1974). Children may possess an early-developing ability to represent small numerosities and then through experience observing additions and subtractions to sets of items in their environment or through recognizing the relationship between linguistic quantifiers and set size, learn the ordinal relationships between the small numerosities. To extend this knowledge to recognize the ordinal relationships between sets of any size, however, children need some way of quantifying larger sets. It may be then, that acquisition of verbal means of quantification allows children to extend their preverbal representations of the ordinal relationships between small sets to larger sets. We call this the ‘‘weak language hypothesis.’’ On this account, children should be able to make ordinal judgments only between set sizes ranging from one to about three before they have acquired any verbal counting knowledge at all. The ability to compare larger set sizes should be related to the number words a child comprehends.

Finally, it is possible that children's preverbal numerical representations are inherently ordered and that children can easily access this knowledge. We call this the ''language-irrelevant hypothesis.'' For example, one model for nonverbal numerical representations posits that each to-be-enumerated item results in a constant amount incremented to an accumulator (Meck & Church, 1983). The resulting representations are internal magnitudes that are inherently ordered. If children use internal magnitude representations then they should be able to make approximate ordinal numerical comparisons entirely irrespective of comprehension of the verbal counting sequence (Wynn, 1995).[1] Moreover, the extent of this ability should be entirely unrelated to degree of knowledge of the verbal counting sequence.

Currently, two sources of data cast some doubt on the strong language hypothesis that all ordinal numerical competence is related to an understanding of the verbal system of counting. In one (Bullock & Gelman, 1977), children between 2.5 and 4 years of age were shown sets of 1 and two objects and taught that one of the two numerosities was ''the winner.'' Subsequently, the arrays were surreptitiously altered such that one array contained three and the other four objects, and children were again asked to identify the winner. Thus, children were required to generalize the relational rule taught on the one vs two comparison to a novel, nonoverlapping comparison. Bullock and Gelman found that under some circumstances, even their 2.5- to 3-year-old participants chose relationally, suggesting that even very young children can make ordinal comparisons, at least between numerosities ranging from 1 to 4.

More recently, Huntley-Fenner and Cannon (2000) found that 3- to 5-year-old children were reliably able to make relative numerosity judgments and that this ability was not correlated with the ability to give a cardinal response in a verbal counting task. In their task, stimulus sets were arrays of black squares presented in parallel rows on a single piece of paper. In comparisons where the rows differed in number, row length was always pitted against numerosity. Both surface area and density, however, varied systematically with number on these comparisons. Further, the vast majority of the children in this study possessed at least some knowledge of the verbal counting system. For example, only 6 of 48 children failed to give a cardinal response on the counting task, and only 2 were unable to list the number words in order through five.

Neither the Bullock and Gelman (1977) nor the Huntley-Fenner and Cannon (2000) studies definitively rule out a relationship between ordinal numer-

[1] Even on this view, however, knowledge of the verbal counting system likely increases the precision and range of ordinal numerical judgments.

ical knowledge and verbal counting competence. In Bullock and Gelman's studies, only 3- to 4-year-old children robustly succeeded at ordinal comparisons. While verbal counting competence was not directly assessed in that study, other data suggest that mastery of the verbal counting system begins to occur at around this age (Wynn, 1990, 1992b). Perhaps more importantly, however, neither experiment controlled for either cumulative surface area or size of individual elements. Currently, little or no evidence bears on the question of the role of surface area on young children's numerical judgments. However, recent research suggests that many previous findings that infants are sensitive to cardinal number may be explained instead by sensitivity to perceptual, nonnumerical correlates of set size, such as contour length or spatial extent (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, in press). Given these findings, strong conclusions about the early ability to make purely numerical ordinal relational judgments should await more stringent controls for nonnumerical dimensions.

This article is an investigation of nonverbal numerical knowledge in young children. Our goals were threefold. First, we sought to design a task that would assess ordinal knowledge in children as young as 2 years of age, who are younger than any previously tested and the majority of whom should possess little if any knowledge of the verbal counting system. Second, we sought to determine whether children could compare sets of items based on their relative numerosity even when the surface area of the items was not available as a cue. Finally, we sought to investigate the relationship between children's verbal counting ability and their ability to make ordinal numerical comparisons.

Experiment 1 tested a new method to investigate nonverbal ordinal knowledge in 2-year-old children using an explicit choice paradigm. This age group was chosen because in previous studies few if any children under the age of 3 demonstrate any significant understanding of the verbal counting system (Fuson, 1988; Schaeffer et al., 1974; Wynn, 1990, 1992b). Children were tested on their ability to choose the larger of two numerical sets ranging in size from one to five. The comparison objects shared a constant size. Therefore, the correct response was specified both by overall numerosity and by total surface area of each set. In Experiment 2, the comparison objects varied in size such that the numerically larger set was sometimes larger and sometimes smaller in overall surface area compared to the numerically smaller set. Therefore, only numerosity consistently predicted the correct response. In addition, Experiment 2 incorporated two assays of verbal numerical knowledge. The age range was expanded to include both 2- and 3-year-old children in order to capture the relationship between verbal counting and ordinal ability in children both before and during the time at which many children are in the process of learning the verbal counting system. We tested only children's ability to choose the larger numerosity because previous research suggests that children might be biased toward choosing the larger of two quantities (Sophian & Adams, 1987; Strauss & Curtis, 1984). Since surface area was not always congruent with numerosity, a bias toward choosing the larger numerosity would nonetheless constitute evidence of sensitivity to ordinal numerical relations.

EXPERIMENT 1

Method

Participants

Participants were 46 2-year-old children (*M* = 2;5; range 2;0–2;11), 21 of whom were female. Data from an additional 21 children was discarded, 5 because of a side bias (child chose the tray on one side on at least 9 of 10 training trials), 10 because of a failure to complete the task, 4 because of equipment failure, and 2 because of experimenter error. Participants were initially recruited by letter and phone calls through commercially available lists of names of parents in the area. Some participants were recruited through brochures handed out at local parks and playgrounds or posted in local pediatricians' offices or children's activity centers. Parents received reimbursement for their travel expenses and a token gift for their child. Participants were compensated with stickers. All participants were tested in a university child development laboratory. The majority of the children were from middle-class backgrounds and most were Caucasian although a small number of Asian, African American, and Latino children participated. Seven of the 46 children were bilingual.

Stimuli

Stimuli were sets of red, square, foam board boxes with open bottoms, each of which measured 6 × 6 × 3 cm. The boxes were presented on a pair of white trays with purple rims, each measuring 29 × 36 cm. For each pair of stimuli, a small, brightly colored sticker was placed, out of view of the child, under each box on the tray with the greater number of boxes. Each child was also given a sheet of colored construction paper on which to place his or her stickers.

Design

The experiment involved a 2-trial demonstration phase, a 5- to 10-trial training phase, and a 5-trial generalization phase. On each trial during training and generalization, the child was asked to indicate which of two trays had the greater number of boxes. During training, the comparison was always between a tray with two boxes and a tray with one box. Children were randomly assigned to one of two pseudorandom left–right orders of stimulus presentation. Orders were constructed with the restriction that the demonstration trials were on different sides and that the numerically larger stimulus never appeared on the same side more than twice in a row. Children were also randomly assigned to one of four generalization orders for the five generalization pairs (1–3, 2–3, 3–4, 3–5, and 4–5). These comparisons were chosen to encompass numerical disparities of 1 and 2 and to include a range of numerosities both within and beyond the range that children might be able to subitize. Orders were constructed such that each pair was tested first in one order with the exception of the 4–5 pair, which was always presented last. This pair was presented last because we thought it would be difficult and might overwhelm the children. Both left–right and generalization orders were counterbalanced across subjects, and boys and girls were roughly equally distributed across all orders.

Procedure

Children were seated beside a parent and across a small table from the experimenter (E). All sessions were videotaped, and a second observer verified all responses. The E never used number words or the words ‘‘more’’ or ‘‘less.’’ Parents were instructed not to use number words or help the child make a choice.

Demonstration phase. The E simultaneously placed both trays on the table in front of the child. The E lifted the box on the 1-tray to reveal that nothing was under it and exclaimed, ‘‘Look, this is the loser. There’s nothing there.’’ She then placed the box back on the tray and lifted the boxes on the 2-tray to reveal the stickers, exclaiming, ‘‘Look, this is the winner. There’s stickers under the boxes, and the stickers are for you!’’ She then gave the child the stickers and asked the parent to help the child place the stickers on the construction paper. The second demonstration trial was presented in the same manner, except that after the E revealed the stickers, she covered them again, switched the left–right position of the trays, and said, ‘‘And look, even if I put this tray over here it’s still the winner! See?’’ She then uncovered the stickers again and gave them to the child. This was done in an effort to clearly demonstrate that the correct tray was independent of a particular location.

Training phase. After the demonstration trials, the child was given up to 10 training trials with a 1- and 2-tray. On these trials, the E placed the trays simultaneously on the table and simply asked the child to indicate the winner, saying, ‘‘Can you point to the winner?’’ or ‘‘Where are the stickers?’’ If the child failed to point, the E asked the child to guess. If the child correctly chose the 2-tray he or she was told, ‘‘Yes, that’s the winner,’’ and was allowed to take the stickers and put them on construction paper. If the child incorrectly pointed to the 1-tray the E lifted the cover to reveal that there was no sticker, and he or she was told, ‘‘Nope, that’s not the winner. Let’s try again.’’ The E quickly removed the trays and presented the same trial again. If the child correctly pointed to the winner on 5 consecutive trials the E skipped directly to the test phase; otherwise, 10 trials were completed.

Generalization phase. Following training, all children were presented with the five generalization trials. Generalization trials were presented in the same manner as training trials, with the exception that when the child selected the wrong tray, he or she was allowed to directly uncover the stickers on the other tray.

Results and Discussion

Preliminary analyses revealed no effect of left–right order or gender on training or test (all t’s < 1, *ns*). Therefore, all subsequent analyses are collapsed across these variables. The generalization performance of the bilingual subjects was similar to that of the English-speaking subjects (bilingual 69% correct, English 62% correct). Therefore, the two groups are reported together.

Children quickly learned the 1 vs 2 training rule. Thirty-five of the 46 children correctly selected the 2-tray on five consecutive trials. On average, children made the correct response on 75% of training trials ($SE = 3\%$), significantly more than would be expected by chance [$t(45) = 10.64$, $p < .001$].

During the generalization phase, children correctly chose the tray with the larger number of boxes significantly more than would be expected by chance [$M = 64\%$, $SE = 3\%$; $t(45) = 4.71$, $p < .001$]. Performance on each of the five numerical comparisons is listed in Table 1. Performance did not differ

TABLE 1
Percentage Correct on Each Numerical Comparison for Experiment 1

Comparison	% Correct	*p* Value
2 vs 3	73	0.02
3 vs 4	61	0.00
4 vs 5	60	0.04
3 vs 5	61	0.04
1 vs 3	64	0.05

significantly across the five pairs [$\chi^2(4, N = 99) = 2.6, p > .1$]. Using the binomial probability table ($P = .5$), performance was significantly above chance for each of the five numerical comparisons. Furthermore, the significant performance on novel numerosity comparisons was not solely due to the older children in our sample. The correlation between age and performance was not significant ($r = -.16, p > .2$). This pattern of results shows that children as young as 2 years of age can learn a relational rule such as, ‘‘choose the larger quantity’’ and can apply it to comparisons as large as 4 vs 5.

How did children determine which of the two trays had the greater number of boxes? It is conceivable that children actually counted the boxes on each tray and chose the tray with the greater number. Indeed, several parents of participants reported that their child could recite a count sequence. However, three pieces of evidence argue against this interpretation. First, no evidence in the existing literature suggests that children this age can count in a meaningful manner. Although some children younger than 3.5 years of age possess a memorized count sequence, they appear to have no idea how this sequence relates to numerosity (Fuson, 1988; Schaeffer et al., 1974; Wynn, 1990, 1992b). Second, counting ability develops with age, but age and performance were not related on the ordinal comparison task. In fact, the youngest half of the sample (mean age = 2;2) chose the larger value on 65% of the novel numerical comparisons, while the oldest half of the sample (mean age = 2;8) chose the larger value on 64% of the comparisons. Thus it was not the case that the older 2-year-old children who might have begun to master the verbal counting system were primarily responsible for the overall success on the task. Third, none of the 46 subjects spontaneously used number words during the experimental session, and in no case was a child observed exhibiting any behavior that might indicate counting such as systematic pointing to or verbally counting each object before making a choice.

If children did not use counting to solve the ordinal comparison task, how did they succeed? The results are consistent with at least two possibilities. Children may have formed nonverbal numerical representations and then determined the ordinal relations between them. It is also conceivable, however, that children did not base their judgments on numerical distinctions between the arrays. Rather, they may have responded on the basis of the overall surface area or the ''amount of redness'' on each tray. While this is in some sense a magnitude comparison, it is not numerical. Experiment 2 distinguishes these possibilities.

It is also worth noting that although the children performed significantly above chance on the generalization trials, their performance clearly did not approach ceiling levels. One plausible explanation for why the children did not do better on the generalization trials is that in training they may have learned an absolute rather than a relative rule. Because children were given limited training on only a single numerical comparison (1 vs 2), they could have learned to ''choose 2'' or ''avoid 1'' rather than to choose the greater quantity. However, the data provided no evidence that the children relied on an absolute rule. As is shown in Table 1, the children did not score particularly poorly on the 2 vs 3 pair or particularly well on the 1 vs 3 pair as would be expected by an absolute numerical rule.

EXPERIMENT 2

The results of Experiment 1 demonstrate that children as young as 2 years of age are sensitive to ordinal relations as evidenced by their ability to choose the larger of two quantities. However, it is unclear from Experiment 1 whether children were using a numerical ordinal rule or a nonnumerical ordinal rule that was contingent on the cumulative surface area of the boxes (Clearfield & Mix, 1999; Feigenson et al., in press). To investigate this issue, we varied the size of the boxes such that neither cumulative surface area nor the size of individual boxes consistently predicted the correct response. On some trials, boxes in the numerically larger set were smaller than the boxes in the numerically smaller set and the relative cumulative surface area was incongruent with relative numerosity. On the remaining trials, boxes in the numerically larger set were larger than the boxes in the numerically smaller set. Both trial types are necessary to prevent the children from solving the problems through a nonnumerical strategy of choosing the tray for which the boxes had either the larger or smaller cumulative surface area or size. In combination, these two trial types insured that only the relative numerosity of the sets consistently predicted the correct response.

An additional goal of Experiment 2 was to examine the relationship between ordinal comparison abilities and the development of the verbal counting system. To this end we included two verbal counting tasks to assess children's understanding of the verbal counting system. The How Many? task was modeled after Wynn (1990, 1992b) and was designed to assess both children's counting ability and their ability to provide a coordinated count and cardinal response. The What's on This Card? task was loosely modeled after Gelman (1993). This task is both simple for young children and also more effective than the How Many? task at eliciting spontaneous cardinal responses (Gelman, 1993). It was therefore aimed at assessing even minimal understanding of the cardinal principle. The two verbal counting tasks always followed the ordinal comparison task. We also expanded the age range to include children up to the age of 4 years.

Method

Participants

Thirty-four 2-year-old (*M* = 2;6; range = 2;0–2;11) and 27 3-year-old children participated (*M* = 3;6; range = 3;1–4;0). Fourteen 2-year-old and 10 3-year-old children were female. Data from an additional 10 2-year-old children was discarded, 2 because of a side bias, 5 because of a failure to complete the task, 1 because of equipment failure, and 2 because of experimenter error. Data from one additional 3-year-old child was discarded because of experimenter error. Participants were recruited as in Experiment 1 or through letters sent to parents through day care centers. Participants were tested either at a university child development laboratory or at local day care centers or nursery schools. Participants' socioeconomic and racial background was similar to that in Experiment 1. Seven of the 34 2-year-old children and none of the 27 3-year-old children were bilingual.

Stimuli

Area-controlled ordinal comparison task. Two sets of training and generalization boxes were constructed such that on some trials, each box in the set with the larger numerosity was also larger than each box in the set with the smaller numerosity and the overall surface area of the larger set was approximately ⅓ larger than the overall surface area of the smaller set (''area-congruent'' trials). On other trials, each box in the set with the larger numerosity was smaller than each box in the set with the smaller numerosity and overall surface area of the numerically larger set was slightly smaller than or roughly equal to the overall surface area of the smaller set (''area-incongruent'' trials). Surface area was calculated to account for both the top and two sides of each box, since at most two sides of each box would be visible from the child's perspective on any given trial.[2] Within each comparison, all boxes in a set were the same size. The same five numerical comparisons were used as in Experiment 1, and a 4–6 comparison was added to include three comparisons that differed by one unit and three that differed by two units.

Training boxes were all red and involved only two sizes. Training boxes were presented on the same trays as in Experiment 1. The color of the boxes varied across generalization trials (blue, green, orange, yellow, or light or dark pink) as did the trays (purple, green, blue, pink, or red). Within each trial, all boxes were the same color, and both trays were the same color, with the restriction that the boxes differed in color from the trays. This was done in an attempt to draw and maintain children's attention to the stimuli during the generalization phase.

How Many? task. Stimuli consisted of two sets of 2, 3, 5, and 6 small toy animals (e.g., frogs, puppies, and whales). All the animals within each trial were identical and were presented to the child lined up in a row on a tray.

[2] Volume was correlated with surface area such that volume was similarly congruent or incongruent with number on the same one-third and two-thirds of the trials respectively.

What's on This Card? task. Stimuli consisted of four sets of eight cards with different numbers of stickers placed on them. One set was green with apple stickers on it, one was pink with bear stickers, one was blue with cow stickers, and one was yellow with turkey stickers. Each set contained the numerosities 2–8. The 1-card was always presented first, followed by sets 2–3, 4–5, and 6–8, with each subset in a different pseudorandom order across the four sets of cards. This was done because children occasionally appeared to become overwhelmed by the larger numbers, simply responding, for example, ''apples'' or ''I don't know.'' Order of presentation of the four sets of cards was fixed across children.

Design

All children participated first in the ordinal comparison task and then on the two verbal counting tasks. Order of the What's on This Card? task and the How Many? task was counterbalanced across children.

For the ordinal comparison task, all training trials consisted of a 1 versus 2 comparison as in Experiment 1. A single training order was constructed such that 6 of the 10 trials were area-incongruent. The correct response appeared on the same side no more than two times in a row, and the correct response was area-incongruent no more than two times in a row. For generalization, children were randomly assigned to one of two pseudorandom left–right orders and to one of six generalization orders. The generalization orders differed both in the order in which the numerical comparisons (1–3, 2–3, 3–4, 3–5, 4–5, and 4–6) were administered and in surface area congruency of each comparison. Orders were constructed such that each comparison appeared first in one generalization order. Because our primary interest was in children's performance when area did not predict the correct response, each comparison was area-incongruent on four of the six generalization trials. No more than two area-incongruent trials appeared successively. Left–right and generalization orders were counterbalanced across children. Finally, because the covers on the generalization trials differed from those in the training trials, immediately following the first generalization trial, one additional area-congruent 1 vs 2 trial was inserted as a ''reminder.'' This was done in an attempt to demonstrate to children that even though the covers might vary in color, the ''game'' of choosing the greater number remained constant. As on the other generalization trials, when children selected the wrong tray, they were immediately allowed to uncover the stickers on the correct tray.

Procedure

Testing for each child was completed in one or two sessions that typically lasted from 20 to 30 min. Because of its length, the What's on This Card? task was generally split such that two sets of cards were administered on the first testing session and two on the second. Only children who spoke English as their dominant language were tested on the two verbal counting tasks, as these tasks could be consistently administered only in English. Therefore, we did not collect data on the verbal counting tasks for 7 2-year-old children. An attempt was made to test the remaining 27 children at each age on both verbal tasks; however, we were unable to obtain complete sets of data for some children, either because a second session could not be conducted or because the child became bored or noncompliant before the completion of a session. Of the 27 English-speaking 2-year-old children who participated in the ordinal comparison task, 24 completed the How Many? task and 27 completed at least two sets of the What's on This Card? task. Of the 27 3-year-old children who participated in the ordinal comparison task, 24 completed the How Many? task and 25 completed at least two sets of the What's on This Card? task.

Area-controlled ordinal comparison task. The procedure was similar to that used in Experiment 1 with the following differences. First, three rather than two demonstration trials were presented, two of which (first and third) were area-incongruent. Second, throughout the task when the E told the child that the 2-tray was the winner she labeled the winning tray as having ‘‘more’’ (e.g., ‘‘This tray is the winner. It has more.’’). Pilot testing suggested that use of the term seemed to decrease children’s initial confusion, and in this version of the task, the word ‘‘more’’ is ambiguous, since it could refer either to greater surface area or to the greater number.

How Many? task. Children were introduced to a Big Bird puppet and were told, ‘‘Big bird has a problem. He forgot how to count! Could you help Big Bird learn how to count?’’ The child was then shown a tray of two, three, five, or six identical toys on a plastic tray. The child was asked to count the toys for Big Bird. Each set size was tested twice in a pseudo-random order, and on one of the trials for each set size the child was probed after the count to give a cardinal response. The child was asked, ‘‘OK, so how many toys does Big Bird have here?’’ No feedback was given about whether the child’s cardinal or count response was correct.

What’s on This Card? task. Children were shown the card with one apple and were asked, ‘‘What’s on this card?’’ The expected response was ‘‘an apple,’’ ‘‘a apple,’’ or ‘‘apple.’’ Regardless of the child’s response the E responded, ‘‘That’s right, that’s *one* apple.’’ The child was then tested on the cards with 2–8 apples, followed by the other sets of cards. If a child gave nonnumerical responses (e.g., ‘‘apples’’ or ‘‘I don’t know’’) to three consecutive cards, that set was terminated, and the E continued with the next set of cards. Four of the eight cards in each set were designated as probe cards such that each number was probed twice across the four sets. On probe trials, if the child had given a cardinal response (e.g., two cows) the E asked, ‘‘Can you show me?’’ in an effort to elicit a count response. If the child had spontaneously counted, the experimenter asked, ‘‘So, what’s on this card?’’ which was meant to elicit a cardinal response.

Dependent Measures

How Many? task. The dependent measure for this task was the highest number to which the child could both correctly count and provide a correct cardinal label, either spontaneously or in response to a probe. This measure was chosen because previous research (e.g., Fuson, 1988; Wynn, 1990) suggests that while children often count successfully in response to the question ‘‘How many?’’, this may reflect a learned routine rather than an understanding of how counting relates to numerosity. Indeed, only 11 of the 48 children who completed this task failed to count correctly up to 6, and only 4 failed to count at all. Requiring both a cardinal response and a correct count is therefore a somewhat more stringent measure of comprehension of the verbal counting system. Counts were considered correct if the child counted precisely or if the child made a single error by either double counting or skipping a single object. Cardinal labels were considered correct if they matched the correct count and/or if they matched the number of objects on the tray. Because we only administered two trials for each of the four possible numerical values (2, 3, 5, 6), a single correct occurrence was considered sufficient for the child to receive credit for that numerosity, provided that the child did not also respond with that number more than 50% of the time when presented with sets of all greater numerosities. Finally, to get credit for having counted to or having given a correct cardinal response for a particular numerosity, the child had to have either received credit for a correct response or given no response for all lesser numerosities.

What’s on This Card? task. The dependent measure for this task was the highest number for which the child could provide a correct cardinal label. This measure was chosen for this task because its primary goal was to elicit cardinal, not counting, responses. Cardinal labels were considered correct when they matched the numerosity of the card or if the child’s cardinal label matched the number to which he or she counted and that count contained a single mistake (double counting or skipping an item). To receive credit for a given number, the child had to respond correctly for greater than 50% of the trials for a given number. The child must also have responded with that number to cards with greater numerosities infrequently (50% or less of the correct percentage usage). Finally, to be given credit for any number, the child must have either gotten credit for correctly labeling all lower numerosities or given no response at all to those numerosities.

Results and Discussion

Area-Controlled Ordinal Numerical Comparison Task

Preliminary analyses revealed no effect of left–right order or gender on training or test (all *t*'s < 1, *ns*). Therefore, all subsequent analyses are collapsed across these variables. Generalization performance was similar for the English-speaking and bilingual 2-year-old children (bilingual 64% and English 59%).

Training performance was significantly better than that expected by chance [$M = 78\%$, $SE = 3.3\%$; $t(60) = 8.70$, $p < .001$]. Forty-four of the 61 children correctly answered five consecutive training trials. Children correctly answered an average of 74 and 81% of the trials where number and surface area were congruent and incongruent respectively. This difference was significant [$t(60) = -2.11$, $p < .05$]. It is unclear why children performed somewhat better on the area-incongruent than the area-congruent trials during training, but this trend was not evident during test. Finally, 86% of the children correctly chose the 2-tray over the 1-tray on the area-congruent 1 vs 2 reminder trial that was interspersed in the generalization trials.

Generalization performance was also significantly better than that expected by chance [$M = 65\%$, $SE = 2.7\%$, $t(60) = 5.60$, $p < .001$]. Table 2 shows accuracy for the six different numerical comparisons. Using the binomial probability table ($p = .5$), performance was significantly above chance for all six numerical comparisons. Chi-square tests revealed that the differences in performance between the six pairs were not significant [$\chi^2(5, N = 240) = .5$, $p > .1$]. Furthermore, performance did not differ for trials where number and surface area were congruent (66%) vs incongruent (65%) ($t < 1$, *ns*). Finally, age was not correlated with performance on the ordinal comparison task ($r = .13$, $p > .3$).

TABLE 2
Percentage Correct on Each Numerical Comparison for Experiment 2

Comparison	% Correct	*p* Value
2 vs 3	62	0.02
3 vs 4	69	0.00
4 vs 5	64	0.01
3 vs 5	69	0.00
1 vs 3	67	0.00
4 vs 6	64	0.01

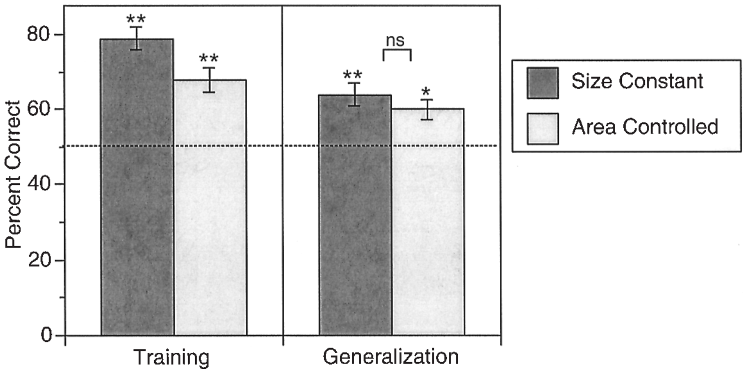

FIG. 1. Performance on training and test in the ordinal comparison task of children in Experiment 1 and 2-year-old children in Experiment 2 for both area congruent and area incongruent trials. Asterisks reflect above-chance performance as follows: $*p < .05$; $**p < .01$.

To further assess the role of surface area in young children's performance we compared the performance of children in Experiment 1 with the subset of children from Experiment 2 who fell in the same age range (2;0–2;11). Figure 1 shows that generalization performance was equivalent in these two samples [$t(78) = 0.87$, $p = .39$]. This result is important for two reasons. First, it demonstrates that by the age of 2, children can make purely numerical discriminations that are independent of surface area. Second, it shows that children as young as 2 years of age appreciate the ordinal numerical relationships between numerosities as large as 5 or 6. As in Experiment 1, children did not appear to accomplish this task through a process of verbally counting and comparing the sets. Of the 61 children who participated in the study, 11 children uttered number words a total of only 13 times. Of these, 11 comments referred to the stickers the child received (e.g., ''There's two Donald Ducks'' and ''Another sun. Two suns!''). One comment referred to the trays themselves (''There's two winners''). Only a single comment referred to the numerosity of the boxes (''Three has more. That's how old I am''), and given that this child chose the correct response on only 50% of the generalization trials, he did not appear to use counting as a consistent or successful strategy. We address the possible nonverbal means children may have employed in their ordinal comparisons under General Discussion. Despite the fact that children did not appear to use counting in the ordinal task, it is nonetheless possible that comprehension of the verbal counting system is related to success on the ordinal task. We turn next to this issue.

Relation between Ordinal Performance and Verbal Counting Tasks

The order in which the two verbal counting measures were administered did not affect performance on either task (all t's < 1, *ns*). Therefore, all

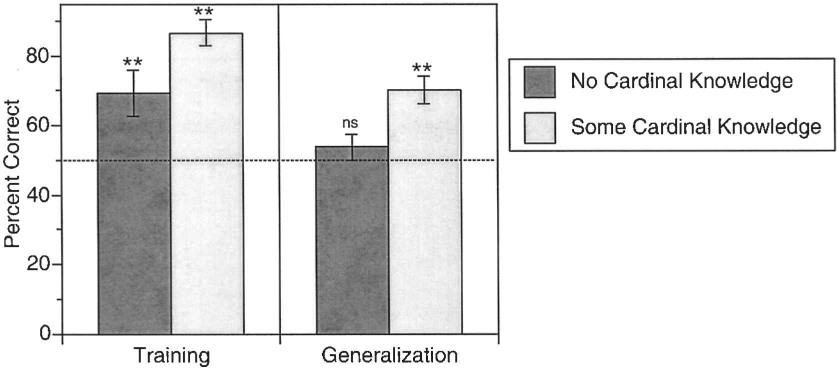

FIG. 2. Performance during training and generalization on the ordinal comparison task for children who provided no correct cardinals on the What's on This Card? task vs children who provided at least one correct response. Asterisks reflect above chance performance as follows: $*p < .05$; $**p < .01$.

subsequent analyses are collapsed across this variable. Both verbal counting measures were significantly correlated with performance on the ordinal comparison task.[3] The relation between performance on the ordinal comparison task and the What's on This Card? task was $r_s = .30$, $p < .03$. The relation between performance on the ordinal comparison task and the How Many? task was $r_s = .33$, $p = .02$.

A closer look at the data revealed that the relationship between the verbal counting tasks and performance on the ordinal comparison task was almost entirely due to the children who exhibited the lowest level of verbal counting knowledge. Eighteen of the 52 children who completed the What's on This Card? task never provided a correct cardinal response.[4] These 18 children ranged in age from 2;0 to 3;4 (mean = 2;7); the remaining 34 children ranged in age from 2;0 to 4;0 (mean = 3;3). This age difference was significant [$t(50) = -4.95$, $p < .001$].

Six of these 18 children never provided any cardinal responses at all. Nine children responded with ''two'' regardless of the numerosity presented (one child responded with ''three'' in this manner), and two children provided random cardinal responses using a small, idiosyncratic set of numbers. Few of these children ever counted correctly, and none coordinated counting with their cardinal responses either spontaneously or in response to a probe. The performance of this group of children vs the remaining group of 34 on the ordinal comparison task differed significantly [$t(50) = -2.77$, $p < .01$]. Figure 2 shows that on the ordinal comparison task, the 18 children who

[3] A complete report of the data from the verbal counting tasks alone will be presented in a separate article.

[4] Two children completed the What's on This Card? task but failed to complete the How Many? task.

TABLE 3
Percentage Correct on Each Numerical Comparison for Experiment 2 Segregated by Performance on the What's on This Card? Task

Comparison	No number word knowledge	Some number word knowledge
2 vs 3	59	61
3 vs 4	53	73
4 vs 5	41	70
3 vs 5	59	73
1 vs 3	53	73
4 vs 6	65	65

never provided a correct cardinal response answered an average of only 54% (SE = 3.7%) of the generalization trials correctly, which is not significantly different from chance [$t(17) = 1.02$, $p > .1$]. In contrast, the 34 children who gave at least one correct cardinal response correctly answered an average of 70% (SE = 3.8%) of the ordinal comparison generalization trials, which is significantly greater than chance [$t(33) = 5.25$, $p < .001$]. Table 3 shows that neither group of children performed better with small numbers compared to large numbers as might be expected if ordinal numerical knowledge was learned first by observing transformations between small numbers.

Given that the age difference between the 18 children who produced no correct cardinals and the 34 remaining children was significant, we also conducted an additional analysis to ensure that the difference in performance on the ordinal task was related to verbal numerical competence and not simply to age. This analysis compared performance on the ordinal task for the 18 children who produced no correct cardinals with that of the subset of children whose mean age was equivalent to this group ($N = 13$, age range = 2;2 to 3;1, mean age = 2;8). This subset of children performed well on the ordinal task, averaging 68% correct on generalization (SE = 5.14%). Crucially, these children performed significantly better on the ordinal task than the 18 children who never gave a correct cardinal response [$t(29) = -2.29$, $p < .05$], providing further evidence that performance on the ordinal task is related to verbal numerical competence rather than to age alone.

When the 18 children with no cardinal knowledge were removed from the sample, performance on the ordinal comparison task was no longer related to performance on the What's on This Card? task ($r_s = .05$, $p = .92$). Thus the original correlation between the What's on This Card? task and the ordinal comparison task can be attributed to poor ordinal comparison performance by the 18 children that exhibited a complete lack of verbal counting knowledge.

Results from the How Many? task provide converging evidence that a complete lack of verbal counting knowledge is correlated with poor performance on the ordinal comparison task. Eighteen children never responded to any number with both a correct cardinal and a correct count response on the How Many? task. Of these 18 children, 6 never gave any cardinal responses at all, 6 responded to all numerosities with a single cardinal label (either 1 or 2), and 6 responded with no consistent pattern. All but four of these children occasionally counted correctly, but none were ever able to coordinate a count and cardinal response, even in response to a probe. On the ordinal comparison task, these 18 children only correctly answered an average of 54% ($SE = 4.4\%$) of the generalization trials. In contrast, the 30 children who gave both a cardinal and count response on at least one trial correctly answered an average of 70% ($SE = 3.9\%$) of the ordinal comparison generalization trials. This difference was significant [$t(46) = -2.65, p < .02$]. Similarly, when those 18 children were removed from the sample, the relationship between the How Many? task and the ordinal comparison task vanished altogether ($r_s = .07, p = .73$). Thus the significant correlation between the How Many? task and the ordinal comparison task can be attributed to poor performance by children who exhibited a complete lack of verbal counting knowledge.

Although the group of 18 children who scored zero on the What's on This Card? task and the 18 children who performed poorly on the How Many? task were not identical, the groups overlapped substantially (13 children scored zero on both tasks), and in general, performance on the two tasks was highly correlated ($r_s = .83, p < .001$).[5] Five children scored zero on the How Many? measure and scored 2 or 3 on the Card measure. These children appeared to have perhaps learned the meaning of the word ‘‘two’’ or ‘‘three’’ without having any idea how these words relate to the verbal counting system, since none ever counted correctly at any point on the Card task. Three children scored zero on the Card task but 2 on the How Many? task. These children did so by providing a correct count and cardinal for the numerosity 2 one time only. None of these children ever coordinated their count and cardinal responses for any other numerosity, despite the fact that they occasionally counted the objects. In general, children in both groups of 18 demonstrate either no grasp whatsoever of the relation between the verbal counting sequence and numerosities in the real world, or this knowledge is at best highly sporadic and piecemeal.

[5] Spearman's nonparametric correlations are used to analyze the relations between the verbal and ordinal tasks because performance on the verbal tasks strongly violates the assumption of normal distributions. Indeed, the modal response for both verbal measures was zero—that is, no correct response at all. Results using Pearson's product–moment correlations are essentially identical results throughout.

GENERAL DISCUSSION

This section is divided into three parts. First, we discuss our main finding that children as young as 2 years of age represent number on an ordinal scale. Second, we discuss the relationship between verbal number knowledge and the ability to make ordinal comparisons. Third, we explore the implications of our results for the format of children's early nonverbal numerical representations.

Ordinal Numerical Knowledge Independent of Surface Area

The results of Experiments 1 and 2 indicate that children as young as 2 years of age represent the ordinal relations between numerosities. Furthermore, in Experiment 2, children performed equally well when surface area was incongruent and when it was congruent with number. These results contrast with previous findings suggesting that children under 3.5 or 4 years of age (Mitchie, 1985; Siegel, 1972, 1974, 1977) and sometimes as old as 5 or 6 years of age (McLaughlin, 1981) have difficulty making purely numerical ordinal judgments, particularly when nonnumerical cues are randomized, as they were in the current research. Several methodological differences between these studies and the current research may at least partially account for children's early success in our task. First, children may have been more engaged in our task because we used brightly colored, three-dimensional, manipulable boxes instead of the rows of black shapes drawn on index cards that have been used in most previous research. In the same vein, the rewards in the current task were integrally related to the task itself—a sticker was under each of the boxes on the correct tray. Children may learn more rapidly when rewards are spatially contiguous with the discriminitive stimuli (Ramey & Goulet, 1971). A final methodological distinction between these studies concerns the dependent measure used to evaluate performance. Previous research frequently has employed a criterion of 9 of 10 consecutive correct responses to establish success on ordinal tasks (e.g., McLaughlin, 1981; Siegel, 1974). Such a criterion may be overly stringent for very young children who may be unable to sustain focused attention for such an extended period.

Although our method revealed knowledge of ordinal numerical relations that was statistically significant even in the subset of 2-year-old children, performance was by no means at ceiling. Two-year-old children's performance was only 60% on novel numerical pairs. This raises the question of why performance was not better. One possibility is that the task was difficult and not sensitive enough to detect the full range of young children's ordinal numerical knowledge. In comparison with prior research using explicit choice paradigms, however, children in the current research performed well, suggesting that the task was in fact quite sensitive. Even the youngest participants appeared to be very interested and engaged in the task. On the other hand, our method did require that children make an explicit choice between the alternatives. Children may have knowledge of ordinal numerical relations but not have explicit access to this knowledge. It is conceivable that use of an implicit measure such as the kind of looking time tasks typically used with infants would reveal more impressive early competence. A second, related issue is that children were free to try out any number of strategies besides selecting the larger numerosity. For example, children could have attempted some version of a ''win-stay, lose-switch'' strategy based on either box size or tray position as well as number. A final possibility is that young children's ordinal numerical abilities may indeed be more limited than those of adults. For example, it may be that, without language, number is represented approximately and that precision increases with age. If so, then accuracy in ordinal comparisons should be limited by the lack of precision in the numerical representations.

Nevertheless, the success we report here is significant for two reasons. First, the newly developed ordinal judgment method appears to be quite sensitive and appropriate for use with children at least as young as 2 years of age. Second, to our knowledge, this is the first demonstration that children younger than the age of 3 can reliably make ordinal numerical judgments even when nonnumerical perceptual correlates of number such as length or surface area are unavailable. The success of 2-year-old children in our task clearly demonstrates that before the age at which children have fully mapped the verbal count list onto their preverbal numerical representations, number is represented on an ordinal scale.

Relationship between Ordinal Numerical Knowledge and Verbal Numerical Knowledge

Our findings, like those of Huntley-Fenner and Cannon (2000), suggest that sensitivity to ordinal numerical relations does not improve with increasing mastery of the verbal counting system for children who demonstrate at least some verbal numerical competence. However, unlike Huntley-Fenner and Cannon, we did indeed find a relationship between ordinal competence and verbal counting skill as measured by the ability to provide the cardinal label for at least one numerosity both correctly and spontaneously in the What's on This Card? task or to provide both a correct count and cardinal response for at least one numerosity in the How Many? task. Children unable to meet that minimal criterion on the verbal number knowledge tasks were consistently at chance both individually and as a group on the ordinal task. When these children were removed from the analyses, however, the relationship between ordinal competence and verbal counting competence disappeared entirely. In other words, once children had gained at least enough verbal numerical knowledge to correctly verbally identify one numerical quantity, the accrual of further verbal knowledge did not facilitate children's ordinal judgments in the slightest.

A simple explanation of this relationship might be that the children who scored particularly poorly on the verbal tasks were also poorly motivated on the ordinal comparison task, or perhaps these children were simply not as globally intelligent or attentive as their more successful peers. Without having conducted any nonnumerical assessment of such global factors, we cannot entirely rule out this possibility. Nonetheless, at least one source of data casts some doubt on either of these alternatives. These children, like the group as a whole, performed well above chance on the ordinal training phase of the study [$M = 69\%$ correct, $t(17) = 2.98$, $p < .01$]. In addition, 76% of these children correctly chose the 2-tray on the 1 vs 2 reminder trial interspersed in the generalization trials.

A more interesting possibility, then, is that nonverbal ordinal and verbal numerical knowledge are interrelated. In the Introduction, we set forth three ways in which verbal counting knowledge might be related to ordinal numerical knowledge. The strong-language hypothesis proposes that children arrive at ordinal numerical knowledge through learning the ordinal relationships between the count words. The weak-language hypothesis proposes that language allows children to extend their knowledge of ordinal relations beyond the small numerosities (i.e., 1 through 3) that can be quantified without counting. And finally, the language-irrelevant hypothesis suggests that the ability to make ordinal numerical judgments precedes verbal counting knowledge. Our findings clearly fail to support either the strong language hypothesis or the language-irrelevant hypothesis. We therefore discuss these first and then turn to a discussion of the weak language hypothesis.

Our data, like those of Huntley-Fenner and Cannon (2000), argue clearly against the ‘‘strong-language’’ hypothesis. Children do not need to know the precise mapping between a number word and the numerosity to which it refers before they are able to make ordinal comparisons with that numerosity. We did not find better performance on pairs of small numerosities compared to large numerosities in the ordinal comparison task, despite the fact that many of the children only knew the words for numerosities up to 2 or 3. Further, once we eliminated the children with no verbal numerical competence whatsoever, neither we nor Huntley-Fenner and Cannon found any evidence of a relationship between verbal and ordinal numerical knowledge.

On the other hand, our data also do not support the proposal that language is entirely irrelevant to ordinal numerical competence. Across two different tasks, ordinal numerical ability was correlated with comprehension of the way in which the verbal counting system relates to actual numerosities in the real world. As with the ordinal task, it is possible that this relation stems from the fact that these tasks were difficult, and children who performed worse on the ordinal task simply found them more difficult than children who as a group performed better on the ordinal task. Further research will clearly be needed to assess this possibility. However, as with the ordinal task, both the What's on This Card? and the How Many? measures were designed to be as simple and ‘‘child-friendly’’ as possible while still providing some assessment of children’s spontaneous (or minimally experimenter-supported, in the How Many? task) understanding of the way in which the verbal number system encodes numerosity. Children participated in both tasks quite readily and rarely hesitated in giving a response.[6]

Our findings are not consistent either with language playing a strong role or no role at all in children’s ordinal competence. However, they also do not clearly support the weak language hypothesis, at least as it has been offered in the literature. On this account, children initially represent small numerosities, and they learn the ordinal relations among these numerosities through creating and observing transformations between sets. Language permits children to extend their ordinal competence to larger set sizes by providing a means through which children can quantify such sets (e.g., Cooper, 1984; Hurford, 1987; Schaeffer et al., 1974). This suggests that even quite young children should understand the ordinal relations between small numerosities and also that the extent of children’s ordinal knowledge should be related to the extent of their verbal numerical knowledge. However, for children who knew at least one number word, we saw no relation whatsoever between verbal and ordinal knowledge. More strikingly, neither the group as a whole nor the subset who possessed no verbal numerical competence demonstrated even a hint of better performance for comparisons between small sets than large sets (see Table 3).

Our data are compatible, however, with a somewhat different relation between language and ordinal knowledge. It may be that for young children, number is not automatically a salient dimension of the environment. Unlike the referents of many other words young children are in the process of acquiring, instances of distinct numerosities may differ on many perceptually salient dimensions. What, after all, is common between three socks, three zebras, and three trips to the store other than the abstract concept of ‘‘threeness’’? Indeed, some evidence suggests that when presented with discrete physical objects, infants may prefer to encode nonnumerical stimulus dimensions such as contour length or spatial extent (Clearfield & Mix, 1999, Feigenson et al., in press). It is possible that beginning to learn about how number words map onto numerosity serves to highlight number as a relevant feature of the environment for children. As young children begin to acquire knowledge of the cardinal principle and make the first steps toward being able to use number words to count, ordinal relationships might become more salient to them.

[6] Some of the children who participated in the current research also participated in a third verbal number task in which they were required to give a puppet a specified number of objects. In this task, children often verbally expressed confusion or difficulty with the task and frequently hesitated for long periods before responding. In contrast, children virtually never hesitated or expressed reluctance to participate in the How Many? task and rarely did so in the What’s on This Card? task, at least for numerosities smaller than 4.

Such an account would be consistent with Mix and colleagues' (Mix, 1999; Mix, Huttenlocher, & Levine, 1996) findings that young children's ability to identify numerical equivalence relations is related to mastery of the verbal counting system. In Mix et al. (1996), 3- and 4-year-old children participated in two types of matching tasks. In the visual-visual task, children had to select the numerical equivalent of a target array ranging in number from two to four from two length- or density-controlled alternatives. In the auditory-visual task, children had to match a sequence of claps with one of two arrays of dots. Even when the arrays were presented simultaneously, performance on both tasks was related to degree of mastery of the verbal counting system. Children with less mastery of the verbal counting system were at chance on the nonverbal auditory-visual matching task. Similarly, Mix (1999) found that children with very limited verbal counting knowledge were able to make numerical equivalence judgments for sets that were superficially similar (disks-to-dots) but were unable to do so for sets with low surface similarity (shells-to-dots). Together, Mix and colleagues' findings suggest that some minimal knowledge of the verbal counting system is necessary for an abstract notion of numerical equivalence that can support cross-modal and low surface similarity numerical matching. We find the parallels between the findings in the Mix studies and our study striking, since both indicate a role for the comprehension of the verbal counting system in children's nonverbal numerical competence.

Of course, it may be that it is not verbal counting mastery that produces knowledge of ordinal relations, but rather the other way around: ordinal numerical knowledge may be a prerequisite for beginning the mapping of numerical representations onto the verbal count list. We think this possibility is unlikely, given that our research and that of others (e.g., Wynn, 1990, 1992b) suggests that children learn their first number words as isolated units that refer to distinct numerosities rather than as ordered relations. Nonetheless, we cannot rule out the possibility that children must appreciate ordinal relations between set sizes before learning the verbal label for even a single discrete numerosity.

Finally, it is possible that verbal counting ability and ordinal knowledge are not causally related but instead are both influenced by the development of a third factor, such as the ability to think relationally. For the same reasons as those just discussed, we consider this last possibility unlikely as well, at least as a complete explanation. Further, it is exceedingly difficult to identify global factors that operate exclusively independently of domain knowledge. Clearly, the finding of a relationship between the earliest stages of verbal numerical competence and ordinal numerical knowledge presents an important direction for future research on the early development of numerical competence.

The finding that young children who lack verbal numerical knowledge appear unable to make ordinal numerical comparisons seems on the face of it to be inconsistent with findings that nonlinguistic animals such as monkeys succeed at making the same kind of judgments. The monkey data provides firm evidence that linguistic ability is not essential for ordinal numerical competence. However, the monkeys in Brannon and Terrace's (1998, 2000) experiments were tested on novel ordinal comparisons only after a great deal of training on the sequence 1-2-3-4. Presumably, the extended training (hundreds of trials over the course of several months) on a four-item numerical sequence (essentially six numerical pairs) highlighted the salience of number as a relevant dimension to the monkeys. In contrast, the children in the current experiments received a maximum of 10 training trials on a single numerical pair (1 vs 2). If we had provided extended training on multiple numerical pairs it is possible that all of the children would have recognized number as the relevant dimension and consequently made relational numerical judgments.

A second, related question is whether children who lack verbal numerical knowledge also lack *any* understanding of the relational concepts of more and less. Anecdotal evidence suggests that children may be capable of making relational judgments on the basis of nonnumerical dimensions such as ''amount of stuff.'' A number of parents reported before the study began that their children understood ''more'' as in ''more applesauce,'' for example. Further, current research suggests that infants appear to be capable of making same/different judgments on the basis of nonnumerical dimensions such as contour length or spatial extent (Clearfield & Mix, 1999; Feigenson et al., in press). On this account, one might expect children to have performed better in Experiment 2 on area-congruent trials where area and number both specified the correct response than on area-incongruent trials, where area and number were in conflict. However, children also had ample evidence that area did not predict the correct response, which may have led them to abandon a strategy based on area relations. Current research is beginning to address the role of nonnumerical correlates of number in both infants' and toddlers' relational skills.

To summarize, we suggest that the significant but limited relationship we observed between nonverbal ordinal numerical knowledge and verbal counting ability is explained by the relative salience of the numerical dimension. As children begin to learn the meaning of number words, number is highlighted as a clearly salient, albeit abstract, dimension of the environment. As number becomes salient for young children, they may begin to recognize the many ways in which different numerosities are related to one another and to the verbal counting system. If this is the case, it is important to note that the monkey data shows that there are alternative, nonlinguistic ways of making number a salient dimension. Further, both the monkey research and the current research suggest that one need not possess verbal labels for distinct numerosities in order to appreciate the ordinal relations between them. We therefore turn next to a consideration of how success in our task might be accomplished.

Implications for Representational Format for Number

What are the implications of our results for the format of the representations children use in making ordinal comparisons? One possibility is that children used a one-to-one correspondence algorithm to compare the boxes on each tray and learned to choose the tray that yielded a remainder. We doubt that children used such a strategy. Given the difficulty children as old as 4 years of age experience constructing one-to-one correspondence relations (e.g., Piaget, 1952), it seems likely that they would have had to engage in some sort of systematic comparison behavior. However, in our studies, children virtually never glanced systematically back and forth between the two trays and never systematically touched the covers. Nonetheless, at least some children may have employed a one-to-one correspondence strategy in solving the ordinal task. If so, these children were demonstrating a rather sophisticated numerical skill. The successful use of one-to-one correspondence requires the recognition that such a computation would be useful, the ability to apply the computation correctly, and finally to understand the implications of the comparison to select the tray with the remainder (that is, the tray with more).

With respect to representational capacity, such a strategy clearly would relieve children of having to construct and compare numerical representations maintained exclusively in memory with no concurrent visual support. Indeed, we know of no developmental research on ordinal knowledge with children this young that demands such a representational capacity. Children must realize, nonetheless, that the relevant dimension for one-to-one comparison is at the level of individual objects (as opposed to trays, spatial locations, object edges or corners, etc.), which requires at the very least the ability to individuate each object to be compared and to keep track of the serial comparisons being conducted. Representations of distinct objects are precisely the type of midlevel perceptual representations that ‘‘object files’’ describe and over which a putative accumulator or numeron list computation might operate. We turn next to a consideration of these possibilities.

One proposal concerning early representations is that the apparent numerical abilities of infants and young children are supported not by specifically numerical representations but rather by representations of distinct individuals of the same type that support parallel, preattentive processing in adults (Leslie et al., 1998; Scholl & Leslie, 1999; Simon, 1997; Uller et al., 1999). Under this scenario, there is no symbol that represents the numerosity of the set; instead each distinct entity in the set is represented by its own symbol. This ‘‘object-file’’ mechanism is limited in that it can only represent three or four items simultaneously (Trick & Pylyshyn, 1994). A second proposal is that infants and young children, like nonhuman animals, represent numerosities in an analog numerical format (Gallistel & Gelman, 1992; Wynn, 1995). Sets of discrete items may be represented as continuous magnitudes that bear a direct relationship to the discrete sets that they represent. For example, if two were represented as this much (—), then four would be represented as this much (——). Finally, it is possible that children were relying on symbolic but nonverbal numerical representations of number akin to those encoded in the verbal counting sequence (Gelman & Gallistel, 1978).

Two aspects of our data suggest that analog magnitude representations support children's performance in our task. First, children were able to make judgments about the relative numerosity of sets as large as five or six entities, which exceeds the capacity of object-file representations. Second, if children were accessing a set of nonverbal, symbolic representations of number to succeed in our task, one would expect exceptional performance within the range for which children knew the verbal labels in addition to the nonverbal symbols. For the subset of children who possessed at least a modicum of such verbal numerical knowledge, the ability to make ordinal comparisons was not at all correlated with the degree to which they had mastered the verbal counting system. The idea that children are using analog representations in our task is also consistent with findings demonstrating that children as young as 5 years of age, demonstrate latency and accuracy distance effects similar to those that have been taken as evidence of such representations in adults (Temple & Posner, 1998; see also Huntley-Fenner & Cannon, 2000; Sekuler & Mierkowicz, 1977). Our paradigm could easily be employed to test a larger set of numerical comparisons and to obtain latency measures from children as young as 2 years of age, providing a strong test of the nature of very young children's ordinal representations.

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