Numerical abstraction by human infants*

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Abstract

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Across several experiments, 6- to 8-month-old human infants were found to detect numerical correspondences between sets of entities presented in different sensory modalities and bearing no natural relation to one another. At the basis of this ability, we argue, is a sensitivity to numerosity, an abstract property of collections of objects and events. Our findings provide evidence that the emergence of the earliest numerical abilities does not depend upon the development of language or complex actions, or upon cultural experience with number.

Introduction

Until recently, historians of mathematics widely believed that very young children and individuals from relatively isolated societies lack the ability to think about number and consequently treat singletons, doublets or triplets only as visual patterns (e.g., Dantzig, 1954; Kline, 1972). Similar beliefs

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appear to be common among anthropologists and linguists who have studied adults in illiterate societies, (e.g., Menninger, 1969; Tylor, 1874), and among developmental psychologists (e.g., Gast, 1957; Piaget, 1952; Werner, 1957). Despite its popularity, this description of both the young and the non-Western mind has been discredited wherever it has been tested.

Recent cross-cultural studies reveal that mathematical thinking is a pursuit of peoples throughout the world (Ginsburg, 1982; Lave, 1977; Saxe & Posner, 1983; Zaslavsky, 1973). For example, unschooled tailors in Liberia have been found to measure and to solve mathematical problems (Lave, 1977); and merchants all over Africa use money (Zaslavsky, 1973). Indeed, a counting process that enumerates collections of items has been found in the mathematical system of each culture that has been studied (Ginsburg, 1982; Saxe & Posner, 1983; Zaslavsky, 1973). Some of the surface characteristics of the enumeration process vary widely. In Western societies, counting proceeds by bringing an ordered set of number names into correspondence with the things being enumerated; in Papua New Guinea, the enumeration process proceeds by bringing an ordered set of body parts "thumb, wrist, forearm, ..." into correspondence with the things being enumerated. Deeper characteristics of these processes, however, seem to be invariant across cultures. In particular, all counting procedures involve the establishment of a one-to-one correspondence between the objects to be enumerated and a set of items in a stably ordered list.

Young children also engage in mathematical thinking. The conventional counting process starts shortly after children begin to talk and it develops rapidly (Fuson & Hall, 1983; Gelman & Gallistel, 1978; Sophian, 1987). By the time children go to school, their mathematical knowledge includes equivalence and ordering relationships (Bullock & Gelman, 1977; Cooper & Starkey, 1977; Mehler & Bever, 1967), the operations of addition, subtraction, and division (e.g., Blevins-Knabe, Cooper, Mace, Starkey, & Leitner, 1987; Cooper, 1984; Frydman & Bryant, 1988; Gelman & Gallistel, 1978; Klein & Langer, 1987; Siegler & Robinson, 1982; Starkey, 1983; Starkey & Gelman, 1982), rules for establishing one-to-one correspondences over variations in the types and the distribution of elements (Gelman, 1982; Markman, 1979), and a beginning understanding of zero (Evans, 1983). This mathematical system does not function as widely for the young child as for the adult. For example, it is revealed initially only when the child focuses on small sets of concrete objects. Nevertheless, many of the formal properties of arithmetical reasoning such as the inverse relation between addition and subtraction appear to be present in quite young children (Gelman & Gallistel, 1978; Greeno, Riley, & Gelman, 1984; Klein & Starkey, 1988).

The early and spontaneous development of counting has been observed not only in the West, but also in non-Western cultures (e.g., Saxe & Posner, 1983). Where children in either schooled or unschooled environments have been tested on arithmetic tasks, the results are similar to those obtained with the young children in Western cultures (Posner, 1982). Indeed, children on the Ivory Coast have even been known to invent strategies to add large numbers – strategies not provided for them by the culture (Ginsburg, Posner, & Russell, 1981). Such findings support the conclusion that certain numerical abilities are universal.

What accounts for the universality and the early emergence of numerical abilities? It is possible that a mathematical system has been invented or acquired by every society through cultural diffusion, and that children in every culture master this system through some process of instruction. A discontinuity in the child's mental development would occur at the time children learn this system.

A second possibility is that the foundations of mathematical thinking emerge in development as a consequence of more general structural developments. The coordination of schemes of action such as combining and separating, ordering, and putting into correspondence might lead to the inductive discovery of their operational properties (e.g., the discovery that separating negates combining). The functioning of the Piagetian mechanism of reflective abstraction ensures that the child will abstract properties from the action schemes, interiorize and organize them, and form an operational scheme. The child's subsequent coordination of operational schemes would produce a structure capable of supporting deductive numerical reasoning (Beth & Piaget, 1966; Piaget, 1952). Because the child must first make a set of discoveries about mathematical properties of his or her action schemes and then represent and coordinate these discoveries on a more abstract plane, numerical knowledge would not emerge early in development.

As a third possibility, an initial body of mathematical competence might exist in the human infant, and this competence might serve as a basis for the acquisition of a particular mathematical system. The child would acquire a particular system with facility because at least some of its underlying characteristics are already in place. Thus, as in the case of language (Chomsky, 1975), developmental changes and cultural variations in numerical abilities would cover a common, unchanging core of mathematical competence.

We have taken an initial step toward deciding between the first two possibilities and the third, by asking whether infants are sensitive to numerical correspondences between collections of objects. We focus on a set of tasks whose solution depends on the recognition of one-to-one correspondence between the members of different collections of items. One-to-one correspondence is a central concept in arithmetical thinking: the establishment of such a correspondence is a basic component of all existing counting procedures (Greeno et al., 1984). Further, one-to-one correspondence is considered a primitive relation in accounts of the foundations of arithmetic (Beth, 1965; see Kline, 1972, for a review). Studies of infants' sensitivity to numerical correspondences thus could shed light on one of the central components of human mathematical capacity.

It is not easy to show that infants possess procedures for recognizing one-to-one correspondences. One must show that an infant's ability to detect relationships between numerically corresponding collections does not derive from some non-numerical (possibly very subtle) correspondence between the configurations of elements. To illustrate the difficulty, consider some earlier experiments on infants' sensitivity to number. It has been shown that infants can discriminate between two rows of dots that have different numbers of elements: infants from birth to 8 months have been habituated to displays containing two to six dots in a single row. The displays were designed to control for infants' use of overall differences in brightness, density, and row length as a basis for the discrimination. It was found that infants would dishabituate to a display containing a new number of dots, provided that the number was less than or equal to four (Antell & Keating, 1983; Starkey & Cooper, 1980a, 1980b). It is possible that this discrimination depended on the working of a visual numerosity detection process called subitizing rather than a more central process. It has often been argued that the adult's ability to detect the numerosity of small sets of items reflects the working of such a process (Klahr & Wallace, 1976; see Mandler & Shebo, 1982, for an alternative account).

The present experiments investigated whether infants detect numerical correspondences between more disparate sets of items, including items as different as visible objects and audible events. Detection of such correspondences would almost certainly depend on the detection of numerical information, because spatially extended sets of visible objects and temporally extended sets of audible events share no obvious configurational properties. Moreover, detection of numerical information would depend upon some process involving one-to-one correspondence. It would not depend upon a visual subitizing process because such a process could not be applied to audible events. Finally, the use of one-to-one correspondence would imply that the infant knows, on some level, that diverse sets of items can be enumerated. The beginnings of the abstraction principle of counting – the principle that any discrete element is countable (Gelman & Gallistel, 1978) – would therefore be evident during the developmental period of infancy. These experiments should reveal whether human infants have such capacities and conceptions.

Experiment 1

The first experiment investigated whether infants can detect numerical correspondences across photographed collections of heterogeneous objects. At one time, many investigators believed that children begin to enumerate sets of items that are homogeneous in appearance before they can enumerate sets of items that are heterogeneous (e.g., Gast, 1957; Klahr & Wallace, 1976). These investigators reasoned that there are limitations on the criteria young children use to classify objects, and that the bases of classification are salient perceptual properties of objects such as color and shape. It has been found, however, that preschool-age children can enumerate collections that include objects as disparate as people and things in a room (Gelman, 1980). Experiment 1 investigated whether the infant's sensitivity to numerosity likewise extends to collections of heterogeneous objects.

Method

Thirty-two healthy full-term infants (16 boys and 16 girls) participated in the experiment. The infants were between 6 and 9 months of age, with a mean age of 7 months. An additional 14 infants were excluded because they cried, fell asleep, or failed to attend.

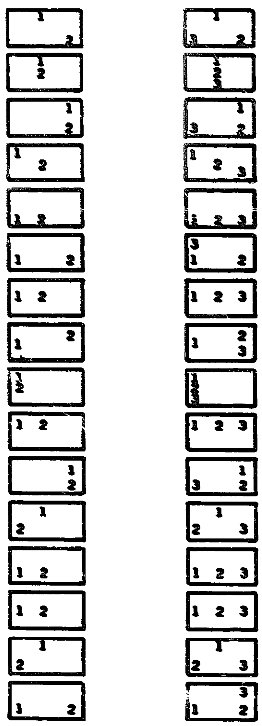
The experimental displays were slides of two or three household objects which had been photographed from an aerial perspective (Figure 1). The color slide photographs, when projected, measured 24 cm × 28 cm. They were projected in dim ambient lighting. The objects in the displays differed in color, shape, size, and surface texture. Each display consisted of an array of two or three distinct objects located on a white, homogeneous surface and oriented canonically in relation to the supporting surface (e.g., an upright cup). The particular objects were substituted from display to display. Their positions varied as well and were determined as follows: the surface on which the objects rested was divided into an imaginary 3 × 3 matrix; no more than one object was assigned to each of the resulting nine regions of the matrix. The positioning of objects was randomly determined with two restrictions: first, each display contained a total of two or three objects; and second, among the displays of three objects, half of the configurations were linear and half were triangular. The subset of two or three regions occupied by objects usually differed across displays.

Three sets of displays were included in the experiment: (1) a set of 16 displays of two objects, designated as habituation displays; (2) a set of 16 displays of three objects, also designated as habituation displays; and (3) a set of eight test displays, half containing two and half containing three objects.

Figure 1. *Habituation and posthabituation displays presented in Experiment 1.*

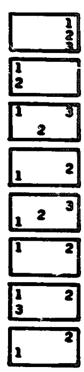
STIMULI

HABITUATION STIMULI: 2-OBJECT ARRAYS, 3-OBJECT ARRAYS



HABITUATION SLIDE #	OBJECTS 1	OBJECTS 2	OBJECTS 3
1	MEMO PAD	COMB	SCRAPER
2	RIBBON	PIPE	YELLOW RUBBER GLOVE
3	ORANGE CASE	PINE BURR	TOY ANIMAL
4	WOODEN BOWL	LEMON	BLUE SPONGE
5	KEY	BLACK DISC	UNPAINTED WOODEN BLOCK
6	WIG	DRAIN PLUG	PINK CASE
7	WATER GLASS	FIGURINE	WOODEN MUSHROOM
8	CANDLE	BLACK CASE	PINK CUP
9	BELL PEPPER	ANIMAL HORN	SCISSORS
10	COIN PURSE	RING BOX	FEATHER
11	DARK BROWN CLOTH	EGG BEATER	WOODEN CARVING 'A'
12	GLASS-HOLDER	RED YARN	BLUE YOYO
13	CORK SCREW	JAR LID	GLASSES CASE
14	STRAP	FLUTE	TEA STEEPER
15	HAIR DRYER CAP	METAL CYLINDER	WOODEN CARVING 'B'
16	PILLOW	ORANGE	VASE

POST-HABITUATION STIMULI



POST-HABITUATION SLIDE #	OBJECTS 1	OBJECTS 2	OBJECTS 3
1	PINK SPONGE	RED CLOTH	PEAR
2	YELLOW SOCK	APPLE	
3	TRASH CAN	TOMATO	WOODEN SHOE
4	HAIR ROLLER	BLACK CLOTH	
5	GREEN SOCK	RED CLOTH GLOVE	BLACK CUBE
6	BLACK BOOK	RED SPHERICAL PAPERWEIGHT	
7	CARROT	RED SOCK	GREEN WASHCLOTH
8	RED DISC	CHOPSTICK	

Sixteen infants were familiarized with the two-object habituation displays, and 16 infants were familiarized with the three-object habituation displays. After a criterion of habituation was met (see below), each infant was presented with the eight test displays of two or three objects. In this phase of the session, half the infants from each familiarization condition were presented first with a test display of three objects. Test displays of two objects and three objects were presented in alternation.

Infants were seated on a parent's lap at a distance of either 30 cm or 60 cm from a 54 cm × 89 cm rear-projection viewing screen. Parents were asked not to look at the screen and were monitored throughout the session. The experimental session began with the presentation of the first habituation display. Observers recorded the infant's looking at the display. The display was presented until the infant had looked at it for at least 1 s on any single look and had subsequently looked away for 2 s continuously. Thereupon the display was removed and another was immediately presented by advancing the slide projector, beginning the next trial. If an infant attended to a display for 30 s, it was removed and the next display was presented. If, after several minutes (approximately four trials) of testing, an infant had failed to attend to a display for a sustained period of at least 1 s, the session was terminated. The habituation displays were presented until the duration of the infant's looking time at a display had decreased by a criterial amount, 50% when averaged across three successive trials, and then the eight test displays were presented. Each of the test trials followed the same procedure as the familiarization trials.

The duration of attention to each display was recorded by two independent observers who viewed the infant through viewing holes located to the left and right of the projection screen. Observers were trained to detect looks in the direction of any part of the projected display. They pressed a button on a hand-held switch box when the infant looked at the display and released the button when the infant looked away. This displaced a pen on a Lafayette high-speed event recorder whose paper speed was operating at 10 cm/s. Durations recorded by the observers were compared, and disagreements greater than 0.05 s were noted. Inter-observer agreement was found to be high (90%). The observers did not know how many objects were in the display that was being presented on any given trial, because their view of the projection screen was occluded by a barrier.

Looking times to the test displays were subjected to a 2 × 2 × 2 × 2 × 2 analysis of variance. Sex, distance from the display, set size of the habituation display, and presentation order of the test displays were the between-subject variables. The within-subject variable was the numerosity of the test display (familiar or novel).

Results

Figure 2 presents the mean durations of looking during the habituation phase and the test phase for the infants in both conditions. It can be seen that looking time gradually decreased over the habituation period. The criterion of habituation was met in an average of 10.1 and 9.3 trials in the two-object and the three-object conditions, respectively. During the test phase, mean looking times to the familiar numerosity and to the novel numerosity were 5.70 ± 3.74 s and 7.00 ± 3.61 s, respectively. Despite high variability in infants' looking times, there was a reliable tendency for infants to look longer at the test displays containing a novel number of objects, $F(1, 24) = 5.31, p < .025$. A reason for the high variability in looking time was suggested by certain aspects of the infants' looking behavior. On some trials, infants appeared to glance only briefly at part of the display before turning away; it is likely that they did not see all of the objects in the display. On other trials, infants appeared to stare fixedly at one region of the display; it is likely that their attention was drawn to one particular object in the display rather than to the set of objects or its total numerosity. This behavior is not surprising because all objects in the test displays were novel: none had been presented during the habituation phase.

To address these problems, a further analysis was undertaken. From the four test trials of each numerosity for each infant, the trial with the longest looking time and the trial with the shortest looking time were eliminated. The looking times of the remaining two test trials of each numerosity were averaged. The resulting two scores reflect the median looking time to displays of two objects and displays of three objects during the test period, and they are given in Table 1. These scores were log-transformed and then were subjected to a $2 \times 2 \times 2 \times 2 \times 2$ analysis of variance. The between-subjects factors of this analysis were the same as in the original analysis of looking times. The sole within-subjects factor was the numerosity (familiar or novel) of the test display. There was a main effect of the set size of the habituation display. Infants who had been familiarized with displays of two objects subsequently attended longer to the entire set of test displays than did infants who had been familiarized with displays of three objects, $F(1, 16) = 5.78$, $p < .05$. More importantly, there was a main effect of the numerosity of the test display:[1] infants in both conditions looked longer at numerically novel displays than at numerically familiar displays, $F(1, 16) = 7.07$, $p < .025$. Twenty-four of the 32 infants exhibited this pattern. No other main effects and no interactions were significant.

[1]A variety of analyses of both raw scores and log-transformed scores have all yielded the same pattern of results.

Figure 2. *Mean looking times during the familiarization phase and the test phase of Experiment 1.*

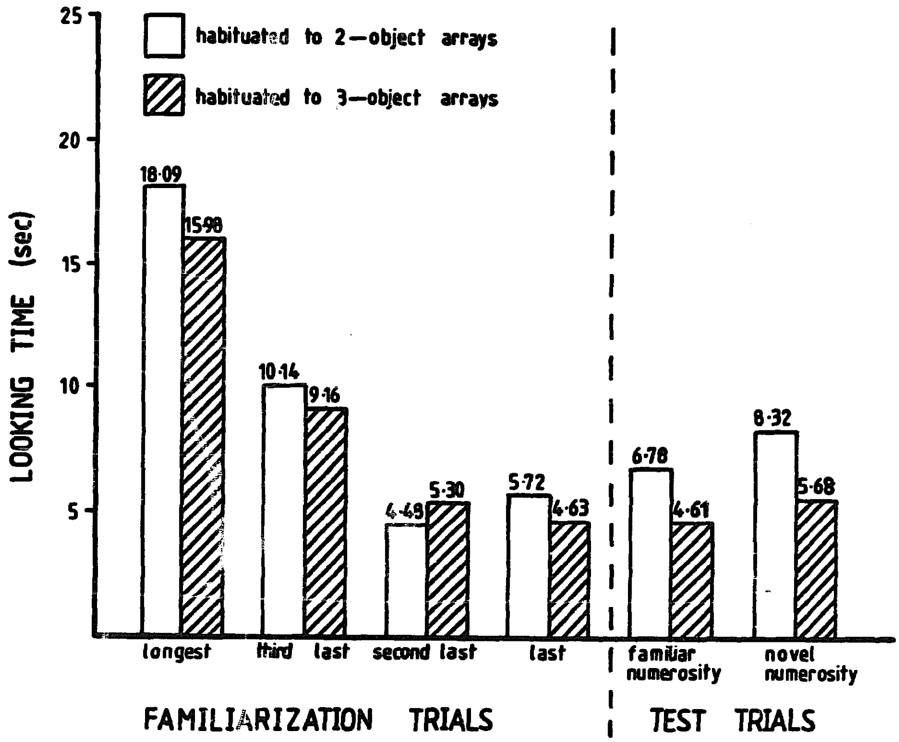


Table 1. *Median duration of looking (seconds) in the test phase of Experiment 1*

	Test displays	
Habituation displays	2 objects	3 objects
2 objects	6.55	7.94
3 objects	5.00	3.88

Discussion

The experiment revealed that infants treated the numerically novel test displays as more novel than the numerically familiar displays. The stimulus property determining this pattern could not have been the objects themselves or their spatial arrangement, because these properties were novel in all the test displays. Similarly, the determining property could not have been the brightness, contour density, or surface area of the displays, because these properties varied along with variations in the objects. We conclude, therefore, that the infants detected the novel number of objects contained in the numerically novel test displays.

The findings of an experiment by Strauss and Curtis (1981) are consistent with the findings of Experiment 1. Using a habituation procedure, Strauss and Curtis presented 1[illegible]-month-old infants with a set of slides of the line-drawn figures. Different figures appeared in different slides, although all the figures were the same within a single slide. Male and female infants detected a change from two to three objects and from three to two objects; female infants detected a change from three to four objects and the reverse. Neither group of infants detected a change from four to five objects or the reverse.

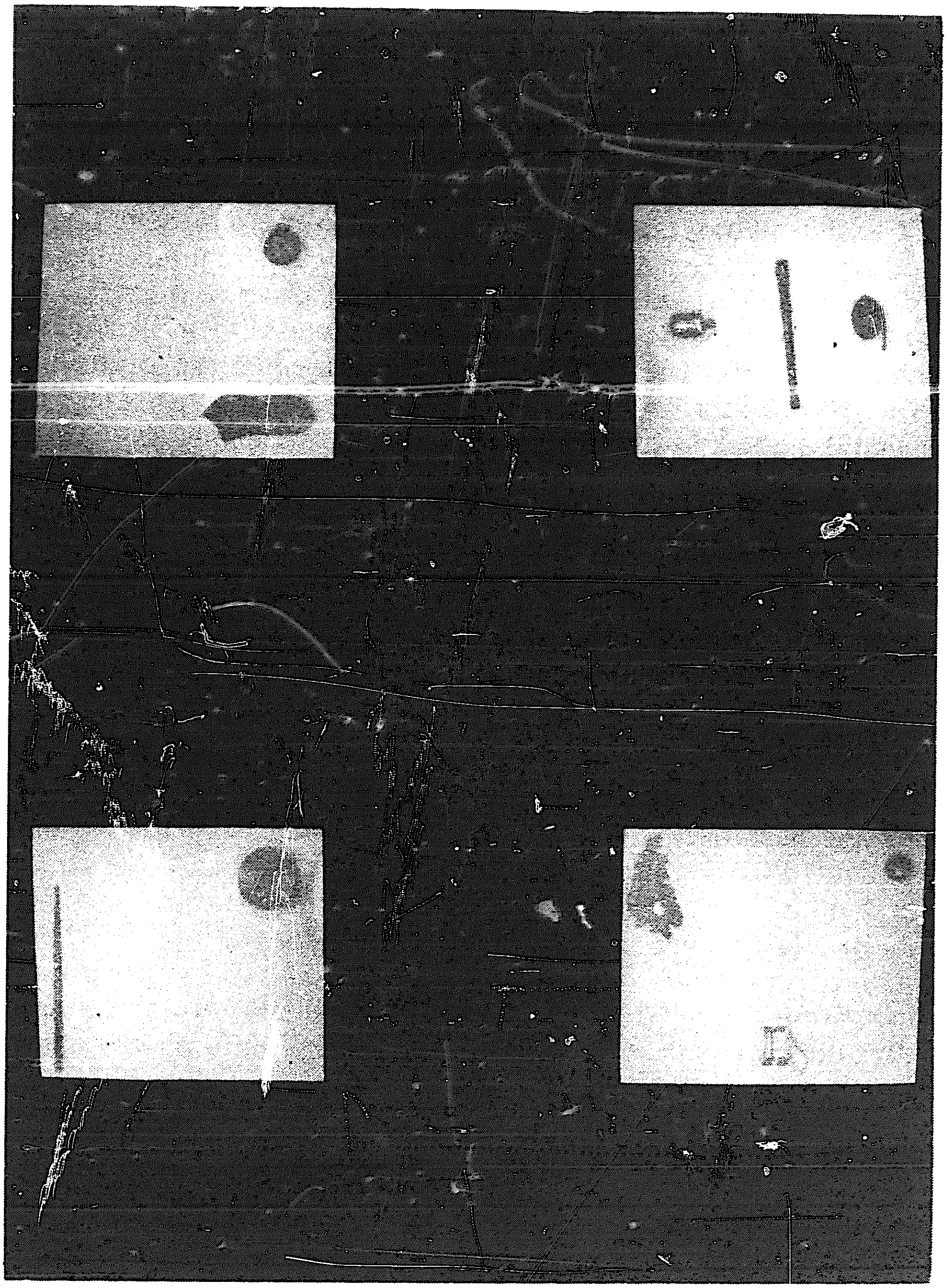
In summary, infants detect changes in the number of items in a collection not only when the items are the same but also when they are different. Infants evidently are able to disregard differences in color, shape, size and surface texture among individual objects, as well as differences in the arrangements of objects in a display. Infants detect numerical properties of sets of objects irrespective of these non-numerical but perceptually salient differences.

This experiment does not reveal, however, whether infants are sensitive to number when they are presented with sets of elements that cannot be perceived visually. The question has considerable significance for accounts of early number competence. According to one theory, young children enumertate objects by means of a specifically visual process – subitizing (Klahr & Wallace, 1976). This process, however, could not be used to enumerate objects or events perceived in other modalities. The next set of experiments, therefore, investigated whether infants can detect numerical correspondences between displays of visible objects and sequences of sounds.

Experiment 2

The experiment used an auditory–visual preference procedure (Spelke, 1976). Infants were presented with a pair of visual displays placed side by side (see Figure 3). While the displays were shown, a sound accompaniment was played from a central location. This accompaniment consisted of sounds that corresponded in number to one of the visible displays. Specifically, one display was a photograph of two objects, the other display was a photograph of three objects, and the sound accompaniment was a single sequence of two or three drumbeats. Looking time to the two displays was recorded for 10 s after the offset of the sound. In many experiments, infants have been found to look preferentially at a visible display that corresponds to a sound (see Spelke, 1987). Therefore, if infants detected the numerical relationship be-

Figure 3. *Photographs of arrays of two and three objects as displayed in Experiment 2.*



tween the sounds and objects, they were expected to look preferentially to the display of objects whose number corresponded to the number of sounds.

Method

Sixteen healthy full-term infants (eight boys and eight girls) participated in the experiment. The infants ranged in age from 6 to 8 months (mean age, 7 months). One additional infant was excluded because of persistent crying.

The slide photographs used in Experiment 1 were presented in pairs. When projected, each display pair measured 24 cm × 29 cm, and the two slides in a pair were separated from one another by a distance of 29 cm. Each display pair consisted of one two-object slide and one three-object slide, depicting different objects. The two-object slide appeared on the left for half the trials given to each infant.

The drumbeat sequences were produced by rapping a drumstick on a biscuit tin. The tin was located out of the infant's view, and it was centered between two visible displays. Sounds were presented at a tempo of 1.3 beats per second.

Infants were seated on a parent's lap or in an infant seat at a distance of 60 cm from the projection screen. Parents wore opaque glasses which occluded their view of the screen. Each trial of the experiment began with the presentation of a display pair on the viewing screen, followed 1 s later by the onset of the sequence of drumbeats. The presentation of the display pair continued for 10 s after the end of the final drumbeat. Then the displays were removed and were immediately replaced by the next display pair, thus beginning the next trial. Each infant was presented with at least one complete block of 16 trials. A second 16-trial block, consisting of the same displays as the first block, was also presented unless an infant cried or became drowsy. Eleven infants completed both blocks, receiving a total of 32 trials; the remaining five infants completed 17–29 trials. The trials were presented in one of four orders that counterbalanced the number of drumbeats accompanying a given display pair and the lateral positions of each photograph in a display pair.[2] Sex of infant was also counterbalanced.

The duration of the infants' looking at each member of a display pair was measured only during the 10-s period that followed the final drumbeat. Look-

[2]Four types of trials were presented:

Type *I*: An auditory sequence of two sounds (*A2*) accompanied a visual display of two objects (*V2*) projected on the left viewing screen and a visual display of three objects (*V3*) on the right.

Type *II*: *A2* accompanied *V2* on the right and *V3* on the left.

Type *III*: An auditory sequence of three sounds (*A3*) accompanied *V3* on the left and *V2* on the right.

Type *IV*: *A3* accompanied *V3* on the right and *V2* on the left. →

ing was recorded by two independent observers who were stationed at the same locations as in Experiment 1. Inter-observer agreement was high (93%).

From the observers' records, the duration of looking to the numerically equivalent display and to the nonequivalent display was assessed for each trial. These durations were averaged across the 16 trials comprising a trial block, and the resulting values were averaged across the two trial blocks. These duration scores were compared by analysis of variance and *t*-tests. In addition, the effect of the sounds on looking to displays of each numerosity was separately examined. Looking time to displays of two objects when accompanied by two sounds was divided by total looking time to displays of two objects when accompanied by two or three sounds. Similarly, looking time to displays of three objects when accompanied by three sounds was divided by total looking to displays of three. The *t*-tests compared these proportions with the chance value of 0.50. Scores reliably greater than 0.50 indicated that the looking to a display of a given numerosity was enhanced by the introduction of a numerically corresponding sound.

Results

The infants looked at one or the other member of a display pair on 88% of the trials, and they looked at both members on 54% of the trials. The average duration of their attention was 3.81 s of the 10-s trials; it decreased from an average of 4.10 s per trial on Block I to 2.53 s per trial on Block II. Occasionally, an observer or a parent reported that an infant moved its hand up and down in synchrony with drumbeats.

The principal findings are given in Table 2. A 2(sex) × 2(block) × 2(display: equivalent or nonequivalent) analysis of variance revealed that the infants looked longer at the numerically equivalent display than at the numerically nonequivalent display, $F(1/14) = 9.66, p < .01$. Twelve of the 16 infants looked longer at the numerically equivalent displays. There was no effect of sex on this preference. Similar levels of preference were observed for the

Trial order varied across infants and experiments. Four orders were included in Experiment 2:
(1) Trials 1–4 were type *I*; 5–8, *IV*; 9–12, *II*; 13–16, *III*.
(2) 1–4, *IV*; 5–8, *I*; 9–12, *III*; 13–16, *II*.
(3) 1–4, *II*; 5–8, *III*; 9–12, *I*; 13–16, *IV*.
(4) 1–4, *III*; 5–8, *II*; 9–12, *IV*; 13–16, *I*.
Four orders were included in Experiments 3 and 4:
(1) 1–8, *I*; 9–16, *IV*.
(2) 1–8, *IV*; 9–16, *I*.
(3) 1–8, *II*; 9–16, *III*.
(4) 1–8, *III*; 9–16, *II*.
The second block of trials (17–32) was presented in the same order as the first block.

Table 2. *Patterns of looking at corresponding and noncorresponding displays in Experiment 2*

	Mean duration of looking (s) to:		Proportionate effect of sound		
Trial block	Corresponding display	Noncorresponding display	2-object display	3-object display	Overall
I	2.11	1.99	.54	.50	.51
II	2.02	1.51	.57*	.60*	.58**
Mean	2.06	1.75	.55*	.55*	.55*

$^*p < .05$; $^{**}p < .01$.

numerically equivalent two-object display (proportion of looking, 0.55, $p < .05$, one-tailed) and for the numerically equivalent three-object display (proportion of looking, 0.55, $p < .05$, one-tailed).

This preference was largely limited to the second block of trials (Block I: $t(15) = 0.61$, $p > .10$; Block II: $t(15) = 2.87$, $p < .01$, one-tailed).[3] In the first block of trials, infants attended to displays of three objects longer than they attended to displays of two objects, regardless of the number of drumbeats presented on a trial, $t(15) = 2.81$, $p < 0.25$, two-tailed. This pattern was not present in the second block of trials, $t(15) = 1.15$, $p > .10$. Finally, infants showed a reliable decrease in looking at numerically nonequivalent displays from Block I to Block II (0.48 s per trial). The decrease in looking at numerically equivalent displays, in contrast, was slight (0.09 s per trial). Thus, the infants came to attend less and less to nonequivalent displays, but their attention to equivalent displays did not decline.

Discussion

Infants' preferences between two displays of visible objects depended on the number of objects in the displays, and especially on the relation of the number of objects to the number of sounds in the audible accompaniment. Infants looked longer at displays of two objects when they heard two sounds and at displays of three objects when they heard three sounds. Over the course of the session, attention to the corresponding visible display remained high,

[3]One infant received only one trial in the second trial block. Winer's (1971) technique for estimating missing data was used to generate a mean value for other trials. The general pattern of findings was not changed by including or excluding this infant.

whereas attention to the noncorresponding display declined. These findings provide evidence that infants detect numerical correspondences between objects and sounds.

Experiment 3

In order to assess the reliability of the preceding findings, a replication experiment was conducted. Except for minor modifications, the method was the same as that of Experiment 2.

Method

Eight healthy full-term infants (four boys and four girls) participated in the experiment. The infants were between 6 and 8 months of age, with a mean age of 7 months. No infants were excluded from the experiment.

The experimental materials and procedure followed those of Experiment 2, with three modifications. First, the number of drumbeats presented on any given trial changed from two to three beats or from three to two beats after every eight trials. In the preceding experiment, the number of beats had changed after every four trials. Second, the relative positions of the two-object displays and the three-object displays did not change over trials (although the positions continued to be counterbalanced across infants). In the previous experiment, the displays were reversed after every four trials. Third, only one of the two original orders of display pairs was used in this experiment. Three variables were counterbalanced across infants: 2 (sex) × 2 (number of drumbeats accompanying a given display pair) × 2 (relative position of displays forming a given display pair). Seven infants completed all 32 trials, and one infant completed 16 trials. Inter-observer agreement was high (90%).

Results

The infants attended to at least one member of a display pair on 95% of the trials and they attended to both members on 67% of the trials. These proportions, as well as the average duration of looking time (5.26 s) were somewhat greater in Experiment 3 than in Experiment 2. The decrease in looking time (from 5.84 s in Block I to 4.66 s in Block II) was also somewhat greater in Experiment 3.

The infants looked preferentially at the numerically equivalent display (Table 3). This preference again was largely limited to the second block of trials (Block I: $t(7) = 0.06, p > .10$; Block II: $t(7) = 7.30, p < .01$, one-tailed).

Table 3. *Patterns of looking at corresponding and noncorresponding displays in Experiment 3*

	Mean duration of looking (s) to:		Proportionate effect of sound		
Trial block	Corresponding display	Noncorresponding display	2-object display	3-object display	Overall
I	2.93	2.91	.52	.48	.50
II	2.74	1.92	.55	.59	.58**
Mean	2.84	2.42	.54	.54*	.54*

*$p < .05$; **$p < .01$.

It was present in all eight infants on the second block of trials and in six of the eight infants overall. There was no effect of sex. The presentation of two sounds appeared to increase looking time to displays of two objects, and three sounds appeared to increase looking time to displays of three objects. This tendency, however, was significant only when the data from the two display conditions were combined (Table 3).

In the first block, infants looked longer at the three-object displays regardless of the number of drumbeats presented on a trial, $t(7) = 1.89$, $p < .05$, one-tailed. This preference did not occur in the second block, $t(7) = 1.02$, $p > .10$. Looking time to the numerically nonequivalent displays decreased (by 0.99 s per trial) from Block I to Block II. In contrast, looking time to the numerically equivalent displays decreased only slightly (by 0.19 s per trial).

Discussion

The infants in Experiment 3 were more attentive than those in Experiment 2 perhaps because of the various modifications of procedure. Nevertheless, the principal findings of Experiment 3 closely replicated those of Experiment 2. Both experiments provided evidence that infants responded to the numerical equivalence of a sequence of sounds to a display of visible objects. Infants detected this equivalence despite the difference in modality of presentation of the numerically corresponding displays and the difference in their spatio-temporal characteristics.

Before concluding that infants respond to numerical properties of visible displays and audible sequences, however, we must consider the possibility that infants detected an intermodal temporal correspondence. Prior research has found that infants can detect temporal relationships between audible and visible events (for reviews, see Gibson & Spelke, 1983; Spelke, 1987). In

Experiments 2 and 3, some temporal correspondence might have united the sounds and objects, because the duration of the sequences of three drumbeats was greater than the duration of sequences of two drumbeats, and the displays of three objects might have required more scanning time than did the displays of two objects. Experiment 4 investigated whether infants could detect the numerical correspondences in the absence of this temporal relationship.

Experiment 4

Experiment 4 followed the procedure of Experiment 3, except that temporal information and numerical information were dissociated by equating the durations of the sequence of two beats and the sequence of three beats. In this experiment, no temporal information could possibly unite a sound sequence with the corresponding display of visible objects.

Experiment 4 also incorporated a check on the possibility of observer bias. Although the observers in the earlier experiments could not see the displays presented to the infants, they might have been able to infer the number of objects in a given display from the infants' patterns of visual scanning. For example, a display of two objects might have elicited a pattern of scanning between two locations, and a display of three objects might have elicited a pattern of scanning among three locations. Accordingly, the experimental procedure was modified to determine whether observers could detect such patterns.

Method

Sixteen healthy full-term infants (eight boys and eight girls) participated in the experiment. The infants were between 6 and 8 months of age, with a mean age of 7 months. Three additional infants were excluded because their persistent crying forced an early termination of the experiment. In the present experiment, infants were required to complete all 32 trials to be included in the sample.

The experimental materials were those used in Experiments 2 and 3 except for modification of the sound sequences. The tempo of the sequence of two drumbeats was slowed such that its total duration equalled that of the sequence of three drumbeats.

The procedure followed that of Experiment 3, except for one modification of the task assigned to one of the two observers. The secondary observer was asked to attend to the visual scanning patterns produced by each infant while the infant was inspecting the displays. On the basis of these patterns, the observer was asked to guess which of the photographs contained the display of two objects. She was asked to judge the location of the display of two objects on each trial.

Results

The infants fixed their gaze on at least one member of a display on 97% of the trials, and they gazed at both members on 61% of the trials. The average duration of infants' looking was 5.30 s per trial; it decreased from 5.62 s per trial on Block I to 4.96 s per trial on Block II.

The principal results are given in Table 4. Infants showed a reliable visual preference for the numerically corresponding displays, $F(1, 14) = 4.74, p < .05$. This preference was observed in 12 of the 16 infants. There were no sex differences. Looking time to displays of two objects was greater when accompanied by two sounds, and looking time to displays of three objects was greater when accompanied by three sounds (Table 4).

Within each block of trials, the infants' preference for the numerically equivalent display was only marginally significant (Block I: $t(15) = 1.70$, $p < .10$, one-tailed; Block II: $t(15) = 1.53$, $p < .10$, one-tailed). There was no overall preference for the displays of three objects in either block of trials, $p > .10$. The decrease in looking time to the numerically equivalent and the nonequivalent displays, from Block I to Block II, were nonsignificant and about equal.

The secondary observer's judgments that were based on infants' scanning patterns revealed that observers could not infer the numerosity of a display from these patterns. The proportion of correct judgements about the location of the two-object display ranged from 0.14 to 0.70 and averaged 0.50, as would be expected by chance.

Table 4. *Patterns of looking at corresponding and noncorresponding displays in Experiment 4*

	Mean duration of looking (s) to:		Proportionate effect of sound		
Trial block	Corresponding display	Noncorresponding display	2-object display	3-object display	Overall
I	3.03	2.91	.55	.54	.54
II	2.64	2.32	.53	.55	.54
Mean	2.84	2.46	.54*	.55*	.54**

$*p < .05$; $**p < .01$.

Discussion

The findings of the present experiment differed from those of its predecessors in three respects. First, infants' preference for the numerically equivalent display was observed on the first as well as the second block of trials. Second, there was no preference for displays of three objects during either block of trials. Third, there was no greater decrease over trials in attention to the nonequivalent display than to the equivalent display. These differences suggest that infants detected the intermodal correspondences at an earlier point in the present experiment than they did in the previous experiments. This difference probably did not depend on the new requirement that infants complete all 32 trials in order to be included in Experiment 4, because the changes in infants' preferences over trial blocks in Experiment 3 are still present if one includes only the data from infants who completed all 32 trials of that experiment. The difference was probably due to the slower tempo of the two-drumbeat sequence. Recall that the two- and three-drumbeat sequences differed in tempo as well as numerosity in the present experiment but not in the previous experiments. These sequences, therefore, may have been more discriminable for the infants. Despite these differences, however, the principal findings of Experiment 4 were the same as in the previous experiments: infants detected numerical correspondences between sets of visible objects and sequences of sounds.

In regard to the question of possible observer bias, the experiment provided evidence that the observers were not able to use the infants' scanning patterns to infer the number of objects contained in individual displays. Observer bias thus does not account for our findings.[4]

One might question the conclusion that infants detected numerical correspondences in any of Experiments 2, 3 and 4, because the size of the experimental effects appear to be small. It is important to note, however, that these small effects are consistent across experiments. The combined results of the three experiments, given in Table 5, show reliable tendencies to look at

[4]One might propose an additional source of observer bias: perhaps observers can determine the lateral positions of the displays of two and three objects by detecting reflections from infants' corneas. To test this possibility, four 7-month-old infants were brought into the laboratory and were shown the complete set of visual displays used in Experiments 2, 3 and 4. The displays were presented in pairs as in the experiments, but with no accompanying sounds. Two observers watched each infant, as in the earlier experiments, but they were instructed to attend to any reflections of the displays that they could discern in the infant's eyes, and to use these patterns to attempt to infer which side of the screen contained the display of two objects. A forced choice procedure was used. The observers performed at chance: the proportion of correct judgments of the location of the display of two objects averaged 0.49. The observers also reported that they were unable to see any reflections of individual objects. We may conclude that observer bias does not account for the results of Experiments 2, 3 and 4.

Table 5. *Patterns of looking at corresponding and noncorresponding displays: Experiments 2–4 combined*

	Mean duration of looking (s) to:		Proportionate effect of sound		
Trial block	Corresponding display	Noncorresponding display	2-object display	3-object display	Overall
I	2.64	2.41	.54*	.51	.52
II	2.41	1.92	.55**	.58**	.57**
Both	2.53	2.17	.55*	.54**	.54**

*$p < .05$; **$p < .01$.

numerically corresponding arrays of objects. This effect has been replicated, moreover, in an investigation recently completed in England,[5] in another investigation using two-dimensional objects (Moore, Benenson, Reznick, Peterson, & Kagan, 1987; see our discussion following Experiment 5, below), and in an investigation using three-dimensional objects (Termine, Spelke, & Prather, 1984). A variety of experiments converge on the conclusion that infants detect numerical correspondences between displays of visible objects and accompanying sequences of sound.

Experiment 5

The final experiment investigated whether infants can detect numerical correspondences between sounds and objects that are not present at the same time. This experiment was undertaken as an initial attempt to study the process for detecting numerical correspondences. It is possible that detection of a correspondence depends on a process that relates a pattern of sound to a simultaneous pattern of visual activity. On the presentation of each sound, infants might shift their gaze from one object to another. They might perceive a sound–object correspondence only if they encounter a new object with every new sound. Infants utilizing such a mechanism would not be able to detect correspondences between nonsimultaneous sounds and objects. Alternatively, detection of numerical correspondences could depend on processes that are more properly considered as components of an enumerative proce-

[5]A replication of Experiment 3 was conducted by the first author at the Medical Research Council. In this experiment as well, infants looked preferentially at the numerically equivalent display, $t(7) = 3.30$, $p < .01$, one-tailed.

dure. For example, infants might be able to detect the number of sounds, detect the number of objects, and compare the resulting numerosities.

As a first attempt to distinguish among possibilities, an experiment was conducted in which infants were familiarized with displays of objects and then were presented with sequences of sounds. The method was similar to that of Experiment 1, except that sequences of two or three sounds rather than displays of two or three objects were presented during the test phase.

Method

Thirty-two healthy, full-term infants between 6 and 9 months of age participated in the experiment. An additional 15 infants were excluded because they cried, fell asleep, or failed to attend.

The experimental materials consisted of the displays of objects and the sequences of sounds used in the previous studies. Infants were seated on a parent's lap at a distance of 60 cm from the viewing screen. A three-phase procedure that was similar to a method developed by Horowitz (1975; also see Colombo & Bundy, 1981) was used. During the pretest phase, infants heard six sequences of sounds. Half of these were sequences of two sounds and half were sequences of three. Presentation order was counterbalanced across infants. The sound sequences were produced behind a circular (25-cm diameter) black disk that was displayed on a rear-projection screen. Attention to these sequences was assessed by the duration of infants' looking toward the sound source. A sound trial began with the appearance of the disk display. One second later, a single sequence of two or three drumbeats began to sound from the location of the disk display. The disk was displayed until the infant had first looked at it for at least 1 s after the offset of the final drumbeat in the sequence and had then looked away for two consecutive seconds. Thereupon, the display was removed, the viewing screen was blank and dark for 5 s, and the disk was again displayed, beginning the next trial. This initial phase of the experimental session provided a measure of any intrinsic preference for one type of sequence over the other.

The next phase was a familiarization phase in which infants only saw slides of collections of objects. Half of the infants saw a set of displays containing two objects and half saw displays of three. Presentation of these displays exactly followed the procedure of Experiment 1, such that the presentations continued until an infant's looking time declined to half its original level. When this level was obtained, the test phase was begun. During the test phase, infants once again heard the sequences of sounds that had been presented in the pretest. Across all phases of the experiment, interobserver agreement was high (91%).

The central analysis concerned infants' looking time toward the source of the sound sequences. As in Experiment 1, the median durations of looking on the test trials was calculated and then log-transformed. Looking time when sound sequences were numerically equivalent to habituation displays was compared with looking time when sound sequences were numerically novel. This comparison was made by a 2 × 2 × 2 × 2 analysis of variance, with sex, set size of the habituation display, and presentation order of the sound sequences during the test phase as between-subject variables, and numerosity of the sound sequence during the test phase (familiar or novel) as a within-subject variable.

Results

Figure 4 presents the mean duration of looking throughout the experiment, and Table 6 presents the median looking times during the pretest and test trials. Looking times to the slides of two or three objects declined over the familiarization phase, much as they had in Experiment 1, and infants met the criterion of habituation in an average of 8.8 trials in each of the two familiarization conditions.

After familiarization with the displays of two or three objects, infants

Figure 4. *Mean looking time during the familiarization phase and the test phase of Experiment 5.*

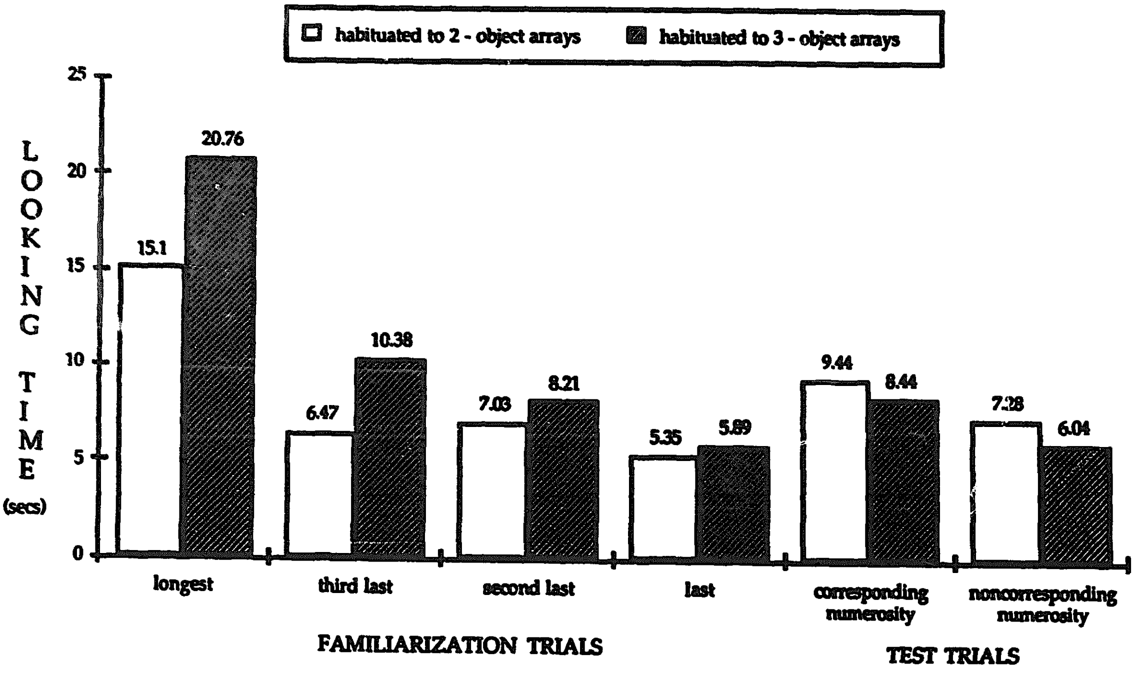


Table 6. *Median duration of looking (s) in Experiment 5*

	Pretest		Test	
Habituation displays	2 sounds	3 sounds	2 sounds	3 sounds
2 objects	7.34	6.59	8.04	5.62
3 objects	7.65	7.34	5.17	8.01

looked longer toward the sound source when it produced numerically familiar sequences than when it produced numerically novel sequences, $F(1, 24) = 10.33$, $p < .005$ (Table 6). Twenty-one of the 32 infants exhibited this preference. No other main effects were significant. Only the presentation order and the numerosity of the sound sequences during the test phase interacted: infants who were presented with the familiar numerosity on the first test trial looked longer during the familiar-numerosity test trials than during the novel-numerosity test trials; whereas infants who were presented with the novel numerosity during the first test trial looked equivalent amounts of time during the familiar- and the novel-numerosity test trials, $F(1, 24) = 4.77$, $p < .05$.

Median looking times on the pretest trials were also log-transformed and compared by a 2 × 2 × 2 × 2 analysis of variance, with numerosity of the pretest sequence (two or three) as a within-subject variable. The analysis of variance revealed that infants looked equivalent amounts of time during the two- and three-drumbeat pretest trials, $F < 1.0$. No main effects and no interactions were significant.

A further analysis compared looking on sound trials of the pretest phase with looking in the test phase. Difference scores were calculated for both phases of the experiment, and these scores were compared. Scores by infants familiarized to displays of two objects were calculated by subtracting log-transformed median looking time to sequences of three sounds from looking time to sequences of two sounds. Scores by infants familiarized to displays of three objects were calculated by subtracting looking time to sequences of two from looking time to sequences of three. Larger difference scores were found in the test phase, $t(31) = 2.54$, $p < .01$, one-tailed. Thus, in the test phase, infants preferred sequences of sounds that were numerically equivalent to displays of objects from the familiarization phase.

Discussion

This experiment provided evidence that infants can detect an intermodal numerical correspondence when sounds and objects are not simultaneous.

Infants responded to the intermodal correspondence by attending more to sound sequences that corresponded in number to the displays of objects they had previously seen.

The direction of preference in this cross-modal habituation experiment – preference for a numerically corresponding display – was the same as in the cross-modal preference experiments (Experiments 2–4). A question one might ask is why infants in the cross-modal habituation experiment (Experiment 5) preferred the corresponding display, rather than the noncorresponding display, on the test trials, given that they preferred the nonequivalent numerosity in the intramodal habituation experiment (Experiment 1). Prior research using cross-modal habituation procedures does not provide a clear answer to this question. Like our subjects in Experiment 5, infants usually show a preference for a corresponding test display (Gibson & Walker, 1984; Meltzoff & Borton, 1979; Ruff & Kohler, 1979), but they sometimes show a preference for a noncorresponding test display (Gibson & Walker, 1984; Gottfried, Rose, & Bridger, 1977; Spelke, 1981).

Both directions of preference have also been observed in research using cross-modal preference procedures. In Experiments 2–4 (above), infants preferred the display that corresponded numerically to the accompanying sequence of sounds. However, in a related experiment by Moore et al. (1987), infants preferred a noncorresponding display over a corresponding one. Several critical aspects of the methodology and the data analysis used in these two sets of studies differed. In both studies, two blocks of trials were presented, and infants were found to be sensitive to intermodal numerical relations in Block II. (Moore et al. (1987) reported no intermodal effect in Block I.) A procedural discrepancy exists in regard to the events that ensued between trial blocks. In our study, Block II began a few seconds after the end of Block I; whereas, in the Moore et al. (1987) study, Block II began after a break of several minutes in which the infant was taken out of the testing room for a short walk. We have reason to believe that this procedural discrepancy was nontrivial.

Analyses we will describe below support the hypothesis that the experimental procedure used by Moore et al. (1987) set up the infants to exhibit a novelty preference rather than a familiarity preference in Block II. The infants had already begun to detect the correspondence between the numerosity of the sound sequence and the numerosity of the corresponding display during Block I, but their activity was interrupted by the break taken after Block I. When subsequently presented with the Block II trials, infants behaved as if they were in the test phase of a standard habituation experiment, exhibiting a novelty preference by looking longer at the noncorresponding display than at the corresponding display.

This hypothesis was supported by an examination of our Block I results from Experiments 2–4 combined. As reported above (Table 5), our infants were already detecting an intermodal numerical correspondence during Block I. Block II followed Block I smoothly and immediately in our experiments, so the infants' activity was not interrupted, and they continued to detect correspondences in Block II.

We obtained further support for the hypothesis by reanalyzing the data collected by Moore et al. (1987), who provided us with raw data on 21 infants. Two infants' data were excluded from our analyses by the criteria for excluding trials and subjects as described in Experiments 1 and 2 above: sessions were to be terminated if infants cried, fell asleep, or failed to attend to the visual stimuli, and infants were to be excluded if they failed to complete Block I. Both infants who were excluded failed to complete Block I. We have no information as to whether these infants failed to attend to the Block I trials due to a state problem or due to lack of interest in the displays. The data on the remaining 19 infants from the Moore et al. (1987) study were analyzed in the same way as the data in Experiments 2–4.

Across the 16 trials of Block I, infants attended to displays of three objects (mean looking time: 2.45 s) longer than they attended to displays of two objects (mean: 1.87 s), regardless of the number of drumbeats presented on a trial, $t(18) = 2.88$, $p < .01$, two-tailed. Across the 16 trials of Block II, infants looked longer at the numerically nonequivalent display (mean: 2.13 s) than at the numerically equivalent display (mean: 1.56 s), $t(18) = 2.99$, $p < .01$, two-tailed. So far, this pattern of findings is the same as the pattern reported by Moore et al. (1987). We next divided the Block I data into halves (trials 1–8 and trials 9–16), as Moore et al. had done in a similar analysis of the Block II data. Our reason for halving the trial block was to determine whether infants exhibited a strong preference for three-object displays early in the block which masked a weaker but significant preference for the numerically corresponding display later in the block. An initial preference for three-object displays would occur if infants tend to visually explore both displays but explore three-object displays longer because these displays contain the greater number of objects to be examined. Later in the block, infants may begin to relate the display to the auditory stimulus and thus detect the intermodal numerical correspondence as indicated by a preference for the numerically corresponding display. Our reanalysis revealed this pattern. Across the final eight trials of Block I, infants looked longer at the numerically *corresponding* display (mean: 2.34 s) than at the numerically noncorresponding display (mean: 1.86 s), $t(18) = 2.19$, $p < .05$, two-tailed. Thus, our finding that infants detect intermodal numerical correspondences was confirmed.

In order to understand why Moore et al. (1987) did not report this effect, we reanalyzed the data from the final eight trials of Block I using their criteria for excluding trials and subjects. Use of their criteria resulted in the exclusion of a large proportion (43%) of the trials and six infants, including the two who had been excluded by our criteria. Under these criteria, the intermodal effect was much diminished (means: 2.42 and 2.27 s to the corresponding and the noncorresponding displays, respectively) and was not statistically significant, $t(14) = 0.87, p > .10$. The criterion that was primarily responsible for diminishing the intermodal effect was one that deleted from the database the trials in which infants did not look at both displays. No rationale was given for deleting these trials We believe that trials in which infants look at only one display should be included in the experiment: infants could be attempting to relate the display to the accompanying audible stimulus. If infants are already detecting intermodal correspondences and, on a given trial, happen to look at the corresponding display first, there would be no reason for them subsequently to look at the other display. Moore et al. (1987), therefore, excluded a large number of trials in which infants were engaged in cross-modal matching. To summarize, the Block I finding of Moore et al. (1987) confirms our finding that infants can detect intermodal numerical correspondences. This suggests that the correspondence phenomenon would have persisted into their second block, as it did in ours, had Moore et al. (1987) not introduced a methodological change: including a break of several minutes between Block I and Block II may decrease the likelihood of a continuing familiarity preference and increase the likelihood of provoking a novelty preference. Accordingly, their Block II finding reveals that the direction of infants' preference in intermodal experiments can be influenced by aspects of the methodology.

The preference patterns we observed in Experiments 2–4 and in our reanalysis of the data collected by Moore et al. (1987) also constitute evidence against a model of the interaction of sensory modalities during infancy which has been used to explain preference patterns (Lawson & Turkewitz, 1980; Lewkowicz & Turkewitz, 1981). According to this model, young infants seek an "optimal" level of stimulation which is the sum of stimulation from different modalities. Moore et al. (1987) invoke this model to explain infants' cross-modal numerical preferences. They argue that the noncorresponding sets in their experiment (i.e., two sounds with three objects or three sounds with two objects) produced an "optimal" level of stimulation; whereas, the corresponding sets produced too little stimulation when two sounds were paired with two objects and too much stimulation when three sounds were paired with three objects. They further argue that differences between our stimuli and theirs, specifically, in the loudness or pitch of the sounds and in the size and brightness of the visible displays, account for the directional differences in infants' preferences. Our data and their Block I data, however, do not support the Moore et al. (1987) version of the above model: two sounds paired with two objects would produce the lowest level of stimulation and three sounds paired with three objects would produce the highest level. Infants were found to prefer precisely these pairings, a finding exactly opposite to that predicted by Moore et al. (1987).

In conclusion, research on cross-modal phenomena in infants has begun only recently, and little is known about the factors that lead to a particular pattern of preference when cross-modal habituation or cross-modal preference procedures are used (see Walker-Andrews & Gibson, 1986, and Spelke, 1984a, for discussions). In any case, Experiment 5 provided further evidence that infants are sensitive to numerical information. Detection of this information does not depend on processes of scanning visible objects in time with an accompanying sequence of sound. Infants can detect intermodal numerical correspondences by virtue of mechanisms that operate separately on audible events and on visible scenes.

General discussion

These experiments provide evidence that infants detect numerical correspondences. Infants not only perceive colors and sounds, shapes and movements, they also detect the number of distinct entities in a sequence of sounds or a visible scene. Furthermore, infants can relate the number of entities in one set to the number in another set, at least in regard to the equivalence or nonequivalence of the numerical magnitudes of the sets. They compute this relation even when the entities are objects and events that are presented in different modalities and bear no natural relation to one another. Infants thus detect relations not just between entities themselves but between sets of entities as well.

This finding suggests that infants are able to operate at a remarkably abstract level, a level that could serve as a starting point for numerical reasoning. In order to engage in numerical reasoning, it is necessary to have some knowledge of the types of relations into which numbers can enter. Our findings indicate knowledge of equivalence and nonequivalence relations. Further research is needed to investigate the point in development at which knowledge of other types of relations is first present. Research is just beginning on infants' and toddlers' knowledge of the ordinal numerical relations, *more than* and *less than* (see Cooper, 1984; Strauss & Curtis, 1984), and numerical functions or operations such as addition (see Klein & Langer, 1987; Starkey, 1983, 1987). Investigations of these capacities may help elucidate the nature of the relationship between numerical abilities which are present during infancy and the subsequent development of mathematical thought.

Our experiments have begun to shed light on the processes that subserve infants' numerical abilities. They provide evidence against the view that early numerical abilities derive exclusively from a visual numerosity detection process. Infants clearly can perform at least one numerical computation – establishing a one-to-one correspondence – on representations of sets of entities.

In order to perform this type of computation, infants must represent sets of visible or audible entities in a way that preserves the discreteness of individual entities and yet colligates the entities comprising the set. We will speculate about two possible ways of accomplishing this. First, infants may perform one-to-one correspondence computations on analogical representations of sets. For example, they may compute correspondences between discrete entities in a visible (or remembered) scene and discrete entities in a sequence of sounds directly by pairing objects and sounds. Alternatively, infants may utilize some of the component processes of counting. They might, using symbols that Gelman and Gallistel (1978) call numerons, tag the objects in a visible scene, tag the sounds in the sequence, and then compare the results of both. The one-to-one correspondence would thus be made indirectly through a symbolic intermediary. In either case, infants must be granted a capacity to establish a one-to-one correspondence – either a correspondence between a set of visible or remembered objects and set of sounds, or a correspondence between a set of objects or sounds and a specific set of internal symbols.

As these questions suggest, the study of the developmental foundations of knowledge of number has only begun. Our research shows, nevertheless, that these foundations are present in human infancy. The emergence of the first numerical abilities does not depend on the development of language, the development of complex actions, or the acquisition of a culture-specific counting system, though skilled counting clearly takes advantage of such developments. Our finding may help explain why counting and other numerical abilities develop so early, so spontaneously, and so universally across human cultures. Central aspects of these abilities are already present during infancy.

Our work, along with that of others, suggests that number is a natural domain of cognition, with foundations of its own. The work supports an approach to cognitive development that is both domain specific and rationalist. Infants do not appear to be endowed only with general all-purpose abilities to sense and learn. They seem to have capacities to form and transform representations in particular domains of knowledge: knowledge of space (e.g., Landau, Spelke, & Gleitman, 1984; Pick, Yomas, & Rieser, 1978), knowledge of objects and physical causality (Leslie, 1982; Spelke, 1984b), and perhaps knowledge of persons (see Damon & Hart, 1982, for a review), as well as knowledge of number. In each of these domains, children's knowledge will undergo development. Nevertheless, structures and principles of adult functioning are discernible near the beginning of life, before the acquisition of language and the assimilation of culture.

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