

Newborn infants perceive abstract numbers

Véronique Izard^{a,1}, Coralie Sann^b, Elizabeth S. Spelke^a, and Arlette Streri^b

^aDepartment of Psychology, Harvard University, 33 Kirkland Street, Cambridge, MA 02138; and ^bUniversité Paris Descartes, Laboratoire Psychologie de la Perception, Centre National de la Recherche Scientifique Unité Mixte de Recherche 8158, Paris, France

Edited by Charles R. Gallistel, Rutgers, The State University of New Jersey, Piscataway, NJ, and approved May 5, 2009 (received for review November 28, 2008)

Although infants and animals respond to the approximate number of elements in visual, auditory, and tactile arrays, only human children and adults have been shown to possess abstract numerical representations that apply to entities of all kinds (e.g., 7 samurai, seas, or sins). Do abstract numerical concepts depend on language or culture, or do they form a part of humans' innate, core knowledge? Here we show that newborn infants spontaneously associate stationary, visual-spatial arrays of 4–18 objects with auditory sequences of events on the basis of number. Their performance provides evidence for abstract numerical representations at the start of postnatal experience.

development | numerical cognition | cognitive

Are humans endowed with abstract representations of the surrounding world? In the domain of number, animals and preverbal infants have been shown to react to the cardinal values of sets presented in a variety of different stimulus formats, and this core number sense is thought to guide learning of numeric symbols and arithmetic in human children and adults (1–5). For example, by the age of 4.5 to 6 months, infants are able to discriminate between numbers differing in a 1:2 ratio (e.g., 16 vs. 32, 8 vs. 16, 4 vs. 8), when presented with arrays of dots (6, 7), sequences of sounds (8), or sequences of actions (9). In each of these experiments, however, infants were tested with only 1 type of stimulus, raising the question of the level of abstraction of these numeric representations.

From the early 1980s to present, several investigations have tested for numeric cross-modal matching in infants with mixed results. Although infants initially were reported to look longer at a set of objects that matched a sequence of sounds played simultaneously (10, 11), subsequent experiments yielded either no such preference (12) or a reversed preference (13). Failures to match sounds and objects on the basis of number have been documented until 3–4 years of age, eventually resolving as children start to master verbal counting (14). By using more natural stimuli, later research showed unequivocally that infants and animals could detect the numerical correspondence between 2 or 3 items in different modalities (15–18). In all of these studies, however, matching was elicited either by drawing on cross-modal correspondences that were familiar [faces and voices (15, 16) or objects with similar features presented across the visual and tactile modalities (18)], or by presenting a familiarization phase in which events in different modalities occurred in synchrony (17). In these situations, cross-modal matching might be achieved by calling on amodal representations of objects rather than amodal representations of abstract, cardinal values. For example, presentation of a voice may elicit an image of a face; when 3 distinct voices are played, therefore, infants may represent 3 correspondingly distinct faces that then can be quantified and compared to a matching or nonmatching visual stimulus. Indeed, the numbers tested in these studies were small enough to allow for simultaneous object representations (3 objects at most); infants failed to respond to amodal correspondences when tested with larger numbers (18). In sum, infants appear able to construct amodal representations of faces and other objects, but they may not match sets of unrelated objects and events on the basis of their common abstract, cardinal value.

Still, some lines of evidence suggest that infants might possess abstract number representations. First, infants discriminate numbers with the same precision in all modalities (19). Second, in monkeys, children and adults, the representation of numerical information involves an area in the intraparietal sulcus that responds to numbers presented in a variety of formats (20–25); a precursor of this intraparietal activation has been found in infants as young as 3 months of age (26). Third, presentation of redundant information in the auditory and visual modalities increases the precision of infants' numerical discriminations (27), although it is not clear whether the convergence of information occurs at the level of numerical representation or at a later processing step (e.g., response selection). Moreover, auditory and visual events were presented in synchrony, and therefore, here again, numerical matching may have been grounded in amodal representations of individual events, not in an abstract representation of the cardinal values of the sets.

Clear evidence for abstract numerical representations comes from studies of trained animals and of human children and adults who are presented with sets where cardinal values exceed the limits of object-based attention (beyond 3). For example, monkeys trained to match numerical values (2, 3, 5, 8) across auditory and visual formats were able to generalize this competence to all numbers up to 9 (28). However, the animals developed this ability only after thousands of training trials involving sequences of visual and auditory events presented in synchrony, that could have induced the formation of abstract representations by association of modality-specific number representations. Evidence for generalization of numerical quantities across modalities has also been reported in rats (29, 30). After learning to associate 2 response levers to auditory sequences differing in number, rats generalized the trained responses to new sequences mixing auditory and tactile stimuli, even though they were never reinforced on such compound sequences (29). Moreover, rats showed a cost for learning new associations between response levers and visual sequences if the mapping did not match the associations learned in the auditory modality (30). In both these conditions, however, the initial training may have induced the animals to form abstract representations of relative quantity (less/more), rather than number (31), leaving open the question of whether animals spontaneously form abstract number representations.

In contrast, human adults and 5-year-old children show evidence for spontaneous, abstract concepts of number. For example, they can compare numerical quantities presented in different formats and modalities as easily as they compare numbers within 1 modality and format (32, 33), with no specific training at matching formats. Nevertheless, these adults and children have already mastered symbols that refer to abstract numbers,

Author contributions: V.I., E.S.S., and A.S. designed research; V.I., C.S. and A.S. performed research; V.I. and C.S. analyzed data; and V.I., C.S., E.S.S., and A.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

¹To whom correspondence should be addressed. E-mail: veronique.izard@polytechnique.org.

This article contains supporting information online at www.pnas.org/cgi/content/full/0812142106/DCSupplemental.

Familiarization (2 min)

... " tu-tu-tu-tu-tu-tu-tu-tu-tu-tu " ... " ra-ra-ra-ra-ra-ra-ra-ra-ra-ra " ...
or
... " tuuuuu-tuuuuu-tuuuuu-tuuuuu " ... " raaaaa-raaaaa-raaaaa-raaaaa " ...

Test (4 trials)

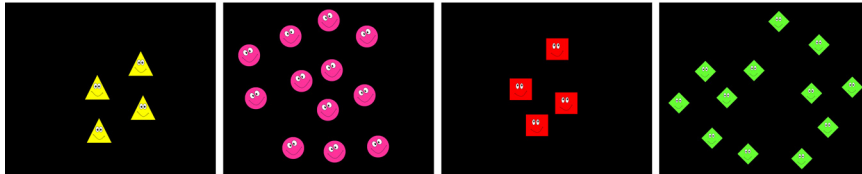


Fig. 1. Newborn infants were familiarized with auditory sequences containing a fixed number of syllables, and were then tested with images of the same or a different number of items (here 4 or 12). Auditory sequences were equated across numbers on extensive parameters (total duration), and visual arrays were equated on intensive parameters (size of each item, density of the array).

therefore, raising the possibility that abstract representations of number arise only with the acquisition of numeric symbols. In sum, no experiments yet reveal whether abstract numerical representations are spontaneously available to any species.

The absence of a spontaneous generalization of number across modalities and formats could be explained in 2 ways. First, infants and animals may possess neural mechanisms for representing numbers of objects and numbers of events, but the 2 types of numerical representations may be functionally distinct. In the absence of language, there may exist no truly abstract numerical representations. Second, animals and infants may possess abstract numerical representations, but those representations may be overshadowed by the salient differences between objects and events. On the former view, abstract numerical representations are a product of language and culture; on the latter view, language and culture make more prominent a preexisting representational capacity.

The present experiments sought direct evidence for the detection of numerical correspondences across modalities in newborn human infants. In contrast to older infants, newborn infants have sharply diminished sensitivity to the visual and auditory features that characterize specific objects and events (34). Nevertheless, they are sensitive to abstract geometric properties of objects (35) and actions (36). Perceptual development has been proposed to begin with sensitivity to these abstract distinctions and proceed to an analysis of more concrete ones (37). If humans and animals are endowed with abstract numerical representations, therefore, these representations may be more prominent to newborn infants than to older children.

Accordingly, we conducted 3 experiments assessing newborn infants' cross-modal discrimination among large numbers of objects. Each infant was familiarized with sequences of syllables repeated a fixed number of times in a continuous auditory stream. After 2 min of familiarization, looking time was tested with 4 visual images containing either the same number of objects as the auditory sequences (congruent number), or a different number (incongruent number). To prevent matching of visual and auditory stimuli on a non-numerical stimulus dimension, the familiarization and test stimuli varied using procedures that controlled for a host of quantitative variables including intensity, duration, and spatial or temporal frequency (see *Methods* and Fig. 1). In each experiment, infants were tested with a pair of numbers in a design that counterbalanced both the numerical value of the familiar and novel numbers and the order of the congruent and incongruent tests.

Results

In the first experiment, infants were familiarized with sequences of either 4 or 12 sounds, accompanied by visual arrays of either 4 or 12 objects. Newborn infants in both familiarization conditions looked longer at the visual image with the matching number of objects (15 out of 16 infants showed this preference; $T_{(15)} = 5.3$, $P < 0.0001$, see Fig. 2). To examine the generality of this finding, a new group of infants were tested in a second experiment with auditory sequences and visual arrays of either 6 or 18 sounds and objects. Again, the infants looked longer at the matching visual array (15 out of 16 infants; $T_{(15)} = 6.0$, $P < 0.0001$). The preference for the numerically matching image was equivalent in the 2 experiments, showing no effect of numerical size on the infants' performance ($F_{(1,30)} < 1$). Accordingly, the last experiment tested for an effect of ratio on the infants' performance by presenting auditory sequences and visual arrays of 4 vs. 8 elements. In contrast to the previous experiments, infants showed only a weak preference for the numerically matching display (11 out of 16 infants looked more at the congruent image; $T_{(15)} = 1.9$, $P = 0.071$). A comparison across experiments revealed a reliable effect of numerical ratio on the infants' performance (3:1 vs. 2:1 ratio; $F_{(1,46)} = 8.7$, $P = 0.0050$). Newborn infants, therefore, show the ratio-dependent numerical processing that is characteristic of older children and adults*.

Discussion

In the present experiments, human newborns responded to abstract numerical quantities across different modalities and formats (sequential vs. simultaneous). In previous research, older infants had shown evidence for intermodal numerical matching, but only under conditions in which matching could be

*Looking times were analyzed with a general ANOVA including the results of all 3 experiments. The ANOVA included 3 between-participants factors (experiment: 4 vs. 12, 6 vs. 18, or 4 vs. 8; number used in habituation: smaller or larger; order of presentation of the test images: congruent or incongruent first) and 2 within-participant factors (test condition: congruent or incongruent; trial number: first or second images pair). This analysis revealed a main effect of test ($F_{(1,36)} = 53.8$, $P < 0.0001$) and an interaction between test and experiment ($F_{(2,36)} = 4.0$, $P = 0.027$), which correspond to the effects reported in the main text. In addition, we observed a decrease in looking time between the first and second image pairs ($F_{(1,36)} = 7.6$, $P = 0.0090$), and differences in average looking time across experiments ($F_{(2,36)} = 6.0$, $P = 0.0058$), revealing that infants tended to look longer when the arrays contained more objects. Crucially, however, this effect cannot explain the main findings, because the number used as familiarization (smaller or larger) was counterbalanced across participants. Finally, the preference for the congruent number interacted with the order of presentation of test trials and the trial number in a 4-way interaction between experiment, test condition, order of test images, and trial number ($F_{(2,36)} = 5.3$, $P = 0.0095$).

image was limited to 60 s, all looking times fall within 2.5 standard deviations of the mean, and therefore no outlier was excluded from the analyses.

ACKNOWLEDGMENTS. We thank Aurélie Coubart, Josette Serres, and Louise Goyet for technical support, and Pr. Dominique Mahieu-Caputo, Laetitia de

Lorgerie, and the staff of the Maternity in Hôpital Bichat (Paris) for providing research space and access to newborn infants. This work was supported by a Institut Universitaire de France grant (A.S.), grants from National Institutes of Health and National Science Foundation (E.S.S.), and a travel grant of the French Ministry of Research (V.I.).

1. Dehaene S (1997) *The Number Sense: How the Mind Creates Mathematics* (Oxford Univ Press, New York).
2. Butterworth B (1999) *The Mathematical Brain* (Macmillan, London).
3. Feigenson L, Dehaene S, Spelke E (2004) Core systems of number. *Trends Cogn Sci* 8:307–314.
4. Gilmore CK, McCarthy SE, Spelke ES (2007) Symbolic arithmetic knowledge without instruction. *Nature* 447:589–591.
5. Halberda J, Mazocco MM, Feigenson L (2008) Individual differences in non-verbal number acuity correlate with maths achievement. *Nature* 455:665–668.
6. Xu F, Spelke ES (2000) Large number discrimination in 6-month-old infants. *Cognition* 74:B1–B11.
7. Xu F (2003) Numerosity discrimination in infants: Evidence for two systems of representations. *Cognition* 89:B15–B25.
8. Lipton JS, Spelke ES (2003) Origins of number sense. Large-number discrimination in human infants. *Psychol Sci* 14:396–401.
9. Wood JN, Spelke ES (2005) Infants' enumeration of actions: Numerical discrimination and its signature limits. *Dev Sci* 8:173–181.
10. Starkey P, Spelke ES, Gelman R (1983) Detection of intermodal numerical correspondences by human infants. *Science* 222:179–181.
11. Starkey P, Spelke ES, Gelman R (1990) Numerical abstraction by human infants. *Cognition* 36:97–127.
12. Mix KS, Levine SC, Huttenlocher J (1997) Numerical abstraction in infants: Another look. *Dev Psychol* 33:423–428.
13. Moore D, Benenson J, Reznick JS, Peterson M, Kagan J (1987) Effect of auditory numerical information on infants' looking behavior: Contradictory evidence. *Dev Psychol* 23:665–670.
14. Mix KS, Huttenlocher J, Levine SC (1996) Do preschool children recognize auditory-visual numerical correspondences? *Child Dev* 67:1592–1608.
15. Jordan KE, Brannon EM (2006) The multisensory representation of number in infancy. *Proc Natl Acad Sci USA* 103:3486–3489.
16. Jordan KE, Brannon EM, Logothetis NK, Ghazanfar AA (2005) Monkeys match the number of voices they hear to the number of faces they see. *Curr Biol* 15:1034–1038.
17. Kobayashi T, Hiraki K, Hasegawa T (2005) Auditory-visual intermodal matching of small numerosities in 6-month-old infants. *Dev Sci* 8:409–419.
18. Féron J, Gentaz E, Streri A (2006) Evidence of amodal representation of small numbers across visuo-tactile modalities in 5-month-old infants. *Cogn Dev* 21:81–92.
19. Feigenson L (2007) The equality of quantity. *Trends Cogn Sci* 11:185–187.
20. Piazza M, Izard V (2009) How humans count: Numerosity and the parietal cortex. *Neuroscientist* 15:261–273.
21. Piazza M, Izard V, Pinel P, Le Bihan D, Dehaene S (2004) Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron* 44:547–555.
22. Piazza M, Pinel P, Le Bihan D, Dehaene S (2007) A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron* 53:293–305.
23. Eger E, Sterzer P, Russ MO, Giraud AL, Kleinschmidt A (2003) A supramodal number representation in human intraparietal cortex. *Neuron* 37:719–725.
24. Venkatraman V, Ansari D, Chee MW (2005) Neural correlates of symbolic and non-symbolic arithmetic. *Neuropsychologia* 43:744–753.
25. Nieder A, Diester I, Tudusciuc O (2006) Temporal and spatial enumeration processes in the primate parietal cortex. *Science* 313:1431–1435.
26. Izard V, Dehaene-Lambertz G, Dehaene S (2008) Distinct cerebral pathways for object identity and number in human infants. *PLoS Biol* 6:e11.
27. Jordan KE, Suanda SH, Brannon EM (2008) Intersensory redundancy accelerates pre-verbal numerical competence. *Cognition* 108:210–221.
28. Jordan KE, Maclean EL, Brannon EM (2008) Monkeys match and tally quantities across senses. *Cognition* 108:617–625.
29. Meck WH, Church RM (1983) A mode control model of counting and timing processes. *J Exp Psycho Anim Behav Process* 9:320–334.
30. Church RM, Meck WH (1984) The numerical attribute of stimuli. *Animal Cognition*, eds Roitblat HL, Bever TG, Terrace HS (Erlbaum, Hillsdale, NJ), pp 445–464.
31. Davis H, Albert M (1987) Failure to transfer or train a numerical discrimination using sequential visual stimuli in rats. *Bull Psychonomic Soc* 25:472–474.
32. Barth H, Kanwisher N, Spelke E (2003) The construction of large number representations in adults. *Cognition* 86:201–221.
33. Barth H, La Mont K, Lipton J, Spelke ES (2005) Abstract number and arithmetic in preschool children. *Proc Natl Acad Sci USA* 102:14116–14121.
34. Kellman PJ, Arterberry ME (2000) *The Cradle of Knowledge: Development of Perception in Infancy* (MIT Press, Cambridge, MA), p 383.
35. Meltzoff AN, Borton RW (1979) Intermodal matching by human neonates. *Nature* 282:403–404.
36. Meltzoff AN, Moore MK (1977) Imitation of facial and manual gestures by human neonates. *Science* 198:75–78.
37. Gibson EJ (1969) *Principles of Perceptual Learning and Development* (Appleton-Century-Crofts, New York).
38. Hauser MD, Tsao F, Garcia P, Spelke ES (2003) Evolutionary foundations of number: Spontaneous representation of numerical magnitudes by cotton-top tamarins. *Proc Biol Sci* 270:1441–1446.
39. Xu F, Arriaga RI (2007) Number discrimination in 10-month-old infants. *Br J Dev Psychol* 25:103–108.
40. Halberda J, Feigenson L (2008) Developmental change in the acuity of the "Number Sense": The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Dev Psychol* 44:1457–1465.
41. Wilson AJ, Dehaene S (2007) Number sense and developmental dyscalculia. *Human Behavior, Learning and the Developing Brain: Atypical Development*, eds Coch D, Dawson G, Fisher K (Guilford, New York).