Do constraints on word meanings reflect prelinguistic cognitive architecture?

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Children learn new words at a prodigious rate, over nine words a day during early childhood. Further, they often converge on the adult meaning of a new word after hearing it only a few times in a single context. As many have noted, the inductive processes that underlie such efficient word learning must be highly constrained. One source of constraint derives from the fact that words in different syntactic categories differ systematically in meaning. Young children exploit information about syntactic subcategorization to inform their hypotheses about word meanings.

This paper asks to what extent such constraints reflect prelinguistic cognitive architecture, i.e., conceptual distinctions antecedently available to constrain syntax acquisition as well as word learning, and to what extent such constraints reflect language specific, culturally constructed, conceptual categories which must be induced in the course of language learning. This question is explored via a case study within the domain of noun semantics and the representation of number, five aspects of which are examined: the representations of integers in counting sequences ("one, two, three..."), quantifiers such as one, another, the criteria for individuation and identity embodied in the sortal concepts the language lexicalizes, the distinction between count and mass nouns, and the distinction between count nouns and predicates.

In this paper I sketch data from infant studies that suggest that all but the first of these (the representations of integers) are part of prelinguistic cognitive architecture. These elements of constraints on word meanings are not induced from language learning; rather language learning, including lexical learning, builds upon them.

Keywords: infant mental representation, lexical development, numerical concepts, criteria for individuation

1. Introduction

Acquiring a lexicon poses all the classic problems of induction. Every use of a new word is consistent with a vast number of hypotheses concerning the word's meaning and yet children usually converge quickly onto the adult meaning of new words, often after just one or a few encounters with them (a process called "fast mapping;" Carey, 1978; Markman, 1989). As in all cases of successful induction, this process requires constraints on the space of hypotheses the learner entertains. Therefore, any theory of lexical development requires a characterization of the constraints on lexical meanings that enable efficient learning, as well as an account of their origin. Many researchers have contributed to this enterprise (e.g., Bloom, 1994; Carey, 1978, 1982; Clark, 1987; Gleitman, 1990; Landau, 1994; Markman, 1994; Osher-

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son, 1978; Soja, Carey, & Spelke, 1991, 1992; Waxman, 1994).

Two closely related controversies enliven this literature. First (the nativist/empiricist debate): to what extent are the constraints on word meanings innate and to what extent are they learned, abstracted from patterns of lexical meanings acquired to date? Second (the universality/Whorfian debate): to what extent are constraints on word meanings universal across natural languages and to what extent does each lexicon reflect language unique conceptual packaging of experience? These two dimensions are interrelated; nativism favors universality and empiricism favors Whorfianism. However, they do not collapse upon each other; many mixed positions occupy the logical space of theories of lexical development.

Constraints on lexical meanings are of many types. Some, such as Clark's contrast principle (the principle that words tend to contrast with each other in meaning), apply to all words (Clark, 1987). Others are specific to classes of words, especially classes determined by syntactic subcategorizations. For example, many have attempted to characterize the constraints on possible meanings of newly heard count nouns, suggesting for example that children project the meanings of count nouns to other individuals of the same kind as the original referent (Bloom, 1994), or to other whole objects of the same kind as the original referent (Markman, 1994; Soja et al., 1991, 1992) or to whole objects of the same shape as the original referent (Landau, Smith, & Jones, 1988). Similarly, it has been suggested that newly heard mass nouns are projected to other nonindividuated entities of the same kind as the original referent (Bloom, 1994), or to other substances of the same kind as the original referent (Soja et al., 1991) or on the basis of color and texture (Landau, 1996). Many researchers have explored the role of syntactic information in constraining the meanings of newly heard words, finding effects as early as late toddlerhood (e.g., adjective/noun: Waxman, 1994; Landau, Smith, & Jones, 1992; object/preposition, Landau, 1994; verb subcategorization: Gleitman, 1990; Naigles, Gleitman, & Gleitman, 1993, count/mass distinction: Soja, 1992; Bloom, 1994; Brown, 1957; proper/common distinction: Katz, Baker, & Macnamara, 1974; Gelman & Taylor, 1984; Hall, 1991, 1994, 1996).

The early use of syntactic information in constraining hypotheses about word meaning is often given a nativist/universality interpretation (e.g., Macnamara, 1982, Gleitman, 1990; Pinker, 1984). These writers begin with the observation that there is a distinction between concepts that are grammaticized in natural languages of the world (e.g., number), and those that are not (e.g., color). They posit that all languages draw on the same small set of grammaticized notions, although each language exploits only a subset. Language learning is then a complex mapping problem—discovering which of the set of possible grammaticized notions are exploited in the language being learned and how. Each grammaticized notion constrains the meanings of all the lexical items that share a syntactic subcategorization (e.g., in English, count nouns vs. mass nouns, nouns vs. adjectives, transitive vs. intransitive verbs). The child's discovery of which grammatical distinctions are exploited in a given language makes available a powerful source of constraints on the meanings of newly heard words.

This view admits of a certain degree of nonuniversality. On it, the language acquisition faculty includes antecedently the whole stock of grammaticized notions. Those grammatical distinctions not expressed in a given language are lost (e.g., nouns in Japanese are not obligatorily marked for count/mass status), just as those phonemic distinctions not expressed in a given language are lost early in infancy if a language does not exploit them (e.g., the r/l distinction in Japanese).

This position differs from an extreme empiricism/Whorfianism, in which the conceptual categories of each language are cultural constructions mastered anew by each child as he/she masters the language which embodies them. On the Whorfian alternative, those conceptual categories that are syntactically marked are no different from other concepts as far as being cultural constructions, but they are particularly important, because they are marked with every use of relevant constructions—every noun phrase, every verb—and thus serve to entrench a cultural and language specific experience of the world.

There is a long history of attempts to decide with a priori arguments the debates between nativism and universality, on the one hand, and empiricism and Whorfianism, on the other (see for example, the philosophical literature on the nativist/empiricist debate, with its history back to the Greeks, and its flowering in the debates between the British empiricists and Kant). Ultimately, of course, it is an empirical issue. In this paper, I sketch one approach to bringing empirical data to bear on these debates. The research program has several steps: first, identify candidates of universally grammaticized notions. Second, establish whether these articulate the mental representations of prelinguistic human infants. Insofar as they do, the nativist/universality position receives support. Third, for conceptual resources marked in languages that do not articulate infant representations of their word, establish when these conceptual resources become available to children, and explore the mechanisms by which they do so. These latter cases are candidates for empiricist and Whorfian influences.

My example here concerns aspects of noun semantics and the expression of numerical concepts in thought and language.

2. The expression of number and sortal concepts in human language

Not all languages have a counting sequence that expresses natural numbers. Nonetheless, numerical concepts are universally reflected in grammaticized contrasts, the most important numerical primitive being the concept one. Number is typically grammatically marked on both nouns and verbs, usually reflecting the basic distinction between one/many (singular plural), or sometimes reflecting three distinctions: one/two/many. In addition, noun quantifiers express numerical concepts (e.g, "an, another, few, many"). "An" expresses one, "another" expresses numerically distinct individual, and "few/many/some" all express subtly different contrasts from one. Finally, all languages have a grammatical particle that expresses numerical identity, sameness in the sense of same one.

"One" must be applied to an individuated entity. Thus, languages must represent concepts (called sortals) which pick out individuals. Sortals have been extensively studied in the philosophical literature on logic and semantics (Wiggins, 1967, 1980; Hirsch, 1992; see Macnamara, 1987; Xu & Carey, in 1996, for a discussion of sortal concepts within the context of psychological studies of concepts) In languages with a count/mass distinction, sortal concepts are expressed by count nouns, naturally, which is why they are called "count nouns"; they provide the criteria for individuation and numerical identity that enable entities to be counted. Recently Lucy (1992) has argued for language variation in the dividing line between grammatically individuated entities and nonindividuated entities (e.g., some languages individuate only people, others only people and animals, others only people, animals and inanimate objects, and still others, such as English, people, animals, artifacts with complex structure, plus any objects that are bounded, coherent, wholes which maintains their boundaries as they move through space, plus a variety of abstract entities such as opinions and naps). Note that this cross linguistic variation does not deny that all languages mark the distinction between individuated and nonindividated entities, even if nouns are not marked for count/mass status.

The final contrast we will explore here is that between the concepts that establish the individuals in the world (sortals) and the properties that can be attributed to them (predicates). This distinction is reflected grammatically in the distinction between nouns and verbs/adjectives.

Thus, number is reflected in language in five different but interrelated ways, explicitly in counting sequences ("one, two, three..."), grammatically in number markers on nouns and verbs and in quantifier systems, in the criteria for individuation and identity embodied in the sortal concepts the language lexicalizes, in the distinction between count and mass nouns, and in the distinction between count nouns and predicates. In the following sections, I ask which, if any, of these five representational resources language makes use of in expressing numerical concepts are available to prelinguistic infants.

3. Object as a primitive sortal, the quantifiers one, another

Piaget was the first to attempt to bring empirical data to bear on the question of whether human infants have a representation of objects as existing apart from themselves, apart from their own actions upon them and apart from their perceptual contact with them. Studies of object permanence are, in part, studies of criteria for numerical identity, for they involve the capacity to establish a representation of an individual, and trace this individual through time and through loss of perceptual contact. When we use the term "object permanence" to describe the baby's knowledge, we presuppose that he/she recognizes that the object retrieved from behind the barrier is the same one as the one that was hidden.

Piaget, of course, did not believe that prelinguistic infants have the capacity to establish representations of permanent, individuated, objects. In his celebrated studies of infants' reaching for hidden objects, he charted a protracted developmental sequence from failing to reach for hidden objects altogether, to perseverative errors (A, not B errors), to finally being able to reason about invisible displacements, which he took as conclusive evidence for representations of object permanence (Piaget, 1955). Piaget saw the achievement of this representational capacity as part of the transition to symbolic thought, intimately bound up with the early stages of language acquisition.

In the past ten years, massive evidence has become available revealing that Piaget's reaching studies underestimated infants' conceptual resources. Babies as young as 2 1/2 to 3 months represent the continued existence of objects that have gone behind barriers (Baillargeon & DeVos, 1991) and have spatiotemporal criteria for individuation and numerical identity of objects (criteria such as one object cannot be in two places at once; objects trace spatiotemporally continuous paths; Spelke, 1991; Spelke, Kestenbaum, Simons, & Wein, 1995; Xu & Carey, 1996). The research exploits a recently developed method for characterizing human infants' spontaneous cognitive capacities: the "violation of expectancy method" which measures visual preference for impossible events over possible events (Spelke, 1985). Put simply, babies stare at the outcomes of magic tricks more than at the outcomes of ordinary events. This fact enables us to separate knowledge that they have from that they don't have (after all, they must be sensitive to the impossibility of a given magic trick to respond to it). If we are clever we can design studies that constrain our theories of how that knowledge is represented.

Many experiments using the violation of expectancy method support the conclusion that very young babies represent object permanence. Here I briefly describe two, chosen because they illuminate the relation between object permanence, on the one hand, and spatiotemporal criteria for individuation and numerical identity of objects, on the other, and because they also show that prelinguistic infants' representations are quantified by one and another.

Spelke et al. (1995) showed that 4 1/2 month old babies do not merely expect objects to continue to exist through time, when out of view, but also that they interpret apparent evidence for spatiotemporal discontinuity as evidence for two numerically distinct objects. Infants were shown two screens on a stage, from which objects emerged as in Figure 1. The objects were never visible together; their appearances were timed so that the movements would be consistent with a single object going back and forth behind the two screens, except that no object ever appeared in the space between the screens. Rather, one object emerged from the left edge of the left screen and then returned behind

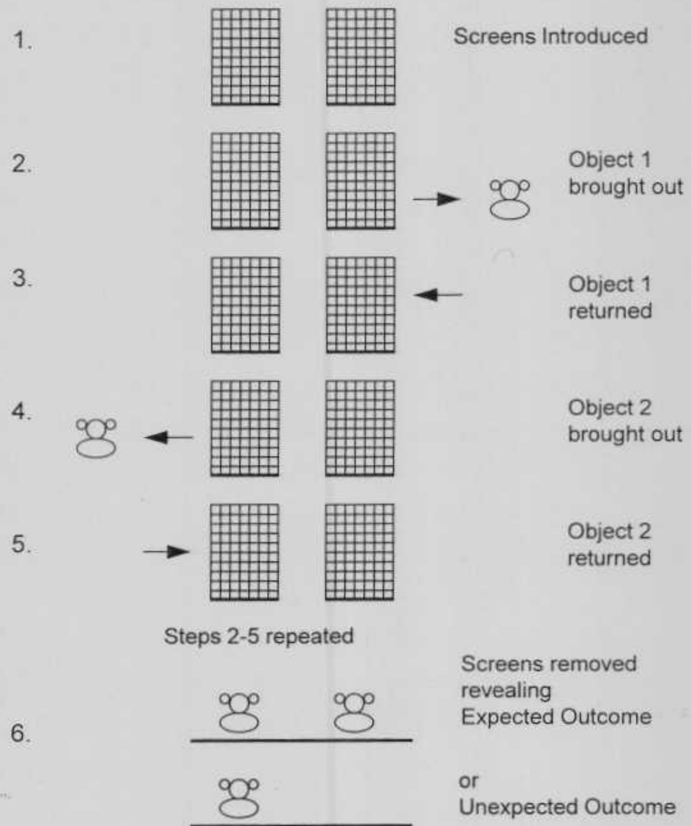

Figure 1 Procedure for probing infants' spatiotemporal criteria for individuation. From Xu & Carey (1996); modeled on Spelke, et al. (1995).

that screen, and after a suitable delay, a second object emerged from the right edge of the right screen and then returned behind it. Babies were habituated to this event. Adults draw the inference that there must be two numerically distinct objects involved in this display, for objects trace spatiotemporally continuous paths—one object cannot get from point A to point B without tracing some continuous trajectory between the points. Spelke et al.'s babies made the same inference. If the screens were removed and only one object was revealed, they were surprised, as shown by longer looking at outcomes of one object than at the expected outcome of two objects. Control experiments established that infants were indeed analyzing the path of motion, and not, for example, expecting two objects just because there were two screens. That is, a different pattern of results obtains if an object appeared between the screens as it apparently went back and forth, emerging as before from either side. (See Xu & Carey, 1996, for a replication with 10-month-olds). These data show:

(1) Infants know that objects continue to exist when they are invisible behind barriers.

(2) Infants distinguish one object from two numerically distinct but physically simi-

lar objects (i.e., they have criteria for object individuation and numerical identity, and they distinguish one object from one object, another object.).

(3) Infants use spatiotemporal criteria for object individuation; if there is no spatiotemporally continuous path between successive appearances of what could be one or more than one object, they establish representations of at least two numerically distinct objects.

Additionally, Wynn's (1992a, 1995) studies of infants' abilities to add and subtract provide further conclusive evidence that infants represent object permanence, and that spatiotemporal criteria determine object individuation and numerical identity. Wynn (1992a) showed 4 1/2 month-old infants an object, a Mickey Mouse doll, placed on a stage. She then occluded the doll from the infant's view by raising a screen, introduced a second doll behind the screen, and then showed the infant an empty hand withdrawing from behind the screen. Then she lowered the screen, revealing either the possible outcome of 2 objects, or the impossible outcome of 1 object or of 3 object. Infants looked longer at the unexpected outcomes of 1 object or 3 objects than at the expected outcome of 2 objects. Wynn (1992a) also carried out a subtraction version of this study, beginning with 2 objects on the stage, occluding them with a screen, removing one from behind the screen, and upon lowering of the screen, revealing either the possible outcome of one object or the impossible outcome of two objects. Again, 4 1/2 month olds looked longer at the unexpected outcome. Wynn interpreted these studies as showing that infants can add 1 + 1 to yield precisely 2, and that they can subtract 1 from 2 to yield 1. These studies have been widely replicated (Baillargeon, Miller, & Constantino, unpublished; Koechlin, Dehaene, & Mehler, in press; Simon, Hespos, & Rochat, 1995; Uller, Carey, Huntley-Fenner, & Klatt, under review). Before considering exactly how infants represent number (section 7), here we emphasize the implications of these studies for infant representations of objects; they provide convergent evidence for the conclusions drawn from the Spelke et al. (1995) study described above. Namely, infants represent objects as continuing to exist behind invisible barriers. Also, infants distinguish two numerically distinct but physically similar dolls from one doll (i.e., infants have criteria for individuation and numerical identity; they distinguish one object from one object, another object). And finally, infants' criteria for individuation and numerical identity of objects are spatiotemporal, including principles such as one object cannot be in two places at the same time.

These studies contradict Piaget's conclusion that the sortal concept, object, is built up slowly over the first two years of human life. Rather, it is most likely an innate primitive of the human conceptual system that serves to guide how experience shapes the development of physical knowledge. It is certainly available by 2 1/2 to 3 months, way before it is expressed in natural languages. Also, the prelinguistic infants' representational resources include the basic quantifiers one, another. The capacity to represent sortals and at least some basic quantifiers, central to human language, articulate infants' representations of the world prior to language production or comprehension. Thus, the nativist/universalist position receives strong support with respect to these components of lexical constraints.

4. Do preverbal human infants represent the count/mass distinction?

The studies reviewed above demonstrate that preverbal infants individuate objects, bounded coherent wholes that maintain their boundaries as they move through space. In Wynn's studies, and in the replications by Simon et al. (1995) and by Koechlin et al. (in press), the objects were small human/animal figures (clothed Mickey Mouses, Bert/Ernie, etc.) In terms of Lucy's continuum, these are representations of animate beings, which are universally grammatically individuated. However, one replication used stimuli which have what Soja et al. (1991) and Imai & Gentner (in press) call "simple shapes," namely small objects shaped like piles of sand (Uller et al., under review). Eight-month-olds enumerated these simple objects as well in $1+1=2$ or 1 experiments. Apparently, in spite of the cross-linguistic differences Imai & Gentner (inpress) found in the meanings assigned to such objects (English speakers as young as 2 extend the meanings of words applied to such objects to other objects of the same kind; Japanese speakers as young as 2 extend the meanings of words applied to such objects equally to other objects of the same kind or to other entities made of the same substance), prelinguistic infants see simply shaped bounded, coherent, rigid objects as countable individuals.

The non-individuated end of Lucy's continuum consists of non-solid substances, which are noncohesive and do not maintain boundaries as they move through space. We sought to open the question of whether infants represent the count/mass distinction by exploring whether they would enumerate piles of sand. The studies with the sand-pile shaped objects cited above (Uller et al., under review) were part of a series of studies that systematically compared enumeration of objects with enumeration of piles of sand (Huntley-Fenney & Carey, under review). Babies were assigned either to the object condition or the sand condition. Infants in the object condition were familiarized with a sand object before the experiment—they were shown it up close and allowed to handle it. Similarly, infants in the sand condition were familiarized with sand before the experiment; they were shown sand being poured back and forth between containers, and then onto a plate right before them, and were allowed to handle it. The sand object was suspended by a thin black thread, and thus obviously maintained its boundaries as it moved through space. The sand was poured from a clear measuring cup. Thus, although the final appearance of a sand object resting on the stage was identical to that of a pile of sand resting on the stage, infants had ample evidence that the former was a bounded, coherent object whereas the latter was neither bounded nor coherent.

These studies address two related questions: first, exactly what is being individuated in these studies? The objects on the

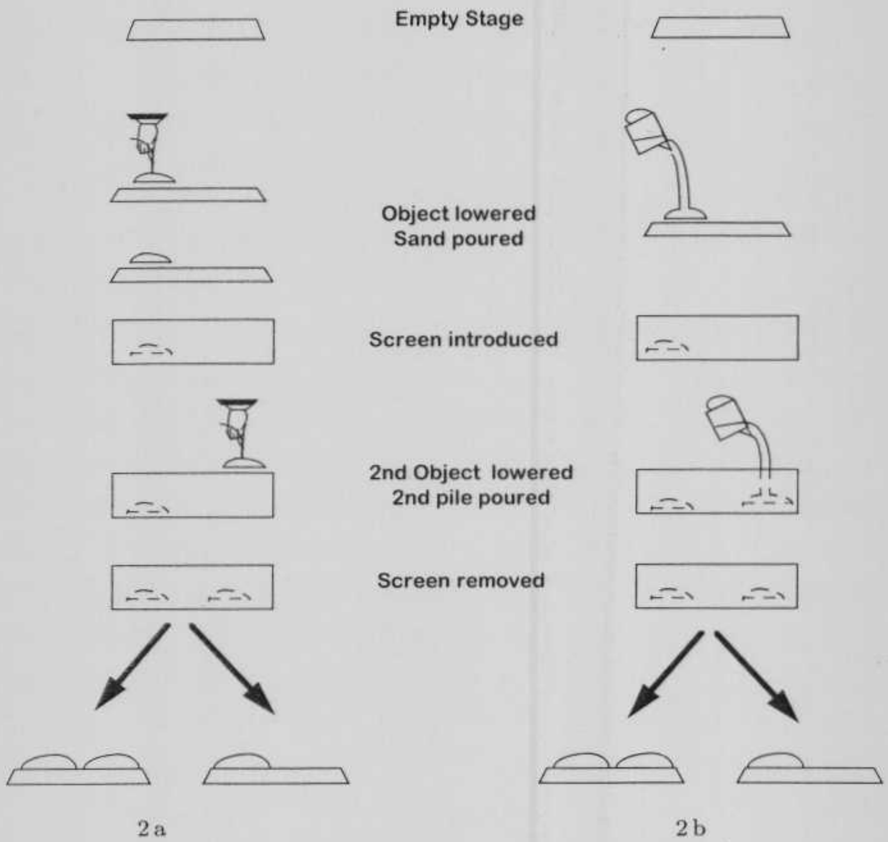

Figure 2 Test trials in object condition (2a) and in sand condition (2b) of $1+1=2$ or 1 study. From Huntley-Fenner & Carey (under review).

stage are good perceptual individuals—they have clear boundaries. In this sense, a pile of sand is also a good perceptual individual. However, a pile of sand is not a canonical –conceptual– individual. It can also be construed, "some sand" or "some stuff." If babies are enumerating perceptual individuals in these studies, they should also enumerate piles of sand. But if they are enumerating conceptual individuals, objects perhaps, they may fail to enumerate piles of sand. Second, and related, do babies represent the distinction between countable material entities, on the one hand, and uncountable material entities on the other? Failure at enumerating piles of sand would be consistent with the claim that they naturally encode sand as "some stuff" or "some sand," representations for which number of individuated portions is irrelevant.

Our first study was a comparison of a $1+1=2$ or 1 procedure with our sand-pile objects, on the one hand, and piles of sand, on the other. Half of the infants (8-month-olds) were in the object condition and some in the sand condition. The $1+1=2$ or 1 object condition (Figure 2a) was closely modeled on Wynn's procedure. The infants saw an object lowered onto the stage floor, after which a screen was raised that hid it. They then saw a second object lowered behind the screen, and the screen was removed, revealing either the expected outcome of two objects or the unexpected outcome of one object. Given that 4-month-olds succeed on this task, it is not surprising that our 8-month-olds did; they looked longer at the unexpected outcome of one object than at the expected outcome of two objects. The important question in these studies is how the infants did in the sand condition, which was made to be as parallel as possible (Figure 2b). A pile of sand was poured onto the empty stage, the screen hid it, a second pile of sand was poured, and the screen was then removed, revealing either the expected outcome of two piles of sand on the stage or the unexpected outcome of just one. Eight-month-old infants failed at this task, showing absolutely no tendency to look longer at the unexpected outcome of one pile of sand; rather, they looked slightly longer at the expected outcome of two, which is also the baseline preference (Huntley-Fenner & Carey, under review).

Infants' failure to enumerate piles of sand in this condition is consistent with a representational distinction between some stuff, on the one hand, and an object, another object, on the other. However, it is also possible that infants did not notice that the two piles of sand were being poured in distinct positions behind the screen. If the second portion were poured on top of the first, then one pile of sand (albeit a larger pile) would be expected. To address the possibility that infants had not encoded the distinct locations of the two pourings, an easier $1 + 1 = 2$ or 1 sand pile problem was posed (see Figure 3). In this version, a pile of sand was poured onto the stage, and then two separate screens were introduced and a second pile of sand was poured behind the second screen. Then, the screens both were removed, revealing either two piles of sand (possible outcome) or just one pile of sand (impossible outcome). Again, 8-month-old infants failed to look longer at the impossible outcomes, nor did 12-month-old infants (Huntley-Fenner & Carey, under review). Thus, fully 8-months later than infants succeed at $1 + 1 = 2$ or 1 object enumeration tasks (4 months; see Koechlin et al., in press; Simon et al., 1995; Wynn, 1992) infants fail to enumerate two piles of sand. Clearly they are enumerating individuated objects in these infant addition experiments, not perceptually defined individuals, as the outcomes in the object conditions of this experiment are perceptually indistinguishable from the outcomes in the sand conditions.

The failure in the two screen version of this experiment (Figure 3) underlines the conceptual relation between individuation and permanence. The two screen task can be thought of as a sand permanence task; to succeed, all the baby need to represent is sand which continues to exist when poured behind the second screen. But permanence is the continued existence of an individuated portion of sand (same sand means same portion of sand, but not same kind of sand). Apparently even 12-month-old babies cannot set up a representation of an individuated portion of sand under these circumstances.

These experiments admit of other interpretations. Perhaps the event of pouring sand is much more complex than the event of low-

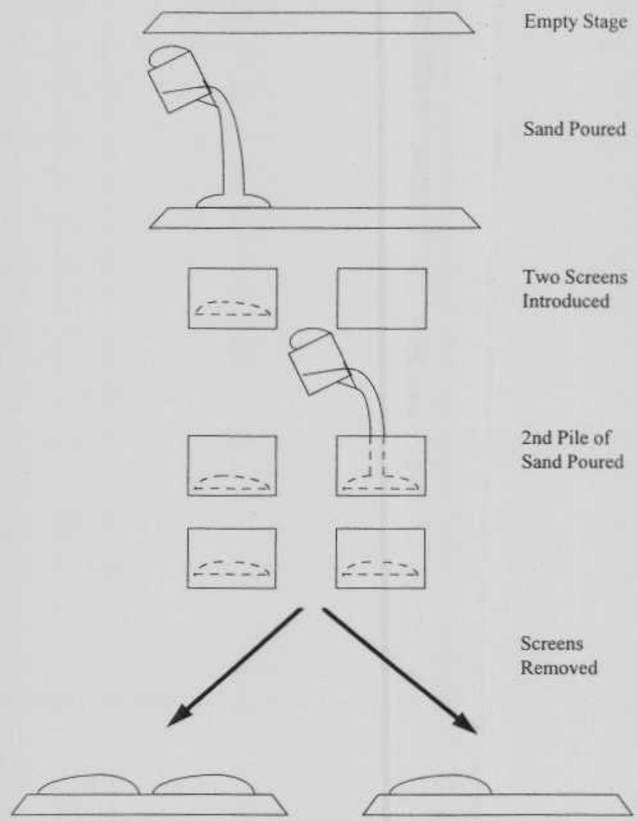

Figure 3 Test trials in sand condition, split-screen version of $1 + 1 = 2$ or 1 study. From Huntley-Fenner & Carey (under review).

ering a sand object. After all, the sand is in three different states during this event; in the cup, in a long thin stream, and gathered into a pile, whereas the object is always in its pile-like configuration. Maybe babies just have a harder time predicting the outcomes of the sand events, especially because they have much less experience with nonsolid substances than with solid objects. Ongoing studies in my laboratory will establish whether the noncohesiveness of the sand is crucial to the failure in the above studies. If so, it would seem that prelinguistic babies make a principled distinction between individuated and nonindividuated material entities. That is, prior to the acquisition of language, the conceptual system makes a rudimentary count/mass distinction.

5. Sortals more specific than object

In section 3, I argued that prelinguistic infants represent at least one sortal concept, object, which provides spatiotemporal criteria for individuation and identity. But human adults use other types of information in establishing individuals and tracing their identity through time: property information and membership in kinds more specific than physical object. An example of use of property information: if we see a large red cup on a window sill, and later a small green

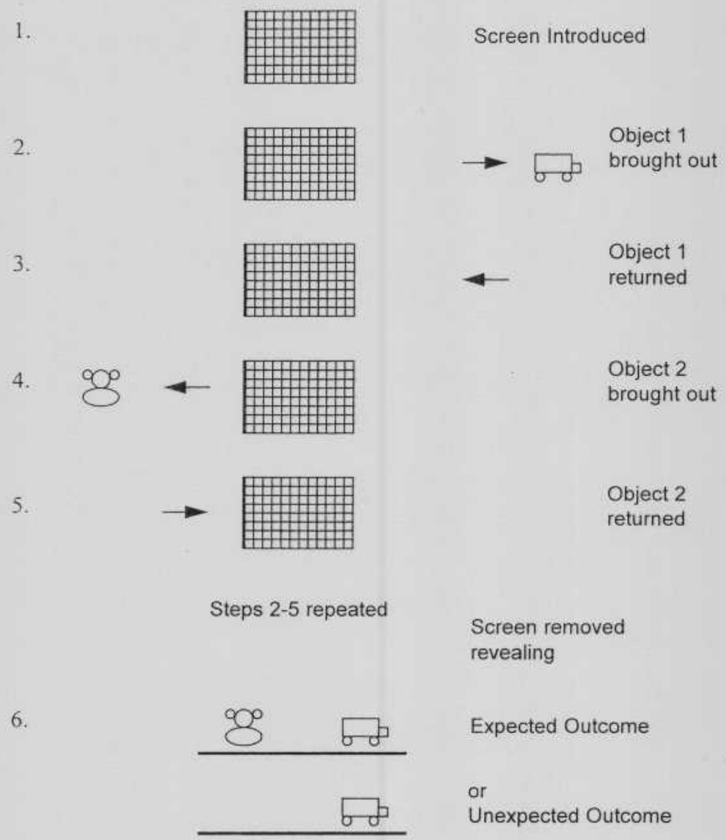

Figure 4 Procedure for probing infants' criteria for individuation based on kind differences between objects. From Xu & Carey (1996).

cup there, we infer that two numerically distinct cups were on the sill, even though we have no spatiotemporal evidence to that effect (i.e., we didn't see both at once in different locations). With respect to kind information, adult individuation and numerical identity depends upon sortals more specific than physical object (Hirsch, 1982; Macnamara, 1987; Wiggins, 1967, 1980). When a person, Joe Schmoe, dies, Joe ceases to exist, even though Joe's body still exists, at least for a while. The sortal person provides the criteria for identity of the entity referred to by the same "Joe Schmoe"; the sortal body provides different criteria for identity.

Recent data suggest that young infants represent only the sortal object and no more specific sortals such as book, bottle, car, person, dog, ball. That is, they represent only spatiotemporal criteria for individuation and identity, and not criteria that specify more specific kinds. Consider the event depicted in Figure 4. An adult witnessing a truck emerge from behind and then disappear back behind the screen and then witnessing an elephant emerge from behind and then disappear behind the screen would infer that there are at least two objects behind the screen: a truck and an elephant. That adult would make this inference in the absence of any spatiotemporal evidence for two distinct objects, not having seen two at once or any suggestion of a

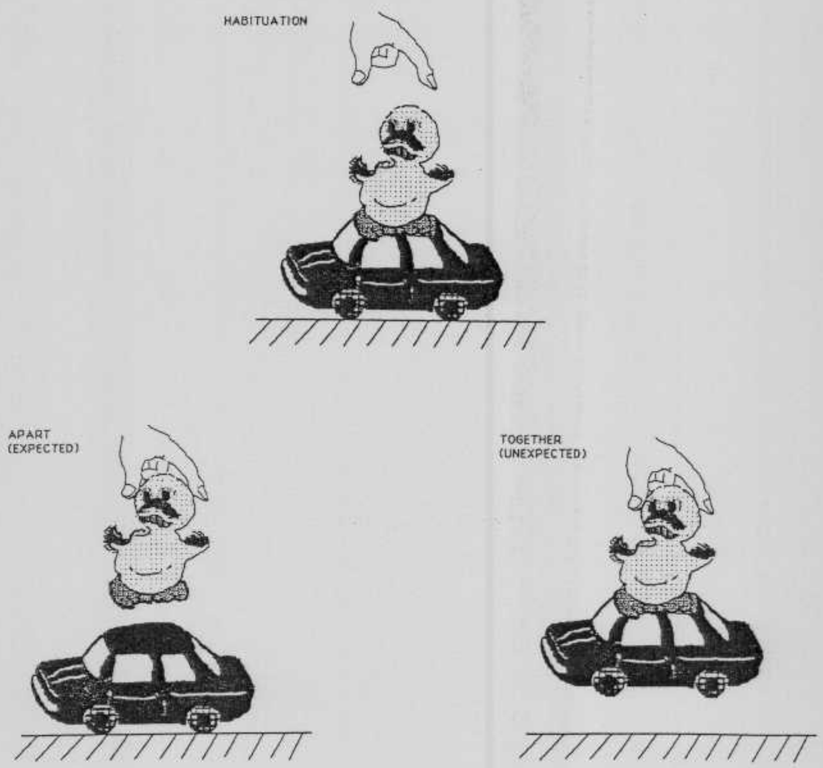

Figure 5 Procedure for probing infants' criteria for individuation based on kind differences between objects. From Xu et al. (under review).

discontinuous path through space and time. Adults trace identity relative to sortals such as truck and elephant and know that trucks do not turn into elephants.

Xu & Carey (1996) carried out four experiments based on this design, and found that 10-month-olds infants are not surprised at the unexpected outcome of only one object, even when the objects involved are highly familiar objects such as bottles, balls, cups and books. By 12-months of age, infants make the adult inference, showing surprise at the unexpected outcome of a single outcome. Importantly, we found that if 10-month-old infants were given spatiotemporal evidence that there were two objects involved (that is, they saw the truck and the elephant at the same time to each side of the screen for a few seconds before the series of emergences), they succeed. The method is sensitive to enumeration ability; 10-month-olds use spatiotemporal evidence for individuation whereas 12-month-olds use kind information as well.

Xu, Carey, & Welch (under review) found convergent evidence that sortals more specific than object begin to articulate infants' representations of the world between 10 and 12 months of age. They habituated infants to the display of Figure 5, which adults see as a duck standing on top of a car. That is, adults use the kind difference between a yellow rubber duck and a red metal car to parse this display into two distinct individual objects, even in the absence of spatiotemporal evidence of the two objects moving independently of each other. In the test trials, the hand reached down and picked up the duck from its head; in the unexpected outcomes the single duck/car came up as a piece; in the expected outcomes, just the duck was lifted by the hand. Ten-month-olds were not surprised at the unexpected outcome; 12-month-olds, like adults, revealed surprise by longer looking when the duck/car was raised as a single object. Xu et al. (under review) replicated 10-month-olds' failure to use kind differences for individuation in this paradigm with a shoe and a cup, as well.

I interpret these results as showing that before 12-months of age, infants use only the spatiotemporal criteria provided by the sortal object when establishing representations of distinct objects in their mental models of the world. By 12-months, infants have constructed more specific sortals, such as cup, bottle, car, ball, book, duck, and so on.

I am not claiming that young infants cannot represent properties of objects, nor that they cannot recognize similarity among different objects with some of the same properties. Indeed, very young infants can be habituated to different exemplars of animals, or dogs, or tigers, or vehicles, and will dishabituate if shown an exemplar of a new category (e.g., Cohen & Younger, 1983; Eimas & Quinn, 1994; Quinn & Eimas, 1993). Young infants clearly recognize bottles, cups, books, toy cars, toy ducks and balls, for they know some object specific functions for them (which ones to roll, which ones to drink from, etc.) Similarly, young infants clearly recognize examples of person, for they expect people to move by themselves and to be able to causally interact without contact. And very young infants recognize particular people, such as their mothers. But none of these phenomena show that infants represent concepts like a bottle, a book, a cup, Mama..., specific sortals or proper names that provide criteria of individuation and identity. One could recognize examples of objects which exemplify cuphood, or Mamaness, and have particular expectancies about objects with such properties, without representing Mama as a single enduring individual, or representing cup as a distinct sortal from book. The results of Xu and Carey suggest that prior to age 12 months or so, such is the human infant's representational system.

It is significant that babies begin to comprehend and produce object names at about 10 to 12 months of age, the age at which they begin to use the differences between cups and elephants to individuate objects. In two different studies of highly familiar objects (bottle, ball, book, cup), Xu & Carey (1996) found that comprehension of the words for these objects predicted the small number of 10-month-olds who could use these contrasts for object individuation. That is, babies do not seem to learn words for bottle shaped or bottleness; they begin to learn words such as "bottle" just when they show evidence for sortal concepts such as bottle that provide criteria for individuation and numerical identity.

The infant has constructed the notions needed for the lexical constraints charted by Bloom (1994), Landau (1994), Markman (1989, 1994) and Soja et al. (1991) by 12-months of age. These include: individual (object) of the same kind, or individual (object) of the same shape. The mastery of sortals more specific than object comes way before language production, and before the mastery of any of the syntactic reflexes of sortals in natural language. However, the correlation Xu & Carey found between word comprehension and success in the individuation task leaves open the possibility that word learning plays some role in the acquisition of specific sortals.

6. The sortal/predicate distinction

The studies outlined in Section 5 provide good evidence that 10-month-olds do not represent sortals more specific than object, but the successes at 12-months do not provide unambiguous evidence that older babies do. After all, as mentioned above, under the conditions of these experiments, adults would use property differences between objects as well as sortal differences as sufficient evidence for individuation. Shown a red cup emerge from one side of the screen and return, followed by a green cup, adults would infer that there were at least two numerically distinct objects behind the screen. The successes of 12-month-olds in the above studies could be due to property differences between the objects (yellow vs red; rubber vs metallic). Xu and I have just carried out a series of 4 studies with 12-month-old babies, using the design of Figure 4, except that the objects differed on the basis of properties that would be lexicalized in most languages as adjectives rather than as count nouns; big cup vs small cup; red ball vs blue ball; red and white fuzzy striped block vs blue and green plaid vinyl block. In all cases we showed that the infants are sensitive to the property differences under the conditions of these studies. For example, they take longer to habituate to the big cup and the small cup emerging alternately from the sides of the screen than to just a small cup emerging from the sides of the screen. But in no case did the 12-month-olds use these property differences to infer that there were two objects behind the screen. That is, when the screen was removed, revealing what for adults is the unexpected outcome of just one of the two objects, they did not look longer than when the expected outcome of both objects was present. Remember, at this age babies succeed at this task if the two objects differ in kind. It appears that prior to learning any words for adjectives, infants represent a distinction between sortal concepts, such as cup, and property concepts, such as red. Only the former provide criteria for individuation in the experiments of Xu & Carey.

7. Interim conclusions. The nativist / universality hypothesis receives support

We have examined spontaneous infant representations of their world for four reflections of number that articulate syntactic distinctions in natural language: criteria of individuation and numerical identity, the quantifiers one, another, the count/mass distinction, and the sortal/property distinction. In each case, we see that spontaneous infant representations are articulated in terms of the same conceptual contrasts that are marked syntactically in the world's languages. These aspects of conceptualization of the world are not learned through a process of mastering culturally constructed, language specific, syntactic devices. In these cases, at least, the nativist/universality hypothesis receives support.

It is important to see, however, that the answer that emerges from empirical examination of a given set of cases need not necessarily generalize to the next case. That is, the empiricist/Whorfian position may be true of other aspects of language. Indeed, I believe it is true of the fifth representational resource related to number considered here: the representation of integers.

8. The representation of integers by human infants

In Sections 3, I discussed the infant addition/subtraction studies as they bore on nonlinguistic representations of objects—object permanence, principles of individuation and numerical identity for objects—and on nonlinguistic representations of basic quantifiers such as one, another. Here I return to the infant addition/subtraction studies as they bear on the question of prelinguistic infants' representation of the first three natural integers, 1, 2, 3.

Simple habituation experiments provide ample evidence that young infants, even neonates, are sensitive to numerical distinctions among sets of one, two, and three entities (e.g., dots: Antell & Keating (1983); sets of varied objects: Starkey & Cooper (1980), continuously moving figures: van Loosbroek & Smitsman (1990), jumps of a doll: Wynn (1996). In such studies, infants are habituated to arrays of a given set size (e.g., 2 entities), and then shown to dishabituate to arrays of a different set size (e.g., 1 or 3 entities.) Wynn's addition and subtraction studies confirm that prelinguistic infants discriminate among sets of 1, 2 and 3 objects, and additionally, that they know some of the numerical relations among them, for they have been shown to succeed at $1+1$, $2-1$, $2+1$, and $3-1$ tasks (Koechlin et al., in press; Simon et al., 1995; Uller et al., under review; Wynn, 1992a, 1995).

The results presented so far leave open the nature of the representations underlying infants' performance. What these representations might be, and the senses in which they may or may not be "genuinely numerical" is a source of intense debate. In order to engage this debate, one must distinguish among classes of models that may underlie performance, and attempt to bring data to bear on which, if any, underlies infant performance. I know of three serious proposals for infant representation of number that could account for their successes in the studies cited above.

The Numeron List Proposal (Gelman & Gallistel, 1978). Gelman and Gallistel proposed that infants establish numerical representations through a counting procedure that works as follows. There is an innate mentally represented list of symbols called "numerons": !, @, +, %, $, ... (Of course, we do not know how such symbols would actually be written in the mind). Entities to be counted are put in one-to-one correspondence with items on this list, always proceeding in the same order through the list. The number of items in the set being counted is represented by the last item on the list reached, its numerical values determined by the ordinal position of that item in the list. For example, in the above list, "@" represents the number 2, because "@" is the second item of the list.

The Accumulator Proposal (Meck & Church, 1983). Meck and Church proposed that animals represent number with a magnitude that is an analog of number. The idea is simple—suppose that the nervous system has the equivalent of a pulse generator that generates activity at a constant rate, and a gate that can open to allow energy through to an accumulator that registers how much energy has been let through. When the animal is in counting mode, the gate is opened for a fixed amount of time (say 200 ms) for each item to be counted. The total energy accumulated will then be an analog representation of number. This system works as if length were used to represent number, e.g., "—" being a representation of 1, "——" a representation of 2, "———" a representation of 3, and so on (see Gallistel, 1990, for a summary of evidence for the accumulator model).

The Object File Proposal (Uller et al., under review; Simon et al. 1995). Babies may be establishing a mental model of the objects in the array. That is, they may be constructing an imagistic representation of the stage floor, the screen and the objects behind the screen, creating one object-file (Kahneman, Triesman, & Gibbs, 1992) for each object behind the screen. Such a model represents number, e.g., the number 2, in virtue of being an instantiation of: $(\exists\, x)(\exists\, y)((\text{object}(x)\ \&\ \text{object}(y))\ \&\ x \neq y\ \&\ \forall\, z(\text{object}(z) \longrightarrow (z = x) \vee (z = y))$. In English this states that there is an entity and there is another entity numerically distinct from it, that each entity is an object, and there is no other object. This sentence is logically equivalent to "There are exactly two objects," but note that, in such a representation, there is no distinct symbol for the number 2 at all, not "2" or "@" or "——" or any other. This model exploits no representational resources other than those demonstrated in the previous sections; object sortals and the capacity to distinguish one from another.

Besides differing in the nature of the representation of integers, the three models differ in the process underlying discrepancy detection between the representation formed as objects are introduced (or removed from, in subtraction) behind the screen and the representation of the resultant display after the screen is removed. Take a $1+1 = 2$ or 1 event as an example. On the two symbolic models, the results of two counts are compared—the symbol for the number of objects resulting from the operations of adding (e.g., "@" or "——") is compared to the symbol resulting from a count of the objects in the outcome array ("@" or "——" in possible outcomes vs. "!" or "—" in impossible outcomes). According to the object model proposal, a representation consisting of two object-files constructed during the addition portion of the event is compared to a representation of two object-files (possible outcome) or one object-file (impossible outcome) by a process that detects 1-1 correspondence between the object files in the two representations.

These three proposals for nonlinguistic representational systems for number are genuinely different from each other. The first two (the numeron list model and the accumulator model) embody distinct symbols for each integer, but differ in the nature of the symbols they use. In the numeron list model, each symbol bears a discrete and arbitrary relation to the number it represents. In the accumulator model, in contrast, an analog representational system exploits the fact that the symbols are magnitudes linearly related to the numbers they represent. And, as previously noted, in the object model system, there is no distinct symbol that represents each integer at all. In this model, there is nothing that corresponds to counting in terms of a set of symbols, whether arbitrary (numerons) or analog (states of the accumulator).

Not all languages have an explicit system for representing integers, but those that do exploit the numeron list model ("one, two three..., un, deux, trois...; etc.). Thus, particularly relevant to our present concerns is evidence that the numeron list model underlies the infant habituation and infant addition/subtraction results. If the numeron list system is available to infants, then learning to count in a natural language is simply a mapping problem, learning the list in the language that corresponds to the list in mentalese, and this state of affairs would be another case in support of the nativist/universalist position. However, as I read the available evidence, this state of affairs does not obtain.

Uller et al. (under review) present several arguments in favor of the object file model as that which underlies performance on the infant addition and subtraction experiments. The main argument is empirical: several experimental manipulations that might be expected to influence the robustness of mental models of the objects in the arrays, but not a symbolic representation of the number of individuals such as "@" or "——," are shown to affect performance of infants in the addition studies. To give just one example: the timing of the placement of the screen on the stage, relative to the placement of the objects behind it, determines success on a $1 + 1 = 2$ or 1 addition study. The classic Wynn study (1992a), and most of the replications (Koechlin et al., in press; Simon et al., 1995; Wynn, 1995) use an "object-first design" (see Figure 3). The first object (1) is placed on the stage, then the screen is introduced, and then the second object (+1) is introduced behind the screen. Infants as young as 4 months of age succeed in this design. Uller et al. (under review) contrasted this design with a "screen-first design," in which the screen is placed on an empty stage, and then one object (1) is introduced behind it, and then a second (+1) is introduced behind it. Note, on the symbolic models, both of these designs simply require incrementing the counting mechanism twice, yielding a representation of two ("@" or "——"), and holding this symbol in memory until the screen is removed, so these two experimental designs should be equivalent in difficulty. But if we make some reasonable assumptions about the factors that might influence the robustness of mental models, then it seems likely that the object-first design will be markedly easier than the screen-first design. These assumptions are: 1) a mental model of an object actually seen on the stage is more robust than one constructed in imagery and 2) each update of a mental model in imagery decreases robustness of the model. The object-first condition begins with a representation of one object on the stage constructed from perception and requires only one update in imagery; the screen-first condition requires that the representation of the first object on the stage is constructed in imagery, and requires two updates in imagery. And indeed, infants succeed in object-first tasks by age 4-5-months of age, but in comparable screen-first tasks not until 10-months of age (Uller et al., under review).

Other considerations favor the object file model as well, not the least of which is the finding of a sharp limit on the numerosities infants represent. Simple habituation experiments with infants, as well as the addition/subtraction studies, have shown that infants represent the numerical values of 1, 2 and 3, but in general fail to discriminate among higher numerosities. There is no such limit on the accumulator model, or the numeron list model, but this limit is predicted by the object file model, on the assumption that there is a limit of parallel individuation of three object files in short term memory (see Trick & Pylyshyn, 1994).

In sum, we suggest that the weight of evidence currently available supports the proposal that the representation of number underlying infants' successes and failures in the addition/subtraction experiments, as well as habituation studies, consists of mental models of the objects in the arrays. These representations are numerical in that they require that the infant have criteria for numerical identity, because a representation that instantiates $(\exists\, x)(\exists\, y)((\text{object}(x)\ \&\ \text{object}(y))\ \&\ x \neq y\ \&\ \forall\, z(\text{object}(z) \longrightarrow (z = x) \vee (z = y))$ is logically equivalent to "There are exactly two objects," and because comparisons among models are on the basis of 1-1 correspondences among object files. However, they fall short of symbolic representations of integers, as there is no unique symbol for each integer, and because there is no counting process defined over them.

The upshot of this argument is that there is no evidence for a prelinguistic representational system of the same structure as natural language count sequences, such as "$1, 2, 3, 4, 5, \ldots$". There is no evidence from the infant studies that such a system is an antecedent available representational system, available to be exploited in the learning of language. The difficulty children experience learning the meanings of the words "two" and "three," the process taking a whole year after they have learned the meaning of "one" and know how to recite the counting list, lends further credence to this conclusion (Wynn, 1990, 1992b). It is likely that this symbolic representation of integers is a cultural construction, mastered anew by each child as he/she comes to understand natural language counting systems. The empiricist/Whorfian position is most likely correct in this case.

9. Conclusions. Ontogenetic building blocks for constraints on lexical meanings, the case of number

Early in the conceptual history of the child, several of the building blocks for constraints on noun and quantifier meanings are firmly in place. Those discussed here include criteria for individuation and numerical identity (the sortal object; more specific sortals like cup, book), quantifiers such as one and another, the distinction between individuated entities and nonindividuated entities, and the distinction between sortals and predicates. These distinctions articulate the constraints on lexical meanings described in studies such of those as Landau et al.(1988), Imai & Gentner (in press), Soja et al.(1991), Bloom (1994) and Brown (1957). Apparently, these are not induced from experience with language; rather, they support language learning from the beginning. Hauser & Carey (in press) argue that the history of these distinctions articulating cognitive architecture is longer still, way back in evolutionary time. They have shown that the violation of expectancy method yields interpretable data both in the wild (rhesus macaques) and in the laboratory (cottontop tamarins). The spontaneous conceptual representations of rhesus macaques and cottontop tamarins are like those of human babies with respect to the representations of object as a sortal, the distinction between one, another, and in the case of rhesus, probably also the representation of more specific sortals such as carrot, squash (Hauser & Carey, in press). These are some of the conceptual primitives from which language is built, both in phylogenesis and in ontogenesis. They are not language specific cultural constructions.

Finally, there is no doubt that babies are sensitive to numerical distinctions among sets of objects; that is, they represent number as one dimension of their experience of the world. These include representations of small numerosities (perhaps in the form of one, two or three object files held in parallel in short term memory). All of these aspects of representations of number are prior to the linguistic expression of numerical concepts in the lexicon or syntax of natural languages.

However, the representation of the integers in terms of a list of numerals, or numerons (mentally represented numerals), is most likely a human cultural construction. Mastering it requires months, or years, of training, suggesting that it is importantly different from the prelinguistic representations of numbers available to both infants and animals. The object file and accumulator models are importantly different from the numeron list model in respects that explain why the numeron list systems of natural languages are so hard for children and animals to learn. That is, neither of these models involves a representational system in which the value of a given symbol for an integer is determined solely by its place in an arbitrarily ordered list; in the object file model there is no symbol for integers at all and in the accumulator system, the comparative values of two symbols for integers can be directly read off the magnitude of the symbols themselves, as this is an analog system of representation.

It is possible that this construction was made possible by human language, but also required a long history of cultural development. Human children learn the list of numerals, and the counting procedure, well before they map any of the numerals beyond 1 onto the numbers they represent. They then laboriously learn what "2" means, and then "3." By the time they have learned what "4" means, they have induced the principle by which the whole list represents number, and they immediately know what all the numbers in their count sequence mean (Wynn, 1992b). This occurs by around age 3 and 1/2 years in normally developing children learning a language with a system of numerals. It can also be mastered by nonhuman animals, chimpanzees (Boysen & Bernston, 1989; Matsuzawa, 1985; Matsuzawa, Itakura, & Tomanga, 1991; Rumbaugh & Washburn, 1993) and an African gray parrot (Pepperberg, 1987, 1994), and as with children extensive training (in the case of animals years of daily training) is required. Humans and other animals have the capacity to build representational systems that transcend those that get cognition and language learning off the ground, systems that may be culturally constructed just as posited by the empiricist/Whorfian position.

This case study makes clear the vast amount of work that remains to be done. We need to examine aspects of language case by case for their ontogenetic and phylogenetic history in creatures without language (human infants, nonhuman animals). This enterprise gives us candidates for those aspects of language that fall on the nativist/universalist ends of the continua of origins/natures of constraints on word learning. And for those aspects of language for which we can find no evidence in these nonlinguistic creatures, we must provide detailed proposals for how such new representational resources might be culturally constructed, and how they are created anew by children as they master the language that embodies them.

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