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Different Faces of Language in Numerical Development

EXACT NUMBER AND INDIVIDUATION

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INTRODUCTION

How does language influence conceptual development? This question has long been the subject of debate among linguists, philosophers, and psychologists (e.g., Boroditsky, 2011; Carey, 2009; Choi & Bowerman, 1991; Fodor, 1983; Gentner & Goldin-Meadow, 2003; Gleitman & Papfragou, 2005; Whorf, 1956). In thinking about this question, Carey (2009) distinguishes between two broad stances on how language learning can influence concepts: 1) *strong or Quinian linguistic determinism*—language learning allows children to represent concepts that they could not previously represent, and 2) *weak linguistic influence*—language learning makes concepts that children can already represent more salient or accessible. Gentner and Goldin-Meadow (2003) refer to these views, respectively, as "language as a lens" (i.e., language provides new ways to represent the world) and "language as a tool" (i.e., language highlights or augments representations that are already available), terminology we adopt in this chapter. We also consider a third way in which language influences cognitive development that crosscuts these views, "language as data": Whatever the influence of language on concepts, strong or weak, the amount and quality of language input a child receives that is relevant to a concept may affect the timing and even the nature of its influence on this concept.

Carey (2009) argues that there is no single answer to the question of how language influences thought; rather, cases of development need to be considered in detail, one by one, to determine what role(s) language plays in each case. In this spirit, we consider two aspects of numerical development, one more advanced (the representation of exact number) and one more rudimentary (object individuation), and examine the influence of language on each.

The chapter is organized in two sections. In the first (written by Susan Levine), we consider how children construct a representation of natural number. As detailed later, existing evidence supports Carey's bootstrapping claim that language, in particular a count list, is essential to the child's construction of natural number. In addition, we discuss recent evidence suggesting revisions to two aspects of Carey's bootstrapping account. In the second section (written by Renée Baillargeon), we turn to infants' ability to individuate and track objects from event to event. As we will see, recent evidence has led Carey to conclude that language serves as an important, although not unique, tool for supporting this ability. After reviewing this evidence, we outline a new account of how infants individuate and track objects and of how language is implicated in this ability and its development.

Together, the two sections of the chapter support Carey's view that there is no single answer to the question of how language influences thought—even within the domain of numerical development, language appears to play multiple, different roles in cognition.

LANGUAGE AS A LENS: NATURAL NUMBER

Carey (2004, 2009) presents convincing evidence that the development of children's understanding of the exact cardinal value of sets constitutes a strong example of how language—in this case the language provided by the cultural invention of the count list—can qualitatively change representations, providing a new way to conceptualize number. She argues that without the symbol system provided by the count list, the ability to represent number exactly—for example, exactly 6 vs. exactly 7—is not possible. According to Carey (2004, 2009), the ability to represent exact number for any set size is tied to understanding that the last number reached when counting a set represents the set size (the cardinal principle) and to understanding that each successive number, $N + 1$, in the count list represents a set size that is exactly one unit larger than its predecessor, N (the successor principle).

Consistent with Carey's theory, the ability to represent the exact number of elements in sets beyond three elements (referred to as the subitizable range, e.g., Trick & Pylyshyn, 1994) appears to be lacking in infants as well as toddlers, even after they can recite the count list from 1 to 10 and beyond, which children typically do when they are 2-year-olds (e.g., Fuson, 1988; Le Corre, Van de Walle, Brannon, & Carey, 2006; Wynn, 1990). In a seminal study, Wynn (1990) found that most 2- and 3-year-olds were able to count objects, but if asked, "How many are there?" they seldom produced a response corresponding to the last number in their count. Instead, they typically re-counted the objects. Even more compelling, Wynn found that young children are unable to give requested numbers of objects on the Give-A-Number (GN) task. Most children start off not even knowing the meaning of *one*, and it takes them 18 months or longer to map the first three or four number words onto their cardinal values (Wynn, 1990, 1992). At a time when children correctly respond to requests for *one* by giving exactly one item, they respond to requests for higher numbers by grabbing a bunch of objects. Several months later, they respond correctly to requests for *one* and *two*, but grab a bunch of objects when larger numbers are requested. This pattern then repeats for *three* and sometimes *four*. At this point, Carey and colleagues argue that children are "cardinal principle knowers" (CP-knowers) and understand the meanings of all the numbers in their count list (e.g., Carey, 2004; LeCorre & Carey, 2007; Wynn, 1990). Importantly, this slow, sequential, mapping of number words onto their cardinal values does not depend on the specific performance demands of the GN task. Children who understand only the meanings of *one* and *two* on the GN task show a similar pattern on the "What's on this Card?" task, where they are asked to provide the number word that corresponds to the set size, and on the "Point-to-N" task, where they are asked to point, for example, to the set that has three items where the contrasting set has four items (Le Corre et al., 2006).

TWO CORE NUMBER SYSTEMS

Why is mapping of the count list to cardinal number so difficult? The answer, according to Carey, lies in the mismatch between the representations that core number systems provide and the natural numbers. As argued by Carey and others (e.g., Carey, 2004, 2009; Feigenson, Dehaene, & Spelke, 2004; Le Corre et al., 2006), there are two core number systems, the object tracking system and the analogue magnitude system, and neither captures the representation of exact number afforded by natural numbers.

Object-Tracking System

The object-tracking system (OTS) is a working-memory model that tracks a limited number of objects by assigning an index to each (e.g., Carey, 2009; Feigenson & Carey, 2003, 2005; Trick & Pylyshyn, 1994). Carey (2004, 2009) refers to this system as the parallel-individuation system since it can track up to three individuals via pointers that pick out and track "this," "this," "this" without a summary symbol for the set size "three." The set size limitation of the OTS is clearly demonstrated by the ability of infants and toddlers to discriminate sets of three vs. two elements, but their inability to discriminate sets of four vs. two elements or even four vs. one element, which would seem to be much more discriminable (Feigenson & Carey, 2003).

The inability of the OTS to provide a summary symbol for set size is highlighted by a recent study we conducted (Gunderson, Spaepen, Gibson, Goldin-Meadow, & Levine, 2015). We showed that before children could provide a correct verbal response on the traditional "What's on this Card?" (WOC) task for sets of two or three, they were able to answer correctly on a WOC-Gesture task (Nicoladis, Pika, & Marentette, 2010), where they were asked to respond to the number of objects on the card by holding up the correct number of fingers. Moreover, on the WOC-Verbal task, which was administered after the WOC-Gesture task, children frequently provided mismatching responses, where they were typically correct with their gestures but incorrect with their words. We posit that this is because gestures provide an item-based representation of set size, which aligns better with the item-based representation of quantity provided by the OTS than does the summary symbol representation provided by number words. These findings are consistent with Carey's theory, which posits that the OTS does not provide a summary symbol for set size but rather represents each item in the set via a pointer.

Analog-Magnitude System

The other core number system, the analog-magnitude system (AMS), does provide a summary representation of set size, but, in accord with Weber's law, this representation is approximate and becomes more so with increasing set size (e.g., Dehaene, 1997; Gallistel & Gelman, 2000, Xu & Spelke, 2000). Thus, although this system can differentiate two from three elements, it cannot consistently differentiate larger sets, for example, 12 from 13 elements.

Indeed, the signature of the AMS is its ratio limitation, which is coarser in infants than in adults, gradually becoming more refined over the course of development. For example, 6-month-olds can discriminate 8 vs. 16 items, but not 8 vs. 12 items; by 9 months, infants can discriminate sets with a ratio of 8 vs. 12 but not 8 vs. 10 in both the visual and auditory modalities (Lipton & Spelke, 2003, 2005; Xu & Arriaga, 2007). Ratio limitations also characterize the ability to differentiate other magnitudes (e.g., area, time, brightness), and there is debate about whether the approximate discrimination of number by infants is specifically numeric or whether it reflects a more general ability to represent magnitudes that only gradually becomes differentiated for different kinds of magnitudes (e.g., Cantrell & Smith, 2013; Mix, Huttenlocher, & Levine, 2002; Mix, Levine, & Newcombe, in press; Newcombe, Levine, & Mix, 2015). Whatever the starting state is for this second core system, it also does not appear to have the representational capacity of the natural numbers, because it is limited to approximate representations of quantities (Carey, 2004, 2009; Condry & Spelke, 2008; cf. Gallistel, 2007, and Gallistel & Gelman, 1990, 1992, 2000).

HOW DO CHILDREN ACQUIRE AN UNDERSTANDING OF CARDINALITY? CAREY'S SEMINAL THEORY

Carey (2009) takes on the question of how young children construct an understanding of exact number, considering the role that the OTS and/or AMS may play. She posits that Quinian bootstrapping, which involves associative learning, natural language learning, analogical reasoning, induction, and, importantly, the ability to integrate previously distinct representational systems to create a new and qualitatively different representational system, plays a central role.

Role of the AMS

Carey (2009) argues that the count-list representation of natural number is not built on the back of the AMS (e.g., Dehaene, 1997; Gallistel, 2007; Gallistel & Gelman, 1992, 2000; Wynn, 1998) for the following reasons. First, in contrast to the prediction of the accumulator model (Gallistel & Gelman, 2000), magnitudes in the AMS are constructed in parallel, as it does not take longer to estimate larger than smaller set sizes (Wood & Spelke, 2005). The lack of a relation of longer times to estimate larger set sizes obscures the relationship between set size and the order of numbers in the count list. Second, nothing in the AMS accounts for the sequential development of children's set-based quantification—for example, first understanding the meaning of *one* in contrast to all plural sets, which are undifferentiated at this point, then understanding *one* and *two* in contrast to all other sets, and so on (Bloom & Wynn, 1997). Third, the AMS does not provide a representation of the successor function that defines the +1 relationship between successive numbers in the count list—for example, the difference between 1 and 2 is larger in the ratio-dependent AMS than the difference between 12 and 13. Foruth, the scalar variability that is the signature of the AMS (*M estimated set size/SD estimated set size = constant*) is not seen for the first four numbers in the count list. And finally, perhaps most importantly, LeCorre and Carey (2007) provide evidence that children learn the cardinal principle without being able to map number words onto approximate set sizes, indicating that mapping number words to the AMS cannot be a prerequisite for becoming a CP-knower.

Role of the OTS

Carey (2009) also considers the possibility that the OTS is a building block for the count list representation of natural number. She argues that the OTS is implicated by the finding that initial meanings are assigned only to the first few number words. However, she also argues that the OTS alone is insufficient to bootstrap natural number because it provides representations for individual objects and not for sets, whereas the count words represent set size. She then posits an important role for the set-based quantification system, in combination with the OTS, which she dubs "enriched parallel individuation." Set-based quantification provides the distinction between individual and plural sets and is captured in natural languages through symbols such as the word *a* for individual items, and *plurals* and *some* for sets (e.g., Bloom & Wynn, 1997; Carey, 2009). Bloom and Wynn (1997) showed that children use the word *a* appropriately before age 2 and use other natural language quantifiers as well as number words soon thereafter (e.g., *some* trees, *all* trees, *two* trees). Bloom and Wynn also provided direct support for the role of set-based quantification in constructing natural number, showing that "one-knowers" make the singular–plural distinction of set-based quantification, providing sets of one for *one* but undifferentiated pluralities when asked for larger sets; this suggests that *one* may initially mean *a* and larger numbers may initially mean *some* or *plural*. However, Barner and colleagues provide compelling evidence that *two* does not function as a plural marker for young children (Barner, Lui, & Zapf, 2011).

According to Carey (2009), 2-year-olds begin to understand the number words by combining the resources of the set-based quantification system and the parallel-individuation system (OTS). For example, when they count "1, 2" they relate the pointers provided by the OTS to the set size corresponding to the dual marker. In fact, there is evidence that the mapping of number words to their meanings is accelerated in children learning languages with rich systems for marking set size (Almoammer et al., 2013; Sarnecka, et al., 2007). For example, Almoammer et al. (2013) found a much higher frequency of "two-knowers" among children learning languages that have a dual marker for sets of exactly two elements (Slovenian, Saudi Arabic) than in children learning English (which marks singular and plural but not dual) or Japanese or Mandarin Chinese (classifier languages with no plural marking).

BECOMING A CP-KNOWER: A QUALITATIVE CHANGE

Several studies provide evidence that acquiring the cardinal principle is a watershed milestone. That is, once children become CP-knowers, they exhibit a web of important interrelated mathematical abilities that were not present previously (e.g., Le Corre et al., 2006; Sarnecka & Carey, 2008). These include the use of counting to determine set size (e.g., Le Corre et al., 2006; Sarnecka & Carey, 2008; Wynn, 1990), particularly for larger than smaller set sizes, a behavior that is not typical for subset knowers (Sarnecka & Carey, 2008). According to Sarnecka and Carey (2008), becoming a CP-knower also coincides with knowledge of the successor function—knowing that adding one item to a set of N results in a set of $N+1$, which corresponds to the next number in the count list. They tested this using the Unit Task, on which they told children that there were N items in a box where N was 4 or 5. Children were then shown either one or two items going into the box and were asked, "Now is it $N+1$ or $N+2$?" CP-knowers but not subset knowers succeeded on this task.

Carey's bootstrapping account of the acquisition of the cardinal principle has had a major impact on the field of numerical cognition and has garnered support from studies of diverse populations. For example, adult members of Amazonian tribes without a well-developed count list show evidence of core number systems but are unable to represent large set sizes exactly (Gordon, 2004; Pica, Lemer, Izard, & Dehaene, 2004). Similarly, deaf homesigners in Nicaragua, who live in a numerate culture but who lack a count list, are unable to represent large set sizes exactly (Spaepen, Coppola, Spelke, Carey, & Goldin-Meadow, 2011). These studies, taken together, support Carey's claim that the representation of natural number is language dependent.

But subsequent research also has provided some challenges to Carey's theory, albeit not challenges that cast doubt on her main thesis that language enables the representation of natural number. In the next section, we briefly consider two of these challenges. The first concerns her claim that children make an induction over *all* numbers in their count list when they become CP-knowers (Davidson, Eng, & Barner, 2012). The second challenge concerns her claim that subset knowers cannot map the count list onto AMS representations, thus the AMS does not play a role in bootstrapping natural number representations.

Do CP-Knowers Make a Semantic Induction over Their Count List?

As summarized earlier, Carey and colleagues posit that children make a semantic induction that allows them to understand the meanings of all of the numbers in their count list after learning the meanings of the first three or four numbers. Sarnecka and Carey's (2008) finding that CP-knowers had greater success than subset knowers on the Unit Task (described earlier) is consistent with the view that CP-knowers have an important understanding that is lacking in subset knowers. However, even CP-knowers had difficulty on this task, scoring, on average, only 67% correct (chance was 50% correct). Moreover, 13 out of 29 CP-knowers did not perform at an above-chance level on this task.

Davidson, Eng, and Barner (2012) point out that these findings are difficult to square with the conclusion that becoming a CP-knower involves a semantic induction over all the numbers in the child's count list. They found that CP-knowers were significantly more likely to succeed on the Unit Task for small numbers (4 or 5) than for medium (13, 14, or 15) or high numbers (24 or 25). As in Sarnecka and Carey's (2008) study, many CP-knowers lacked knowledge of the successor function even for low-number problems. Even more telling, high counters often performed well on the Unit Task for low but not medium or high numbers, indicating that their difficulty was not attributable to lack of task understanding. These findings provide a challenge to the claim that children make a semantic induction over their entire count list at the time they succeed on the GN task. Rather, children appear to lack knowledge of the successor principle or to have only limited, piecemeal knowledge of this principle at a time when they are CP-knowers as measured by the GN task. Among CP-knowers, performance on two tasks—fluent counting and mapping larger numbers onto approximate set sizes on a Fast Dots task where counting the dots is not possible—differentiated those children with little or no understanding of the successor principle from those with more robust understanding of this principle. Thus, becoming a CP-knower on the GN task may not represent the kind of qualitative change that Carey posits.

Is the Ability to Map Number Words onto Approximate Representations Exclusive to CP-Knowers?

Le Corre and Carey (2007) argue that the mapping of number words to approximate set size does not play a role in learning the cardinal principle, given their findings that many CP-knowers do not succeed at this mapping and that those who do succeed are approximately 6 months older than those who do not. These findings suggest that the mapping of number words to approximate representations develops only after children learn the cardinal principle (e.g., for contrasting view see Gallistel, 2007; Gallistel & Gelman, 1992). If LeCorre and Carey are right, it is indeed not logically possible for the AMS to help children gain knowledge of the cardinal principle. However, recent studies show that even subset knowers (those who do not understand the cardinal principle) sometimes have approximate knowledge of the number words up to 10 (e.g., Gunderson, Spaepen, & Levine, 2015; Wagner & Johnson, 2011), opening up the possibility that the mapping of number words to the AMS could potentially play a role in learning the cardinal principle, at least for some children. We found that success on approximate-mapping tasks was correlated with children's age but not with their "knower-level" (Gunderson, Spaepen, & Levine, 2015). Based on this finding, we proposed that the development of these two kinds of number word mappings—approximate, involving the AMS, and exact, involving the OTS—may unfold independently. The correlation of approximate number word mapping with age but not with knower level suggests that it may rely on cognitive capacities that increase with age (e.g., executive functioning, associative mapping ability), as well as with increases in count list fluency, spatial skills, and nonverbal AMS acuity (e.g., Davidson et al., 2012; Halberda & Feigenson, 2008; Sullivan & Barner, 2014; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). In contrast, exact number word knowledge and performance on the GN task may depend more on children's exposure to number talk (e.g., Gunderson & Levine, 2011; Levine, Suriyakham, Rowe, & Huttenlocher, & Gunderson, 2011).

It is possible that the knowledge children have at the time they acquire the cardinal principle, as measured by the GN task, varies depending on their age at the time they reach this milestone. Children who learn the cardinal principle at early ages may not be able to map number words onto AMS representations, whereas children who acquire the cardinal principle at later ages may already have this mapping ability. This opens the possibility that the AMS may play a role in helping children learn the cardinal principle when they acquire this principle relatively late. Nonetheless, as Carey points out (personal communication), mapping number words onto AMS representations cannot be necessary to learning the cardinal principle if some children become CP-knowers without having this ability. Our age-related hypothesis could be tested by comparing children from different socioeconomic groups, who, on average, hear varying amounts of number talk at home and at school and consequently tend to succeed on the GN task and related tasks at different ages (e.g., Gunderson & Levine, 2011; Jordan & Levine, 2009;

Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006; National Mathematics Advisory Panel, 2008). In the next section, we review research investigating the relation of children's cardinal number knowledge to variations in the number talk they hear. We consider how this relationship can inform our understanding of developmental pathways in numerical cognition.

VARIATIONS IN NUMBER KNOWLEDGE: EARLY NUMBER TALK AS DATA

Knowledge of the cardinal principle, as assessed by the GN task and related tasks, emerges at widely different ages in different children, from as early as 3 to as late as 5 years of age (Gunderson, Spaepen, & Levine, 2015; Sarnecka & Lee, 2009). These findings raise the possibility that the number talk children are exposed to plays a role in explaining these variations, serving as data that inform their mapping of number words to set size and their understanding of natural number. This variation in the age at which children succeed on the GN task also opens up the possibility that the kinds of surrounding knowledge children have at this point vary depending on the age at which they reach this milestone. For example, it is possible that the children who hear a lot of number talk will succeed on the GN task early, but will not immediately induce the successor principle for all the numbers in their count list. At this early age, the two skills that Davidson et al. (2012) identified as predicting this induction may be fragile: Their counting ability may not be fluent, and their approximate number word mapping ability may be limited. In contrast, children who hear less number talk and hence succeed on the GN task only at later ages may be more likely to make the semantic induction Carey describes. At this later age, they may have already acquired the age-related counting and mapping skills that Davidson et al. (2012) found to predict understanding of the successor principle among CP-knowers.

We examined the relationship between children's cardinal number knowledge and the number talk their parents provide, in a longitudinal study that involved videotaping 90-minute natural interactions of parent–child dyads in their homes, once every 4 months, with children between 14 and 30 months of age (Gunderson & Levine, 2011; Levine et al., 2010). Over the approximately 450 minutes that comprised the five videotaped sessions, parents ranged from saying a low of 4 number words to a high of 257 number words. Extrapolating from the assumption of 8 waking hours each day, this amounts to hearing parents say as few as 1,200 number words per year to as many as 100,000—definitely not a level playing field. Importantly for our question, the amount of number talk children heard between 14 and 30 months predicted their cardinal number knowledge at 46 months, controlling for other aspects of parent talk, family socioeconomic status, and the child's own number talk. In a related study with a different sample of children, we found that preschool teachers' number talk predicted the growth of children's mathematical knowledge over the school year (Klibanoff et al., 2006).

In a follow-up to Levine et al.'s (2010) parent number talk study, we found that the quality of parent number talk also mattered (Gunderson & Levine, 2011). Parent number talk that referred to sets that were visible to the child (objects, pictures in books) was a significant predictor of cardinal number knowledge at 46 months of age, whereas number talk with no visible sets present did not (e.g., rote recitation of the count list or throwing the child in the air and saying, "one, two, three, wheee"). Further, parent number talk referring to set sizes higher than three, which is much rarer than number talk referring to smaller sets, was a significant predictor of cardinal number knowledge, whereas the amount of parent number talk in the one to three range was not. We are now conducting a follow-up experiment in which we are boosting the number talk children are exposed to either in the one-to-three range or the four-to-six range over the period of a month, through books their parents read to them. Preliminary data indicate that the growth of children's number knowledge from pretest to post-test depends on the child's knower level, with the small-number books being more beneficial for children who are one- and two-knowers at pretest, and both the small and large-number books being beneficial for children who are at higher knower levels at pretest (Gibson, Gunderson, & Levine, 2015).

These findings add to a growing body of research showing that knowledge of the symbolic system for number fundamentally changes children's understanding of natural number, as posited by Carey. The widely differing amounts of number talk children receive at home and in preschool partly account for children's understanding of natural number. A 3-year-old who understands the cardinal principle is likely to have received more and better data—to have heard a lot more number talk referring to present objects than a 5-year-old who has yet to understand this principle. A still unanswered question is whether we are correct in our hypothesis that children who acquire the cardinal principle at older ages (based on the GN task) may immediately make the semantic induction across all of the numbers in their count list—as Carey posits—because they have the requisite counting and mapping skills that Davidson et al. identify as being important, whereas children who acquire the cardinal principle at younger ages may need to await the acquisition of better counting and mapping skills. Studies that focus on individual differences in numerical cognition will enable us to address this question.

LANGUAGE AS A TOOL: OBJECT LABELS AND INDIVIDUATION

In the first section, we examined how children come to represent exact cardinal values (e.g., exactly nine objects), what interlocking factors contribute to this achievement, and what essential role language plays in this developmental process. In this second section, we turn to research on object individuation (OI), which examines infants' ability to determine how many objects are involved in a physical event and to keep track of these objects from event to event. As Carey (2009) argued, language plays an important—though not an essential—role in augmenting infants' ability to individuate and track objects across events.

Initial Findings and Claims by Xu and Carey

In ground-breaking experiments, Xu and Carey (1996) used a novel OI task to examine whether infants could use categorical or featural information to determine (1) how many objects were present behind an occluder and, hence, (2) how many objects should be revealed when the occluder was removed. In one experiment, 12- and 10-month-olds received two pairs of test trials: One pair involved a ball decorated with green and pink stripes and a baby bottle decorated with small blue bears, and the other pair involved a red sippy cup and a yellow baby book. In each test pair, one object (e.g., the ball) emerged from one side of a large screen and then returned behind it; next, another object (e.g., the bottle) emerged from the other side of the screen and then returned behind it. This occlusion event was repeated several times, and then the infants saw a new event: The screen was removed to reveal either both objects (two-object event) or only one of the objects (one-object event). Results indicated that the 12-month-olds succeeded in detecting the violation in the one-object event, but the 10-month-olds did not. This striking developmental shift was confirmed in multiple laboratories (e.g., Bonatti, Frot, Zangl, & Mehler, 2002; Futó, Téglás, Csibra, & Gergely, 2010; Krøjgaard, 2000; Leslie, Xu, Tremoulet, & Scholl, 1998; Surian & Caldi, 2010; Wilcox & Baillargeon, 1998a).

In interpreting their findings, Xu and Carey made three main claims (e.g., Xu & Carey, 1996; Xu, Carey, & Quint, 2004). First, they proposed that the 12-month-olds succeeded because they represented the two occluded objects as members of *contrastive categories*. The objects actually differed in multiple respects: They emerged on opposite sides of the screen; they had different featural properties; and they belonged to distinct basic-level categories. According to Xu and Carey, only this last difference mattered: It was because the 12-month-olds encoded the objects' contrastive basic-level categories, whereas the 10-month-olds did not, that their responses to the one-object event diverged. Supporting this claim, further experiments revealed that 12-month-olds no longer succeeded when the two occluded objects were drawn from the same basic-level category (e.g., a large red ball and a small soccer ball; Xu et al., 2004; see also Kingo & Krøjgaard, 2011).

The second claim by Xu and Carey was that language learning, and more specifically the acquisition of *object labels*, plays a role in the developmental shift between 10 and 12 months. Evidence for this claim came from two additional results of the experiment described earlier: (1) parental reports indicated that most of the 12-month-olds understood at least two of the labels for the four objects used in the two test pairs ("ball," "bottle," "cup," "book"), whereas most of the 10-month-olds did not, and (2) those few 10-month-olds who did know two or more of the labels performed like the 12-month-olds (Xu & Carey, 1996; see also Rivera & Zawaydeh, 2006). As Carey (2009) put it, "it is not until between 10 and 12 months that infants spontaneously draw on many kind-sortals (e.g., bottle, book, shoe, duck, car, truck) in support of individuation in non-linguistic tasks, and language learning is implicated in this change" (p. 279).

In their third claim, Xu and Carey attempted to spell out exactly how the acquisition of labels might facilitate success in the OI task. They speculated that learning labels causes an important development in infants' conceptual system: It brings about the formation of specific *object concepts* with stable, enduring properties. Thus, the infants who knew the labels "ball" and "bottle" and had formed these concepts realized that the ball could not turn into the bottle when passing behind the screen; they therefore inferred that the ball and the bottle were distinct objects, and they expected to see both objects when the screen was removed. In contrast, the infants who had not yet learned the labels "ball" and "bottle" and still lacked these concepts were uncertain whether the ball and the bottle were two distinct objects or a single object with varying properties; as a result, the infants were agnostic about whether there should be one or two objects when the screen was removed.

Revisions

The first two claims by Xu and Carey—12-month-olds succeed at OI tasks involving contrastive basic-level categories because they encode these categories, whereas 10-month-olds fail because they do not yet encode these categories; language acquisition is implicated in this developmental shift—have both withstood further experimental scrutiny. However, the third claim—learning object labels results in the formation of stable object concepts, which are necessary for success at the OI task—has not fared as well. Carey (2009) has now relinquished this claim, as various strands of evidence have shown that young infants can (1) form and use categorical representations without linguistic support and (2) give evidence of feature-based individuation in modified OI tasks. Each point is elaborated next.

Early Category-Based Individuation

As Carey (2009) has argued, there is now considerable evidence from individuation, categorization, and other tasks that young infants can form and use categorical representations without linguistic support: "Prelinguistic infants represent kinds and clearly have the logical capacity to bring kind membership to bear on object individuation" (p. 277). Focusing on the OI task, positive findings have now been obtained with two types of categorical representations.

First, 10-month-olds succeed at the OI task (i.e., detect the violation in the one-object event) if the two occluded objects belong to contrastive *ontological* categories that young infants spontaneously encode, such as human-like vs. nonhuman (e.g., a doll and a toy dog; Bonatti et al., 2002; Bonatti, Frot, & Mehler, 2005) and inert vs. self-propelled (e.g., a self-propelled bee and a block moved by a hand; Surian & Caldi, 2010).

Second, young infants succeed at the OI task if they are induced to assign the two occluded objects to contrastive *basic-level* categories via nonlinguistic manipulations. In one such manipulation, 9-month-olds first saw two static arrays, one at a time; one array was composed of three different cups, and the other was composed of three different shoes (Stavans, Li, & Baillargeon, 2016). In the test trial, half the infants (different-object condition) saw one of the cups and one of the shoes brought out in alternation from behind a screen, which was then lowered to reveal only one of the objects (e.g., the shoe); the other infants (same-object condition) saw the same object (e.g., the shoe) brought out on either side of the screen. Infants in the different-object condition looked reliably longer at the one-object event than did infants in the same-object condition, and this effect was eliminated if the cups and shoes were scrambled in the arrays (i.e., two cups and one shoe in one array, two shoes and one cup in the other array). Similar results were obtained in another experiment with blocks and cylinders, indicating that even novel basic-level categories can induce success in the OI task.

In another nonlinguistic manipulation, 4-month-olds were induced to assign the two occluded objects to contrastive basic-level categories via functional demonstrations (Stavans & Baillargeon, 2016). Infants first received two familiarization trials: In one, an experimenter's hand used tongs to lift sponges, and in the other, the hand used a masher to compress the sponges. In the test trial, half the infants (different-tool condition) saw the hand bring out the tongs and masher in alternation from behind a screen, which was then lowered to reveal only one of the tools (e.g., the masher); the other infants (same-tool condition) saw the same tool (e.g., the masher) brought out on either side of the screen. Infants in the different-tool condition looked reliably longer at the one-object event than did infants in the same-tool condition, and this effect was eliminated if in the familiarization trials the tools were used in similar but nonfunctional demonstrations. A second experiment with two other tools (a marker that was used to draw lines and a knife that was used to cut dough) produced similar results. These findings support Carey's (2009) proposal that in addition to lexical evidence, many nonlinguistic types of evidence may "trigger establishing a new kind representation, including . . . evidence of inductive potential (e.g., a particular shape predicts functional or causal affordances)" (p. 284).

Early Feature-Based Individuation

Further evidence that the acquisition of relevant labels and concepts is not necessary for success at the OI task comes from the positive findings obtained with young infants in modified OI tasks (for reviews, see Baillargeon et al., 2012; Wilcox & Woods, 2009). Although these tasks use occluded objects from contrastive basic-level categories that young infants do not yet spontaneously encode (e.g., a box and a ball), the modifications introduced enable infants to take advantage of the objects' contrastive *featural properties* (e.g., different sizes and shapes) to determine how many objects should be present when the screen is removed. As Carey (2009) pointed out, these results make clear that "property information is sometimes drawn upon in object individuation" (p. 82). We describe next three types of modified OI tasks.

In *no-reversal* OI tasks, the occlusion event is greatly abbreviated so that each occluded object moves in a single direction on one side of the screen. For example, infants see a box move behind the left edge of a screen; next, a ball emerges to the right of the screen and stops in full view. Following this event, the screen is lowered to reveal no box—only the ball is present to the right of the screen. Infants ages 5.5–9 months detect the violation in this one-object event, and this effect is eliminated if the occlusion event is made even slightly longer (Wilcox & Baillargeon, 1998a; Wilcox & Schweinle, 2002; Wilcox, Alexander, Wheeler, & Norvell, 2012).

In *trajectory-outline* OI tasks, infants receive typical test trials; for example, a box and a ball emerge twice in alternation from behind a screen, which is then lowered to reveal only the ball. Prior to these test trials, however, infants receive two familiarization trials designed to introduce them to each object and its trajectory separately. In one trial, the box emerges to the left of the screen and returns behind it; this sequence is repeated a second time, and then the box pauses behind the screen until the trial ends. The other familiarization trial involves the ball, which emerges to the right of the screen. Positive results have been obtained in trajectory-outline tasks with infants ages 7.5–10.5 months; this effect is eliminated if during the familiarization trials the object moves back and forth next to the screen and never becomes occluded (Wilcox, 2003, 2007).

Finally, in *transparent-screen* OI tasks, a transparent screen stands directly behind the opaque screen so that the occlusion event continues on when the opaque screen is lowered. For example, infants see a box and a ball emerge in alternation from behind an opaque screen; next, the screen is lowered to reveal only the ball, which is visible through the transparent screen. Positive results have been found in transparent-screen tasks with infants ages 9.5–10.5 months (Wilcox & Chapa, 2002; Wu & Baillargeon, 2016).

A NEW ACCOUNT

As Carey (2009) has pointed out, the positive findings presented in the last section (as well as additional evidence she reviewed) (a) contradict the original conclusion by Xu and Carey that "infants under 11 or 12 months of age never use property information or kind information in the service of object individuation" (p. 82), and (b) "rule out the hypothesis that the construction of kind-sortals at the end of the first year of life requires Quinian bootstrapping" (p. 281). However, several questions remain unanswered. Why does categorical information play a privileged role in the OI task? Why do infants begin to spontaneously encode basic-level categories around their first birthday? What role does language play in this development? Finally, why are infants capable of feature-based individuation in some OI tasks, but not others?

To address these questions, Baillargeon and her collaborators have been "scaling up" their account of early physical reasoning, which until recently focused mainly on causal interactions between two objects (e.g., one occluder and one occludee; Baillargeon, Li, Gertner, & Wu, 2011; Baillargeon, Li, Ng, & Yuan, 2009; Wang & Baillargeon, 2008b). The hope is that by specifying what cognitive systems are activated in OI tasks, what information is represented by each system, and how the systems exchange information as events unfold, we will be in a better position to answer these questions (e.g., Baillargeon et al., 2012; Stavans & Baillargeon, 2013, 2014). Following is an overview of this new account, organized into four main points.

Three Systems

Imagine that infants see a toy duck moving gently next to a large screen. The object-tracking system (OTS) assigns an index to each object (this index serves as an attentional pointer that "sticks" to its object, enabling infants to keep track of it without using any of its properties or descriptors; e.g., Pylyshyn, 1989, 2007). Next, the object-file system (OFS) creates a file for each object (e.g., Kahneman, Treisman, & Gibbs, 1992), which includes two types of information: spatiotemporal and identity information. Each type of information includes *categorical* information as well as more detailed or fine-grained *featural* information (e.g., Huttenlocher & Lourenco, 2007). In the file for the toy duck, for example, the spatiotemporal information might specify that it is next to the screen (categorical), a short distance from its left edge (featural); the identity information might specify that it is a closed, nonhuman, self-propelled, and nonagentive object (categorical), with a particular size, shape, pattern, and color (featural).

Now, imagine that the duck moves behind the screen and pauses out of view. Because the two objects are involved in a causal interaction (i.e., the screen occludes the duck), the physical-reasoning system (PRS) becomes activated (e.g., Baillargeon et al., 2009, 2011, 2012). The PRS is a core system for reasoning and learning about physical events, used for both prediction and action. To help the PRS build a representation of the event, the OFS passes on all of the categorical information at its disposal. The PRS then uses this information to categorize the event as an occlusion event and to assign appropriate roles (occluder, occludee) to the objects.

Next, the PRS taps the OFS for the specific featural information that has been identified as helpful for predicting the progression of occlusion events. By 10 months, for example, most infants have identified occludee shape, size, and pattern as predictive features in occlusion events (e.g., Wilcox, 1999; Wilcox & Baillargeon, 1998b). Once added to the event's representation, this featural information becomes subject to the PRS's core knowledge, which includes a principle of *persistence*: All other things being equal, objects persist, as they are, in time and space (e.g., Baillargeon, 2008).

Why does the OFS not pass on all of its categorical *and* featural information to the PRS? Why does the PRS have to request selected featural information from the OFS? There are two main advantages to this process of feature selection. One is that it makes learning possible: In each event category, infants begin with sparse event representations that become gradually richer as predictive features are identified (through a process of explanation-based learning; e.g., Wang & Baillargeon, 2008a). The other reason is that feature selection facilitates the rapid online physical reasoning necessary for adaptive prediction and action because the PRS is not swamped with irrelevant featural information. Recent research indicates that even in adults, intuitive physical reasoning involves the recruitment of event categories and their predictive features (Strickland & Scholl, 2015).

Category-Based Individuation

Imagine that infants see a duck and a human-like doll emerge in alternation from behind a screen. Because the OTS is a nonconceptual system that uses spatiotemporal information to track the identity of objects (e.g., Pylyshin, 2007), only one index is assigned; as far as the OTS is concerned, there is no evidence to suggest that there is more than one object moving back and forth behind the screen.

The situation is very different for the PRS, however. As each object comes into view, the OFS passes on its identity categorical information. Because the first object (the duck) is nonhuman whereas the second object (the doll) is human-like, the PRS infers that two objects are present: According to the persistence principle, a nonhuman object cannot spontaneously change into a human-like object. The PRS then updates the OTS that an additional index is required.

Following this update, the OTS and PRS hold consistent representations of the number of objects involved in the occlusion event. This consistency is necessary for the PRS to make predictions about *new* events involving the objects. To see why, consider what happens when the screen is removed: At that point, the occlusion event ends, and the descriptors occluder and occludee no longer apply. As long as the OTS has an index pointing to each object, however, the PRS can reidentify the objects and form predictions—for example, about the number of objects that should be revealed (two) and their properties (one nonhuman and one human-like) (for an extensive discussion of how indexes solve the reidentification problem, see Pylyshyn, 2007).

The preceding analysis explains the evidence reviewed earlier about early category-based individuation in the OI task. Basically, any time the OFS passes on contrastive categorical information for the objects that emerge alternately from behind the screen, the PRS (a) infers that these must be separate objects (due to the persistence principle) and (b) updates the OTS that a second index is needed. Moreover, it does not matter whether the OFS encodes this contrastive categorical information spontaneously (e.g., Bonatti et al., 2002; Surian & Caldi, 2010) or as a result of experimental manipulations (e.g., Futó et al., 2010; Stavans & Baillargeon, 2016; Stavans et al., 2016; Xu, 2002)—*any contrastive categories* will cause the PRS to update the OTS, leading to a consistent two-object representation in the two systems.

Label Effects at 12 Months

The developmental shift uncovered by Xu and Carey indicates that an important change takes place in the OFS by about 12 months of age: When representing an object, the OFS now specifies its basic-level category in the identity categorical portion of its file. This change has important consequences for infants' performance in the OI task. To see why, imagine that 12-month-olds see a duck and a ball emerge in alternation from behind a screen. The OFS will include "duck" and "ball" in the identity categorical portion of the objects' files. Upon receiving these contrastive basic-level categories, the PRS will infer that two occludees are present: According to the persistence principle, a duck cannot spontaneously change into a ball. The PRS will then signal the OTS that a second index is needed, resulting in a consistent two-object representation in the two systems and thereby leading infants to expect two objects when the screen is removed.

Why does the OFS begin to specify objects' basic-level categories by the end of the first year? As Xu and Carey suggested, this change is likely to be due to language acquisition, although the exact mechanism involved is as yet unclear. One possible hypothesis is as follows. Between 6 and 12 months, infants begin to learn labels for objects (e.g., Bergelson & Swingley, 2012; Parise & Csibra, 2012). As they do so, infants realize that labels often refer to objects' basic-level categories, with different labels being used for different categories (e.g., Balaban & Waxman, 1997; Dewar & Xu, 2007). In the course of everyday conversations, infants learn that having this basic-level information explicitly specified in an object's file (e.g., "duck") makes it easier to identify what object speakers are talking about (e.g., "Where's the duck?"). Over time, the OFS begins to spontaneously and routinely include basic-level information in its files, even in nonlinguistic contexts and even when representing objects whose labels are not yet known.

The preceding hypothesis is consistent with Carey's (2009) proposal that language learning plays a facilitative role in the OI task. As infants learn object labels, they begin to routinely encode basic-level information; this information, in turn, enhances their ability to track objects from event to event. This provides a nice illustration of what Carey describes as "the weak effects of language on thought" (p. 283).

Feature-Based Individuation

Imagine that infants see a small dotted duck and a large striped duck emerge in alternation from behind a screen. In this event, the categorical information that the OFS passes on for the two objects is identical (as both are ducks, even 12-month-olds cannot distinguish them categorically). However, the selected featural information that the OFS provides (upon request from the PRS) differs: One object is small and dotted, whereas the other object is large and striped. This contrastive featural information is sufficient for the PRS to infer that two objects are present: According to the persistence principle, an object cannot spontaneously change size or pattern. Why, then, do 10- and 12-month-olds fail to detect a violation when the screen is lowered to reveal only one object (e.g., Xu & Carey, 1996; Xu et al., 2004)? And why do they succeed in the modified OI tasks described earlier?

The most likely answer to these questions has to do with limitations in infants' *working memory*. The first time that the second object (e.g., the large striped duck) comes into view, the PRS taps the OFS for the appropriate featural information for this object, compares it to that for the first object, and infers that two objects are present. Next, the PRS must signal the OTS that a second index is needed. The positive results of the no-reversal and trajectory-outline OI tasks described earlier indicate that the PRS has no difficulty doing this update *as long as there are no further emergences in the occlusion event*, so that there are no competing demands on infants' limited working-memory capacity. If, however, a further emergence occurs (e.g., the large dotted duck returns behind the screen and the small dotted duck reappears on the other side of the screen), the PRS cannot cope: Instead of updating the OTS, it attends to this new emergence. In a nutshell, the PRS cannot simultaneously communicate with the OTS (to update it) and communicate with the OFS (to request selected featural information about the newly emerged object).

Because the OTS is not updated, the PRS and the OTS hold inconsistent views: The OTS assumes that a single object is present behind the screen, whereas the PRS assumes that two objects are present. In light of this inconsistency, computations about new events are not possible. Thus, when the screen is lowered, infants fail to detect a violation whether they are shown two objects, one object, *or even no object* (Stavans & Baillargeon, 2013, 2014); it is as though an "error message" had been produced, leading to no expectation at all.

The preceding analysis helps explain why (a) infants give evidence of feature-based individuation in no-reversal and trajectory-outline OI tasks (because there are no further emergences after the second object comes into view, the PRS has the opportunity to update the OTS), but (b) infants fail to give evidence of feature-based individuation in the standard OI task, which has multiple emergences (the PRS cannot both communicate with the OTS to update it and communicate with the OFS to request featural information about the newly emerged object).

Finally, the preceding analysis helps explain why infants succeed at transparent-screen OI tasks. Because the occlusion event continues, first with the opaque screen and then with the transparent screen, the PRS can correctly monitor the ongoing progression of the event; as a result, infants expect to see two occludees (e.g., two ducks) behind the transparent screen, and they detect a violation if shown only one occludee. Together, the results of the original OI task and those of transparent-screen tasks make clear that although the PRS alone can track objects *within* an event, the OTS and the PRS must work together to track objects *across* events.

CONCLUSIONS

In thinking about how language influences cognitive development, Carey (2009) has argued that there is no single answer to this question; rather, cases of development need to be considered in detail, one by one, to determine what role language plays. In this chapter, we revisited two aspects of numerical development that Carey has extensively studied: how children construct a representation of natural number and how infants individuate and track objects across events.

In her work on natural number, Carey argued that language qualitatively changes the representational capacities that were previously available based on the AMS, the OTS, and set-based quantification. This work has inspired numerous studies, some providing additional support for her bootstrapping theory, others leading to revisions of some of the details of her theory (Davidson et al., 2012; Gunderson, Spaepen, et al., 2015), and still others calling the theory into question (Gallistel & Gelman, 2007; Rips, Bloomfield, & Asmuth, 2008). What is unquestionable is that her theoretical stance has provided a framework for understanding the development of numerical cognition, and that her theoretical and empirical contributions will continue to influence future research and advances in the field.

In her work on individuation in infancy, Carey argued that development in this area reveals only weak effects of language on thought. New findings are supporting this view and are beginning to shed light on the mechanisms responsible for these effects. As we saw, one such mechanism may be that label learning leads infants to spontaneously encode objects' basic-level categories; these are then recruited in infants' representations of physical events, where they help circumvent working-memory limitations that can curtail infants' ability to track objects from event to event.

Together, the findings reviewed in this chapter provide strong empirical support for the claim by Carey and others that language sometimes serves as a lens that makes possible new representations and sometimes serves as a tool that simply enhances existing representations. In the first case we considered, language provided a way to represent number that was not afforded by prelinguistic representational systems. In the second case, language played a helpful role in highlighting basic-level categories and facilitating individuation and identity tracking; language did not play a unique role, however, because nonlinguistic evidence could also be used to form these categories, and other categorical and featural information could also be used to individuate and track objects. Another message that emerged from our review is that access to relevant language input—language as data—can influence trajectories of children's conceptual development. As Carey has pointed out, by studying how language contributes to developmental change in specific cases, we can advance our understanding of development more generally.

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