

Chapter 1

Object representation as a central issue in cognitive science

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1.1 Knowing objects

Philosophers of mind make a distinction between knowledge that is derived or mediated and knowledge that is immediate. Mortals must derive mediated knowledge whereas divine knowledge is immediate. Oddly enough, cognitive scientists interested in the nature of human object knowledge have their fair share of arguments about a rather similar distinction. Indeed, the question of where knowledge comes from has pervaded debates in object cognition since the field's inception. Do humans begin life privileged with the capacity to immediately detect and represent objects? Or is our object knowledge instead derived only as the result of prolonged experience in the external world? Are we simply able to perceive objects by watching their actions in the world, or do we have to act on objects ourselves in order to learn about their behavior? Finally, do we come to know all aspects of objects in the same way, or are some aspects of our object understanding more epistemologically privileged than others?

Thankfully, over the past few decades, psychologists interested in the development of object knowledge have made remarkable empirical headway even in the face of this philosophical controversy. Such empirical headway is in large part due to a growing interest in the origins of object knowledge among psychologists outside the developmental sphere. Indeed, researchers in disciplines as varied as vision science, comparative cognition, and cognitive neuroscience have added to the investigational furor surrounding the origins of human object knowledge. The result is a veritable explosion of work in this area, with each field taking on the classic problem of object representation from different but often equally important perspectives.

This volume aims to provide a snapshot of the current state of this comparative research explosion, with an emphasis on the current results shaping our theories of the origins of human object understanding. In particular, the

goal of the book is to have researchers in each field pause, take a step back, and theoretically reflect on what new results from these intersecting perspectives on object knowledge origins have taught us to date. The goal of this chapter, however, is to take a few more steps back, and to provide some theoretical and historical background for the issues to be discussed in later chapters.

In this chapter, we draw attention to some of the most relevant historical work on object representation to have emerged from developmental and comparative research. Our focus, unfortunately, will have to be rather narrow, as any summary chapter on a topic as central to cognitive science as object representation could potentially occupy volumes. Nonetheless, there are several characteristic questions about the nature of object representation that have historically had a rather important bearing on the course of research in developmental psychology, and thus will likely be areas where a comparative approach can have its greatest impact. With this in mind, we will focus on three specific areas here:

- 1 The question of objects as permanent entities
- 2 The question of objects as entities with properties
- 3 The question of objects as entities to be manipulated

1.1.1 Objects as permanent entities

Historically, one of the most important questions facing developmental psychologists has concerned the question is when infants come to represent objects as permanent entities, ones that persist across time, space, and occlusion. Of course, the concept of object permanence itself is really a misnomer, as all objects comprise energy in continuous states of change. Nervous systems, however, are not built to be metaphysical realists. Their job is not to represent objects as a quantum physicist might. Instead, nervous systems were developed via natural selection to represent objects so that organisms may interact with the external world in an adaptive way, and thus, brains are built to capture what is functionally relevant about objects.

One of the most functionally relevant aspects of physical objects is the fact that they persist—standardly speaking, objects do not go in and out of existence and, thus, it is important that an organism be able to represent their continued presence even when they cannot be directly perceived or apprehended. Consequently, most human adults are, at least implicitly, committed to the notion that objects are external entities that exist independently of the observer and that—all things being equal—they will continue to exist as they move across time and space.

So how do we come to know that objects are permanent entities? This seemingly simple question is one of the oldest and perhaps the most controversial issues in both philosophy and in the field of developmental psychology. For example, Idealist philosophers such as George Berkeley argued with Realists such as John Locke about the priority of the mind over matter. In short, how was the experience of an external physical reality generated? Did the mind create objects or did objects impose themselves on the mind? Such philosophical considerations about the origin of perceiving objects as enduring entities led to the first empirical investigations of what infants—who lack experience in interacting with objects—actually know about the external physical world. These metaphysical issues motivated investigations by the Swiss psychologist Jean Piaget who was primarily interested in how biological systems could represent and adapt to their physical environments. Piaget's approach to the problem of investigating infant knowledge involved allowing infants to act on the world and observing what they did and did not seem to know about the world based on these active behaviors. Through a long series of painstaking observational studies on his own children, Piaget was able to develop hypotheses about how the youngest infants ultimately come to represent their world in more adult-like ways (see Piaget, 1955).

Based on his observations, Piaget theorized that infants gain more adult-like knowledge of the physical world by constructing it themselves through their actions on the world. He hypothesized that preverbal infants experience their world in a way that is radically different than adults do—without the capacity to act on the external world, infants have no way of knowing about it and, more specifically, no way to recognize that objects are tangible, permanent entities. In one famous example of this phenomenon, Piaget hid his daughter's beloved toy duck under a sheet and observed how she reacted. Surprisingly, the young infant did not continue searching for the missing toy. Observations such as this led Piaget to his famous notion that infants lack 'object permanence', the understanding that objects continue to exist when one is not in perceptual contact with them. In this sense, 'out of sight' (and similarly, 'out of hand') literally meant 'out of mind'.

As Piaget noted, it is only around 6–8 months of age that infants begin to search for hidden objects. Prior to this, he argued, infants have no enduring representation of objects when they are out of sight. Moreover, even when infants do begin to search for hidden objects, their early representations of the missing objects do not correspond to separate entities, ones that are independent of the infants' own actions with their own spatial temporal coordinates. For example, Piaget observed that when infants successfully find an object, if the object is then moved to a new location 'B', the infant

returns to search in the original location 'A'. Even though the infant saw the object moved in full view to a new position, it is as if the act of searching would recreate the object at the original location. This became known as the A not B error. Based on errors such as these, Piaget hypothesized that infants only come to represent objects in any meaningful way after they have had substantial experience acting on objects in a coordinated way and internalizing the consequences of such action. This achievement, which Piaget hypothesized occurred at around 18 months of life, was thought to represent a major conceptual change for the developing child, one in which mere sensory–motor information was somehow transformed into more adult-like representational thought.

Although he was one of the first to empirically investigate the origins of object knowledge, Piaget's study of and hypotheses about object permanence highlight several of the major themes still at work in the study of object representation today—ones that will be debated in detail in the chapters that follow. The first issue concerns *the role of perceptual and motor experience in the development of adult-like object understanding*. Piaget, of course, championed that sensory–motor experience is essential for the development of object permanence as well as any concrete object understanding. Although, as we will discuss in the following sections, more recent methods have called Piaget's evidence into question, the issue of what motor experience provides the developing child is one that is still unsettled in the field today. The second issue highlighted by Piaget's initial work concerns *the role of conceptual changes in the development of our adult-like object understanding*. Here, Piaget came down on the side of the conceptual change theorists, arguing that the developing child undergoes major and stage-like conceptual shifts in the understanding of the permanence of objects. But as many of the chapters in this volume will attest, the question of how (and even whether) conceptual change is relevant to our object knowledge is one that drives much current empirical work.

From constructivist piagetianism to nativist core knowledge theories

Although Piaget was the first to look at these issues, in the decades that followed his pivotal observations, many of his textbook conclusions have come to be questioned. Although he did an impressive job of chronicling the development of infants' early object manipulation skills,¹ most of his observations involved the use of infants' reaching behavior as a proxy for what the developing child

¹ As the psychologist Steven Pinker allegedly once put it, 'for a guy who just played with his three kids, his observations have stood the test of time astonishingly well' (*New Yorker*, September 4, 2006).

knows about the physical world. In the decades since his initial work, many researchers have begun doubting the extent to which his reaching measures indeed provide a valid measure of infants' object competence. First, researchers have observed that young infants reach for objects that are out of sight. Filming with infrared cameras in total darkness, Hood and Willatts (1986) observed that infants reach more to the correct side for a previously seen object when the room lights go out, suggesting that infants are able to represent objects with which they have no direct perceptual access (for similar findings, see Clifton et al., 1991; Clifton et al., 1999; Goubet & Clifton, 1998; Shinsky & Munakata, 2003). These studies indicate that search rather than representation is problematic. In particular, the use of other objects to occlude the target presents a means-end problem wherein the infant has to coordinate a means (remove cover) to achieve the goal (retrieve toy). Means-end coordination taxes the problem-solving capacity of young infants (for review, see Willatts, 1989) and occluders can themselves become the focus of interest thereby disrupting the original goal. Such response biases present a difficulty that affects infants' performance on any reaching measures designed to illustrate their competence (e.g., Diamond, 1991; Munakata et al., 1997).

The problems with reaching measures led infancy researchers to seek out an alternative method for examining infant object competencies. In the 1980s, experimental psychologists turned to a response that young infants had more control over than their reaching—their looking. Indeed, other researchers had previously used infants' looking responses as a measure of discrimination. For example, Fantz and colleagues (Fantz, 1965; Fantz & Fagan, 1975) presented infants with different visual displays and observed that the infants preferred to look at more complicated over less complicated patterns. The researchers were then able to use this preferential looking method to explore whether infants were able to discriminate some patterns and not others.

Using insight from these early habituation and discrimination looking procedures, developmental psychologists were able to establish a method for using infants' looking to get at their expectations. In a now-renowned example, Baillargeon et al. (1985) presented five-month-old infants with an event in which an opaque drawbridge-like screen occluded a box and then began rotating toward it. They found that infants expected the drawbridge to stop rotating when it hit the box, looking reliably longer at unexpected events in which the drawbridge completed a full rotation as though the box had disappeared. This technique of looking time afforded the possibility to investigate all sorts of knowledge that could be contextualized as a violation. These early results and others (e.g., Baillargeon, 1987, 1993; Baillargeon & Graber, 1987; Baillargeon et al., 1990; Leslie, 1984; Leslie & Keeble, 1987; Spelke, 1988;

Spelke & van de Walle, 1993; Spelke et al., 1992; Spelke et al., 1995; Wynn, 1992) directly contradicted Piaget's hypotheses about infants' object understanding. Not only was the idea that there was no representation of the unseen object untenable, but infants also had expectations about the nature of unseen objects' properties as well.

In the 1990s, Spelke and colleagues (Spelke et al., 1994; see also Spelke et al., 1992) synthesized findings from these new looking method studies and proposed three principles that govern infants' reasoning about objects as permanent entities: cohesion, continuity, and contact. The first of these principles—cohesion—is the idea that moving objects maintain their boundaries and connectedness. Infants appear to recognize that objects are cohesive and have been shown to look longer at events in which an individual object violates its connectedness (e.g., Spelke et al., 1989; Spelke et al., 1993). Second, infants recognize that objects move on *continuous* paths through time and space. Infants look longer at violations of continuity, ones in which two solid objects appear to move through each other (Baillargeon et al., 1985; Spelke et al., 1992) and ones in which a single object appears to have moved through space in a discontinuous manner (see Spelke et al., 1994; Spelke et al., 1995; Xu & Carey, 1996). Finally, infants appear to recognize that inanimate objects move if and only if they are *contacted* by another object (e.g., Leslie, 1984; Leslie & Keeble, 1987).

Interestingly, although infants appear to reason about objects in terms of cohesion, continuity, and contact, they do not appear to understand *all* the aspects of inanimate object motion that adults do. Spelke and colleagues, for example, observed that infants fail to use the principles of inertia and gravity to predict how objects will move in space (see Spelke et al., 1992; Spelke et al., 1994). Similarly, although young infants represent objects as having coherent boundaries over motion, they fail to represent them as having coherent properties until almost at one year of age (see Simon et al., 1995; Leslie et al., 1998; Xu & Carey, 1996). Infants therefore appear to possess some but not all of adults' intuitions about the nature of objects. Indeed, infants' patterns of successes and failures on looking time tests of object knowledge suggest that infants are built to recognize the most fundamental properties of objects (see Spelke, 1994, for a similar argument).

These results and others led Elizabeth Spelke and her colleagues to propose what is now a dominant theory of the origins of object knowledge, the *core knowledge hypothesis* (see Spelke, 2000; Spelke et al., 1994). The core knowledge (hereafter, CK) hypothesis argues that our adult human knowledge of the physical world stems from experience-independent, innate principles for reasoning about entities within the domain of inanimate physical objects.

Under this view, adults possess their basic intuitions about objects and motion from birth. The CK hypothesis, thus, differs in two critical ways from the constructivist theories of Piaget that preceded it. First, CK proposes that our knowledge of objects has many of the properties of a Fodorian module: our knowledge of objects is specific to the domain of objects and encapsulates itself from other kinds of inputs (Fodor, 1983). Therefore, our knowledge of objects is unlikely to require much motor experience to get off the ground developmentally. In this way, the CK hypothesis differs radically from all constructivist approaches in that it argues not only that experience plays little role in getting our object knowledge off the ground to begin with, but also that experience plays little role in shaping our basic object understanding through the life course. Second, because experience plays little role, the CK hypothesis argues for continuity across development, rejecting the Piagetian notion of drastic conceptual change. According to the CK hypothesis, our basic understanding of objects and their motion is not subject to change—the principles that underlie our understanding of objects are with us from cradle to grave.

Although the CK hypothesis was originally proposed to account for the development of human understanding of objects, the theory made interesting predictions about the evolutionary history of these principles. Even in some of their earlier inceptions (e.g., Carey & Spelke, 1996; Spelke, 1994), the principles that make up our CK of objects were meant to be adaptive responses to constraints on the physical world that had been present throughout a long evolutionary history. Therefore, it would make sense that other species facing similar physical constraints may have developed similar, or even homologous, systems for representing objects. If the CK hypothesis is correct, one might expect that humans share their innately specified object representation mechanisms with other animals, particularly other closely related primates.

Using this logic, comparative researchers have used expectancy violation looking methods such as those used with human infants to demonstrate that a variety of nonhuman primates appear to represent objects according to the three principles originally outlined by Spelke and colleagues (see Santos, 2004, for review). Adult rhesus monkeys (*Macaca mulatta*), for example, appear to represent objects as *cohesive* entities: similar to human infants, rhesus macaques look longer at events in which an object appears to break apart as it moves in space (Munakata et al., 2001). Similarly, adult primates appear to reason about objects in terms of their *continuity*: a number of primate species tested with looking measures successfully tracked objects behind occluders (Flombaum et al., 2005; Hauser & Carey, 2003; Hauser et al., 1996; Santos et al., 2005;

Uller et al., 2001) and look longer when the objects violate *solidity* by appearing to move through each another (Santos & Hauser, 2002; Santos et al., 2006). Finally, there is some evidence that primates also utilize the principle of *contact*: monkeys look longer when inanimate objects appear to move on their own (Hauser, 1997). These observations have led to the view that infants share their core principles of objects with closely related species, and thus, that our core ideas of objects as permanent entities are both developmentally and evolutionarily central.

Since its original articulation, the CK hypothesis has generated considerable controversy (see, for example, Bogartz et al., 1997; Haith, 1998, 1999; Melkman & Rabinovitch, 1998; Smith, 1999). Some of the controversy surrounding the hypothesis had to do with its experience-independent nativist take on infant object knowledge. Others have criticized the CK hypothesis with the view that infants' performance on looking tasks reflects their *perceptual* processing of the displays rather than a *conceptual* knowledge of objects (e.g., Bogartz et al., 1997; Haith, 1998). Perceptual representations, under this view, are transient and tied to the immediate input-processing stream in contrast to the conceptual representations proposed by the CK hypothesis. Critics have argued that the earlier competencies revealed in these violation of expectancy studies are perceptually grounded discriminations that are emergent from the nature of the way infants extract information over the course of testing (Bogartz et al., 1997; see also, Amso & Johnson, Chapter 9).

In their analysis of the dichotomy between perception and cognition of object knowledge, Scholl and Leslie (1999) advocate a middle ground as neither polarized position is sufficient to account for observable phenomena. Three arguments have been raised against a purely perceptual account: (1) input to the perceptual system is inherently continuous and cannot individuate objects, (2) objects can be represented over considerable amounts of occlusion that cannot be accounted for by sensory decay, and (3) perceptual illusions reveal that the system is susceptible to conceptual hypotheses that tell the observer what to experience (Gregory, 1966). However, the weakness of a purely perceptual account of object knowledge does not necessitate abdication to the conceptual position.

In order to resolve these two views, Scholl and Leslie proposed a different account of infants' successful performance on object cognition tasks. They argued that the infants' object principles are best characterized as the operation of object-based attentional mechanisms. Drawing upon several models of object-based attention (e.g., Kahneman, Triesman, & Gibbs, 1992; Pylyshyn, 1994), Scholl and Leslie described how the principles of cohesion and continuity could emerge epiphenomenally from the actions of object

indexing mechanisms of the visual system. These object-based indexes are not considered to be either solely perceptual or conceptual entities but rather have properties from both representational perspectives. Object indexes, for example, have the capacity to survive occlusion, indicating that they are entities that can be represented and so are not transient perceptions. Nevertheless, although the operation of object indexes is constrained by features such as cohesion and spatiotemporal continuity, they do not embody these principles in any explicit or 'theory-like' way, as a rich conceptual account of infant cognition such as the CK hypothesis might suggest.

Object permanence and persistence: the current controversies and questions

Since the time of Piaget, developmental psychologists have gained much insight into how infants come to represent objects as permanent entities. Even today, however, researchers debate over the exact nature of the development of this capacity and the mechanisms that drive it. For example, although much empirical evidence suggests that infants can represent objects from an extremely young age, there is growing evidence that this capacity shows some improvement even in the first few months of life. Johnson and colleagues have observed that infants' capacity to represent objects as permanent, spatiotemporally continuous entities depends on low-level perceptual features and gradually improves early in the first year of life (see Amso & Johnson, Chapter 9). How this early improvement in object tracking translates into infants' object concept is a topic of much debate (see Amso & Johnson, Chapter 9). A second topic of much current work concerns the extent to which adult humans' object cognition also possesses some of the limitations present in infants' early processing. Mitroff and colleagues (Chapter 5) have explored the extent to which adults' object processing can be interrupted by the same limitations that prevent infants from tracking hidden objects. Finally, developmental research focusing on older infants and toddlers has demonstrated that early infants' object knowledge does not always translate into the knowledge that older infants use to act on the world. The issue of what such developmental dissociations in performance really reveal is a topic to which we will return in subsection 1.1.3.

1.1.2 Features to objects

As reviewed in the preceding, there is a growing body of work suggesting that even very young infants conceive of objects as permanent entities, ones that persist across occlusion with coherent boundaries and consistent motion constraints. How then do infants go from recognizing objects merely

as objects to recognizing them as individuals? After all, the infant's world is typically filled with numerous different bounded cohesive objects, and infants must quickly learn to deal with these different objects in different ways. How and when do infants go from thinking of the object feeding them as merely a 'coherent bounded entity' to an 'object with female, mother-looking properties' to 'my mother'?

A growing body of empirical work has come to address how infants come to track objects as particular individuals with particular features that are members of particular kinds. In going through this work, however, it is important to distinguish between the different component processes that infants must use to ultimately track different individual objects over time. Borrowing from Leslie et al. (1998), we here distinguish between *individuation*, the process of locating distinct individual objects that are in a scene, and *identification*, determining whether a previously individuated object is the same as has been seen previously. Note that individuation is a process that is required for *enumeration*, the process of determining how many individual objects are present.

There is much evidence to suggest that infants are able to individuate objects, namely track particular individuals over time and occlusion, from a very early age. Spelke and colleagues (1995) presented infants with events in which a bar moved behind two separate screens. When the bar appeared to move between the two screens, infants expected a single individual bar to be present in the test displays. In contrast, when the bar did not appear to move between the two screens, infants expected more than one individual to be present in the test displays, suggesting that discontinuous motion cues trigger the individuation of a new object. These results and others (e.g., Leslie et al., 1998; Needham, 1998, 1999; Needham & Baillargeon, 1997, 1998; Van de Walle et al., 2000; Needham et al., 2005; Wilcox, 1999; Wilcox & Baillargeon, 1998a,b; Xu & Carey, 1996) suggest that infants can successfully use spatiotemporal and other motion cues to individuate occluded objects. Moreover, infants are able to enumerate objects delineated by spatiotemporal cues so long as the number of objects to be enumerated is less than three or four individuals. (e.g., Feigenson, Dehaene, & Spelke, 2004; Simon et al., 1995; Wynn, 1992; Xu, 2003).

Property/Kind individuation and the role of language

Although the capacity to use spatiotemporal information to individuate objects comes on quite early, the capacity to use other relevant features, such as an object's properties or its kind, appears to develop quite late in infancy. In a landmark study, Xu and Carey (1996) presented infants with events in which a duck and a truck alternatively moved from behind an occluding screen. When the two objects were presented simultaneously, ten-month-old infants

successfully predicted that there should be exactly two objects behind the screen. In contrast, when the two objects were presented sequentially, such that the infants were no longer able to use spatiotemporal cues for individuation, ten-month-old infants were unable to individuate the objects, showing no expectation about the number of objects behind the screen. This study and a number of clever follow-ups (see Xu, 2003; Xu & Carey, 1996; Xu et al. 1999; Xu et al., 2004) indicate that infants undergo a major shift in their capacity to use a combination of property and kind information (hereafter, property/kind information) to individuate objects. Moreover, this shift seems to correspond to the time when infants are first learning the word for new objects (see review in Xu, in press). In one impressive demonstration, Xu et al. (2005) allowed twelve-month-olds to reach into a box to find hidden objects, but not to see the box's contents ahead of time. Before reaching into the box, infants heard an adult say either two different words or the same word twice after looking at the box's contents. Infants who heard two different words expected two distinct individual objects, whereas those who heard the single word repeated expected only one object (for similar findings, see Xu, in press).

For these reasons, Xu and colleagues have hypothesized that infants are able to individuate objects using property/kind information only after they have begun learning words for these objects. According to Xu (1999), language may play a critical role in 'reorganizing' infants' object concepts: rather than thinking about objects merely as bounded entities, linguistically saavy infants come to think of objects in terms of their kind. In support of this view, Xu et al. (2004) observed that twelve-month-old infants succeed in individuating objects using property/kind information when the kind of objects (and thus, their labels) differs, but not when their properties and not kind differ. Similarly, Xu (2002) observed that younger infants are able to succeed on the Xu and Carey (1996) property/kind individuation tests when they are trained with labels for the toys to be enumerated (see Xu, in press, for review).

Although Xu and colleagues have presented a compelling case for the role of language in human infants' kind individuation, work with nonlinguistic animals suggests that language, although important, is not necessary for property/kind individuation. Uller et al. (1997), for example, presented adult rhesus macaques with the original Xu and Carey (1996) property/kind individuation test and observed that they perform similar to older infants, successfully using a combination of property/kind information to individuate food objects placed behind a screen. Rhesus monkeys have exhibited similar successes in property/kind individuation when tested by using other looking methods (e.g., Munakata et al., 2001) as well as searching tasks (Phillips & Santos, 2007; Santos et al., 2002). These findings in primates demonstrate that language is

not necessary for property/kind individuation. In addition, they raise the question of how language in fact allows young infants to succeed on these tasks.

Object tracking and enumeration: evidence for developmental continuity?

Young infants' performance on different types of object individuation tasks leads to the view that spatiotemporal information is the primary means by which they locate individual objects in the world. Indeed, this view of infants' object individuation fits with a growing body of work in adult visual attention. Vision scientists working in the area of mid-level vision have devoted much empirical attention to the question of how and when the visual system is able to focus on and attentionally track a particular individual object. Interestingly, research in this area suggests that the visual system is limited in the same way as infants' object individuation capacities: it is bound to spatiotemporally distinct objects, and appears to ignore other featural information (e.g., Kahneman & Treisman, 1984; Kahneman et al., 1992; Scholl, 2001; Scholl & Pylyshyn, 1999; Yantis, 1995; see Cheries et al., Chapter 5, for review). In addition, similar to infants, adults appear to show deficits on visual tracking tasks in which objects do not cohere across time and space (van Marle & Scholl, 2003, see also Mitroff, Scholl, & Wynn, 2005). These similarities have led to the view that adult attentional mechanisms may underlie infants' performance on object individuation tasks (Carey & Xu, 2001; Chiang & Wynn, 2000; Leslie et al., 1998; Scholl, 2001; Scholl & Leslie, 1999; Simon, 1997; Wynn & Chiang, 1998).

Such a view has been bolstered by another similar limit on infant and adult object individuation: the fact that it is limited in number. Work using the multiple-object tracking (MOT) paradigm has demonstrated that adults are limited in the number of objects that they can simultaneously attend to at any one time (see Pylyshyn, 2001; Pylyshyn & Storm, 1988; Trick & Pylyshyn, 1994), with a limit of around four objects (see Intrilligator & Cavanagh, 2001). The numerical set-size limitation that plagues the adult attentional system appears to be mirrored in young infants' enumeration performance. A growing body of work suggests that young infants are limited in the number of occluded objects they can enumerate (see Feigenson et al., 2004, for review). Infants can successfully discriminate exact quantities of objects up to four individuals, but their performance falls to chance when the number of individuals exceeds four (e.g., Feigenson et al., 2004). This set-size limit also appears in adult nonhuman primate subjects, who can also enumerate exact quantities up to about four individuals (Hauser & Carey, 2003; Hauser et al. 1996; Hauser et al., 2000; Santos et al., 2005; Uller et al., 2001). Therefore, the set-size limit on exact

enumeration is a signature that seems to be continuous both across development and across phylogeny (Hauser & Spelke, 2004?; Spelke, 2000).

A question currently facing researchers, and one that will be discussed in detail in this volume, concerns what information infants have about the objects they have enumerated. A central assumption of researchers today is that enumerated objects are those that are currently being attended to (e.g., Scholl & Leslie, 1999; Xu & Carey, 2000). As several researchers will address in the chapters that follow (see Zosh & Feigenson, Chapter 2; Chen & Leslie, Chapter 4; Cheries et al., Chapter 5; Flombaum et al., Chapter 6), much present work is aimed at exploring the limits on infants' object representations. In particular, much of the research in this volume will examine how human infants, human adults, and nonhuman animals can and cannot use the representations that they have for individuated objects.

A further question concerns how infants' individuation and enumeration processes connect with the other mechanisms they possess for quantity estimation (see Zosh & Feigenson, Chapter 2; Jordan & Brannon, Chapter 3). Although infants cannot exactly enumerate large numbers of objects, much research suggests that infants are able to correctly approximate large numbers of individuals (see Feigenson et al., 2004; McKrinnck & Wynn, 2004; Xu, 2003; Xu & Spelke, 2000). Similarly, although some animals appear to have a set-size limit when enumerating small numbers of individuals exactly (Hauser et al., 2000), animals also possess a system for approximately estimating large numbers of objects (see Brannon & Terrace, 1998; Flombaum et al., 2006; Feigenson et al., 2004; Hauser et al., 2003). A central topic in comparative developmental psychology today is how these two systems interact, and how the limits of one system might affect processing in another system.

1.1.3 Objects as entities to be acted upon

As the computational motor theorist Daniel Wolpert has pointed out, metabolically hungry brains are only found in organisms that actually move around and negotiate their environments. Other, more stationary living things that do not need to move around do not develop nervous systems. Indeed, one organism, the sea cucumber, has a central nervous system during one phase of its life when it is seeking a suitable rock upon which to attach itself; having found the best place to settle, it proceeds to the second phase of its life and digests its own nervous system, no longer having any use for a function that requires metabolic resources.² Even in basic organisms, there seems to be a critical link

² The late Francis Crick used to liken this peculiar neuronal self-absorption to academics who finally achieve tenure and then settle into a period of nonproductivity.

between action and nervous tissue, or as a cognitive scientist might put it, between action and complex cognitive capacities.

How then is action connected with the capacity to represent and reason about objects? As reviewed earlier, Piaget famously argued that infants lack complex, constructed representations of the material world precisely because they are unable to act on objects (Piaget, 1955). But in emphasizing the need for competent action, Piaget curtailed the opportunity for infants to reveal object knowledge that was demonstrated in the looking time studies. Although the CK revolution that followed the use of these looking tasks rejected many of Piaget's claims about the role of experience, even the staunchest CK theorist would have to agree that one of the fundamental purposes of object representations is to support action. The mental machinery that evolves to represent objects is inevitably in the service of actions and behaviors that could benefit the survival of the individual. Nature does not select for a good idea alone (Hood, 2004). So, performance limitations may mask true representational capacity in the infant, but they are neither trivial nor irrelevant in terms of functionality. If infants have such consistent problems in retrieving hidden objects that are not due to a failure of object permanence, then there is arguably an equally important question as to why their search is so poor.

One attitude is to consider infants' failures in reaching measures as uninteresting performance errors. After all, there are a multitude of ways to fail on tasks but relatively much fewer ways to succeed (Leslie et al., 2005). But the flexibility to apply object knowledge across different tasks is as important as the capacity for representation. The world is not set up as a large habituation study and so the onus is on psychologists to explain both the success of looking and the failure of reaching. With this in mind, others have begun to look at the demands that each type of task bears upon the infant with a view to elucidating the nature of domain-general capacities that could operate across tasks. Diamond and colleagues (Diamond, 1991; Diamond & Gilbert, 1989; Diamond & Goldman-Rakic, 1989), for example, have championed the view that success in reaching for hidden objects requires both the working memory capacity to represent objects over time and the inhibitory control to overcome prepotent responses that disrupt search. This theory has been notably successful in the analysis of Piaget's famous A not B error described earlier, in which infants search at a previously correct location 'A' despite observing the hiding of the object at a new location 'B'. Such errors, however, are only characteristic of infants' reaching performance, not their looking behavior. Indeed, even Piaget noted that infants failing his A not B search task occasionally reached to the wrong location but looked at the correct B position, indicating that

infants' eyes were correctly oriented to the goal but the action retrieval system had failed. (see also, Hofstadler & Reznick, 1996; Ahmed & Ruffman, 1998).

Diamond and colleagues (e.g., Diamond, 1988) have hypothesized that young infants' poor inhibitory control selectively affects their reaching but not their eye movements in an object retrieval task (Diamond, 1988, 1989, 1990). To explore this possibility, she examined the role of the dorsal lateral prefrontal cortex (DLPFC)—an area involved both in holding representations of working memory and in inhibiting behavior. Notably, the DLPFC is an area that is still fairly underdeveloped at the age where infants typically fail A not B and other object retrieval tests (Huttenlocher, 1979). Diamond and colleagues presented monkeys with an object retrieval task that was a direct analogue of Piaget's A not B paradigm. Diamond and Goldman-Rakic (1989) demonstrated that the DLPFC is essential for updating the last seen position of a target object in a delayed response task where the animal had to remember in which of two wells an object had just been hidden. Mature monkeys with lesions in the DLPFC and young monkeys with immature DLPFC performed poorly in comparison with controls. The proposed role of the DLPFC in maintaining a representation of the last seen location of an object has been supported by human electrophysiological studies showing a relationship between the coherence of infant prefrontal neuronal activity and their ability to retrieve objects in search tasks (Bell & Fox, 1992). Likewise, increasing the delay between hiding the object at location B and allowing the infant to search comprises this coherent representation as such a manipulation can reinstate the A not B error in older children (Diamond, 1985).

Damage to the DLPFC also impairs inhibitory control, which as explained previously is a crucial capacity for successful object retrieval. For example, on nonmemory tasks such as detour reaching, individuals have to avoid a direct reach to a potent target object in a transparent box by detouring to the side opening of the container. Both animals with lesions in the DLPFC and young infants repeatedly reach directly at the target, failing to suppress this response in order to execute the correct detour reach. The sight of the goal is so potent that it elicits a direct reach even though the individual is thwarted repeatedly in the attempts. This suggests that in addition to maintaining an active representation of the new object location the DLPFC is also responsible for a corresponding inhibition of previously correct responses (Diamond, 1998).

Because they lack a full mature DLPFC, it seems plausible that infants might fail reaching tasks because of domain-general inhibitory control demands rather than problems with their knowledge of objects. Armed with this neural evidence, many developmental psychologists have dismissed infants' reaching failures as the result of the demands of domain-general tasks.

Unfortunately, however, infants' problems in searching tasks do not fully disappear in early infancy as one might expect. A growing body of work suggests that some of infants' reaching failures and search errors persist well into the first few years of life (Berthier et al., 2000; Butler et al., 2002; Hood, 1994; Hood et al., 2000; Hood et al., 2003).

Hood and colleagues (1994, 2000) purposefully designed a search analogue of one of the CK sequences that had been used to demonstrate the solidity principle in infants (Spelke et al., 1992) and showed that search is random at 2 years of age. In this task, children had to search correctly for an object dropped onto a shelf and not underneath it. A similar solidity principle was addressed in a horizontal version where children had to understand that an object could not pass through a solid wall. Berthier and colleagues (2000) found that toddlers fail to use solidity information even at three years of age, a finding replicated in other laboratories (Hood et al., 2003). However, knowledge based on looking is still evidenced in toddlers on these tasks (Hood et al., 2003); so, the underlying core solidity principle is present but does not constrain correct search. Why do infants look so smart and toddlers look so dumb on these object retrieval tasks (Keen, 2003)?

There are a number of plausible alternatives that warrant further investigation. One class of explanations appeals to weak representations of the occluded object and/or wall (Munakata, 2001). The interpretation is that although a weak representation can produce sufficient output for a looking measure, a stronger representation is required to support search behavior (Morton & Munakata, 2002; Munakata et al., 1997). Similarly, but with a neurological flavour, one intriguing hypothesis argues that various dissociations can be understood in light of the functional distinction that is believed to exist between object recognition in the ventral processing stream ('what') as opposed to the dorsal action system ('how') of the cortex (Milner & Goodale, 1995). Objects that are graspable activate the dorsal stream whereas stationary large objects activate the ventral stream (Kaufman et al., 2003; see Mareschal & Bremner, Chapter 10), producing dissociation between looking and reaching.

Another explanation also endorses a representational interpretation but focuses on the spatial layout of unseen critical components of the tasks. In the case of search involving shelves and walls, the children know that walls, shelves, and objects continue to exist behind the occluders but are uncertain as to the spatial relationship between them (Keen & Berthier, 2005;). Another recent interpretation motivated by models of developing executive function argues that all search tasks present children with a multitude of competing demands and that these are most problematic when the correct response involves coordinating actions (see Gjerseoe & Hood, Chapter 13). In this

approach, success could reflect the ability to reject or inhibit all other potentially competing responses in favour of the one that is required to retrieve the object.

Curiously, human infants are not the only organisms to show search errors late into life. Hauser, Santos and colleagues have demonstrated that a number of different nonhuman primates perform poorly on search tasks involving object motion even as adults. For example, adult rhesus monkeys search incorrectly for objects that are dropped onto a stage (Hauser, 2001), despite the fact that they look longer at such violations (Santos & Hauser, 2002). Similarly, adult cotton-top tamarins look longer at objects that appear to roll through a solid barrier, but search incorrectly when asked to look for the same object (Santos et al., 2006). Importantly, to date, adult primates' failures on search tasks appear to exactly mirror the cases in which human toddlers perform poorly (see Santos, 2004, for review). The fact that these are found in adult animals and not in adult humans begs the question as to whether the development observed over human childhood reflects an evolutionarily significant departure between the species. A tantalizing prospect is that there was a leap that made some forms of object representation and not others available to drive the action system selectively in humans but not other primates.

1.2 Objects in cognitive science

Clearly, we have come a long way over the past 30 years in our understanding of the development of object knowledge. What was once pondered from the comfort of the philosopher's armchair is now under investigation in laboratories around the world. Rather than settling the issues surrounding the origins of object knowledge, the discoveries of extremely early object representation in infants have spurred many more researchers on to try and understand how such competencies emerge and how they come to support and underpin later abilities in a variety of species.

Piaget's seminal account of infant object knowledge may no longer be true in terms of how object representation comes about, but his focus on knowledge-based action still remains a theoretically legitimate concern. As we have come to appreciate the fractionation of object knowledge in the developing mind, we have arrived at a better understanding of the underlying architecture of the mature mind. Cognitive scientists who previously focused on object representation in the human adult have come to recognize that developmental findings combined with a comparative perspective can contribute to a richer explanation. Ultimately, a more comprehensive understanding of any complex biological system that has evolved will need to reconcile the

evidence from developmental and comparative perspectives. Object representation is arguably uniquely positioned in this respect as it is essential to most species, which explains why the issues have been successfully pursued from a diverse range of populations, methodologies, and perspectives summarized in this book.

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