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Core knowledge

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Abstract

Human cognition is founded, in part, on four systems for representing objects, actions, number, and space. It may be based, as well, on a fifth system for representing social partners. Each system has deep roots in human phylogeny and ontogeny, and it guides and shapes the mental lives of adults. Converging research on human infants, non-human primates, children and adults in diverse cultures can aid both understanding of these systems and attempts to overcome their limits.

Introduction

Cognitive science has been dominated by two views of human nature. On one view, the human mind is a flexible and adaptable mechanism for discovering regularities in experience: a single learning system that copes with all the diversity of life. On the competing view, the human mind is a collection of special-purpose mechanisms, each shaped by evolution to perform a particular function. The first view traces back to Enlightenment thinkers such as Locke (1689) and Hume (1748) and has been invigorated more recently by cognitive psychologists and neural network theorists (e.g. Rumelhart & McClelland, 1985; Hinton, 1993). The second view was inspired by Darwin (1871) and gained prominence with the rise of evolutionary psychology (e.g. Cosmides & Tooby, 1994; Pinker, 2002). Much public discussion has focused on the diverging ways in which these views explain human behavior. Does a given ethnic group excel in mathematics because its members have studied more diligently, or because they have inherited greater talent? Do some adolescents join violent gangs because they learned aggressive behavior from their communities, or because they inherited a predisposition toward intergroup competition? Behind these specific questions lies a more general concern: To what degree can we human beings determine our fates and choose our futures? With enough cognitive work, can any person develop her mathematical talents and control her aggression?

Developmental science was born from these concerns, and its research bears on these questions. We believe its research has shown that both these views are false: humans are endowed neither with a single, general-purpose learning system nor with myriad special-purpose systems and predispositions. Instead, we believe that humans are endowed with a small number of separable systems of core knowledge. New, flexible skills and belief systems build on these core foundations.

Studies of human infants and non-human animals, focused on the ontogenetic and phylogenetic origins of knowledge, provide evidence for four core knowledge systems (Spelke, 2004). These systems serve to represent inanimate objects and their mechanical interactions, agents and their goal-directed actions, sets and their numerical relationships of ordering, addition and subtraction, and places in the spatial layout and their geometric relationships. Each system centers on a set of principles that serves to individuate the entities in its domain and to support inferences about the entities' behavior. Each system, moreover, is characterized by a set of signature limits that allow investigators to identify the system across tasks, ages, species, and human cultures.

The core system of object representation has been studied most extensively. It centers on the spatio-temporal principles of cohesion (objects move as connected and bounded wholes), continuity (objects move on connected, unobstructed paths), and contact (objects do not interact at a distance) (Aguiar & Baillargeon, 1999; Leslie & Keeble, 1987; Spelke, 1990). These principles allow human infants as well as other animals to perceive object boundaries, to represent the complete shapes of objects that move partly or fully out of view, and to predict when objects will move and where they will come to rest. Some of these abilities are observed in the absence of any visual experience, in newborn human infants or newly hatched chicks (Valenza, Leo, Gava & Simion, in press; Regolin & Vallortigara, 1995; Lea, Slater & Ryan, 1996). Even infants with months of visual experience do not, however,

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have more specific cognitive systems for representing and reasoning about ecologically significant subcategories of inanimate objects such as foods or artifacts (Shutts, 2006), or systems for reasoning about inanimate, non-object entities such as sand piles or liquids (Huntley-Fenner, Carey & Solimando, 2002; Rosenberg & Carey, 2006; Shutts, 2006). Moreover, infants are able to represent only a small number of objects at a time (about three; Feigenson & Carey, 2003). These findings provide evidence that a single system, with signature limits, underlies infants' reasoning about the inanimate world.

By focusing on these signature limits, investigators of animal cognition have discovered the same core system of object representation in adult non-human primates (Hauser & Carey, 2003; Santos, 2004). Like human infants, monkeys' object representations obey the continuity and contact constraints (Santos, 2004) and show a set size limit (of four; Hauser & Carey, 2003). Investigators of cognitive processes in human adults have discovered that the same system governs adults' processes of object-directed attention (see Scholl, 2001, for discussion). Human adults are able to attend to three or four separately moving objects, for example, when the objects' boundaries and motions accord with the cohesion and continuity constraints. Adults fail to track entities beyond this set size limit, and they fail to track entities that do not obey the spatiotemporal constraints on objects (Scholl & Pylyshyn, 1999; vanMarle & Scholl, 2003; Scholl, Pylyshyn & Feldman, 2001; Marino & Scholl, 2005). Of course, adults also have developed knowledge of more narrow domains of objects such as foods and tools (Keil, Smith, Simons & Levin, 1998; Lavin & Hall, 2001; Santos, Hauser & Spelke, 2001). When attentional resources are stretched, however, the properties that mark these finer distinctions often fail to guide object representations, whereas core properties continue to do so (Leslie, Xu, Tremoulet & Scholl, 1998).

If the core system of object representation is constant over human development, then one would expect that system to be universal. Recent studies of the Piraha, a remote Amazonian group, support that suggestion. The Piraha have been reported to differ dramatically from most other contemporary human groups in their language, culture, and cognitive abilities. For example, their language has been said to lack number words beyond 'two' or resources to distinguish past from present, and it may lack basic syntactic devices of recursion and quantification (Everett, 2005). Nevertheless, the Piraha distinguish objects from non-object entities (Everett, 2005), and they track objects with the signature set-size limit (Gordon, 2004).

A second core system represents agents and their actions. Spatio-temporal principles do not govern infants' representations of agents, who need not be cohesive (Vishton, Stulac & Calhoun, 1998), continuous in their paths of motion (Kuhlmeier, Bloom & Wynn, 2004), or subject to contact in their interactions with other agents (Spelke, Phillips & Woodward, 1995). Instead, the intentional actions of agents are directed to goals (Woodward, 1999), and agents achieve their goals through means that are efficient (Gergely & Csibra, 2003). Agents also interact contingently (Johnson, Booth & O'Hearn, 2001; Watson, 1972) and reciprocally (Meltzoff & Moore, 1977). Agents do not need to have perceptible faces (Johnson, Slaughter & Carey 1998; Gergely & Csibra, 2003). When they do, however, infants use their direction of gaze to interpret their social and non-social actions (Hood, Willen & Driver, 1998; Johnson *et al.*, 1998), even as newborns (Farroni, Massaccesi, Pividori & Johnson, 2004). In contrast, infants do not interpret the motions of inanimate objects as goal-directed (Woodward, 1998), and they do not attempt to mirror such actions (Meltzoff, 1995).

Goal-directedness, efficiency, contingency, reciprocity, and gaze direction provide signatures of agent representations that allow for their study in non-human animals and in human adults. Newly hatched chicks, rhesus monkeys, and chimpanzees are sensitive to what their predators or competitors can and cannot see (Agrillo, Regolin & Vallortigara, 2004; Flombaum & Santos, 2005; Hare, Call & Tomasello, 2001). These studies accord well with the physiological signatures of 'mirror neurons', observed in captive monkeys, which selectively respond to specific actions performed by the self and others (see Rizzolatti, Fogassi & Gallese, 2002, for a review). Mirroring behavior and neural activity occurs in human adults as well (Iacoboni, Woods, Brass, Bekkering, Mazziotta & Rizzolatti, 1999), and representations of goal-directed action guide adults' intuitive moral reasoning (Cushman, Young & Hauser, in press). Together, these findings provide evidence for a core system of agent representation that is evolutionarily ancient and that persists over human development.

The core number system is structured around principles that contrast with both the object and the agent systems, and it shows its own distinctive signature limits. Three competing sets of principles have been proposed to characterize this system (Dehaene & Changeux, 1993; Meck & Church, 1983; Church & Broadbent, 1990). Because each of these proposals accounts for the primary properties of numerical representations, their relative merits continue to be debated (see Izard & Dehaene, 2006; Gallistel & Gelman, 1992). There is broad agreement, however, on three central properties of core number representations. First, number representations are imprecise, and their imprecision grows linearly with increasing cardinal value. Under a broad range of background assumptions, Izard (2006) has shown that this 'scalar variability' produces a ratio limit to the discriminability of sets with different cardinal values. Second, number representations are abstract: they apply to diverse entities encountered through multiple sensory modalities, including arrays of objects, sequences of sounds, and perceived or produced sequences of actions. Third, number representations can be compared and combined by operations of addition and subtraction.

Number representations with these properties have now been found in human infants, children, and adults, and in adult non-human primates. Infants discriminate between large numbers of objects, actions, and sounds when continuous quantities are controlled, and their discrimination shows a ratio limit (Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005; Wood & Spelke, 2005; Lipton & Spelke, 2003, 2004; Brannon, Abbott & Lutz, 2004). Infants also can add and subtract large numbers of objects (McCrink & Wynn, 2004). Adult monkeys and humans discriminate between large numbers of sounds, with a ratio limit (Hauser, Tsao, Garcia & Spelke, 2003; Barth, Kanwisher & Spelke, 2003), and they add and subtract large numbers as well (Flombaum, Junge & Hauser, 2005). In adults and children, cross-modal numerical comparisons are as accurate as comparisons within a single modality (Barth *et al.*, 2003; Barth, La Mont, Lipton & Spelke, 2005). The precision of numerical representations increases with development, from a ratio of 2.0 in 6-month-old infants to a ratio of 1.15–1.3 in human adults, depending on the task (van Oeffelin & Vos, 1982; Izard, 2006).

Because core representations of number are present throughout development, they should also be present in all cultures, independently of formal education in mathematics. Studies of the Munduruku, a second remote Amazonian group with no verbal counting routine, no words for exact numbers beyond 'three', and little formal instruction, support this prediction. The Munduruku discriminate between large numbers with a ratio limit on precision, as accurately as do educated adults in France (Pica, Lemer, Izard & Dehaene, 2004). Further, both Munduruku adults and US preschool children who have received no instruction in mathematics can perform approximate addition and subtraction on large approximate numerosities: they can add two successively presented arrays of objects and explicitly judge whether their sum is more or less numerous than that of a third array of objects (Pica *et al.*, 2004; Barth, LaMont, Lipton, Dehaene, Kanwisher & Spelke, 2006) or sequence of sounds (Barth *et al.*, 2005).

The last system of core knowledge captures the geometry of the environment: the distance, angle, and sense relations among extended surfaces in the surrounding layout. This system fails to represent non-geometric properties of the layout such as surface color or odor, and it fails under some conditions to capture geometric properties of movable objects. When young children or non-human animals are disoriented, they reorient themselves in accord with layout geometry (Hermer & Spelke, 1996; Cheng, 1986; see Cheng & Newcombe, 2005, for review). Children fail, in contrast, to orient themselves in accord with the geometry of an array of objects (Gouteux & Spelke, 2001), and they fail to use the geometry of an array to locate an object when they are oriented and the array moves (Lourenco, Huttenlocher & Vasilyeva, 2005). Under some circumstances, children and animals who are disoriented fail to locate objects in relation to distinctive landmark objects and surfaces, such as a colored wall (Margules & Gallistel, 1988; Wang, Hermer & Spelke, 1999; Lee, Shusterman & Spelke, in press). When disoriented children and animals do use landmarks, their search appears to depend on two distinct processes: a reorientation process that is sensitive only to geometry and an associative process that links local regions of the layout to specific objects (Cheng, 1986; Lee *et al.*, in press).

Human adults show much more extensive use of landmarks, but they too rely primarily on surface geometry when they are disoriented under conditions of verbal or spatial interference (Hermer-Vazquez, Spelke & Katsnelson, 1999; Newcombe, 2005). Recent studies of the Munduruku suggest that sensitivity to geometry is universal, and that it allows children and adults with little or no formal education to extract and use geometric information in pictures as well as in extended surface layouts (Dehaene, Izard, Pica & Spelke, 2006).

In summary, research on non-human animals and on human infants, children, and adults in diverse cultures casts doubt on both of the dominant views of human nature. This research suggests that the human mind is not a single, general-purpose device that adapts itself to whatever structures and challenges the environment affords. Humans learn some things readily, and others with greater difficulty, by exercising more specific cognitive systems with signature properties and limits. The human mind also does not appear to be a 'massively modular' collection of hundreds or thousands of special-purpose cognitive devices (Fodor, 2000). Rather, the mind appears to be built on a small number of core systems, including the four systems just described.

Are there other core knowledge systems, with roots in our evolutionary past, that emerge in infancy and serve as foundations for learning and reasoning by children and adults? Recently, we have begun to investigate a fifth candidate system, for identifying and reasoning about potential social partners and social group members.

The social interactions of humans with other humans are a salient feature of every human community, whose adult members show cooperation, reciprocity, and group cohesion. Research in evolutionary psychology suggests that people are predisposed to form and attend to coalitions (Cosmides & Tooby, 2003). A rich and longstanding literature in social psychology confirms this predisposition to categorize oneself and other humans into groups. Any minimal grouping, based on race, ethnicity, nationality, religion, or arbitrary assignment, tends to produce a preference for the in-group, or *us*, over the out-group, or *them*. This preference is shown by adults and children alike, who show parallel biases toward and against individuals based on their race (e.g. Baron & Banaji, 2006).

Studies of infants suggest that these tendencies emerge early in development. Three-month-old infants show a visual preference for members of their own race compared to members of a different race (Kelly, Quinn, Slater, Lee, Gibson, Smith, Liezhong & Pascalis, 2005; Bar-Haim, Ziv, Lamy & Hodes, 2006). This preference is influenced by infants' experience, for it depends both on the race of the infant's family members and the predominance of that race in the larger community. Israeli infants from Caucasian families prefer to look at Caucasian over African faces, Ethiopian infants from African families prefer to look at African over Caucasian faces, and Israeli infants from African families, living in a predominantly Caucasian culture, show no consistent face preferences (Bar-Haim *et al.*, 2006). Infants also look preferentially at faces of the same gender as their primary caregiver (Quinn, Yahr, Kuhn, Slater & Pascalis, 2002).

Race and gender may not be the most powerful or reliable cues to social group membership, however. In the environments in which human social groups evolved, contact with perceptibly different races rarely would have occurred (Cosmides & Tooby, 2003), and all human communities would have contained people of both genders. A better source of information for group membership might come from the language that people speak, and especially from the accent with which they speak it.

Until recently in human history, languages varied markedly across human groups, even groups living in quite close proximity (e.g. Braudel, 1988). From birth, moreover, infants show a preference for the sound of their native language over a foreign language (Mehler, Jusczyk, Lambertz & Halsted, 1988; Moon, Cooper & Fifer, 1993). We have asked, therefore, whether infants use language to categorize unfamiliar people, and whether they prefer people who speak their native language.

In one series of studies (Kinzler & Spelke, 2005), 6-month-old infants were presented with films of the faces of two women who were bilingual speakers of English and Spanish. After the women spoke to the infants in alternation, one in English and the other in Spanish, the two women were presented side by side, smiling without speaking. Although each woman had spoken Spanish to half the infants and English to the others, infants tended to look longer at the woman who had spoken to them in English, their native language.

Further studies revealed that this preference extends to older ages and guides behaviors that are more directly social. For example, 12-month-old infants in Boston were presented with a native speaker of English and a native speaker of French who spoke to them in alternation, while eating two different foods. When later given a choice between the two foods, infants reached preferentially for the snack offered by the English speaker (McKee, 2006).

These findings suggest that the sound of the native language provides powerful information for social group membership in infancy. Together with the studies of infants' sensitivity to race, they raise the possibility that a fifth core knowledge system, distinguishing potential members of one's own social group from members of other groups, may guide infants' and children's learning about the social world.

Core systems for representing objects, actions, numbers, places, and social partners may provide some of the foundations for uniquely human cognitive achievements, including the acquisition of language and other symbol systems, the development of cognitive skills through formal instruction, and the emergence and growth of cooperative social networks. Because learning of words and expressions depends on one's pre-existing concepts, core concepts figure importantly in children's word learning (see Bloom, 2000). Similarly, recent research suggests that core geometric representations guide developing understanding of maps, even in remote cultures with no formal instruction (Dehaene *et al.*, 2006). Core representations of number support preschool children's mastery of counting (Wynn, 1990; Carey, 2001; Spelke, 2003) and older children's and adults' learning and performance of symbolic arithmetic (Dehaene, 1997; Feigenson, Dehaene & Spelke, 2004). Finally, a core system for representing potential social partners may guide infants' and children's 'cultural learning' (Tomasello, 1999): their acquisition of skills and behaviors that sustain life within a particular human group. In all these cases, core knowledge systems may support and advance human cognitive development, because the principles on which they are based are veridical and adaptive at the scales at which humans and other animals perceive and act on the world.

Nevertheless, core systems of representation also can lead humans into cognitive errors and maladaptive actions. At the smallest and largest scales that science can probe, objects are not cohesive or continuous, and space is not Euclidean or three-dimensional. Mathematicians have discovered numbers beyond the reach of the core domains, and astute social observers find many cases where human intentions depart, either deliberately or inadvertently, from their overt, goal-directed actions. The gaps and inaccuracies in core representations cause problems for adults and children alike, who are prone to errors in reasoning about properties of object mechanics, non-Euclidean geometry, or numbers that violate the principles of core knowledge (e.g. McCloskey, 1983; Randall, 2005; Gelman, 1991).

The most serious errors may spring from the system for identifying and reasoning about the members of one's own social group. A predisposition for dividing the social world into *us* vs. *them* may have evolved for the adaptive purpose of detecting safe and trustworthy social partners, but it can be misemployed in modern, interconnected and multicultural societies. It even may support the ravages of discord, violence and warfare among individuals, groups and nations. For example, we need not look far to discover linguistic differences leading to social conflicts and intolerance. In US history, the tongues of slaves who spoke no English were severed, Russian speakers were executed following the Alaskan purchase, and the speaking of German in public was forbidden during World War II (Shell, 2001). A look abroad provides innumerable examples of warfare waged across linguistic lines.

Despite these examples, we believe that the strongest message, from human history and developmental science alike, is positive. Although core conceptions are resilient, they can be overcome. The history of science and mathematics provides numerous examples of fundamental conceptual changes that occurred as thinkers became aware of the mismatches between the principles governing their reasoning and the world of phenomena they sought to understand. Despite the pull of core conceptions of Euclidean geometry and object mechanics, cosmologists and particle physicists can test whether space is non-Euclidean and has higher dimensions (e.g. Randall, 2005) and they can use conceptions of massless, discontinuously moving particles to make predictions of astonishing precision (Hawking, 2002). Conceptual change, moreover, is not the exclusive province of academic science. Preschool children change their conceptions of numbers when they learn to count (Spelke, 2000), and they change their conceptions of agents when they learn about biological processes like eating and breathing (Carey, 1985, 2001).

If core conceptions of social partners lead to errors and harmful conflicts, they too should be open to change, because understanding of human cognitive development yields insight into its malleability. For example, 3-month-old infants' preference for own-race faces is moderated by exposure to other-race faces (Bar-Haim *et al.*, 2006), and biased attitudes toward members of other groups are moderated by certain types of inter-group contact (Pettigrew & Tropp, 2006). Thus, even the deepest-rooted biases are not set in stone. As warring groups in contemporary societies gain ever-greater means for mutual destruction, studies of the conditions that fuel or moderate the development of intergroup bias could be of great importance.

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